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Vascular and Interventional Radiology *Pictorial Essay*

Imaging of penetrating vascular trauma of the body and extremities secondary to ballistic and stab wounds

Dheeraj Reddy Gopireddy[1], Joanna W. Kee-Sampson[1], Sai Swarupa Reddy Vulasala[2], Rachel Stein[1], Sindhu Kumar[1], Mayur Virarkar[1]

[1]Department of Radiology, UF College of Medicine-Jacksonville, Jacksonville, Florida, [2]Department of Internal Medicine, East Carolina University Health Medical Center, Greenville, North Carolina, United States.

***Corresponding author:**
Sai Swarupa Reddy Vulasala, Department of Internal Medicine, East Carolina University Health Medical Center, Greenville, United States.

vulasalaswarupa@gmail.com

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ABSTRACT

In the United States, gunshot wounds (GSWs) have become a critical public health concern with substantial annual morbidity, disability, and mortality. Vascular injuries associated with GSW may pose a clinical challenge to the physicians in the emergency department. Patients demonstrating hard signs require immediate intervention, whereas patients with soft signs can undergo further diagnostic testing for better injury delineation. Although digital subtraction angiography is the gold standard modality to assess vascular injuries, non-invasive techniques such as Doppler ultrasound, computed tomography angiography, and magnetic resonance angiography have evolved as appropriate alternatives. This article discusses penetrating bodily vascular injuries, specifically ballistic and stab wounds, and the corresponding radiological presentations.

Keywords: Vascular trauma, Imaging, Emergency imaging, Body trauma, Extremity trauma

INTRODUCTION

Trauma is the most critical cause of morbidity and mortality in the United States, with around 100,000 deaths reported yearly.[1] While blunt injuries account for 70% of trauma encounters, penetrating injuries cannot be ignored, given their more direct and potentially severe insult to vascular structures.[1] Penetrating injuries include ballistic, non-ballistic, and impalement wounds. Gunshot wounds (GSWs) are the second most common cause of trauma-related deaths.[2-4] In the United States, they have become the most critical public health concern, with substantial annual morbidity, disability, and mortality.[5] Since 2013, there have been 182,000 fatal and 500,000 non-fatal trauma due to firearms.[1] Firearms constitute 60% of homicides in the United States commonly observed among young adults, while suicides are more common in older age groups.[6] This article discusses penetrating bodily vascular injuries, specifically ballistic and stab wounds, and the corresponding radiological presentations.

MECHANISM OF PENETRATING VASCULAR TRAUMA

Discussing the physics behind penetrating vascular trauma to evaluate injury patterns is imperative. The kinetic energy of any moving object is proportional to its mass and velocity. Based on this principle, weapons can have low, medium, or high kinetic energy. As the weapon's kinetic energy enhances, the extent and severity of damage increase. Target tissue injury can be described as (i) a "Tunnel of attrition:" Tissue laceration along the passage of the trajectory and (ii) a "Temporary zone of cavitation:" Tissue contusion due to radial energy transfer perpendicular to the trajectory.[7] The latter explains the tissue damage that is not directly in the path of the trajectory. In the case of high-speed weapons, the cavitation zone can be 25 times the projectile caliber.[8] In addition to velocity, the cavitation depends on the properties of the medium crossed (solid vs. hollow) and the weapon (type, surface area, and stability). For instance, hollow or elastic organs such as lungs readily absorb bullets' energy. Compared to solid and less elastic organs, where the cavitation is extensive, hollow organs are relatively tolerant. Based on the suspected trajectory course, the likely-injured structures and the management can be determined.[9-11]

DIAGNOSTIC APPROACH TO PENETRATING VASCULAR INJURIES

Many vascular injuries are clinically evident and dramatic; however, a few cases may require cautious integration of clinical and imaging findings to determine the treatment modality. During the analysis of vascular injury, it is crucial to inspect for hard and soft signs [Table 1]. In general, patients demonstrating hard signs require immediate intervention, whereas patients with soft signs can undergo further diagnostic testing for better injury delineation. Only 10% of injuries manifest with hard signs; the rest of the injuries can demonstrate soft signs, be asymptomatic, or have a delayed presentation.[11] Hence, high index of suspicion is essential when managing a patient with an increased likelihood of vascular injuries in the emergency department. Integration of artificial intelligence aids in improving the efficiency of emergency and trauma radiologists through image processing and decision support. Nevertheless, it is still being studied for its utility and generalization across trauma centers. The AI implementation faces several barriers, including cost, stakeholder buy-in, and technology education requirements. Elaboration on the role of AI is beyond the scope of this article. Although digital subtraction angiography (DSA) is the gold standard modality to assess vascular injuries, non-invasive techniques such as Doppler ultrasound (US), computed tomography angiography (CTA), and magnetic resonance angiography (MRA) have evolved as appropriate alternatives. In addition, DSA is only readily available at some institutions and requires sedation. CTA has primarily replaced DSA and catheter angiography and has superior spatial and temporal resolution with high accuracy and widespread access.[12]

US

US is a promptly available and non-invasive tool in emergency department. Its versatility in the emergency settings aids in assessing vascular injuries, allowing its application in triage. However, the operator dependency, retained metallic fragments, air from the injury, and hematoma limit the evaluation of damaged vessels on US. The multiple echoes generated from the highly reflective structures, such as metal and air pockets, result in reverberation artifacts manifests as multiple equidistant parallel lines with decreasing amplitude at a progressive depth. Such artifacts can be reduced by reducing the distance between the transducer and reflective structure or modulating the transducer angle of incidence. Color flow Doppler (CFD) US is a reliable vascular imaging modality with a sensitivity, specificity, and accuracy of 95–97%, 95–98%, and 98%, respectively.[12]

CT and CTA

CT is the primary imaging technique for individuals with significant trauma. It provides a better spatial resolution with faster acquisition and shorter reconstruction times which are crucial in receiving definitive care in the "Golden Hour." Golden Hour emphasizes timely trauma patient management for optimal survival and improved outcomes.[13] Vascular integrity can be easily assessed through multiphasic CT imaging studies (arterial, venous, and delayed excretory phases) acquired quickly. CTA is the primary choice of imaging modality in detecting life-threatening vessel injuries. [97-101] It provides axial, 3-D, and multiplanar datasets for the superior and accurate characterization of vascular injuries. CTA is a rapid and inexpensive and non-invasive modality. CT and CTA delineate the path of the wound, thereby determining the damaged organs.[14] With 100% sensitivity, CTA assists in revealing the injuries and localizing the source of bleeding through direct and indirect signs, as described in further sections of this article [Table 2].[14-16]

Table 1: Hard and soft signs of arterial injury.

Hard signs of arterial injury	Soft signs of arterial injury
Severe uncontrolled external arterial bleeding	History of extensive bleeding on scene
Rapidly expanding or pulsatile hematoma	Proximity of trauma to major vessel
Palpable thrill	Subjective diminished pulse
Audible bruit	Small non-pulsatile and stable hematoma
6 P's (pain, pulse, pallor, paralysis, paresthesia, and poikilothermia)	Injury to the anatomically related nerve
Neurologic deficit	Abnormal ankle-brachial index (<0.9)
Refractory hypotension	Abnormal flow velocity waveform on Doppler ultrasound
	Delayed capillary refill

Table 2: Review of studies on the efficacy of computed tomography angiography in the various regions of interests.

	Sensitivity (%)	Specificity (%)
Extremities[97]	95	87
Abdomen and pelvis[98]	80–97	95
Pelvis[99]	90	98.6
Proximal extremities[31]	95	98
Chest[100]	100	81.7
Lower extremities[101]	100	100

CT and CTA protocols in whole-body trauma

Conventional protocol of whole-body trauma consists of three phases: (i) Non-contrast cranial CT, (ii) CTA of the head and neck with an initial contrast bolus, and (iii) scan of the body from the upper thorax to the groin region with a second-contrast bolus. If the patient is suspected of having an extremity injury, the third phase scan can be extended to involve the caudal body part such as the thigh, knee, leg, ankle, or foot. Recently, the conventional protocol has been replaced by the revised protocol given radiation dose and scan duration. Compared to the conventional, the modified protocol has reduced radiation dose (22.9 mSv vs. 15.0 mSv) as well as scan duration (7 min vs. 4 min).[13] The revised protocol consists of two phases: (i) Cranial CT without contrast and (ii) head, neck, trunk, and extremity scan after the split bolus contrast injection. There shall be a delay of 90s between the two contrast boluses injection to permit the better evaluation of arterial and venous phases. Multiple things are needed to be considered in evaluating vascular injuries. These include injection site, saline bolus, location of great vessels, cardiac output, time to peak enhancement, imaging duration, and imaging coverage.[17]

Three imaging acquisition methods are currently being used: (i) Fixed time-delay technique, (ii) test bolus, and (iii) bolus tracking. Among the three techniques, bolus tracking is the most commonly used method. Before the bolus injection, the region of interest is placed over the artery that is being studied, and the attenuation is monitored. The image acquisition is triggered immediately when the attenuation reaches desired levels. For optimal identification of subtle signs of vascular injury, images must be captured at the peak of enhancement. The peak can be identified by performing a low-dose monitoring scan at 5 s and every 1–3 s after that until the enhancement in the region of interest reaches the specified HU (usually 150 HU). In addition, the triphasic injection protocol can achieve the superior arterial and venous enhancement of the abdominal vasculature and near-arterial enhancement of the chest vasculature with a predetermined time lag between the contrast administrations. A delay of 18 s and 13 s was recommended in the studies by Yaniv *et al*. and Atluri *et al*.[18,19]

Image reconstruction and post-processing techniques

Multiplanar reformatting is an imaging reconstruction technique that usually includes axial, sagittal, and coronal images. A sagittal oblique image can be obtained in the circumstances of the aortic injury to examine the longitudinal view of the aorta. The post-processing techniques involve maximum intensity projection (MIP), bone subtraction angiography, and volume rendering. MIP is routinely used among the three techniques as it is superior in visualizing the highly attenuated and small branch arteries. MIP uses only the high attenuation data voxel and selects and combines the multiple thin images. At the same time, the volume rendering technique creates a 3D image of the desired structure which can be manipulated for accurate evaluation. Bone subtraction angiography utilizes non-contrast data sets to separate the bone from the contrast data sets leaving behind the soft tissues and arteries.

