Acute Penetrating Thoracic Trauma

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Penetrating thoracic trauma (PTT) involves a range of injuries, often caused by gunshots or stabbings. Imaging plays a crucial role in assessing stable patients for high-morbidity injuries and determining the next step in management. Evaluation of the penetrating trauma track on CT is key to detecting and characterizing clinically significant injuries. This chapter will review important CT findings of PTT with attention to more challenging and life-threatening conditions.

Penetrating injuries, particularly those affecting the thoracic region, are a significant public health issue globally [1–3]. These injuries result in considerable mortality, morbidity, and disability each year. Firearm-related deaths in the United States have been on the rise over the past decade, claiming over 40,000 lives annually since 2017. Data indicate that large urban cities experienced an increase in gun-related violence during the COVID-19 pandemic in 2020 [2, 4]. The premature mortality rate from gunshot wounds surpasses that from motor vehicle accidents. Further estimates reveal that the number of nonfatal firearm injuries treated in emergency departments is nearly double the number of deaths, bringing the total societal cost of gunshot-related injuries and deaths to approximately US$229 billion (about US$700 per person in the United States) in 2015 [2, 4].

In most trauma centers, MDCT has become increasingly important in diagnostic algorithms for hemodynamically stable patients after a stab or gunshot wound to the chest. CT helps in triaging patients for intervention or expectant nonsurgical management. This chapter reviews important CT findings in penetrating trauma with attention to life-threatening, challenging, and high-morbidity injuries. Given the intricacies and complexities of imaging findings after penetrating trauma to the thoracic cavity, the information provided is of value to all radiologists, particularly those in training or routinely involved in emergency and trauma care.

Triage and Imaging With CT

PTT represents a complex diagnostic challenge, given its association with rapid patient decompensation and high mortality rate. Historically, surgical protocols dictated immediate surgical exploration or extensive invasive investigations for all patients with PTT, particularly those with a transmediastinal trajectory, regardless of their hemodynamic stability. However, since the late 1990s, a more nuanced approach has emerged, emphasizing clinical presentation and risk stratification. CT has been pivotal in this evolution. It allows detailed visualization of mediastinal structures, aiding in trajectory evaluation and risk stratification. Contrast-enhanced CT can identify injuries that may not be immediately life-threatening but that require close monitoring or planned intervention. Series from high-volume trauma centers show the safety and efficacy of this sequential approach. Patients with PTT now benefit from a more individualized assessment, sparing some from immediate surgery while ensuring timely intervention for those at higher risk.

Patients are deemed hemodynamically unstable when presenting with hypotension unresponsive to fluid resuscitation, classically defined as a systolic blood pressure less than 90 mm Hg after 2 L of IV fluids. For all hemodynamically unstable patients, trauma protocols advocate emergent thoracotomy before or after bedside chest radiography and limited pericardial ultrasound. When performed, positive findings in these limited initial examinations often prompt immediate intervention in the trauma bay.

In hemodynamically stable patients, contrast-enhanced chest CT serves as an effective screening tool to assess wound trajectory and the risk of life-threatening structural injury. Positive CT findings may necessitate immediate surgery, while indeterminate results (such as mediastinal hematoma, pneumomediastinum, or bullet fragments near mediastinal structures) can be further evaluated using additional, more invasive methods (angiography, esophagography, esophagoscopy, and bronchoscopy). If CT reveals no surgical thoracic injuries, nonoperative clinical management may suffice. Figure 1A shows a typical penetrating trauma triage algorithm tree.

Most patients with a single PTT are imaged with contrast-enhanced CT of the chest instead of the whole-body CT scan commonly performed in blunt polytrauma. Although trauma protocols vary across institutions, arterial phase imaging of the chest is considered optimal for evaluation of PTT because it provides better characterization of the aorta, aortic branches, and cardiac injuries. My institution uses CTA of the chest with additional delayed images as needed. A quick decision for delayed imaging is made while the patient is on the CT scanner table. Depending on

