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Ballistic Injury Imaging: The Basics

Noah Ditkofsky[1] · **Khaled Y. Elbanna**[1] · **Jason Robins**[1] · **Ismail Tawakol Ali**[1] · **Michael O'Keeffe**[1] · **Ferco H. Berger**[1]

Abstract

Purpose As of 2007, there were estimated to be at least 750 million firearms in worldwide circulation, of which 650 million of them were owned by civilians (Weiss et al. in Severe lead toxicity attributed to bullet fragments retained in soft tissue. BMJ Case Reports, 2017). Of these, approximately 270 million are in the United States, equating to 84 guns per 100 Americans [based on 2016 population statistics (assuming the number of firearms remained stable over the intervening 9 years)] and resulting in 84 997 nonfatal injuries and 36 252 fatalities in the United States in 2015. With statistics like these, it stands to reason that victims of gunshot wounds (GSW) will be imaged by most radiologists at least once in their careers. This article seeks to increase radiologists' knowledge of the pathophysiology of GSW and will review the mechanism of ballistic injury and relate these to commonly encountered imaging findings.

Important Points Ballistic injuries are a combination of the direct injury caused by the bullet along its path through the tissues and the shockwave created around that path as the bullet expends its energy. CT is the gold standard in ballistic injury assessment. MRI is not contraindicated in patients with retained ballistic fragments, but should be used with caution. The number of entry/exit wound and the number of retained ballistic fragments should be an even number, or there is a missing surface wound or a missing bullet. Retained lead in joints can result in plumbism and arthropathy.

Summary As most radiologists will encounter a ballistic injury in the course of their careers, an understanding of this unique mechanism of injury and its complications will aid in both imaging interpretation and patient care.

Keywords Ballistic injury imaging · Emergency radiology · GSW victims · Pathophysiology of GSW

Introduction to Firearms and Ammunition

Firearms (See Fig. 1 Basic Firearm Anatomy) can be classified into two broad categories, smoothbore and rifled, which are distinguished from each other by the internal contour of the barrel (see Fig. 1). Smoothbore firearms have a smooth internal contour to the barrel and include shotguns and muskets. Rifled firearms include handguns and rifles which have barrels with an internal contour of plateaus and valleys called "lands" and "grooves," respectively (Fig. 1), which are cut in a spiral down the barrel. The lands grip the projectile as it passes down the barrel forcing it to spin [1]. This spin increases the

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✉ Noah Ditkofsky
ditkofsky@gmail.com

Khaled Y. Elbanna
khaled.elbanna@sunnybrook.ca

Jason Robins
Jason.robins@sunnybrook.ca

Ismail Tawakol Ali
ismailtawakol.ali@sunnybrook.ca

Michael O'Keeffe
michaelezra.okeeffe@sunnybrook.ca

Ferco H. Berger
ferco.berger@sunnybrook.ca

[1] Medical Imaging – Emergency & Trauma Radiology Division, Sunnybrook Health Sciences Center, 2075 Bayview Ave, Toronto, ON M4N 3M5, Canada

projectile's in-flight stability in a manner analogous to that of a thrown American football. Like a thrown football, the projectile will travel point first in flight; however, due to slight imperfections in the bullet and the muzzle, this spin degrades over time. If one thinks of a projectile's path as occurring on a 3-dimensional axis projection with direction of travel along and spin around the Z-axis, degradation of this spin occurs along both the X-axis and Y-axis in a manner analogous to that of a proton precessing within the magnetic field of an MRI machine. However, unlike the proton which over time decreases its wobble to align with the magnetic field, the projectile will increase its wobble to the point where it begins to tumble and no longer travels point first in flight (Fig. 2). This becomes important in understanding the wound tract (discussed subsequently).

A cartridge of firearm ammunition is composed of four parts: the projectile(s), the propellant (or charge), the casing and the primer (Fig. 3). A primer functions to ignite the propellant which is contained by the casing. The propellant rapidly burns, converting from a solid to a hot, rapidly expanding gas as it burns. The pressure generated by the gas expanding behind the projectile forces it out of the casing imparting it with energy as it travels down the barrel. As the projectile travels down the gun barrel, the expanding gas behind it exerts a positive force until the projectile exits the muzzle, at which point, it has attained its maximal velocity. Consequently, the two factors that control the maximal energy of a projectile are the volume of powder in a cartridge and the length of the barrel the projectile must travel down. Once the projectile leaves the barrel it begins losing energy as a result of friction with the air through which it is travelling. As such, the greater the distance from the muzzle, the less energy the projectile will have to deposit.