Disadvantages of CTA are comparative to standard CT and include beam-hardening artifacts, usually from the shoulder, dental fillings, and retained bullet fragments, which can hinder the visualization of vessels. In addition, failed injection or inaccurate timing of the contrast may result in weak opacification of vessels. Radiation exposure is another factor that requires consideration during imaging in a polytrauma patient. Studies show that a single-pass (continuous whole-body image acquisition) scan instead of a segmental (individual body segment scan with overlap zones) scan helps in reducing radiation exposure.[18] This is because three scans are required in the conventional segmental protocol, while only two are necessary for the single-pass protocol. MRA has been proposed as an alternative to CTA; however, if the patient has retained metallic fragments, they are prohibited from entering the MRI suite safely.[14,20-22] In addition, MRA takes longer to obtain appropriate sequences and is not readily available in all emergency departments.

DSA is the preferred imaging technique in patients with retained metallic fragments, in whom CT is unsatisfactory. It also can perform therapeutic procedures for injuries such as arteriovenous (AV) fistula or pseudoaneurysm (PSA). CTA demonstrating focal arterial narrowing may require further imaging with DSA to differentiate occlusion and dissection from vasospasm. CTA is superior to DSA, given its faster acquisition times and ability to integrate extremity CTA in torso imaging with a single-contrast injection.[22]

MULTIMODALITY IMAGING SIGNS OF VASCULAR INJURY

Patients with vascular injuries can be categorized into four grades through imaging findings: (i) Intimal tear, (ii) intramural hematoma, (iii) PSA, (iv) rupture, and (v) arterio-venous fistula [Table 3].[23] An intimal flap is due

Table 3: Imaging signs of vascular injury.

Sign	US	CT
Intimal flap	Thin echogenic structures floating within the vessel lumen; May cause turbulence or irregular flow on CFD; thrombosis is seen as an echogenic material on B-mode US and have absent flow on PWD and CFD.	Hypoattenuating linear or curvilinear defect arising from the vessel wall into the contrast-enhanced lumen.
Dissection	Hyperechoic mobile intimal flap, dividing the vessel into true and false lumens, can be seen on US. True lumen expands during systolic and compresses during diastolic phase of vascular supply. While false lumen is opposite. Velocity of true lumen is faster than false lumen on CFD.	Enlarged vessel with eccentric or narrowed vessel lumen; A linear hypoattenuation area (represent dissection flap) may be seen projecting into the vessel lumen; If associated with false luminal thrombosis, a crescentic focal narrowing of the vessel can be observed.
Pseudoaneurysm	Anechoic or hypoechoic image with moving echoes on B-mode US; May swell during systole; Typical swirling motion causing Yon-Yang sign on CFD; To-and-fro flow pattern may be observed.	Round, well-defined, outpouching hypoattenuating lesion from the adjacent artery; Organized extraluminal collection of contrast through a disrupted vessel wall in all phases; Does not enlarge on delayed imaging.
Rupture	Hyperechoic irregular or fountain-like-jet or round spot in arterial and delayed phases of contrast-enhanced ultrasound can be noticed.	Irregular blush of contrast outside the vessel lumen; arterial bleed: iso- or hyperattenuated blood pool on arterial phase and subsequently enhancing attenuation on portal venous or delayed phase images. Venous bleed: Enhanced attenuation on portal venous phase that expand further on delayed phase images.
Arteriovenous fistula	Anechoic and anfractuous structure between the vein and artery on B-mode; color mosaic (aliasing) on CFD due to multiple flow velocities in the fistular blood stream. High systolic and diastolic velocities on PWD.	Early and equal enhancement of major vein compared to the artery and asymmetric early filling of involved vein compared to uninvolved veins is observed.

US: Ultrasound, CT: Computed tomography, CFD: Color flow Doppler, PWD: Pulse wave Doppler

to the partition and separation of the tunica intima from the media. It manifests as a thin echogenic band attached to the vessel wall in the US. Turbulence in the blood flow can be seen on color flow and Pulse Wave Doppler (PWD) US, with the flap's size increase. On CT, the intimal flap appears as a hypoattenuating linear or curvilinear defect protruding from the vessel wall into the vessel lumen.[24,25] Such findings may mimic atherosclerotic plaque, which can be excluded through a review of prior imaging.[26] The uncovered media initiates a coagulation cascade, forming an eccentric thrombus along the vessel wall. Acute arterial thrombosis appears as an echogenic material on the B-mode US. Doppler may show decreased or absent blood flow depending on the degree of thrombosis.

In contrast, acute venous thrombosis appears anechoic in the US and becomes more echogenic with chronicity. Typically, the venous flow is continuous and varies with respiration (increase and decrease during inspiration and expiration, respectively). The flow variability with respiration cannot be observed in patients with partial thrombosis. At the same time, the absence of flow indicates complete occlusion of the vessel.[12] On CT, thrombosis appears as a hypodense filling defect in the vascular lumen, causing a partial or total occlusion.[16] The absence of contrast flow on CTA indicates an occluded vessel.[27] The treatment for thrombosis is based on the degree of occlusion and risk of embolization. For instance, aortic intimal tears <10 mm can be treated with blood pressure control and follow-up with imaging. Severe intimal tears (>10 mm) have a high risk of thrombosis or downstream arterial insufficiency, and hence, treatment is on a case-by-case basis.[28]

The intimal flap may progress to dissection, defined as disruption of tunica media secondary to intramural bleeding. It results in the formation of true and false lumens with or without communication. On CTA, dissection appears as an enlarged vessel with an eccentric and narrowed lumen due to intramural hematoma.[27] The circumferential dissection gives the appearance of a targetoid on axial and "wind-stock deformity" ("intussusception-like appearance") in a longitudinal section view.[17] In addition to identifying the extent of dissection, CTA aids in visualizing the true and false lumens. The true lumen has an abnormal eccentric calcification observed on the true lumen side of the dissection flap. False lumen has a typical "cobweb sign," "beak sign," and eccentric vessel wall calcification. The cobwebs are the wispy strings that are extensions of connective tissue in the arterial wall and are absent in the true lumen. The beak sign can be described as an angle between the dissection flap and the outer vessel wall. It is usually filled with hypoattenuated hematoma or contrast-enhancing blood. The dissection has the potential to extend both in anterograde or retrograde directions. A dual-lumen can be observed if the progressive disruption results in a second intimal tear.

Intramural hematoma results from bleeding of the vasa vasorum into the tunica media in the absence of intimal flap or dissection. It is often challenging to differentiate intramural hematoma from partial thrombosis, vasospasm, or extramural hematoma. Non-contrast CT imaging shows a concentric or eccentric hyperdense thickened vessel wall leading to the narrowed lumen. In addition, the displacement of intimal calcifications may be observed if calcifications are present in the native arterial wall. After contrast administration, the hematoma becomes hypodense compared to the luminal blood and is isodense to the standard arterial wall. The transition of hyperattenuating focus to hypoattenuating focus on contrast injection is the only sign of intramural hematoma on CT imaging.

PSA is a focal vascular outpouching secondary to disruption of an artery from trauma, inflammation, or iatrogenic causes.[29] It may be straightforward with one lobe or complex with ≥2 lobes separated by a patent tract. PSA may be bounded by the tunica adventitia alone or covered by a hematoma, while a true aneurysm contains all three arterial wall layers; tunica intima, tunica media, and tunica adventitia. PSA can be identified on the B-mode US by moving an- or hypoechoic signals that may swell during the systole.[12] Color Doppler US is the primary imaging modality for a superficial arterial PSA. It shows the characteristic "Yin-Yang sign" due to the swirling motion of the blood in the PSA cavity.[30] The flow is red during systole and blue during diastole due to toward and away movement of blood from the PSA cavity. However, the Yin-Yang sign can also be demonstrated in a saccular aneurysm and hence cannot be considered the sole diagnostic feature. The presence of connecting channel (neck) with the to-and-fro movement of blood is the hallmark of diagnosis. The US has a sensitivity of 94% and specificity of 97% in detecting PSA and is limited by the difficulty of identifying PSA in visceral arteries.[30]

On non-contrast CT, PSA appears as a well-defined round/oval outpouching from the adjacent parent artery. PSA typically attenuates like the parent vessel on the arterial phase of contrast-enhanced CT, and the contrast washes away with the bloodstream. A filling defect with low attenuation within the PSA sac indicates partial thrombosis. In a study by Soto *et al*., CTA has 95% sensitivity and 99% specificity in evaluating traumatic PSAs.[31] Small peripheral PSAs can be effectively managed through US-guided arterial compression and thrombin injection followed by surveillance.[32,33] Larger PSAs or evidence of contrast extravasation to indicate active hemorrhage are typically managed by open or endovascular procedures.

Rupture is blood extravasation due to disruption of all vessel wall layers without containment. The most crucial imaging finding is active contrast extravasation. Active extravasation can be either due to arterial or venous injuries. They can be differentiated based on CT attenuation in various phases of contrast distribution. For instance, arterial bleeding attenuates similar to or greater than the blood pool in the arterial phase, along with the further enhancement in attenuation and size on later-phase imaging. In venous bleeding, hyperattenuation is observed more in delayed-phase imaging than in the arterial-phase dataset.[5,24] The hyperattenuating crescents can identify impending rupture on unenhanced CT with a specificity of 93%.[34]

Occasionally, rupture into the adjacent vein may lead to the formation of an arteriovenous fistula. On B-mode US, the AV fistula is characterized by an anechoic and anfractuous structure between the artery and vein. CFD reveals red and blue hues (aliasing artifact) due to high turbulence, and PWD shows loss of systolic window and increased systolic and diastolic velocities spectrum. On imaging, diagnosis is based on identifying the early filling of the major vein in the arterial phase. In addition, asymmetric early filling compared to contralateral paired veins is also suggestive of AV-fistula. On CTA, equal enhancement between arteries and veins can be observed in patients with AV fistula. Conventional angiography is recommended in patients with a bruit as it is a diagnostic and therapeutic approach if followed by coiling. Conventional angiography is superior to CTA; in the latter, the early venous filling may be masked by venous contamination.[14]

PENETRATING INJURIES TO THE CHEST

With the increase in availability, firearms contribute to more than 50% of the cases of penetrating thoracic trauma.[35] Around 88–97% of penetrating chest trauma comprises the lung, pleura, and chest wall and presents with pneumo- or hemothorax.[36] Injury to the tremendous intrathoracic vessels is rare. Only 1.2% of penetrating chest trauma patients involves the ascending aorta, arch of the aorta, subclavian artery, and proximal great vessels.[37-39] Trans-mediastinal injuries can occur in several trajectories. Stab wounds are usually in a cephalic direction, while GSW has a transverse trajectory.[40] Transmediastinal GSW is associated with hemodynamic instability and high surgical mortality in 50% of patients secondary to thoracic vascular injury.[40-42] At the same time, only 7–33% of stable patients with similar GSW may require surgical intervention.[43]