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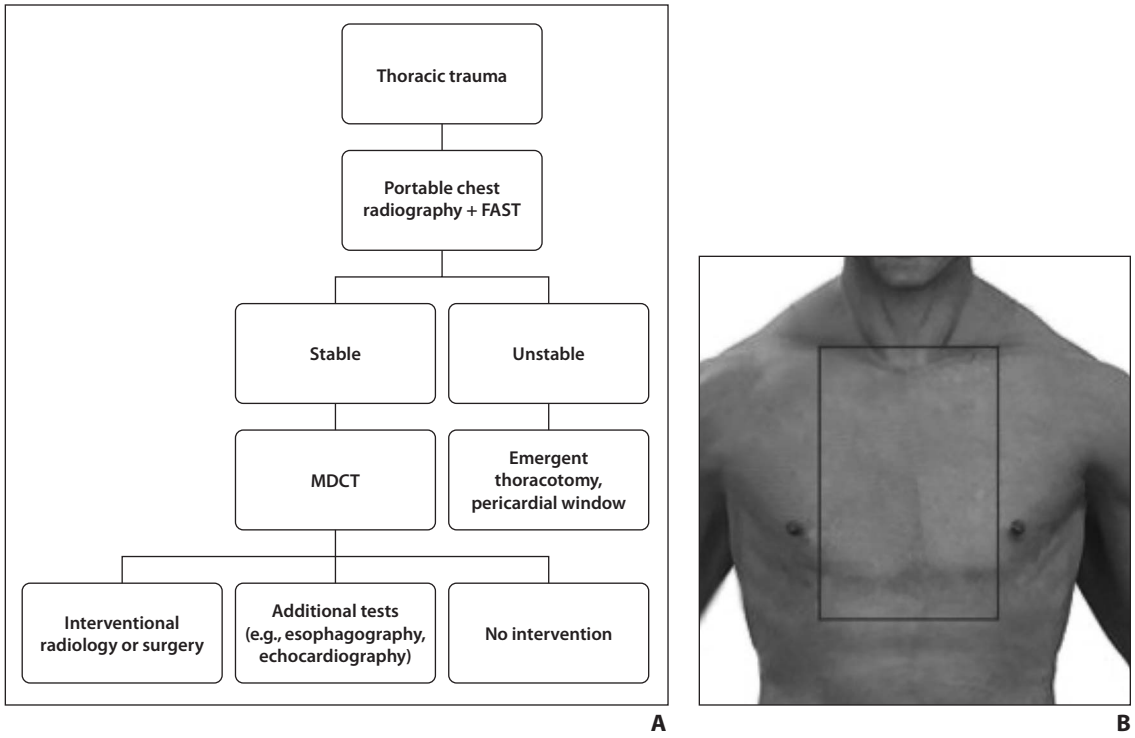


Fig. 1—Penetrating trauma triage.
A, Flowchart shows typical triage algorithm tree. FAST = focused assessment with sonography in trauma.
B, Illustration shows cardiac box.

the wound trajectory, a contiguous body part may also be included in the initial scan. For trajectories near the supraclavicular region, CTA of the neck and chest can be obtained. For those near the thoracoabdominal region, CTA of the chest and abdomen should be obtained for potential transdiaphragmatic injuries. Whole-body CT is reserved for patients with multiple gunshot wounds above and below the diaphragm and those with suspected concomitant blunt polytrauma. Table 1 contains the CT parameters we use for CTA of the chest in patients with traumatic injuries.

TABLE 1: Penetrating Trauma CTA Protocol

Protocol Component	Details
Contrast material	
Type	Iohexol
Iodine concentration	350 mg I/mL
Amount	100 mL
Bolus	4 mL/s for 20 s, then 3.5 mL/s for 20 s, then normal saline 3.5 mL/s for 14 s
Scout image scope	Lower neck through abdomen
Peak kilovoltage setting	120 kVp
Tube current–time product	200 effective mAs
Rotation time	0.5 s
Pitch	0.7
Arterial phase acquisition	
Slice collimation	0.6 mm
Image scope	Lung apices to adrenals
Initial reconstruction	3-mm thickness in the axial, sagittal, and coronal planes
Subsequent reconstruction	1.5-mm slice thickness with 0.7-mm intervals in the axial plane
Postprocessing	Maximum intensity projections and volume-rendered images reconstructed from arterial phase acquisition

Transmediastinal Injuries

Superficial or peripheral penetrating injuries of the chest are rarely life-threatening due to the lack of vital organs along the trajectory and are usually treated conservatively. By contrast, stab and gunshot wounds traversing the mediastinum pose an extremely challenging situation to trauma teams, given the presence of critical structures in the region, such as the heart, tracheobronchial tree, pulmonary artery, and aorta. Transmediastinal injuries carry a high mortality rate; many patients die at the scene of the injury [5]. The improvement of trauma response systems and faster prehospital transport has led to more patients arriving at hospitals with high-risk but potentially treatable injuries [6]. As a result, efficient assessment, usually with CT, is crucial to identify those who require surgical intervention.

A transmediastinal injury is any traumatic injury that traverses or partially traverses the mediastinum. It should be considered in all patients who have entry and exit wounds on either side of the thorax, a single entry wound with imaging showing a bullet on the opposite side of the thoracic cavity or close to the mediastinum, or a penetrating wound in the central

thorax (the cardiac box [Fig. 1B]). Common trajectories for those injuries include transverse, transpulmonary, anteroposterior parasternal, and descending from the root of the neck [7]. Injuries from a cephalic direction are more frequently associated with stab wounds, whereas those with a transverse trajectory are almost exclusively caused by gunshot wounds [5]. Both mechanism and trajectory are predictors of survival. In one study, the overall mortality rate for transmediastinal injuries was 42% for patients who suffered gunshot wounds and 7% for patients with stab wounds. Patients with a transverse transmediastinal trajectory had the highest mortality rate, at 60% [5].

Trajectory and Imaging Findings

Imaging evaluation of PTT is inherently different than that of blunt trauma, for which accurate interpretation is based on an effective search pattern of the torso. CT evaluation is conducted through a thorough analysis of wound tracks in penetrating injuries. CT typically reveals the gunshot or stab wound track, which may include air, blood products, and bullet and/or bone fragments. These features are more evident in higher energy injuries with ballistic fragments along the trajectory. Stab wounds may not reveal the full extent of the wound track immediately. Radiopaque markers (such as paper clips) can be placed superficially at entry and exit sites to aid in determining the track. Trajectory evaluation guides the radiologist and allows fast detection of life-threatening conditions, helping with organ injury characterization and determining whether additional workup is necessary.