Projectiles come in the form of shot pellets and rifled projectiles. Shot pellets (with few exceptions) come from smooth-bore firearms and are readily recognizable by their small size, round shape and multiplicity. Rifled projectiles (with the exception of rifled shotgun slugs) come from rifles and handguns and can be broadly characterized as Full Metal Jacket (FMJ), Semi-Jacketed (SJ) and Non-Jacketed (NJ) (Fig. 4). FMJ projectiles are designed to preserve their shapes without flattening or fragmentation. They are typically constructed of a cupronickel coating or "jacket" surrounding a lead core and are identifiable on radiograph by their retained shape (Fig. 5). These projectiles are used by the military, as well as by recreation shooters due to the availability and inexpensive nature of military surplus ammunition. Although fragmentation can occur, it is less common than with other projectile constructions which are designed to flatten and deform. SJ projectiles have a wide range of tip configurations, but all have a softer material (often simply exposed lead, although polymers are not uncommon) at the tip of the projectile, while the remainder is contained in a harder metal jacket. These bullets are designed

Fig. 1 Basic firearm anatomy. Panel **i** demonstrates a semiautomatic pistol and panel **ii** demonstrates a bolt action rifle both of which have a "rifled" barrel as shown in panel **iii**. *A*: Muzzle *B*: Grip *C*: Trigger *D*: Barrel *E*: Chamber *F*: Bolt *G*: Breach *H*: Buttstock

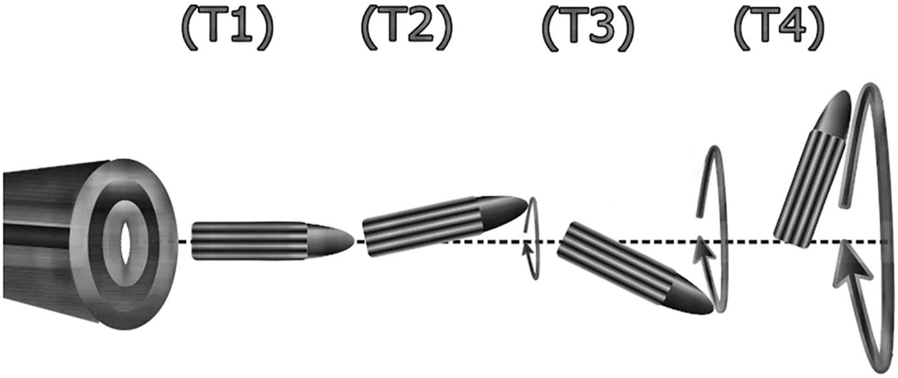

Fig. 2 Bullet tumble: when a bullet leaves the muzzle of a gun, it is rotating about its short axis with its long axis oriented along its direction of travel. However, it is also precessing slightly about its direction of travel as a result of imperfections in the bullet and the muzzle of the gun. Over time, this precession increases until the bullet starts to tumble as illustrated in this figure

Fig. 3 Anatomy of a bullet. On the left is a 7.62 mm NATO FMJ rifle round. On the right it has been broken down into its components the projectile (*), the charge (solid arrow), the casing (bracketed) with primer (arrowheads)

so that the tip flattens out on impact, while the metal jacket at the base of the projectile holds the projectile together (although in the authors' experience, it is often stripped off the lead core). This increases the surface area of the projectile as it passes through tissues and results in a greater energy deposition. SJ projectiles can be recognised on radiographs by the presence of metal of two densities and obvious deformation (Fig. 5). NJ projectiles are made entirely of soft lead, and are commonly used by shooters who cast and produce their own bullets. These projectiles deform and fragment upon impact, more widely dispersing their energy and have only one density of metal associated with their debris on radiograph.

Fig. 4 Different types of bullets: From left to right, a Non-Jacketed .44 magnum, a Semi-Jacketed .44 magnum, a full metal jacket 9 mm and Non-Jacketed 9 mm

A topic of frequent concern is MRI safety of projectiles. Almost all projectiles are MRI safe, the exception being those few that contain steel and can move in vivo [2•] under the influence of magnetic fields. In the authors' experience, it is extremely difficult to reliably determine, based on imaging, if a bullet contains ferromagnetic material—as such MRI should be used with extreme caution in patients who have metal debris adjacent to the spine, the great vessels, or intracranially. Patients who have ballistic debris in an extremity or body wall can be safely imaged, but should be closely monitored during the examination and the exam terminated if the patient experiences discomfort attributable to their retained metal.