GSW and stab injuries constitute 95% of penetrating thoracic aorta cases, with a mortality rate of 90–100%.[37] The severity of the aortic injury depends on the anatomic site and the ballistic properties of the projectile. Hemodynamically, unstable patients with thoracic or vascular trauma often undergo thoracotomy before radiologic imaging; therefore, most imaging is from more stable patients with a presumably lesser degree of injury.[44] CTA of the thoracic aorta can be limited by the cardiac motion artifact, which can be reduced by cardiac gating. Two approaches are achieving cardiac gating: (i) Prospective ECG triggering, (ii) retrospective ECG gating, and (iii) high pitch gating. Prospective gating utilizes ECG signals to trigger the scan only during cardiac diastole, while retrospective gating images during the entire cardiac cycle.[45] Heart rate determines the optimum phase for image acquisition. For instance, in patients with a heart rate of <75 beats/min, a 70–80% diastolic acquisition is recommended, while, in patients with >75 beats/min, a 30–40% systolic acquisition is preferred.[46]

Imaging findings may include PSA, dissection, active extravasation, and occlusion of the involved vessel [Figures 1-5]. Bullet embolization can be seen in a few cases

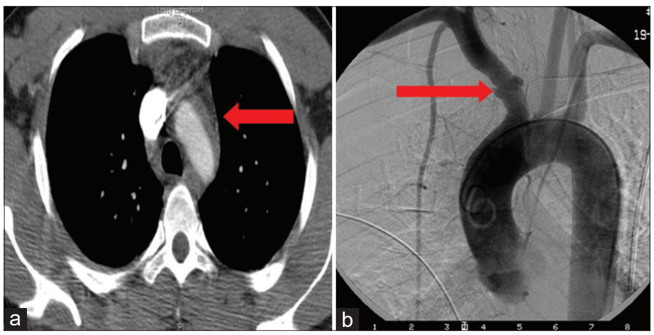

Figure 1: A 29-year-old patient with a gunshot wound to the neck and mediastinum (a) axial contrast-enhanced CT showing mediastinal hematoma (red arrow) and (b) aortogram demonstrates pseudoaneurysm of the brachiocephalic trunk (red arrow).

of mediastinal GSW. Fragments penetrating ascending aorta can embolize the head and neck, and those entering descending aorta may embolize the lower extremities causing acute limb ischemia.[47] Proper surveillance is recommended if a bullet fragment is visualized in a remote region from the trajectory in a vascular structure. In a study by Fisher and Ben-Menachem, PSA was found in 50% of cases in catheter angiography.[48] Most of the vascular injuries in the chest are of closed type (intimal flap, PSA, and dissection) and can be excluded through arterial phase CT.[43] Although PSA s are seen in a small subset of patients with periclavicular injuries involving a great vessel or subclavian artery, they require high suspicion during evaluation. Conventionally, patients with aortic injury were managed through high posterolateral thoracotomy with or without cardiopulmonary bypass. However, it is associated with a mortality rate of 28% and a paraplegia rate of 16%.[49] Hence, the open surgical repair is replaced by the minimally invasive thoracic endovascular aortic repair. It involves the placement of a stent graft into the thoracic aorta through peripheral access under imaging guidance.

Injuries to the pulmonary artery or veins are usually due to stab wounds.[43] Traumatic pulmonary artery pseudoaneurysms (PAPs) are rare, with around 30 cases reported in the literature.[50,51] Unlike systemic arterial PSAs, which enhance the arterial phase, PAPs are focal rounded areas of the contrast pool that corresponds to the pulmonary arterial enhancement.[52] Patients with chest pain, dyspnea, and hemoptysis can be managed through interventional techniques such as percutaneous hemostatic ablation or coil

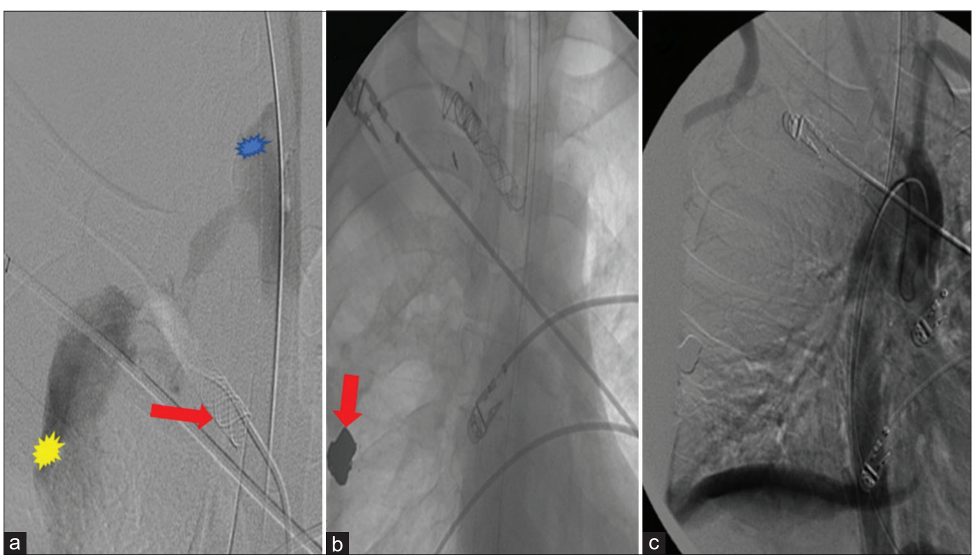

Figure 2: A 32-year-old patient with gunshot injury to the chest (a) selective angiogram of the aberrant RCA stump after surgical ligation for traumatic pseudoaneurysm shows active extravasations of contrast (Star) into the esophagus and right hemithorax and (b and c) post-endovascular coiling (Red arrow) of the stump shows closure of the leak. Notice migrated bullet in the right thoracic cavity.

Figure 3: A 30-year-old patient presented with gunshot injury to the upper chest (a) angiogram is depicting a bullet (arrow) adjacent to an aberrant right subclavian artery in a patient with a transmediastinal bullet injury. (b) Contrast-enhanced axial computed tomography angiography demonstrates aberrant right subclavian artery coursing posterior to esophagus/trachea (c). Selective right subclavian angiograms show a wide neck 2 cm oval pseudoaneurysm measuring 6.0 × 3.5 cm in the distal 1/3 of the right aberrant subclavian artery on day.

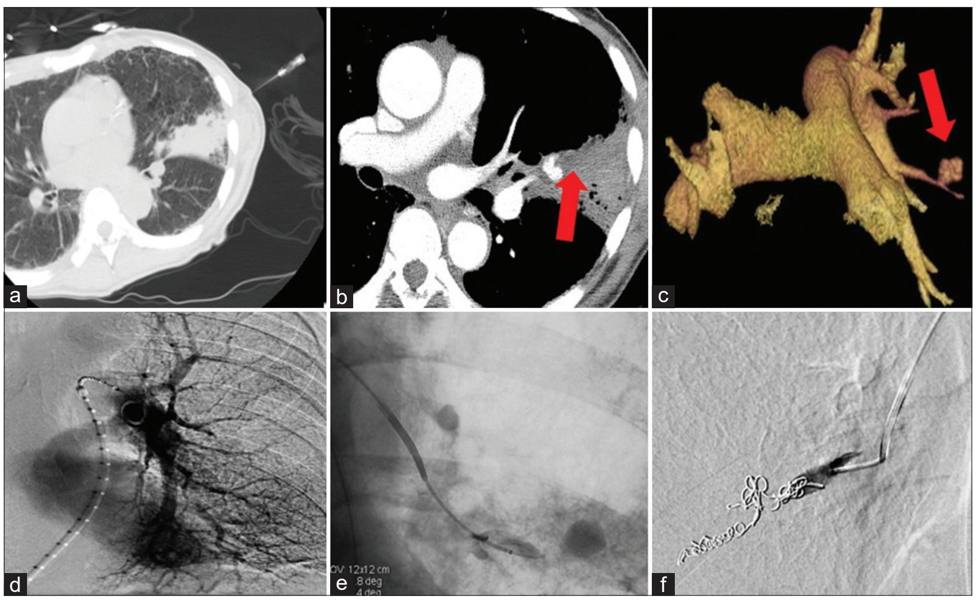

Figure 4: A 40-year-old patient with iatrogenic vascular trauma secondary to biopsy of consolidated lung (a) Contrast-enhanced CT demonstrating biopsy needle entering into the consolidated part of the lung. (b and c) Computed tomography angiography and 3D VR image showing a pseudoaneurysm (arrow) from a lingular branch of the left PA and (d-f) angiogram demonstrating pseudoaneurysm of the lingular branch of the left pulmonary artery and subsequent coiling.

angioembolization and ultimate lung resection.[53,54] Coil embolization can be achieved through platinum or stainless steel coils and detachable balloons.

PENETRATING ABDOMINOPELVIC INJURIES

Penetrating abdominopelvic vascular trauma is a lethal injury with mortality ranging from 20% to 60% due to hemorrhage, multi-organ failure, and shock.[4,55] Aorta, superior mesenteric artery, iliac arteries, inferior vena cava, portal veins, and iliac veins are the most commonly involved vasculature in the abdomen and pelvis [Figure 6].[56] The CT protocol in penetrating abdominal trauma includes images captured in the venous phase (~70 s), delayed scan (~3–5 min) in patients with identifiable injury in the former venous phase, and additional image scan after the rectal contrast administration. The ESER recommends imbricating the neck, chest, and abdomen in the arterial phase, while the abdomen and pelvis are captured in the portal-venous phase.[57]

Abdominal aorta

Approximately 2% of gunshot and 1% of stab wounds account for penetrating abdominal aortic injury.[25,58] The intercostal or epigastric region is the entry site for around

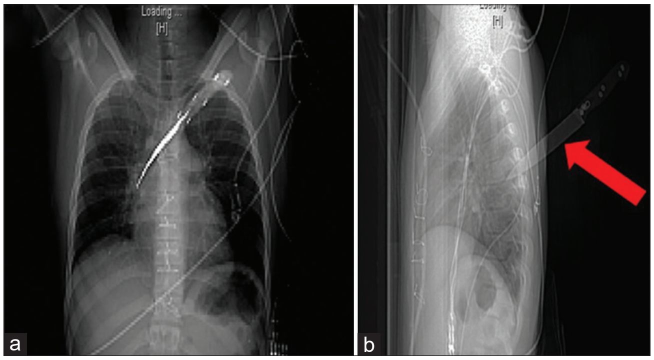

Figure 5: A 34-year-old patient presented with stab injury to the back. (a and b) Radiographs demonstrating stab injury with knife (arrow).