Challenges in assessing wound tracks arise with multiple penetrating injuries and when projectiles rebound off bony structures, leading to nonlinear trajectories. Projectile embolization is a rare phenomenon in which the projectile breaches a vascular structure and travels to a distant location from its entry point. Although mismatches in positioning due to differences in respiration and arm placement between the time of trauma and imaging can introduce errors, they usually do not hinder accurate diagnoses [8]. The routine use of standard and curved multiplanar reformats helps delineate the trajectory and characterize underlying organ injuries.

Vascular Injuries

Vascular injuries in PTT commonly affect the thoracic aorta, aortic arch, and proximal great vessels. Unfortunately, patients with these injuries face a grim prognosis, with 90–100% mortality rates before reaching the hospital. For those who arrive hemodynamically stable, CTA has replaced conventional angiography as the diagnostic tool of choice for traumatic vascular injury evaluation (Fig. 2). In addition to being fast and noninvasive, CTA provides significant clinical advantages by localizing the specific site of vascular injury, defining the lesion severity, detecting end-organ ischemia, and evaluating for nonvascular injuries that may require urgent intervention [9, 10]. Imaging findings of arterial injury may be grouped into direct (less sensitive but more specific) and indirect (more sensitive but less specific)

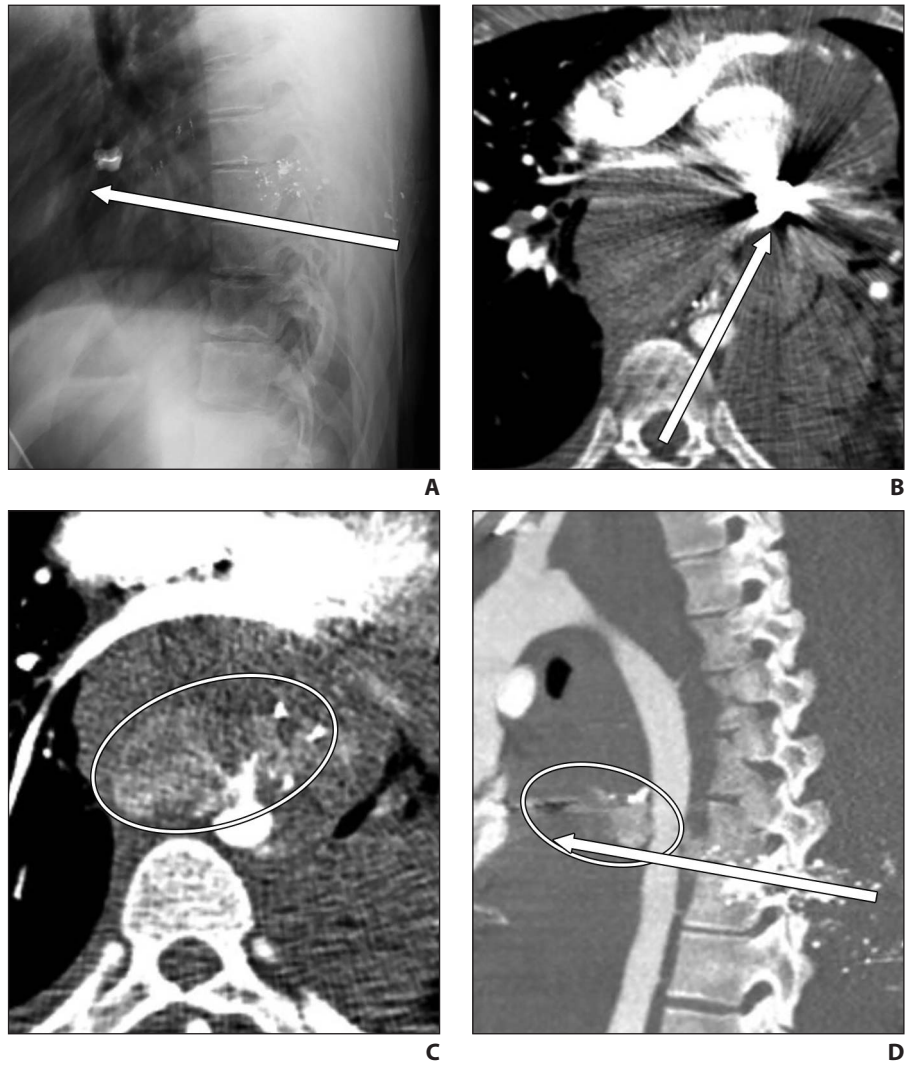


Fig. 2—41-year-old patient with penetrating aortic injury after gunshot wound to mid back. Patient had no exit wound and volatile blood pressure.
A, Cross-table lateral radiograph shows multiple bullet fragments in transmediastinal trajectory (*arrow*), highly concerning for underlying life-threatening injury.
B, Axial CTA image shows trajectory (*arrow*) coursing through descending thoracic aorta, large hematoma surrounding posterior mediastinum, and large bullet fragment embedded in left atrial pericardium. Metal streak artifact limits evaluation of injury to heart.
C, Axial CTA image shows hematoma in posterior mediastinum with evidence of active contrast material extravasation (*oval*) and clear traumatic defect in anterior descending thoracic aorta wall.
D, Sagittal reconstruction shows relationship of trajectory (*arrow*) to traumatic aortic injury (*oval*). Patient underwent endovascular repair and survived. No cardiac injury was reported.

signs. Typical CT findings of arterial injury are listed in Table 2.