Bullet Math and the Trauma Bay Radiograph

In order to properly interpret the imaging of patients with GSWs, clear communication with the trauma team is required. Of paramount importance is the number of entry/exit wounds on the surface of the patient. Trauma

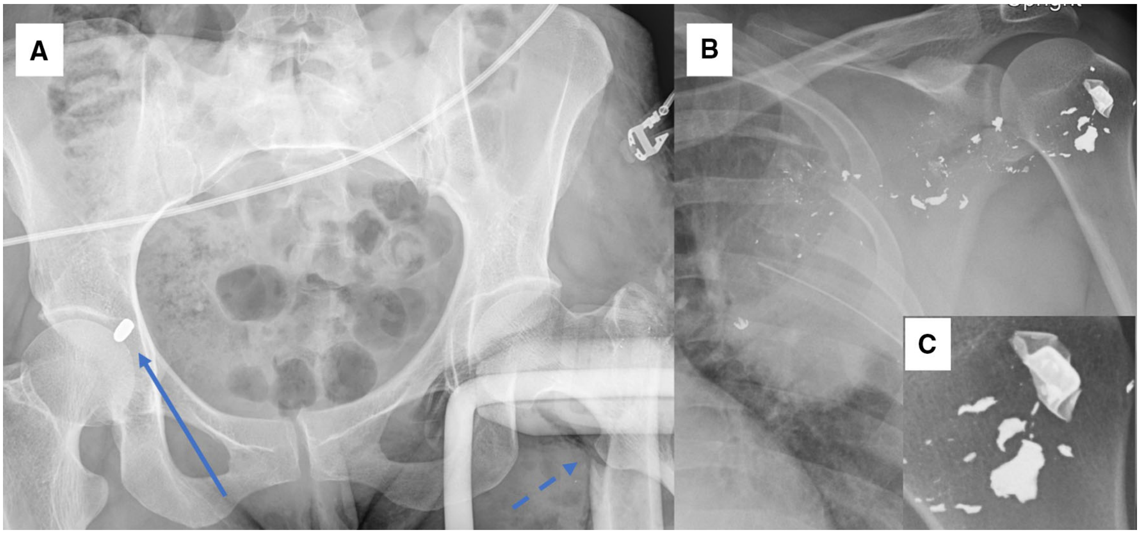

Fig. 5 Bullet identification: Panel A demonstrates a full metal jacketed bullet (solid arrow) that has shattered the left femur but itself remained intact. Panel B demonstrates a transthoracic gunshot wound with semi-jacketed bullet note the pulmonary contusion, the scapular fracture and final resting place of the bullet suggest a front to back and right to left pattern of bullet travel. Panel C is an enlargement of the main bullet mass from panel B. Note the copper jacket (less dense metal) has been stripped off of the lead core (denser metal)

radiographs typically include a chest radiograph, a pelvic radiograph and radiographs of any involved extremities. Entry/exit wounds on the skin surface should be clearly marked with a radiopaque object (BBs, paperclips and surgical gauze containing a radiopaque marker all work equally well). The number of retained projectiles on radiograph and the number of entry/exit wounds should always total an even number (See Table 1 for examples). Should the number of projectiles and the number of surface wounds not total an even number, there are three possibilities: (1) a missed surface wound or a miscount of projectiles are by far the most common in the authors' experience. This is particularly true in the case of frangible projectiles such as SJ or NJ projectiles where it is easy to mistake a single projectile that has fragmented for multiple projectiles. (2) Less common is a projectile that has deflected or embolized outside of the imaged field. It is important to recognize this possibility, particularly in patients with GSW to the chest as it should prompt imaging of the abdomen and may prompt surgical exploration. (3) A pitfall that one must always be aware of is the possibility of retained ballistic material from prior trauma. This can complicate the clinical picture in the absence of prior history or imaging.