Figure 6: A 19-year-old patient presented with penetrating injury to the abdominopelvic region. Angiogram demonstrating a fistula (arrow) between the internal iliac artery and vein (notice early filling of an iliac vein).

40% of penetrating torso injuries.[59] The society of vascular surgery proposed a classification to describe the direct signs of traumatic abdominal aortic injury: (i) Grade I: Intimal flap, (ii) Grade II: Intramural hematoma, (iii) Grade III: PSA, and (iv) Grade IV: Rupture.[25] The classification has significance in the management of patients. Patients with Grade I and II injuries can be managed with serial CT images to document resolution in 48–72 h. At the same time, Grade III and IV injuries require endovascular or open surgical treatment.[4,25]

In addition to the direct signs, indirect signs are crucial in identifying the abdominal injury. Retroperitoneal hematoma (30–70 HU) is an indirect sign 92% sensitive to aortic injury but can be observed in injuries to surrounding arteries or veins.[60] A hematoma, not on the aorta or separating from the aorta by a fat plane, is unlikely to be secondary to aortic injury. The path of the penetrating object also aids as an indirect sign of aortic injury. Any trajectory close to the aorta shall raise the suspicion of aortic injury, particularly in a retroperitoneal hematoma. Patients with indirect signs of aortic injury and those with lower-grade injuries can be followed up with a CT examination within 48–72 h.[25] However, the patient with direct signs of aortic injury requires immediate management. Vascular surgeons divide the abdominal aorta into three zones: (i) Zone I: diaphragmatic hiatus to superior mesenteric artery, (ii) superior mesenteric artery to the renal arteries, and (iii) Zone III: renal arteries to the aortic bifurcation. Zone I injuries often require an extensive open approach but may be amenable to endovascular repair. Zone II injuries are not suitable for endovascular stent placement as the grafts are not suitable in Zone II in acute settings. Zone III can be operated either by open or endovascular approaches.[28]

Inferior vena cava (IVC)

Injury to IVC is seen in 0.5–5% of penetrating abdominal trauma and carries a very high mortality rate of 20–66% [Figure 7].[61,62] It is often due to high-velocity GSW than stab wounds. The former produces an extensive tangential area of vessel transection, and the latter results in linear laceration.[63] Combined aortic and inferior vena cava injury mortality are around 93%.[55] Infrarenal segment (39%) followed by retrohepatic (19%), infrahepatic (18%), juxtarenal (17%), and suprahepatic IVC (7%) are the common sites of IVC segments prone to injury.[64] Locations of IVC injury such as retroperitoneum and posterior surface of pancreas, duodenum, and liver may provide tamponade effect to the IVC bleed; however, the patients can exsanguinate to death if the tamponade is decompressed and not controlled promptly.[63]

Solid organ vascular injury

With the improvement in interventional vascular techniques, most solid-organ injuries are managed nonoperatively. Hence, accurate radiological characterization of injury is essential to avoid misdiagnosis [Figures 8-10]. For instance, in a case of hepatic injury, a radiologist must comment on the size of the hematoma as the percentage of the total surface area, location (subcapsular or intraparenchymal), laceration in centimeters, juxtavenous injury status, and several liver segments involved in the injury.[4] The revised 2018 AAST OIS classified a liver injury with vascular involvement or active bleeding within the hepatic parenchyma as Grade III [Table 4].[65-67] At the same time, Grade IV describes an injury with active bleeding beyond the hepatic parenchyma alongside the lobar parenchymal disruption of 25–75%. Injury to major hepatic veins and inferior vena cava are classified under Grade V.[68] In patients with splenic injury, a radiologist must state the trajectory of injury, whether it

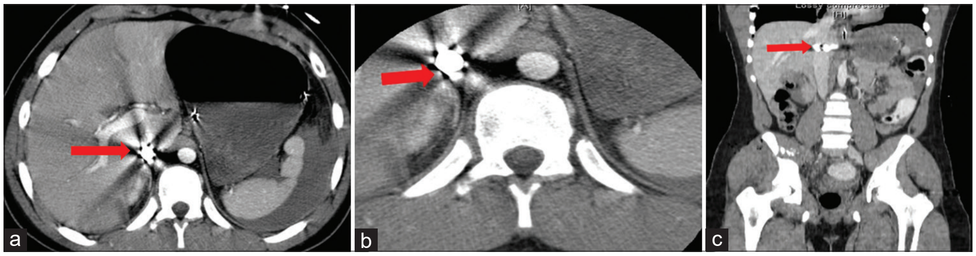

Figure 7: A 35-year-old patient with a gunshot wound to the abdomen. (a-c) Axial and coronal CT scan images demonstrating a bullet (arrows) embolized to the inferior vena cava in a patient with a gunshot wounds to the right iliac bone.

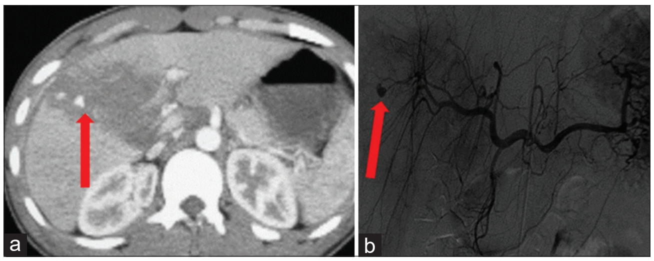

Figure 8: A 34-year-old patient with gunshot wound to the abdomen (a) axial contrast-enhanced CT shows gunshot wound to the liver with a minor laceration and hepatic artery pseudoaneurysm (arrow) and (b) selective angiogram of the celiac artery of the same patient demonstrates a small hepatic artery pseudoaneurysm (arrow).

is traversing the splenic hilum and signs of vascular injury or shattered spleen.[4] The 2018 AAST OIS classified any splenic vascular injury or active bleeding within the splenic capsule as Grade IV. At the same time, the extended active bleeding beyond the splenic capsule or a shattered spleen is classified as Grade V splenic injuries.[66,68] The presence of active extravasation, discontinuation of mesenteric vessels, pooling of contrast material, and inter-mesenteric free fluid (forming triangles) should raise the suspicion of injury to the mesenteric vasculature. Furthermore, the diffuse bowel hematoma in the vascular distribution pattern indicates mesenteric vascular injury.[5]

Penetrating injury to the kidney is relatively less common than blunt injury and accounts for 10–20% of all renal trauma.[1] Patients with a renal vascular injury can be assessed by dual-phase contrast-enhanced CT in the corticomedullary (arterial) and late corticomedullary or early nephrogenic (portal venous) phases [Figure 10]. The former detects arterial injuries, while the latter is ideal for parenchymal evaluation. The renal collecting system may be evaluated in the imaging excretory (delayed) phase.[1] Renal vascular injuries manifest as either subcapsular or perinephric hematomas. Subcapsular hematomas are eccentric and hyperattenuating fluid that does not enhance contrast administration and is enclosed by the renal parenchyma and capsule. The increased size of subcapsular hematomas increases the mass effect on the adjacent renal parenchyma. At the same time, perinephric hematomas are enclosed by the Gerota's fascia and renal capsule and do not exert a mass effect on the adjacent renal parenchyma. These are hyperattenuating fluid collections with indistinct margins. The main renal artery or vein injury is classified as Grade V injury according to AAST OIS [Table 4].[66,67] In addition, hilar laceration, active bleeding of devascularized kidneys, and damaged kidney are categorized under Grade V.

All the above-described solid organ vascular injuries must be characterized and classified accurately for timely and definitive management. At present, non-operative management is the preferred treatment strategy, unlike previous times when penetrating vascular trauma was considered an indication for surgical intervention. Pre-requisites for NOM include hemodynamic stability, a CT scan without diaphragm or hollow viscus injuries, and no signs of peritonitis.[69] A radiologist can help determine the patients at high risk of NOM failure. For instance, the patient with CT findings of active contrast extravasation and free fluid is at increased risk of NOM failure.[68]

PENETRATING EXTREMITY VASCULAR INJURIES

Apart from military settings, peripheral extremity trauma is encountered in 5–15% of civilian trauma center cases.[70,71] Vascular involvement is seen in approximately 1% of patients.[71] Vascular injuries can be attributed to handguns, stab wounds, and shotguns in around 50%, 30%, and 5%, respectively.[72] Femoral and popliteal arteries (50–60%), followed by brachial arteries (30%), are most frequently injured in penetrating extremity trauma.[72,73]

Evaluation of patients with vascular penetrating extremity trauma starts with the history and physical examination followed by diagnostic imaging with Doppler US, CTA, and angiography [Figures 11-23]. The hard signs have 92–95% sensitivity and 95% positive predictive value for penetrating extremity trauma injuries obligating intervention.[74] Soft signs are not highly correlated with vascular injury; hence, arterial pressure index (API) is calculated with Doppler in patients exhibiting soft signs.[71] The API is the ratio of the

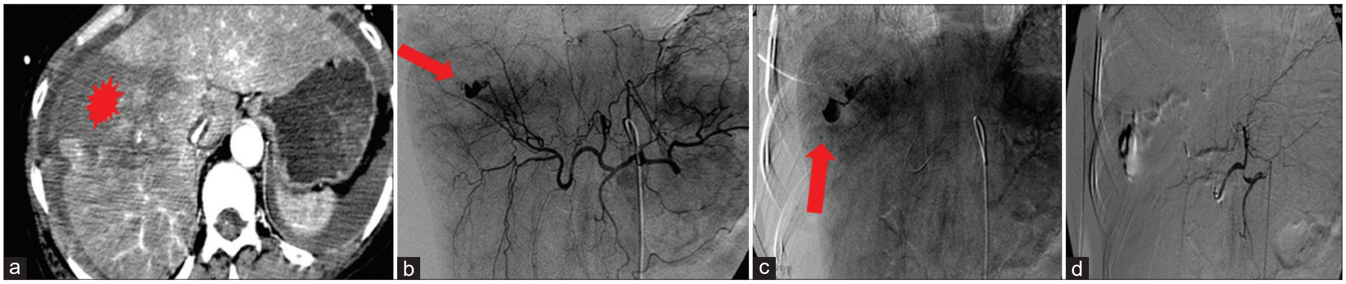

Figure 9: A 29-year-old patient presented with a penetrating trauma to the right upper quadrant of the abdomen (a) axial contrast-enhanced CT demonstrating active extravasation (star) at the right lobe of the liver after penetrating trauma, (b and c) celiac angiogram in the same patient shows active extravasation from a branch of the right hepatic artery without wash out (arrows), and (d) angiogram after coiling the branch of the right hepatic artery demonstrates cessation of extravasation.