In the setting of ballistic injuries, streak artifacts from adjacent bullet fragments may limit evaluation for direct signs of arterial injury. In such cases, further evaluation with conventional angiography may be indicated.

TABLE 2: Imaging Signs of Penetrating Arterial Injury

Direct Signs	Indirect Signs
Abrupt change in caliber and/or contour	Indistinct perivascular fat planes
Vessel occlusion	Perivascular hematoma
Contrast material extravasation	Proximity to ballistic fragment
Intraluminal filling defects (mural thrombi, intimal flaps)	End organ hypoenhancement (distal emboli from intraluminal thrombus)
Pseudoaneurysm	
Arteriovenous fistulas	

Cardiac Injuries

Although penetrating cardiac trauma is rare, accounting for only 0.1% of all trauma admissions, we should consider the possibility of cardiac injury whenever PTT involves the cardiac box. Most cases of penetrating cardiac trauma result from stab or gunshot wounds [1]. Penetrating cardiac injury has a high prehospital mortality rate approaching 94% and an in-hospital mortality rate of 50% for initial survivors [11]. The mechanism of injury and physiologic status on arrival have important prognostic value, with a higher mortality rate for gunshot wounds than stab wounds and for those hemodynamically unstable. Death usually results from cardiac tamponade or active hemorrhage, and immediate surgical intervention is the only meaningful treatment of unstable patients.

Initial screening of patients is performed using an extended focused ultrasound assessment, which is used to evaluate traumatic hemopericardium. CTA has an important role in evaluating trajectory and has high accuracy in detecting hemopericardium and pneumopericardium (Fig. 3). Hemopericardium and/or pneumopericardium detected on CT has a sensitivity of 76.9%, specificity of 99.7%, PPV of 90.9%, and NPV of 99.1% for cardiac injuries [11].

Due to its more anterior and superficial location, the right ventricle is the most injured cardiac chamber, followed by the left ventricle, right atrium, and left atrium [1, 11]. Left atrial and ventricular injuries have the highest mortality rates, approaching 80%, compared with a 63% mortality rate for right atrial injury and a 49% mortality rate for right ventricular injury [1, 11]. Patients with stab wounds have isolated right ventricular involvement (35%) more commonly than left ventricular involvement (25%), but 30% of the time, more than one chamber is injured. Ballistic injuries com-