The Role of CT

In the hemodynamically unstable patient, there is no clear role for CT prior to surgical exploration, except in perhaps in those few centers that have a CT in the trauma bay or a hybrid CT–surgical suite. In the stable patient, CT is the best imaging modality as it is fast and provides high sensitivity and specificity in identifying and characterizing traumatic injuries [3–7]. It permits clear identification of the wound tract and the involved viscera which in turn directs stable patients to operative or non-operative management. Patients with colorectal and left-sided diaphragmatic injuries are almost invariably managed surgically, and the use of CT trajectography has proven useful in delineating these injuries. Trajectographic CT images are those generated in non-standard planes along the wound tract—these have been demonstrated as highly accurate in the detection, localization and delineation of penetrating diaphragmatic injury (83–92% specificity) [8•] as well as highly sensitive in detecting colorectal injuries (88–91% sensitive) [9].

There is no "one-size-fits-all" protocol for the CT imaging of patients with GSW; rather, the protocol should be tailored to the equipment available and the clinical problem at hand. This is only possible if the radiologist is in attendance at the CT scanner at time of image acquisition. At the authors' institution, there are in-hospital radiologists available 24 h a day to attend the scanning of trauma patients and both tailor the protocol and perform trajectographic analysis as needed. If there is any concern (based on trauma bay physical exam and radiographs) for intracranial or c-spine injury, we begin with a non-contrast scan of the head and neck. This permits CT angiography (CTA) of the neck vessels (if warranted) at the same time as the chest and abdomen are imaged. We then initiate our standard contrast-enhanced CT scan of the chest, abdomen

Table 1 Bullet math example

Number of entry/exit wounds	Number of retained bulets	Total	Most likley interpretation
1	0	1	Bullet outside field of view or Missing Surface Wound
2	0	2	Through and Through GSW
1	1	2	Single GSW with retained bullet
1	2	3	Missing surface wound
2	1	3	Bullet outside field of view
2	2	4	Two GSW with retained bullets
3	1	4	One through and through GSW and one GSW with retained bullet

and pelvis, utilizing our institutional trauma protocol (Appendix 1), including CTA of the head and neck if indicated. The acquired images are then immediately reviewed by the attendant radiologist on the scanner's work terminal, and delayed phases are added as needed. These can include a 2–3-min delay to assess venous bleeding or 6–8-min-delayed urography phase if the projectile passes close to the expected course of a ureter (or through a kidney) or CT cystography if there are pelvic fractures or findings suspicious for bladder injury. There has been much debate as regards the administration of oral and rectal contrast in patients with penetrating trauma [10–14]. At our institution, oral contrast is not routinely administered, and the decision to administer rectal contrast is made on a case-by-case basis in consultation with the trauma surgery team. However, recent research has shown little benefit in rectal contrast administration [15•] and we anticipate less usage on this basis. As more institutions acquire and utilize dual-energy CT, this research will need to be revisited as the generation of virtual non-iodine images promises to permit differentiation between vascular and enteric contrast extravasation [16].

When Metal Meets Flesh—Projectile Effects

All injuries are the result of energy deposition in living tissues. Ballistic injuries are no different; with the amount of energy deposited in the tissues relating to the energy of the projectile, its composition, and design as well as the density of the tissues it encounters. As the bullet passes through flesh and bone, it converts its kinetic energy into emulsification of tissues along the direct path of the bullet as well as disruption of those tissues adjacent to the direct bullet path by propagating shock waves [17] which create a temporary cavity (Fig. 6).

The permanent tract carved by the projectile is often thought of as cylindrical, but this is a misconception. As has been discussed previously, the projectile precesses about its axis of flight; consequently, the projectile does not enter tip first. Instead, it usually enters at a slight angle. Have you ever extended your hand out of a car window while driving on the highway? When your hand is flat to the direction of travel, there is equal air pressure on the top and bottom of your hand. However, once you angle your hand, the forces are no longer equal and your hand tends to tilt toward the region of lower pressure. Something analogous happens to the projectile as it enters tissues causing it to tumble and carve an elliptical tract (Fig. 5). This can be observed, particularly when projectiles traverse the liver or lung, as a tract that increases and then decreases in size. Fragments of the projectile may be found along this tract with the largest fragments travelling the farthest by virtue of their greater kinetic energy.

The temporary cavity occurs adjacent to the projectile path and, as the name implies, is a transient phenomenon. However, this transient phenomenon can leave lasting injuries. This is most frequently observed on imaging in the lung parenchyma where the shock wave results in contusion (Fig. 7), but it can also be seen in hollow viscera, where the layers can separate and in vessels which can demonstrate dissection. Although lung contusions are seldom subtle, bowel and vascular injuries are easily overlooked as they occur outside of the permanent tract in tissues that otherwise appear undisrupted.