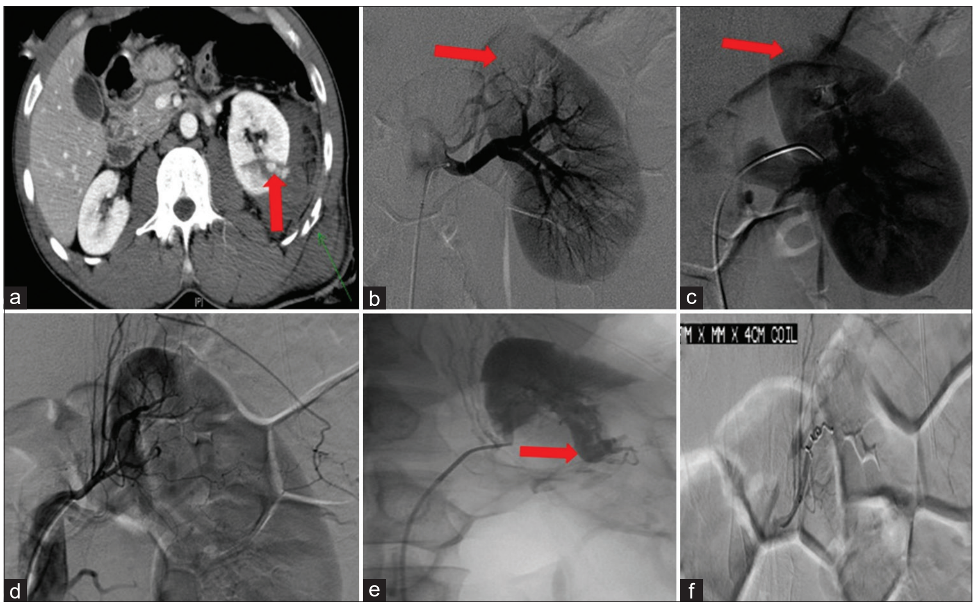

Figure 10: A 38-year-old patient presented with stab injury to his left flank and kidney. (a) Axial contrast-enhanced CT demonstrates serpiginous dilated tubular vessel with a perirenal hematoma (arrow) (b and c). Selective left renal artery angiography shows decreased perfusion in the upper pole of the left kidney. Steal phenomenon from arteriovenous (AV) fistula (arrow) (d-f) selective left renal segmental artery angiography shows perfusion in the upper pole of the left kidney with a large draining vein, indicating renal AV fistula which was embolized with coils (arrow).

systolic blood pressure of the injured limb with the systolic blood pressure of the paired uninjured limb. An API of <0.9 is abnormal, and >0.9 has a negative predictive value of 96–99%, thus making it an excellent screening test.[75,76] deSouza *et al*. reported that one could exclude arterial injury if the hard signs, soft signs, and ankle-brachial index are of the normal range.[77] Doppler US has a sensitivity and specificity of 95% and 98% in evaluating vascular penetrating extremity trauma in stable patients. However, it has a high false-negative rate in individuals with popliteal or subclavian injuries.[78] Recently, the two-Point Fast Doppler protocol is emerging as first-line screening with 100% sensitivity and 100% specificity compared to standard Doppler US. It is normal if the triphasic pattern is observed in the dorsalis pedis and posterior tibialis arteries and abnormal if the monophasic, biphasic, or absent flow pattern is observed in either dorsalis pedis or posterior tibialis arteries.[79] CTA, catheter angiography, or surgery is recommended in patients with high suspicion of significant vascular injury.

Patients with hard signs of bleeding require immediate intervention. In contrast, arteriography in the operating room may manage those without hard signs but with a high suspicion of arterial injury. Patients without hard signs and under observation may be considered for surgery if their hemodynamic stability worsens.[76] Endovascular interventions replace the historical open vascular repairs with various embolizing agents such as gel foam, coil, glue, or stent-grafts. Studies reported technical and clinical

Table 4: Solid organ injury scale of the liver and spleen.

Grade	Type of injury	Liver injury	Spleen injury	Kidney injury
I	Hematoma	Subcapsular hematoma involving<10% of the surface area	Subcapsular hematoma involving<10% of the surface area	Subcapsular hematoma±parenchymal contusion with no laceration
	Laceration	Capsular tear of up to 1% deep into the parenchyma	Capsular tear of up to 1% deep into the parenchyma	
II	Hematoma	Subcapsular hematoma involving 10–50% of the surface area	Subcapsular hematoma involving 10–50% of the surface area	Perirenal hematoma confined to Gerota fascia
	Laceration	Intraparenchymal tear of up to 5 cm diameter	Intraparenchymal tear of up to 5 cm diameter	Intraparenchymal laceration involving≤1 cm depth; no urinary extravasation
III	Hematoma	Subcapsular hematoma involving>50% of the surface area or an expanding type of hematoma Intraparenchymal hematoma of size≥5 cm in size or an expanding hematoma Ruptured subcapsular or parenchymal hematoma	Subcapsular hematoma involving>50% of the surface area or an expanding type of hematoma Intraparenchymal hematoma of size≥5 cm in size or an expanding hematoma Ruptured subcapsular or parenchymal hematoma	Any renal vascular injury±active bleeding confined to the Gerota fascia
	Laceration	Laceration involving>3 cm depth of hepatic parenchyma	Laceration involving>3 cm depth of splenic parenchyma or involving trabecular vessels	Intraparenchymal laceration involving>1 cm depth; no urinary extravasation or collecting system rupture
IV	Laceration	Disrupted 25–75% of hepatic lobar parenchyma or 1–3 Couinaud's segments within single lobe	Major (>25%) devascularization of the spleen due to the involvement of hilar or segmental vessels	Parenchymal laceration with collecting system involvement and the associated urinary extravasation laceration of renal pelvis±complete ureteropelvic disruption
	Hematoma			Segmental renal vein or arterial injury Bleeding beyond Gerota fascia, into the peritoneum or retroperitoneum Segmental or complete renal infarction due to thrombotic vessel rather than active bleeding.
V	Laceration	Disrupted 75% of hepatic lobar parenchyma or>3 Couinaud's segments within single lobe	Shattered spleen	
	Vascular	Injury involving retrohepatic vena cava or central major hepatic veins	Injury involving hilar vessels, thereby leading to devascularized spleen	Laceration of the main renal artery or vein, or hilar avulsion Devascularized with active bleeding or shattered kidney with loss of identifiable renal parenchyma.
VI	Vascular	Hepatic avulsion		

success rates of 80–100% in the endovascular management of penetrating extremity vascular injuries.[80] Gelfoam is the workhorse in patients with penetrating extremity vascular injury as it provides a temporary embolization lasting up to

2 weeks. This provides the time for the damaged vessel to heal before recanalization. Coils and glues are more commonly employed in solid organ injuries than extremity vascular trauma.[71] Stent grafts are often effectively used in patients with post-traumatic vascular PSA or AV fistula.[81,82]

PENETRATING INJURY IN PREGNANCY

Every 3.27 in 100,000 pregnant individuals encounter penetrating trauma.[83] The maternal mortality rate is favorable in penetrating trauma compared to blunt trauma, as the nonreproductive structures are protected by the gravid uterus, which absorbs the penetrating objects.[84] However, the fetal prognosis is poor if the uterus is the main organ of absorption. Fetal mortality is reported in 42% of stabs and 71% of gunshot injuries.[85,86] Evaluation of penetrating trauma in pregnancy poses a clinical dilemma, given that the typical management and imaging paradigm expose radiation risk to both the mother and the fetus. Therefore, alternative measures may be taken. CTA is still the diagnostic modality of choice in penetrating GSW and stab injuries, with concern for vascular injury. However, one must remember the radiation exposure and risk associated with iodinated contrast. A routine head and neck, chest, abdominal, and pelvic CT expose the fetus to a radiation dose of 0.001–0.1, 0.01–0.66, 1.3–35, and 10–50 mGy.[87] Studies show that radiation exposure is low when the fetus is out of field-of-view.[88] According to the 2008 American College of Radiology guidelines, a fetal radiation dose of <50 mGy does not increase the risk of fetal anomalies or loss.[89] Exposure to >50 mGy leads to an increased risk of fatal childhood cancer from 1 in 500 to 1 in 200 and lifetime cancer by 2%.[88,89] Exposure to >100 mGy radiation is associated with central nervous system defects, growth retardation, and intellectual impairment.[88] US Food and Drug Administration states that the iodinated contrast for vascular opacification is considered a category B drug. Advanced imaging, such as MRI, is not routinely indicated due to its longer acquisition times and the need to move the patient from acute care. Instead, it is an excellent option for follow-up or in case of new-onset symptoms. The main limitations of MRI in pregnancy are the effects of energy deposition and tissue heating in the fetus alongside the impact of acoustic noise. Hence, a field strength of ≤1.5 T is recommended. Gadolinium is considered a category C drug by US FDA. Pregnant patients with GSW shall undergo exploratory intervention with tissue debridement. At the same time, the patients with stab wounds with a suspected intrabdominal injury are treated similarly to the non-pregnant patient.[84]

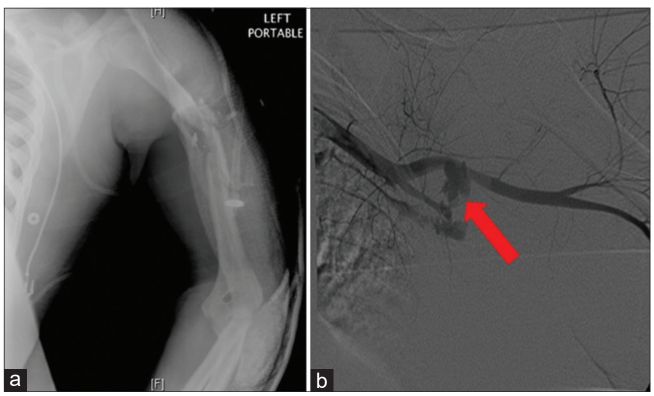

Figure 11: A 27-year-old patient with gunshot injury to the left arm. (a) Radiograph showing a comminuted fracture of the left humerus and (b) angiogram demonstrating a fistula (arrow) between the axillary artery and vein alongside a small pseudoaneurysm.