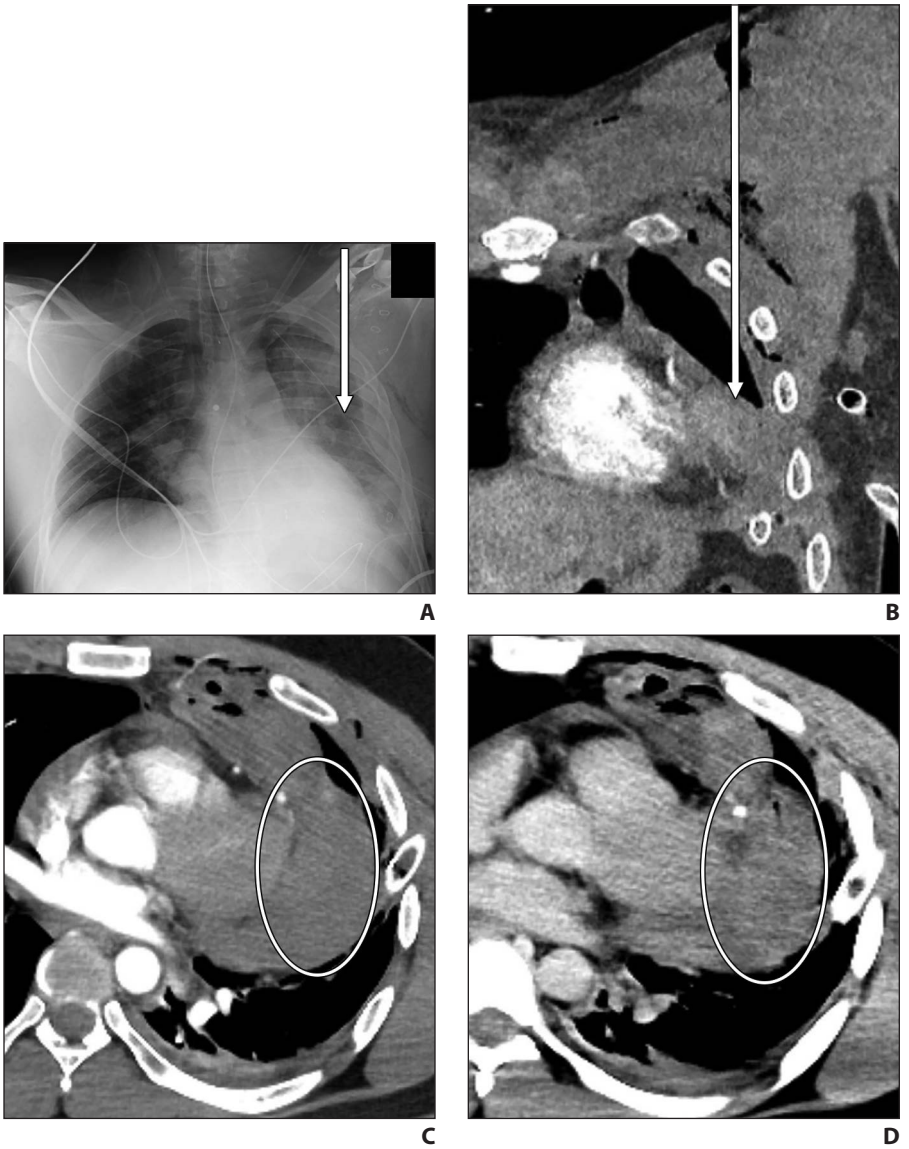


Fig. 3—24-year-old patient with pericardial injury and active bleeding in left axilla after multiple stab wounds to thorax. Chest tube placement and axillary exploration were performed before CTA of chest.
A, Anteroposterior radiograph shows common craniocaudal trajectory (*arrow*) of stab wound to left anterior chest wall from right-handed assailant.
B, Coronal CT shows gas along track (*arrow*).
C and **D,** Arterial (**C**) and delayed (**D**) phase axial CT images show large hemopericardium (*oval*) with no active arterial extravasation. Thoracotomy was performed, which showed pericardium injury with small bleeding veins.

monly have through-and-through injuries with concomitant hemorrhage, cardiac tamponade, and shock [1].

Tracheobronchial Injury

Tracheobronchial injury is a rare imaging finding after PTT. The incidence is uncertain because 30–80% of patients with tracheobronchial injuries die before reaching the hospital [12]. Those who survive usually present with hemoptysis, neck and/or chest emphysema, pneumomediastinum, persistent large pneumothorax, or large air leak despite chest tube placement. Unlike blunt trauma, which affects the fixed distal thoracic trachea, airway injuries from penetrating trauma usually affect the anterior extrathoracic trachea in the lower neck, given the more exposed location.

CT is the most sensitive imaging modality for detection of pneumomediastinum. Pneumomediastinum, although sensitive, is not a specific sign for diagnosing tracheobronchial injury. CT may identify more specific direct tracheobronchial injury signs, such as the site of tracheal wall discontinuity, focal tracheal deformity, and tracheal ring fracture along the trajectory. Indirect signs such as an overdistended endotracheal balloon (> 2.8 cm) or a balloon that extends beyond the normal confines of the trachea should also raise suspicion for a tracheal injury [1]. Bronchoscopy is the reference standard in diagnosing a tracheobronchial injury. These injuries can lead to significant morbidity, including the development of tracheoesophageal fistulas, tracheal stenosis, mediastinitis, and empyema.

Esophageal Injury

Esophageal injury presents a diagnostic challenge and can often be present despite initial lack of symptoms and hemodynamic stability, with delayed detection associated with increased mortality. On CT, identifying a projectile or penetrating injury trajectory close to the esophagus should raise clinical suspicion. Symptoms of dysphagia, hematemesis, or stridor may be present, although these clinical features are unreliable within the context of trauma.

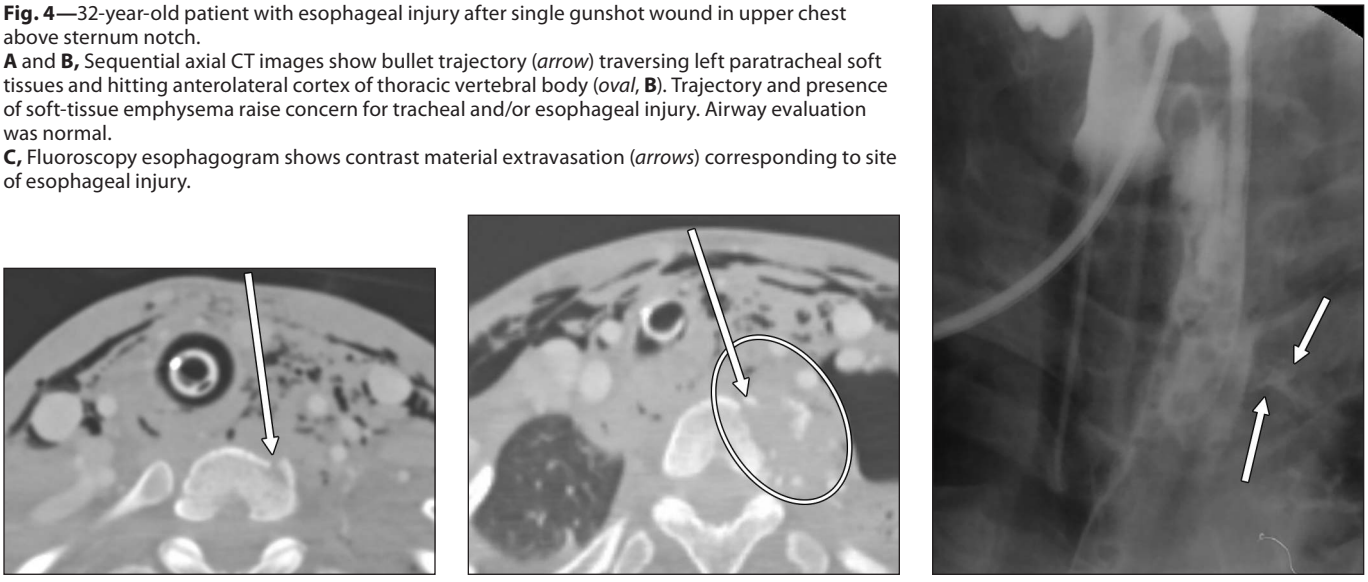
Mediastinitis is a complication of esophageal injury with a high mortality. Classic imaging findings of mediastinitis include left-sided pleural effusion and soft-tissue emphysema, which are neither sensitive nor specific. Initial CTA findings such as air bubbles around the esophagus, thickening of the esophageal wall with adjacent inflammatory stranding, and discontinuity of the wall suggest injury.