Bullet and Bone

Bone is the densest tissue in the human body and is the tissue most likely to both fragment and deflect a projectile. When projectiles pass through bone, there is a characteristic pattern of bevelling along the bullet's direction of travel, with the narrow margin of the bevel on the entry side of the bone and the broad end at the exit side of bone [18, 19] (Fig. 8). This is most apparent on CT and in flat bones such as the iliac wings and the calvarium but can also be seen to lesser degrees at other sites. As projectiles pass through bone, they have a tendency to drag both projectile and bone fragments in the direction of travel along the permanent tract. The importance of this is the

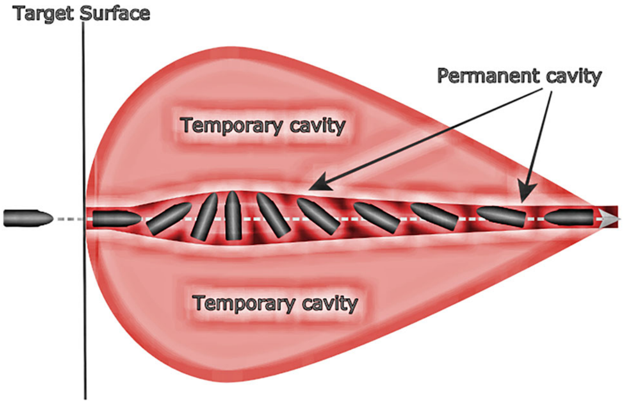

Fig. 6 Permanent and Temporary Cavity: Bullets essentially emulsify the tissue that they directly contact creating a cavity along their course. This is not perfectly cylindrical but ellipsoid due to bullet tumble. Outside of the direct path of the bullet a temporary cavity is created by the shockwave of the bullet passing through the tissues. It is important to be aware of the temporary cavity as it cause injuries outside of the direct path of the bullet

ability to determine the projectile's direction of travel which has forensic considerations in addition to surgical consideration. When there are multiple ballistic injuries, accounting for the paths of projectiles can influence the need for surgical exploration. Sometimes, projectiles become lodged in or get deflected off of bone, causing fracture patterns similar to those observed in blunt injuries [6]. In these cases, two perpendicular radiographic views or CT is useful.

Shotgun Pellets

Shotguns typically do not fire a single projectile, instead fire numerous pellets ("shot") which have the characteristic appearance of many metallic spots on radiograph (Fig. 9). At close range, shotguns produce devastating injuries as the pellets have a large amount of kinetic energy; however, the pellets spread out once they leave the muzzle resulting in a greater surface area and experience a rapid loss of velocity and consequently kinetic energy [20] as the distance travelled increases. Thus, at longer ranges, shot pellet injuries tend to be superficial and not life threatening. Shot pellets range in size from 1.27 mm (#12 bird shot) to 9.14 mm (#000 Buckshot) and can be made of a variety of materials commonly lead and steel but also polymers and tungsten (uncommon) [21]. The composition of shot pellets is important as it is safest to assume ferromagnetic shot to be MRI incompatible [2•]. Lead is non-ferromagnetic and tends to deform on impact—so, the general rule is that if there is deformed shot on radiograph, it is likely lead and MRI safe [2•].