Limitations

Because trauma commonly involves young age groups, radiation exposure is of concern. Radiation can result in two types of effects: deterministic and stochastic. Deterministic effects are the predictable biological effects observed shortly after radiation exposure, such as skin changes or hair loss.[90]

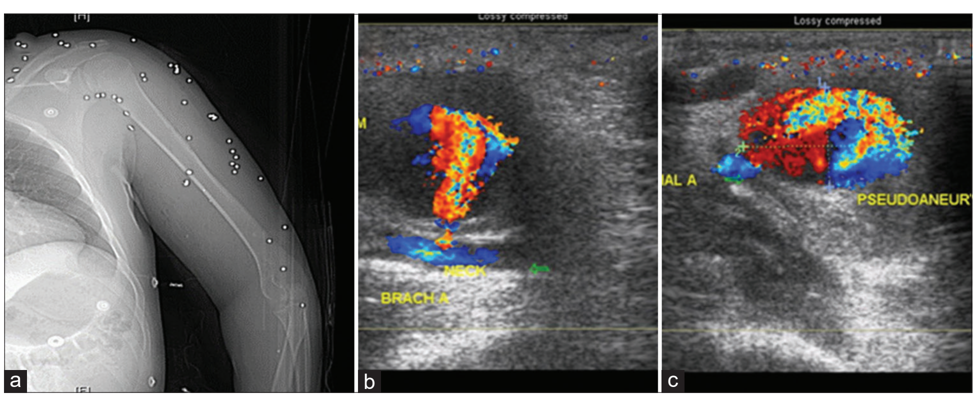

Figure 12: A 45-year-old patient presented with gunshot injury to the left arm. (a) Radiograph of the left arm demonstrating multiple pellets of the gunshot. (b and c) Ultrasound demonstrating pseudoaneurysm of the left brachial artery on the ultrasound.

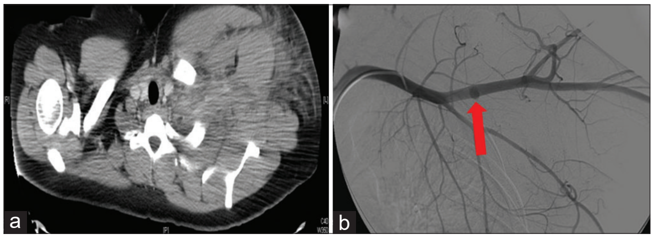

Figure 13: A 35-year-old patient presented with a large axillary hematoma and tingling in his arm alongside the history of gunshot wound. (a and b) Axial CT and angiogram of the same patient showing subclavian artery pseudoaneurysm (arrow).

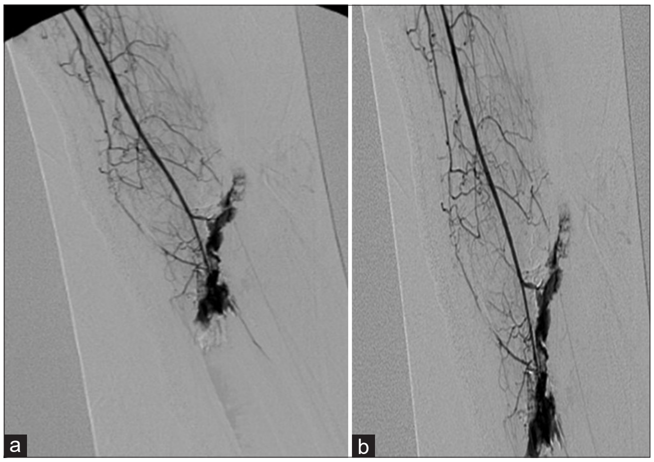

Figure 14: A 45-year-old patient presented with penetrating injury to the upper extremity. (a and b) Angiogram demonstrates the avulsion of the radial artery with active extravasation.

Figure 15: A 35-year-old patient presented with penetrating injury to the upper extremity. Angiogram demonstrates the fistula (arrow) between the brachial artery and vein.

Figure 16: A 39-year-old patent presented with penetrating injury to the upper extremity. Angiogram demonstrating active extravasation (arrow) from the circumflex humeral artery extravasation.

Figure 17: A 34-year-old patient presented with gunshot injury to the upper extremity. Angiogram demonstrating the occlusion (arrow) of distal brachial artery occlusion.

Stochastic effects include cancer mutations demonstrating a linear relationship between radiation dose and biological effect without any definitive safe threshold.[90,91] The radiation dose can be calculated by multiplying the dose-length product (available on the CT system) by the region-specific coefficient "k" [Table 5].[92] Radiation exposure during CT contributes to around 1.5–2% of cancers in the US.[93] The median radiation dose in patients who underwent whole-body CT scans is 34–40.2 mSv, equivalent to 680 chest radiographs.[94,95] Sharma *et al.* reported a mean exposure of 14.56 mSv to all the patients within 24 h of their admission to the trauma center.[96] The lifetime risk of cancer for a 100 mSv exposure is 1 in 100. Transitioning from a single 4-slice whole-body CT to a single 64-slice thoracoabdominal CT has reduced the radiation from 10 mSv to 2 mSv. As a result, the lifetime risk of cancer has improved from 1 in 100 to 1

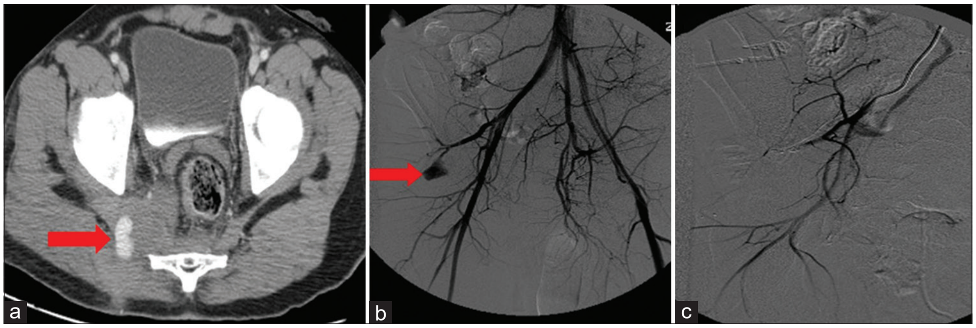

Figure 18: A 36-year-old patient presented with stab injury to the right buttock (a) axial contrast-enhanced CT demonstrating gluteal artery pseudoaneurysm (arrow) and (b and c) selective angiography of the right superior gluteal artery (arrow) and subsequent coil embolization.

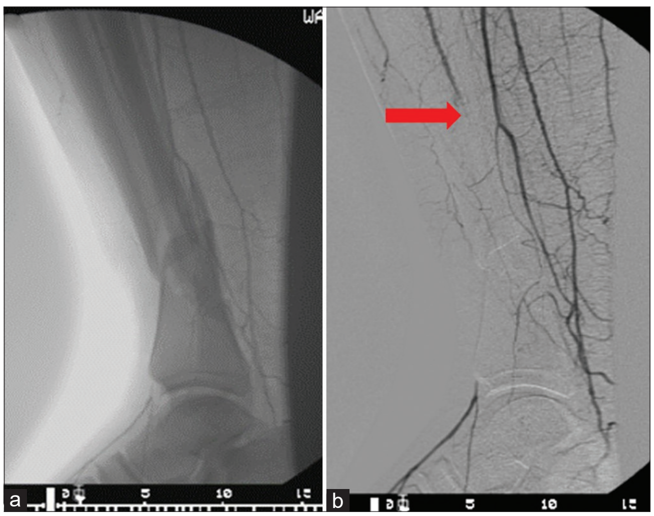

Figure 19: A 33-year-old patient presented with gunshot injury to the lower extremity. (a and b) Angiogram demonstrating an occlusion (arrow) of the anterior distal tibial artery.

Figure 21: A 24-year-old patient presented with penetrating injury to the lower extremity. Angiography demonstrating a fistula (arrow) between the popliteal artery and vein.

Figure 20: A 34-year-old patient presented with penetrating trauma. Angiography demonstrating a fistula (arrow) between the superficial femoral artery and vein.

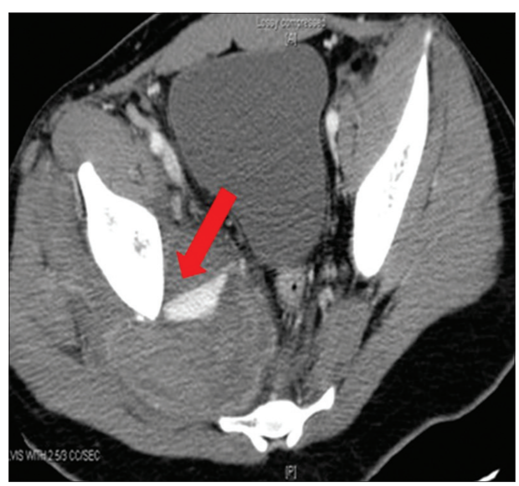

Figure 22: A 49-year-old patient presented with stab wound through the right sciatic foramen. Axial contrast-enhanced CT demonstrates a large hematoma and gluteal artery pseudoaneurysm (arrow).

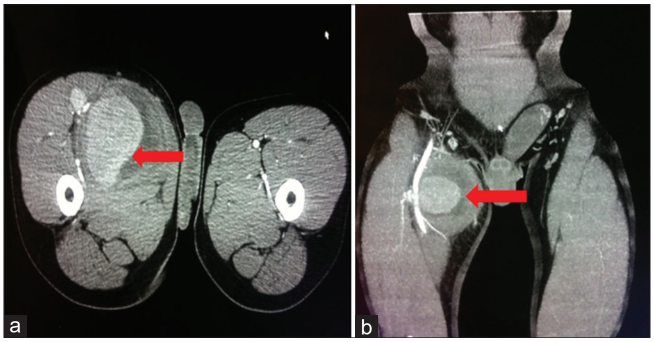

Figure 23: A 40-year-old patient presented with stab injury to the right thigh. (a and b) Axial and coronal contrast-enhanced CT demonstrating well-defined contrast surrounding the main vessel suggestive of pseudoaneurysm (arrow).

Table 5: Calculation of radiation dose due to CT imaging.

Region of body	Adult "k" coefficient
Head and neck	0.0031
Head	0.0021
Neck	0.0059
Chest	0.014
Abdomen and pelvis	0.015
Trunk	0.015

in 15000.[90] Tien *et al*. studied that radiation dose is higher in the neck than in other body areas. This is due to the most radiosensitive organ, the thyroid. In their study, the thyroid received a mean dose of 100 mSv in 22% of patients, posing a significant risk for thyroid cancer.[91] Although the fear of missing life-threatening injuries outweighs the rare long-term effects of radiation, the multiple imaging modalities in a trauma patient accentuate lifetime cancer risk. Hence, attempts should be made to lessen the radiation dose by decreasing tube current, judicious CT scans, and proper shielding practices.