Whenever esophageal injury is suspected, the patient should be assessed with esophagoscopy and/or esophagography (Fig. 4). Flexible esophagoscopy has high sensitivity and specificity for detecting traumatic injury, consistently over 95% when trained endoscopists are available. Whereas esophagography was traditionally performed via fluoroscopy, CT esophagography with contrast material administered either orally or via orogastric tube has shown similar sensitivity and specificity as well as some advantages [13, 14]. Low-osmolality water-soluble contrast materials such as diatrizoate meglumine are the agents of choice. Follow-up esophagography with barium may be performed if no leak is identified during the initial evaluation.

Pulmonary Injury

Pulmonary injuries can be divided into pulmonary contusions, hematomas, lacerations, and herniations [1]. Pulmonary contusions (Fig. 5) are the most common type of injury. They result from disruption of the lung parenchyma, leading to subsequent filling of the airspace and interstitium with hemorrhage or fluid. Contusions appear as fluffy, nonsegmental ground-glass and/or airspace opacities that do not respect the pleural boundaries. They tend to occur close to the chest wall in the periphery of the lung, showing a 2- to 3-mm area of subpleural sparing. Air bronchograms can be present, often as a result of the pressure wave of the ballistic injury, and commonly contour the area of the trajectory cavity. Volume resuscitation may cause contusions

Fig. 4—32-year-old patient with esophageal injury after single gunshot wound in upper chest above sternum notch.
A and **B,** Sequential axial CT images show bullet trajectory (*arrow*) traversing left paratracheal soft tissues and hitting anterolateral cortex of thoracic vertebral body (*oval*, **B**). Trajectory and presence of soft-tissue emphysema raise concern for tracheal and/or esophageal injury. Airway evaluation was normal.
C, Fluoroscopy esophagogram shows contrast material extravasation (*arrows*) corresponding to site of esophageal injury.



