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Penetrating Injuries to the Lung and Heart: Resuscitation, Diagnosis, and Operative Indications

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Abstract Penetrating injuries to the thorax have the potential to disrupt two vital life-sustaining systems: the respiratory and the cardiovascular system. These injuries have the potential to be rapidly fatal and thus a rapid, organized, and logical approach to the evaluation and resuscitation of these patients is critical. This article briefly reviews the basic pathophysiology of penetrating chest wounds and the evaluation of both stable and unstable patients after penetrating chest injury. The recent literature is reviewed, including recent findings on screening for occult penetrating cardiac injuries, the use of needle decompression for pneumothoraces, and the expanding role of ultrasonography in the evaluation of penetrating thoracic trauma. Our goal is to review the initial management and resuscitation of patients with penetrating wounds to the thorax, with an eye toward the injuries most likely to rapidly result in death.

Keywords Pneumothorax · Hemothorax · Penetrating cardiac injury: penetrating lung injury · Diaphragm injury

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Introduction

While penetrating injuries to the thorax can be highly lethal, for patients who reach the hospital alive, mortality in recent military and civilian series has ranged from 8.4 to 18.0 % [1–4]. Overall, injuries to the thorax account for 37 % of deaths associated with penetrating trauma [5]. It is clear that to maximize the chance for patient survival, there is little room for error in the diagnosis and management of these injuries.

Pathophysiology

Regardless of body region, penetrating injury is broadly categorized into stab wounds and ballistic injuries. Ultimately, a comparison of the bullet and knife wound management demonstrates more similarities than differences. However, there is a rationale for approaching them differently. First, gunshot wounds—especially from high-velocity weapons—are associated with more tissue injury, due to their greater kinetic injury. Second, stab wounds may be somewhat more predictable in their course and in the proximity of internal injuries to corresponding skin wounds. However, both of these differences represent potential pitfalls if they lead to underestimation of knife injury, which can be massively destructive and can occur far from the external wound.

Organs Injured

Compared to blunt trauma, penetrating trauma is far less likely to cause significant structural damage to the chest wall, with the exception of shotgun injury and some high-velocity wounds. Lethal thoracic injury typically results from lung, heart, intercostal artery, or great vessel injury. The extreme time-sensitivity of these injuries leads the paradoxical observation that in remote or poorly developed care systems where pre-hospital times are inordinantly long, the survival rate of those who arrive alive will be unusually high, since the most fragile and severely injured patients will die en route [6].

Imaging in Penetrating Thoracic Trauma

Ultrasonography in Penetrating Thoracic Trauma

Over the past 2 decades, the Focused Assessment with Sonography in Trauma (FAST) exam has become the initial imaging test of choice in truncal trauma and is taught as a part of the Advanced Trauma Life Support (ATLS) protocol developed by the American College of Surgeons. On the basis of studies demonstrating ultrasound's superiority to supine chest radiography (CXR) for the detection of hemothorax and pneumothorax, the extended-FAST exam (e-FAST) has been developed, which adds examination of bilateral pleural spaces to the standard pericardial, peri-hepatic, peri-splenic, and pelvic views of the FAST exam. Ultrasonography as an initial test is significantly faster than CXR, taking less than 1 min in some studies [7], and it can identify a variety of life-threatening injuries in multiple body cavities. The e-FAST literature suggests that the sensitivity of e-FAST is significantly higher than CXR for pneumothorax and rivals that of subxiphoid pericardial window for hemopericardium.

Since 2011, seven prospective evaluations [7–13] and three meta-analyses [14, 15, 16••] have compared the extended FAST exam (e-FAST), which includes examination of bilateral pleural spaces for pneumothorax, to CXR and CCT. In the most recent meta-analysis, e-FAST has a sensitivity of 78.6 % (95 % CI, 68.1 to 98.1) for the detection of pneumothorax, whereas supine CXR had a sensitivity of only 39.8 % (95 % CI, 29.4 to 50.3) [16••].

Two studies have examined the value of bedside ultrasound in the diagnosis of hemopericardium. The first was a prospective, multicenter study by Rozycki et al. in 1999, which examined 261 patients and reported a sensitivity of 100 % for ultrasound diagnosis of hemopericardium as compared to subxiphoid pericardial window (SPW) [17]. A weakness of this study was the low incidence of penetrating cardiac injury (PCI) in the study population (29 out of 261 patients). A second, prospective comparison was recently published by Nicol et al., comparing ultrasound to SPW in 172 patients with penetrating thoracic wounds, with 135 PCI amongst them [18••]. Although they found that the sensitivity of ultrasound was 87 %, which is lower than the first study, the authors identified two factors that appeared to account for the majority of the false-negative exams. In 6 of the 18 false-negative exams, pneumomediastinum or pneumopericardium was present on ultrasound which resulted in an equivocal test due to impaired visualization. Of the remaining 12 false-negatives, 11 had hemothoraces which other authors have noted can decrease the sensitivity of ultrasound for detecting hemopericardium due to decompression of the cardiac injury into the hemothorax [19, 20]. There was a single patient who had two negative ultrasound examinations, was discharged home, and returned with a symptomatic pericardial effusion.