CONCLUSION

The victims of ballistic and stab-related vascular injuries are initially evaluated based on the patient's physical examination and hemodynamic status. Imaging aids as an adjunct for prompt triage and diagnosis. With the detailed interpretation of common and uncommon vascular injuries, high-quality CTA is an invaluable imaging modality for evaluating traumatic individuals. Given the advances in CTA, the role of angiography has become more therapeutic than diagnostic in this patient population.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Durso AM, Paes FM, Caban K, Danton G, Braga TA, Sanchez A, *et al*. Evaluation of penetrating abdominal and pelvic trauma. Eur J Radiol 2020;130:109187.
2. Naghavi M, Marczak LB, Kutz M, Shackelford KA, Arora M, Miller-Petrie M, *et al*. Global mortality from firearms, 1990-2016. JAMA 2018;320:792-814.
3. Lozano JD, Munera F, Anderson SW, Soto JA, Menias CO, Caban KM. Penetrating wounds to the torso: Evaluation with triple-contrast multidetector CT. Radiographics 2013;33:341-59.
4. Naeem M, Hoegger MJ, Petraglia FW 3rd, Ballard DH, Zulfiqar M, Patlas MN, *et al*. CT of penetrating abdominopelvic trauma. Radiographics 2021;41:1064-81.
5. Sodagari F, Katz DS, Menias CO, Moshiri M, Pellerito JS, Mustafa A, *et al*. Imaging evaluation of abdominopelvic gunshot trauma. RadioGraphics 2020;40:1766-88.
6. Pinto A, Russo A, Reginelli A, Iacobellis F, Di Serafino M, Giovine S, *et al*. Gunshot wounds: Ballistics and imaging findings. Semin Ultrasound CT MR 2019;40:25-35.
7. Truesdell W, Gore A, Primakov D, Lieberman H, Jankowska D, Joshi G, *et al*. Ballistic and penetrating injuries of the chest. J Thorac Imaging 2020;35:W51-9.
8. Daghfous A, Bouzaïdi K, Abdelkefi M, Rebai S, Zoghlemi A, Mbarek M, *et al*. Contribution of imaging in the initial management of ballistic trauma. Diagn Interv Imaging 2015;96:45-55.
9. Giorgetti A, Giraudo C, Viero A, Bisceglia M, Lupi A, Fais P, *et al*. Radiological investigation of gunshot wounds: A systematic review of published evidence. Int J Legal Med 2019;133:1149-58.
10. Viel G, Gehl A, Sperhake JP. Intersecting fractures of the skull and gunshot wounds. Case report and literature review. Forensic Sci Med Pathol 2009;5:22-7.
11. Slama R, Villaume F. Penetrating vascular injury: Diagnosis and management updates. emergency Med Clin 2017;35:789-801.
12. Montorfano MA, Pla F, Vera L, Cardillo O, Nigra SG, Montorfano LM. Point-of-care ultrasound and Doppler ultrasound evaluation of vascular injuries in penetrating and blunt trauma. Crit Ultrasound J 2017;9:1-14.
13. Studer S, van Veelen NM, van de Wall BJ, Kuner V, Schrading S, Link BC, *et al*. Improving the protocol for whole-body CT scans in trauma patients. Eur J Trauma Emerg Surg 2022;48:3149-56.
14. Steenburg SD, Sliker CW, Shanmuganathan K, Siegel EL. Imaging evaluation of penetrating neck injuries. Radiographics 2010;30:869-86.
15. Núñez Jr DB, Torres-León M, Múnera F. Vascular injuries of the neck and thoracic inlet: Helical CT-angiographic correlation. Radiographics 2004;24:1087-98.

16. LeBlang SD, Nuñez DB Jr. Helical CT of cervical spine and soft tissue injuries of the neck. Radiol Clin North Am 1999;37:515-32.
17. Adler C, Hangge PT, Albadawi H, Knuttinen MG, Alzubaidi SJ, Naidu SG, *et al.* Multi-detector computed tomography imaging techniques in arterial injuries. J Clin Med 2018;7:29695034.
18. Yaniv G, Portnoy O, Simon D, Bader S, Konen E, Guranda L. Revised protocol for whole-body CT for multi-trauma patients applying triphasic injection followed by a single-pass scan on a 64-MDCT. Clin Radiol 2013;68:668-75.
19. Atluri S, Richard HM, Shanmuganathan K. Optimizing multidetector CT for visualization of splenic vascular injury. Validation by splenic arteriography in blunt abdominal trauma patients. Emerg Radiol 2011;18:307-12.
20. Shiroff AM, Gale SC, Martin ND, Marchalik D, Petrov D, Ahmed HM, *et al*. Penetrating neck trauma: A review of management strategies and discussion of the 'No Zone'approach. Am Surg 2013;79:23-9.
21. Bowen BC. MR angiography versus CT angiography in the evaluation of neurovascular disease. Radiology 2007;245:357-61.
22. Uyeda JW, Anderson SW, Sakai O, Soto JA. CT angiography in trauma. Radiol Clin 2010;48:423-38.
23. Azizzadeh A, Keyhani K, Miller CC 3rd, Coogan SM, Safi HJ, Estrera AL. Blunt traumatic aortic injury: Initial experience with endovascular repair. J Vasc Surg 2009;49:1403-8.
24. Baghdanian AH, Armetta AS, Baghdanian AA, LeBedis CA, Anderson SW, Soto JA. CT of major vascular injury in blunt abdominopelvic trauma. Radiographics 2016;36:872-90.
25. Tsai R, Raptis D, Raptis C, Mellnick VM. Traumatic abdominal aortic injury: Clinical considerations for the diagnostic radiologist. Abdom Radiol 2018;43:1084-93.
26. Prado E, Chamorro EM, Marín A, Fuentes CG, Zhou ZC. CT features of blunt abdominal aortic injury: An infrequent but life-threatening event. Emerg Radiol 2021;29:187-95.
27. Saito N, Hito R, Burke PA, Sakai O. Imaging of penetrating injuries of the head and neck: Current practice at a level I trauma center in the United States. Keio J Med 2014;63:23-33.
28. Shalhub S, Starnes BW, Tran NT, Hatsukami TS, Lundgren RS, Davis CW, *et al*. Blunt abdominal aortic injury. J Vasc Surg 2012;55:1277-85.
29. Jindal R. Percutaneus thrombin injection treatment of a profunda femoris pseudoaneurysm after femoral neck fracture. J Vasc Interv Radiol 2004;15:1335-6.
30. Keeling A, McGrath F, Lee M. Interventional radiology in the diagnosis, management, and follow-up of pseudoaneurysms. Cardiovasc Interv Radiol 2009;32:2-18.
31. Soto JA, Múnera F, Morales C, Lopera JE, Holguín D, Guarín O, *et al*. Focal arterial injuries of the proximal extremities: Helical CT arteriography as the initial method of diagnosis. Radiology 2001;218:188-94.
32. Vázquez V, Reus M, Morales MD, Abellán J, Piñero A, Soria F, *et al*. Usefulness of sonographically guided thrombin injection of iatrogenic femoral pseudoaneurysms. Med Clin 2003;121:53-7.
33. Eisenberg L, Paulson EK, Kliewer MA, Hudson MP, DeLong DM, Carroll BA. Sonographically guided compression repair of pseudoaneurysms: Further experience from a single institution. AJR Am J Roentgenol 1999;173:1567-73.
34. Schwartz SA, Taljanovic MS, Smyth S, O'Brien MJ, Rogers LF. CT findings of rupture, impending rupture, and contained rupture of abdominal aortic aneurysms. AJR Am J Roentgenol 2007;188:W57-62.
35. Jogiat UM, Strickland M. Transmediastinal penetrating trauma. Mediastinum 2021;5:25.
36. Shanmuganathan K, Matsumoto J. Imaging of penetrating chest trauma. Radiol Clin North Am 2006;44:225-38, viii.
37. Gunn ML, Clark RT, Sadro CT, Linnau KF, Sandstrom CK. Current concepts in imaging evaluation of penetrating transmediastinal injury. Radiographics 2014;34:1824-41.
38. LeBlang SD, Dolich MO. Imaging of penetrating thoracic trauma. J Thorac Imaging 2000;15:128-35.
39. Staller B, Mùnera F, Sanchez A, Nuñez DB. Helical and multislice CTA following penetrating trauma to the subclavian and axillary arteries (pictorial essay). Emerg Radiol 2005;11:336-41
40. Burack JH, Kandil E, Sawas A, O'Neill PA, Sclafani SJ, Lowery RC, *et al*. Triage and outcome of patients with mediastinal penetrating trauma. Ann Thorac Surg 2007;83:377-82.
41. de Vries CS, Africa M, Gebremariam FA, van Rensburg JJ, Otto SF, Potgieter HF. The imaging of stab injuries. Acta Radiol 2010;51:92-106.
42. Okoye OT, Talving P, Teixeira PG, Chervonski M, Smith JA, Inaba K, *et al*. Transmediastinal gunshot wounds in a mature trauma centre: Changing perspectives. Injury 2013;44:1198-203.
43. Dreizin D, Munera F. Multidetector CT for penetrating torso trauma: State of the art. Radiology 2015;277:338-55.
44. Gunn ML. Imaging of aortic and branch vessel trauma. Radiol Clin 2012;50:85-103.
45. Desjardins B, Kazerooni EA. ECG-gated cardiac CT. AJR Am J Roentgenol 2004;182:993-1010.
46. Murphy DJ, Aghayev A, Steigner ML. Vascular CT and MRI: A practical guide to imaging protocols. Insights Imaging 2018;9:215-36.
47. Habdank K, Nolan RL. Gunshot wound to the thorax with bullet embolization to the external carotid artery. J Thorac Imaging 2003;18:42-4.
48. Fisher RG, Ben-Menachem Y. Penetrating injuries of the thoracic aorta and brachiocephalic arteries: Angiographic findings in 18 cases. Am J Roentgenol 1987;149:607-11.
49. Ott MC, Stewart TC, Lawlor DK, Gray DK, Forbes TL. Management of blunt thoracic aortic injuries: Endovascular stents versus open repair. J Trauma 2004;56:565-70.
50. Shnayderman D, Baginski SG, Lea WB, Erickson SJ. Huge traumatic pulmonary artery pseudoaneurysm. Radiol Case Rep 2017;12:467-71
51. Lafita V, Borge MA, Demos TC. Pulmonary artery pseudoaneurysm: Etiology, presentation, diagnosis, and treatment. Semin Intervent Radiol 2007;24:119-23
52. Lewis BT, Herr KD, Hamlin SA, Henry T, Little BP, Naeger DM, *et al*. Imaging Manifestations of chest trauma. Radiographics 2021;41:1321-34.
53. Sridhar SK, Sadler D, McFadden SD, Ball CG, Kirkpatrick AW. Percutaneous embolization of an angiographically inaccessible pulmonary artery pseudoaneurysm after blunt chest trauma: A case report and review of the literature. J Trauma 2010;69:729.
54. Quartey B, Jessie E. Pulmonary artery and vein pseudoaneurysm after gunshot wound to the chest. J Emerg