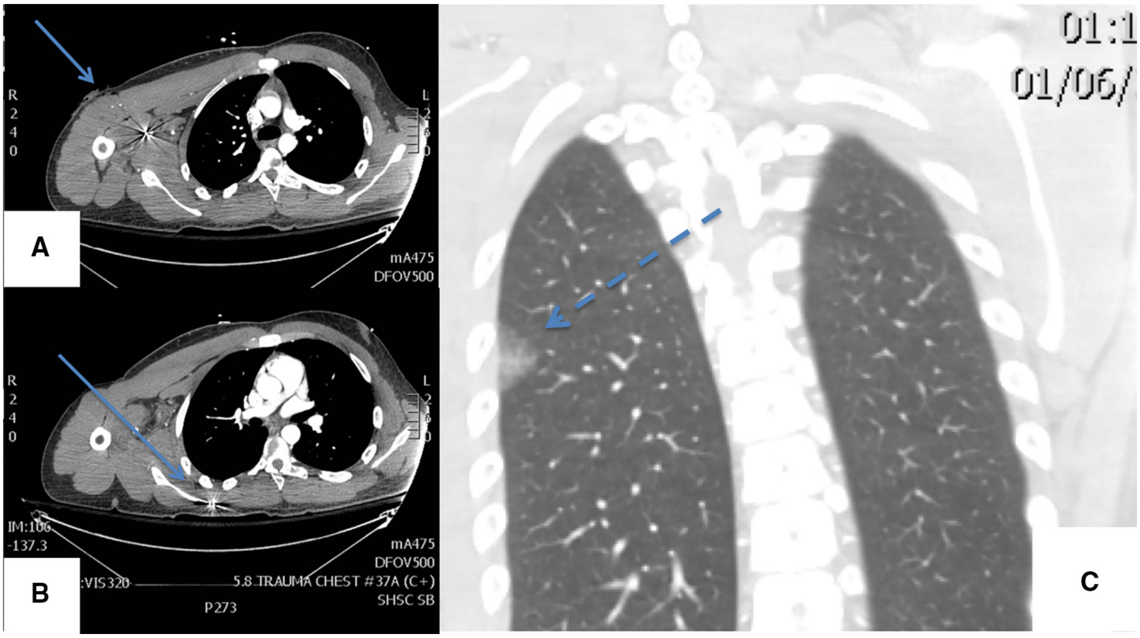

Fig. 7 Shockwave injury: Injuries outside the permanent tract of the bullet are the result of the secondary cavity or "shockwave" that occurs adjacent to the bullet tract. Panels "A" & "B" demonstrate the trajectory (solid arrows) of bullet that passes through the axilla, coming to rest adjacent to the scapula (Note the fat stranding in the axilla). Panel C demonstrates a semi-circular pulmonary contusion in the lung directly adjacent to the bullets path as a result of shockwave. There was no pneumothorax, hemothorax or rib fracture or other evidence that the bullet penetrated the thoracic cavity

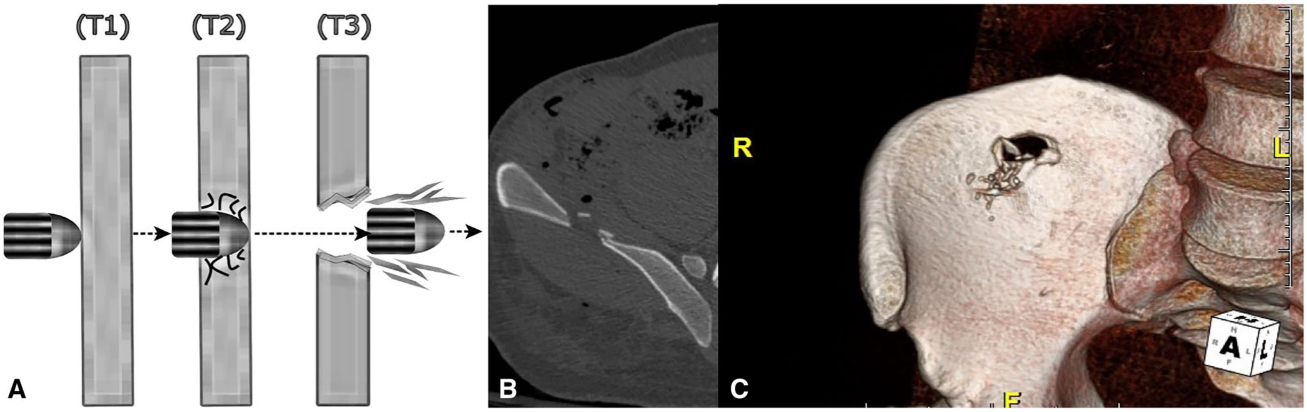

Fig. 8 Bevel pattern: When a bullet passes through bone, particularly flat bones such as the illiac wing or calvarium, the point of entry into the bone is smaller than the point of exit. This creates a beveled appearance to the fracture as graphically represented in Panel A. Panels B & C illustrate this appearance in a patient with a bullet wound through the iliac wing