A **B** **C**

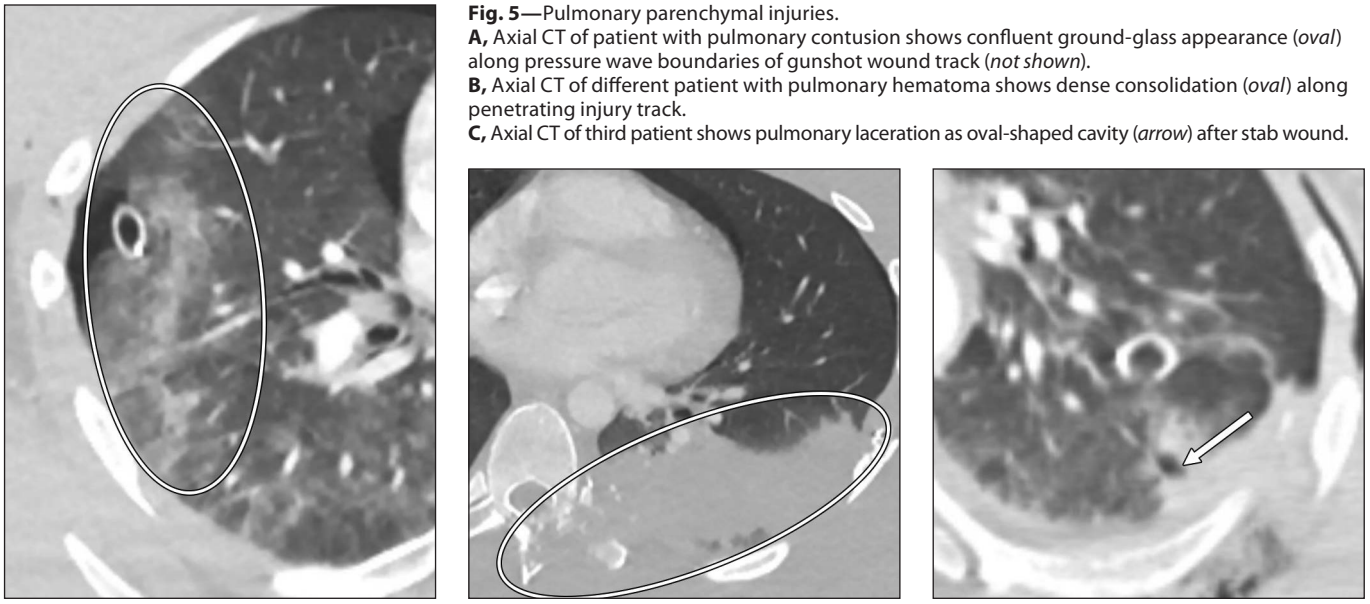


Fig. 5—Pulmonary parenchymal injuries.
A, Axial CT of patient with pulmonary contusion shows confluent ground-glass appearance (*oval*) along pressure wave boundaries of gunshot wound track (*not shown*).
B, Axial CT of different patient with pulmonary hematoma shows dense consolidation (*oval*) along penetrating injury track.
C, Axial CT of third patient shows pulmonary laceration as oval-shaped cavity (*arrow*) after stab wound.

to increase in size, usually in the first 24–48 hours. It may be challenging to visualize contusions on chest radiography, but they are readily apparent on CT within minutes after the injury. A contused lung can result in respiratory distress and serve as a nidus for infection. Most develop within several hours of injury and tend to resolve within 48–72 hours. Some contusions may persist for more than a week. Unresolved contusions should be further assessed for superimposed processes, such as pneumonia or acute respiratory distress syndrome.

Pulmonary hematomas are collections of blood within the lung parenchyma or a confined cavity. They present as dense areas of consolidation with convex borders near or within the penetrating injury track. They may be associated with an adjacent vessel injury and can obscure underlying lung lacerations. Pulmonary hematomas usually resolve more slowly than contusions and can be a nidus for infection.

Pulmonary lacerations are linear, round, or oval lung parenchymal defects filled with air and/or blood that are frequently surrounded by contusions. They are relatively common in penetrating trauma but rare in blunt trauma. They can be filled with air (pneumatocele), blood (hematocele or hematoma), or both (hematopneumatocele). Lacerations may present as a solitary cavity (most common) or numerous small cavities that produce a Swiss cheese appearance. The various appearances of lacerations can be confused for pneumonia, abscess, nodules, mass, or loculated pneumothorax. Lacerations involving the pleura may lead to the development of pneumothorax. If the trajectory causing the laceration involves the pleura and the airway, a bronchopleural fistula may form, resulting in an air leak.

Lung herniation occurs when a portion of the lung parenchyma protrudes through a chest wall defect at sites of penetrating injuries, displaced rib fractures, or chest tube insertions. Lung herniations most commonly occur within the anterior chest wall because of the reduced muscular support. CT allows detection of chest wall defects and lung parenchymal protrusions that often do not resolve independently. Narrow-necked herniations and patients who are mechanically ventilated have a higher risk of incarceration and strangulation of lung parenchyma, which can result in respiratory distress and possibly necrosis [1].

Pleural Injury

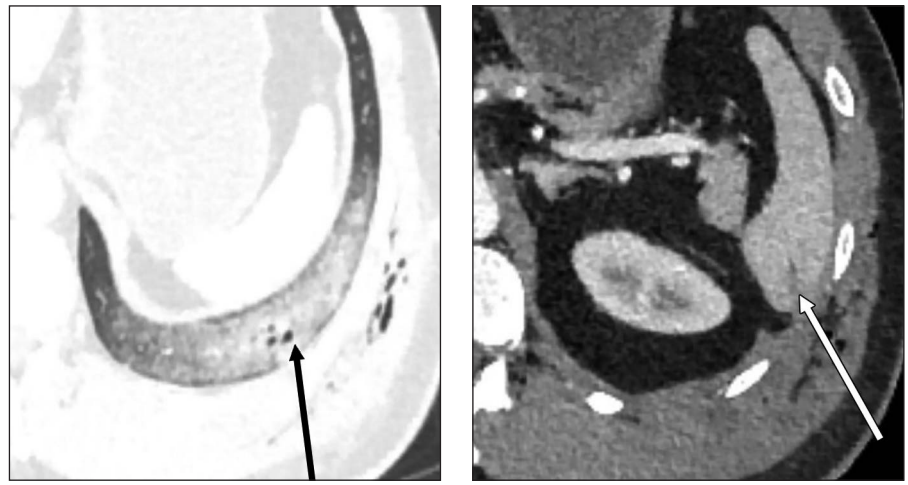
Pneumothorax is a common finding after PTT. It results from disruption of the pleura by the projectile, stabbing object, or associated rib fracture. Its presence should be assumed in most cases of PTT, and most trauma algorithms recommend immediate chest tube placement, sometimes in the field. Pneumothorax can be overlooked on initial triage portable chest radiographs, as air tends to collect in the anterior and inferior pleural space. In one study, almost 40% of pneumothoraces diagnosed via CT were missed on initial trauma chest radiographs.

Small pneumothoraces may be monitored conservatively with repeat radiographs every 4–6 hours. Diagnosing pneumothorax, regardless of size, is critical to managing patients on positive pressure ventilation or those undergoing general anesthesia as they are at increased risk of enlargement and developing tension pneumothorax. Chest tube thoracotomy may be performed, despite the initial small size of a pneumothorax, in these patients. Tension pneumothorax results in mass effect on the mediastinal structures and contralateral lung, impairing oxygenation or reducing cardiac output, contributing to cardiovascular instability after penetrating pleural injuries.