Trauma Shock 2011;4:313-6.
55. Asensio JA, Chahwan S, Hanpeter D, Demetriades D, Forno W, Gambaro E, *et al*. Operative management and outcome of 302 abdominal vascular injuries. Am J Surg 2000;180:528-34.
56. Kobayashi LM, Costantini TW, Hamel MG, Dierksheide JE, Coimbra R. Abdominal vascular trauma. Trauma Surg Acute Care Open 2016;1:e000015.
57. Wirth S, Hebebrand J, Basilico R, Berger FH, Blanco A, Calli C, *et al*. European society of emergency radiology: Guideline on radiological polytrauma imaging and service (short version). Insights Imaging 2020;11:135.
58. Demetriades D, Theodorou D, Murray J, Asensio J, Cornwell EE, Velmahos G, *et al*. Mortality and prognostic factors in penetrating injuries of the aorta. J Trauma Acute Care Surg 1996;40:761-3.
59. Shanmuganathan K, Mirvis SE, Chiu WC, Killeen KL, Scalea TM. Triple-contrast helical CT in penetrating torso trauma: A prospective study to determine peritoneal violation and the need for laparotomy. Am J Roentgenol 2001;177:1247-56.
60. Mellnick VM, McDowell C, Lubner M, Bhalla S, Menias CO. CT features of blunt abdominal aortic injury. Emerg Radiol 2012;19:301-7.
61. Navsaria P, De Bruyn P, Nicol A. Penetrating abdominal vena cava injuries. Eur J Vasc Endovasc Surg 2005;30:499-503.
62. Hampton M, Bew D, Edu S, Nicol A, Naidoo N, Navsaria P. An urban trauma centre experience with abdominal vena cava injuries. South Afr J Surg 2016;54:36-42.
63. Balachandran G, Bharathy KG, Sikora SS. Penetrating injuries of the inferior vena cava. Injury 2020;51:2379-89.
64. Cudworth M, Fulle A, Ramos JP, Arriagada I. GCS as a predictor of mortality in patients with traumatic inferior vena cava injuries: A retrospective review of 16 cases. World J Emerg Surg 2013;8:59.
65. Morell-Hofert D, Primavesi F, Fodor M, Gassner E, Kranebitter V, Braunwarth E, *et al*. Validation of the revised 2018 AAST-OIS classification and the CT severity index for prediction of operative management and survival in patients with blunt spleen and liver injuries. Eur Radiol 2020;30:6570-81.
66. Kozar RA, Crandall M, Shanmuganathan K, Zarzaur BL, Coburn M, Cribari C, *et al*. Organ injury scaling 2018 update: Spleen, liver, and kidney. J Trauma Acute Care Surg 2018;85:1119-22.
67. Sanjay B. Organ injury scaling 2018 update: Spleen, liver, and kidney. J Trauma Acute Care Surg 2020;89:e187.
68. O'Neill SB, Hamid S, Nicolaou S, Qamar SR. Changes in approach to solid organ injury: What the radiologist needs to know. Can Assoc Radiol J 2020;71:352-61.
69. Teuben M, Spijkerman R, Pfeifer R, Blokhuis T, Huige J, Pape HC, *et al*. Selective non-operative management for penetrating splenic trauma: A systematic review. Eur J Trauma Emerg Surg 2019;45:979-85.
70. Feliciano DV, Moore FA, Moore EE, West MA, Davis JW, Cocanour CS, *et al*. Evaluation and management of peripheral vascular injury. Part 1. Western Trauma Association/critical decisions in trauma. J Trauma Acute Care Surg 2011;70:1551-6.
71. Kuwahara JT, Kord A, Ray CE Jr. Penetrating Extremity Trauma Endovascular Versus Open Repair? In: Proceedings of the Seminars in Interventional Radiology. New York: Thieme Medical Publishers; 2020. p. 55-61.
72. Huber GH, Manna B. Vascular extremity trauma. In: StatPearls. Treasure Island, FL: StatPearls Publishing; 2021.
73. Frykberg E, Schinco M. Peripheral vascular injury. Trauma 2008;5:969-1004.
74. Gonzalez RP, Falimirski ME. The utility of physical examination in proximity penetrating extremity trauma. Am Surg 1999;65:784.
75. Lynch K, Johansen K. Can Doppler pressure measurement replace "exclusion" arteriography in the diagnosis of occult extremity arterial trauma? Ann Surg 1991;214:737.
76. Ivatury RR, Anand R, Ordonez C. Penetrating extremity trauma. World J Surg 2015;39:1389-96.
77. deSouza IS, Benabbas R, McKee S, Zangbar B, Jain A, Paladino L, *et al*. Accuracy of physical examination, ankle-brachial index, and ultrasonography in the diagnosis of arterial injury in patients with penetrating extremity trauma: A systematic review and meta-analysis. Acad Emerg Med 2017;24:994-1017.
78. Bynoe RP, Miles WS, Bell RM, Greenwold DR, Sessions G, Haynes JL, *et al*. Noninvasive diagnosis of vascular trauma by duplex ultrasonography. J Vasc Surg 1991;14:346-52.
79. Montorfano MA, Montorfano LM, Quirante FP, Rodríguez F, Vera L, Neri L. The FAST D protocol: A simple method to rule out traumatic vascular injuries of the lower extremities. Crit Ultrasound J 2017;9:8.
80. O Dell MC, Shah J, Martin JG, Kies D. Emergent endovascular treatment of penetrating Trauma: Solid organ and extremity. Tech Vasc Interv Radiol 2017;20:243-7.
81. DuBose JJ, Rajani R, Gilani R, Arthurs ZA, Morrison JJ, Clouse WD, *et al*. Endovascular management of axillo-subclavian arterial injury: A review of published experience. Injury 2012;43:1785-92.
82. White R, Krajcer Z, Johnson M, Williams D, Bacharach M, O'Malley E. Results of a multicenter trial for the treatment of traumatic vascular injury with a covered stent. J Trauma 2006;60:1189-95; discussion 1195-86.
83. Mendez-Figueroa H, Dahlke JD, Vrees RA, Rouse DJ. Trauma in pregnancy: An updated systematic review. Am J Obstet Gynecol 2013;209:1-10.
84. Brown HL. Trauma in pregnancy. Obstet Gynecol 2009;114:147-60.
85. Sandy EA, Koerner M. Self-inflicted gunshot wound to the pregnant abdomen: Report of a case and review of the literature. Am J Perinatol 1989;6:30-1.
86. Sakala EP, Kort DD. Management of stab wounds to the pregnant uterus: A case report and a review of the literature. Obstet Gynecol Surv 1988;43:319-24.
87. Sakamoto J, Michels C, Eisfelder B, Joshi N. Trauma in pregnancy. Emerg Med Clin North Am 2019;37:317-38.
88. Shakerian R, Thomson BN, Judson R, Skandarajah AR. Radiation fear: Impact on compliance with Trauma imaging guidelines in the pregnant patient. J Trauma Acute Care Surg 2015;78:88-93.
89. Raptis CA, Mellnick VM, Raptis DA, Kitchin D, Fowler KJ, Lubner M, *et al*. Imaging of trauma in the pregnant patient. Radiographics 2014;34:748-63.
90. Hui CM, MacGregor JH, Tien HC, Kortbeek JB. Radiation

dose from initial trauma assessment and resuscitation: Review of the literature. Can J Surg 2009;52:147-52.
91. Tien HC, Tremblay LN, Rizoli SB, Gelberg J, Spencer F, Caldwell C, *et al*. Radiation exposure from diagnostic imaging in severely injured trauma patients. J Trauma Acute Care Surg 2007;62:151-6.
92. McCollough CH, Primak AN, Braun N, Kofler J, Yu L, Christner J. Strategies for reducing radiation dose in CT. Radiol Clin North Am 2009;47:27-40.
93. Shanshou L, Wei Z, Xianqi W, Jiangang X, Chaojuan Z, Qianmei W, *et al*. Composition and associated factors of radiological examination in major trauma patients: A prospective observational study. Pediatr Emerg Care 2020;36:34.
94. Leeson A, Adiotomre E, Mannings A, Kotnis N, Morrison G, Wiles M. Cumulative radiation dose due to diagnostic investigations in seriously injured trauma patients admitted to critical care. J Intensive Care Soc 2015;16:12-7.
95. Wheeler JA, Weaver N, Balogh ZJ, Drobetz H, Kovendy A, Enninghorst N. Radiation exposure in patients with isolated limb trauma: Acceptable or are we imaging too much? J Clin Med 2020;9:3609.
96. Sharma OP, Oswanski MF, Sidhu R, Krugh K, Culler AS, Spangler M, *et al*. Analysis of radiation exposure in trauma patients at a Level I trauma center. J Emerg Med 2011;41:640-8.
97. Rieger M, Mallouhi A, Tauscher T, Lutz M, Jaschke WR. Traumatic arterial injuries of the extremities: Initial evaluation with MDCT angiography. AJR Am J Roentgenol 2006;186:656-64.
98. Hamilton JD, Kumaravel M, Censullo ML, Cohen AM, Kievlan DS, West OC. Multidetector CT evaluation of active extravasation in blunt abdominal and pelvic trauma patients. Radiographics 2008;28:1603-16.
99. Pereira SJ, O'Brien DP, Luchette FA, Choe KA, Lim E, Davis K, *et al*. Dynamic helical computed tomography scan accurately detects hemorrhage in patients with pelvic fracture. Surgery 2000;128:678-85.
100. Gavant ML, Menke PG, Fabian T, Flick PA, Graney MJ, Gold RE. Blunt traumatic aortic rupture: Detection with helical CT of the chest. Radiology 1995;197:125-33.
101. Inaba K, Potzman J, Munera F, McKenney M, Munoz R, Rivas L, *et al*. Multi-slice CT angiography for arterial evaluation in the injured lower extremity. J Trauma Acute Care Surg 2006;60:502-7.

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