Ballistic Embolus

Embolization of ballistic material occurs when a projectile or pellet has enough energy to enter a vascular structure but not enough to exit its lumen [6, 22]. Although this is more common for shotgun pellets due to their small size and the relatively low energy of an individual pellet, it can also occur with rifled projectiles. The most common end location for embolized ballistic material is the pulmonary arterial circulation—although there are numerous reports of systemic arterial embolism [23–26]. Ballistic pulmonary embolus should be suspected in the context of ballistic material on chest radiograph in the context of extra-thoracic GSW, with the differential diagnosis of transdiaphragmatic ballistic track. A transdiaphragmatic course should be suspected on radiograph if there is a pneumothorax, pleural fluid collection or findings of diaphragmatic rupture. If the patient is unstable and headed to the operating room, the surgeon will closely scrutinize the diaphragm for defects during laparotomy. If the patient is stable enough for CT, it is simple to adjust the window and level setting to minimize metal artefact and localize the bullet to a pulmonary artery branch. The absence of pneumothorax, hemothorax, findings of diaphragmatic injury, and the presence of extra-thoracic vascular injury clinch the diagnosis (Fig. 10).

Fig. 9 shotgun pellets: Lower extremity radiograph demonstrates the characteristic appearance of shotgun pellets distributed through the soft tissues. Note that many of the pellets are deformed as would be expected of lead shot

Arterial ballistic embolism occurs after a projectile penetrates the heart or the aorta and embolizes distally to occlude an end arterial branch [25]. Imaging findings in these cases typically include arterial vascular injury and ballistic material localized to the lumen of an artery. Clinically, these patients may suffer from end-organ ischaemia as manifest by paresthesia, pain, pallor, pulselessness, poikilothermia, and paralysis [27].

There is no consensus in the literature as to the the necessity of retrieval of embolized ballistic material in asymptomatic patients [28, 29]. In symptomatic patients, a combined interventional radiology and vascular surgery approach should be considered as part of a thorough risk–benefit analysis.

Plumbism and Lead Arthropathy

When lead lodges in soft tissue, it is usually harmless due to encapsulation in fibrous tissue and sequestration from systemic exposure [30, 31]. However, if lead is retained in

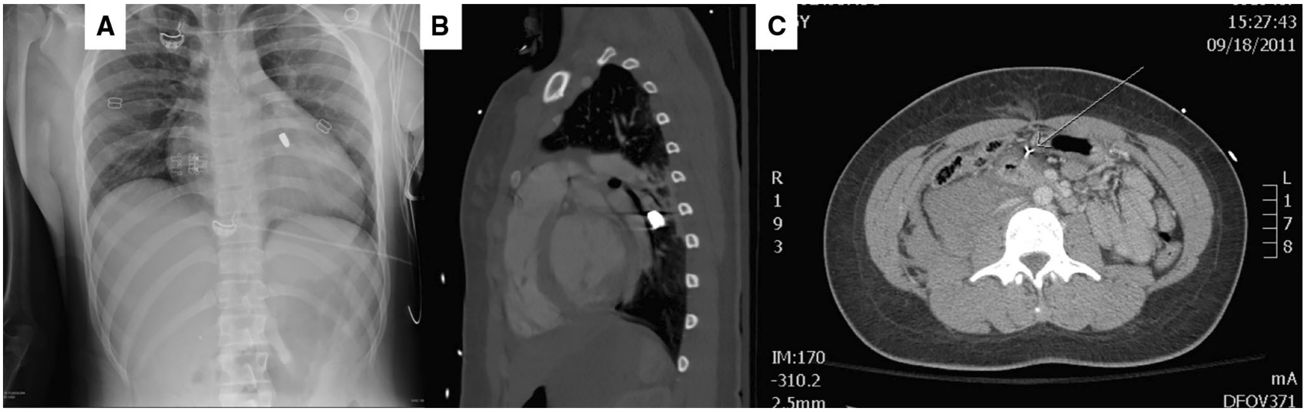

Fig. 10 Bullet embolus: A young male patient presented with a history of single abdominal gunshot wound. Chest radiograph (Panel A) demonstrated a single bullet projecting over the left infra-hilar region, but no evidence of diaphragmatic injury. A CT scan of the chest abdomen and pelvis was performed which localized the bullet to the left lower lobe pulmonary artery (Panel B) and demonstrated an inferior vena cava injury (Panel C). Note the metallic debris in panel C along the bullet tract (arrow) (Case courtesy of Dr. Joel Rubenstein)