Hemothorax is another common complication of PTT, usually from direct tissue injury along the trajectory within the pleura. Significant or ongoing bleeding into the pleural space may arise from injured intercostal vessels, lung parenchyma, or cardiomediastinal vasculature. Cardiac output may be compromised by hypovolemia from a large hemothorax or by increased intrathoracic pressure. Hematocrit levels may be seen in these collections as clotted blood layers. He-

mothoraces from an arterial source often rapidly accumulate and are large, resulting in mass effect and displacement of the mediastinum and lung. Active extravasation on CTA would also indicate an arterial source of hemothorax.

Most hemothoraces are treated with chest tube placement. Undrained pleural blood is a rich nidus for infection and subsequent empyema formation, and fibrothorax is a late complication. Chest radiographs are unreliable in determining the amount of residual clot in the thoracic cavity; therefore, CT is preferred to evaluate their evolution. Many institutional trauma protocols advocate surgical thoracotomy for cases of immediate loss of 1000 mL of blood from the pleural cavity, tube output exceeding 200 mL/h for 4 hours, or a large volume of coagulated blood within the pleural space.



A **B**

Fig. 6—22-year-old patient with diaphragmatic injury and opening in left lower chest wall from stab wound.
A and **B,** Sequential axial CT images on lung (**A**) and soft-tissue (**B**) windows show penetrating track associated with small lung (*arrow*, **A**) and splenic (*arrow*, **B**) lacerations. Adjacent injuries above and below diaphragm should be highly suspicious for concomitant diaphragmatic injury, although typical small penetrating traumatic defect may be impossible to visualize.

Chest Wall Injury

The osseous structures of the chest wall are frequently injured in penetrating trauma and are an important source of morbidity and an important prognostic indicator. Fractures of the first three ribs may be associated with neurovascular and tracheobronchial injuries. Fractures of the lowest three ribs are associated with diaphragmatic and abdominal organ injuries (particularly liver, spleen, and kidneys). Displaced rib fractures can bleed, injure intercostal vessels, or tear the chest wall musculature. Flail chest, characterized by fracture of at least three consecutive ribs in two or more places, is uncommon in penetrating trauma. Sternal fractures may be associated with vascular, cardiac, and mediastinal injuries. The presence of a peristernal or retrosternal hematoma should prompt a search for a sternal fracture and possibly accompanied injuries.

Hemorrhage may occur in the chest wall musculature and extrapleural space. Extrapleural hematomas typically remain contained and do not migrate or change in configuration. They are commonly associated with rib fractures. Extrapleural hematomas appear as a peripheral convex opacity, showing an apex that points toward the lung parenchyma. An expanding extrapleural hematoma should be evaluated with CTA to search for an arterial source of bleeding, particularly when apical.

Diaphragmatic Injury

Diaphragmatic injury (DI) is a relatively rare but severe traumatic finding that remains a diagnostic challenge to radiologists and surgeons. Early detection followed by surgical repair is essential to prevent life-threatening complications such as bowel herniation and strangulation. The estimated incidence of diaphragmatic injury is 10–15% in penetrating injuries of the torso. Although penetrating trauma has a higher incidence of diaphragmatic injury, blunt trauma is responsible for most cases due to its higher prevalence (80–85% blunt vs 15–20% penetrating) [15].

Imaging diagnosis of acute traumatic diaphragmatic injury is difficult and vastly underreported, particularly without organ herniation into the chest. In contrast with blunt trauma, penetrating injuries to the diaphragm usually result in a defect 1–2 cm in length without evisceration. Small fat-containing hernias may be the only sign of penetrating DI. These small diaphragmatic defects are associated with an increased risk of viscus herniation and subsequent strangulation [15].

Stab wounds have a predilection for the left hemidiaphragm that is attributed to the higher incidence of right-handed attackers, with assaults occurring facing the victim (Fig. 6). Gunshot wounds affect both hemidiaphragms with equal frequency and can create a blast effect that may result in a DI without the formation of a defect.

Chest radiographs have low sensitivity for diagnosis of DI, ranging from 24% to 50%. The accuracy of CT is better, with sensitivities around 71–90% and specificity of 98–100% [15]. The generation of multiplanar reconstructions and 3D images on CT aids in diagnosing DI. Many signs on MDCT have also been described to aid the diagnosis of DI [15].

Conclusion

PTT includes a variety of life-threatening injuries and remains a diagnostic and management challenge. The use of a systematic approach to rapidly triage and identify unstable patients in need of immediate intervention and those hemodynamically stable who can benefit from a more thorough imaging investigation is key to improving outcomes. CTA of the chest is the imaging workhorse for evaluating stable patients with PTT, as it allows characterization of the trajectory and detection of underlying organ injuries. The discussed imaging findings in PTT help determine which patients need immediate surgical intervention and which can benefit from nonoperative management and/or more

focused tests such as echocardiography, pericardial window, bronchoscopy, esophagoscopy, or esophagography. This stepwise approach to stable patients has been the standard of care in major trauma centers and helps avoid costly, timely, and often needless interventions.

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