a joint, it can dissolve in acidic synovial fluid resulting in local arthropathy as well as systemic lead poisoning (plumbism) [31–33]. Although arthropathy and systemic heavy metal poisoning are late complications of GSW, the identification of intraarticular lead in the acute phase is important to ensure appropriate referral and management. Lead arthropathy is a monoarticular process involving the joint that has retained lead fragments. On radiograph, the appearance is that of asymmetric joint space narrowing with pathognomonic deposition of high-density particulate material along the synovial and articular surfaces (Fig. 11). Cross-sectional imaging can additionally demonstrate joint effusion, inflamed synovium, and metal deposition [31, 32]. Symptoms of systemic lead poisoning are variable and include fatigue, abdominal pain, and neurological symptoms such as memory loss and rarely encephalopathy [34, 35]—any of which can bring a patient to the attention of radiology. In patients with retained projectiles or pellets and nonspecific symptoms, the radiologist should consider plumbism as it is easily excluded with a blood test [36].

Fig. 11 Lead arthropathy: Lateral radiograph of the knee demonstrates degenerative change as well as synovial staining and bullet fragments in this patient with lead arthropathy. Incidental note is made of an enchondroma in the proximal tibia (Case courtesy of Dr. Monique Christakis)

Conclusion

The assessment of GSW should begin with radiographic evaluation of the region involved, utilizing two perpendicular views if possible. The reporting radiologist should report the location of the retained projectile as well as whether the projectile has fragmented. Close communication with the trauma surgery team will ensure that there are no missing bullets. Missing bullets should prompt a search for additional surface wounds as well as embolized or deflected materials. In the stable patient, advanced imaging can better delineate the projectile path and direct the patient's care. CT can also uncover fractures that are occult on radiograph and the characteristic patterns of ballistic injury discussed above. All these propositions, however, are predicated on an understanding of the underlying pathophysiology of GSW.

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Compliance with Ethical Guidelines

Conflict of interest Noah Ditkofsky, Khaled Y. Elbanna, Jason Robins, Ismail Tawakol Ali, Michael O'Keeffe, and Ferco H. Berger each declare no potential conflicts of interest.

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

Appendix 1

Head and cervical spine protocol	
Oral contrast	None
IV contrast	None
Start location	Series (1) Foramen magnum
	Series (2) Foramen magnum
End location	Series (1) Vertex
	Series (2) T2
Interval	Series (1a) Axial 2.5 mm (for post fossa) then Axial 5 mm
	(1b) Axial 2.5 mm
	Series (2a) Helical 0.635 mm × 0.625 mm
	(2b) Helical 2.5 mm × 1.25 mm
SFOV	Series (1) Head
	Series (2) Small Body
DFOV	25 cm
Detector width	20 mm
kV	Series (1)140 kVp from foramen magnum to petrous ridge
	120 kVp from petrous ridge to vertex
	Series (2) 140 kVp
mA	Series (1)335 mA from posterior arch of C1 to petrous ridge
	300 from petrous ridge to vertex
	Series (2) auto mA
Tube rotation	Series (1) 1.0 s
	Series (2) 0.8 s
Scan delay	None
Algorithm	Standard and bone
Reformats:	Coronal and Sagittal 2.0 mm × 1.0 mm c-spine on Bone and Standard

Chest, abdomen and pelvis protocol	
Oral contrast	None
IV contrast	100cc @ 3.0 cc/s
Start location	Series (1a) Supraclavicular fossa
	Recon (2a) Lung Apex
	Series (1b) Dome of diaphragm
End location	Series (1a) mid kidney
	Recon (2a) Costal phrenic angles
	Series (1b) Ischial tuberosities
Interval	Series (1a) 0.625 mm × 0.625 mm
	Recon (2a) 2.5 mm × 1.25 mm
	Series (1b) 0.625 mm × 0.625 mm
SFOV	Large
DFOV	Series (1a) (1c) and (2) Smallest possible DFOV that will include skin all the way around at largest part of area being scanned
	Series (1b) Smallest DFOV that includes everything inside ribs
Detector width	40 mm
kV	120
mA	Auto
Tube rotation	0.6 sec
Scan delay	Series (1) smart prep
	Series (2) 70 seconds
Algorithm	Series (1a) Standard recon (2) lung
	Series 1b) Standard
Reformats	Series (1a) Axial (2.5 mm × 1.2), Coronal (3 × 3) and Sagittal (3 × 3), Oblique (2 × 1) through the Aortic Arch
	Series 1a) Axial (2.5 mm × 1.2), Coronal (3 × 3) and Sagittal (3 × 3)

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