Chest Computed Tomography in Penetrating Thoracic Trauma

Chest computed tomography (CCT) is the "gold standard" for diagnosing hemothorax and pneumothorax, due to its ability to provide high-resolution cross-sectional imaging [16••]. In addition to providing excellent anatomic information regarding chest wall, pulmonary, and pleural space injuries, a recent study by Plurad et al. demonstrates that CCT is also highly sensitive for PCI. They examined 333 patients with penetrating thoracic injuries and found that, as with ultrasound, the finding of hemopericardium or pneumopericardium on CCT had a sensitivity of 76.9 % for PCI [21]. When they further investigated the patients with "false-negative" CCT, all of them had CT findings that prompted emergent surgical exploration and prompt diagnosis of the injury, including the presence of large caked hemothorax, pneumomediastinum, mediastinal hematoma, or visible tracts in close proximity to the heart. Thus, when factoring in all of the clinically significant findings that changed management, they felt that CCT had a sensitivity of 100 % [21].

Resuscitation, Evaluation, and Management of the Stable Patient

Evaluation of the Stable Patient

In hemodynamically stable patients, the initial evaluation is focused on identification of a number of occult injuries, including cardiac laceration, hemothorax and pneumothorax, diaphragm injury, and occult abdominal injury. Ultimately, the majority of thoracic injuries can be treated with tube thoracostomy alone, but the consequences of missed injury can be dire [22].

Identification of PCI

Significant cardiac injuries can present with stable vital signs, but delayed decompensation can be rapid and catastophic. Various authors have attempted to define a region of the thorax in which penetrating wounds should prompt a heightened level of suspicion for PCI, such as the "cardiac silhouette" or "precordium," [23, 24] "cardiac proximity," [25] "cardiac silhouette," "cardiac box," [26], and "cardiac zone." [18••] A weakness of all of these rules is that they can lead to an inappropriately low degree of clinical suspicion for PCI.

Degiannis et al. found that the mortality of extra-precordial wounds was 25 % compared to 4 % for wounds to the precordium [27], suggesting that this bias exists and can negatively impact patient outcomes.

After completing the primary and secondary survey according to ATLS guidelines, all patients with penetrating thoracic wounds should be examined with FAST or e-FAST. In young, healthy patients, the presence of any amount of fluid within the pericardial sac should be considered a positive exam. In the event of an equivocal US, further evaluation for PCI is recommended, either with subxiphoid pericardial window (SPW) or chest computed tomography (CCT). In the event of a negative ultrasound, a CCT and/or repeat ultrasound at 24 h should be obtained if there is any hemothorax on CXR or ultrasound, and in any patient with high clinical suspicion of PCI [18••].

A recent study from the Nicol and colleagues suggests that pneumopericardium should be managed the same as hemopericardium. Nicol and colleagues studied 21 hemodynamically stable patients pneumopericardium found on CXR, ultrasound, or CCT. All of the patients were initially observed for 24 h prior to performing a delayed SPW. During that time, two patients developed tension penumopericardium requiring emergency SPW; an additional ten patients had hemopericardium at the time of the delayed SPW, four of whom underwent sternotomy. Two sealed cardiac injuries were found, neither requiring repair. Given the 50 % coincidence of hemopericardium and the 10 % incidence of delayed tension pneumopericardium, they concluded that any patient with pneumopericardium present on CXR, CT, or ultrasound should be further evaluated with SPW [28].

In the case of thoracoabdominal wounds, laparoscopic transdiaphragmatic pericardial window has been recently described by Smith et al. in a series of 393 patients with thoracoabdominal wounds and no indication for immediate laparotomy or sternotomy [29]. Diagnostic laparoscopy was performed, and if peritoneal violation was found, they converted to open laparotomy and pericardiotomy. In the 38 patients without peritoneal violation, laparoscopic transdiaphragmatic pericardiotomy was performed through the central tendon of the diaphragm. A negative exam was defined by visualization of clear fluid. One patient had no fluid and five had bloody fluid; in all six patients, cardiac injuries were identified, five of which required median sternotomy for repair. The diaphragmatic defect was not closed.

Indications for Sternotomy in PCI

In recent years, the question has been raised regarding whether the presence of hemopericardium after penetrating trauma mandates median sternotomy, based on the observed high rate of nontherapeutic sternotomy in hemodynamically stable patients without active bleeding at the time of SPW [30, 31]. To address this question, Nicol et al. have recently published a prospective randomized evaluation where 111 hemodynamically stable patients who had undergone SPW with no evidence of active bleeding were then randomized either undergo sternotomy or observation [32•]. They found no injuries at sternotomy that require repair, although four out of 55 patients randomized to sternotomy had full-thickness injuries to the heart that were judged to be "completely sealed." None of the patients undergoing drainage alone required subsequent sternotomy. An important caveat of this study is that they examined a highly selected group of patients at an institution that treats a high volume of PCI (111 out of 348 patients undergoing surgery for PCI during the 7.5 years of the study). This management strategy rests on the premise that "sealed" cardiac injuries will never re-bleed—an assumption that will only be proven with more experience with this approach. Less experienced surgeons should exercise great caution before considering nonoperative management of a PCI. A delayed bleed from an unrepaired injury can be catastrophic.

Pneumothorax and Hemothorax

Blood or air in the pleural space may diagnosed clinically or using imaging. The noise and distraction of a trauma resuscitation often make a nuanced chest exam difficult. In a stable, well-oxygenated patient, it is usually safe to wait for imaging confirmation before placement of a chest tube if only subtle abnormalities are present. As discussed above, ultrasound has sensitivity in detection of pneumothorax that exceeds supine CXR. Nonetheless, CCT is the gold standard, detecting even tiny air or blood collections not seen on CXR. If a hemothorax is identified, management with tube thoracostomy drainage will be sufficient in 96 % of patients without cardiac injury [33]. Traditionally, a 36–40 Fr tube has been inserted; however, recent evidence suggests that smaller tubes of 28–32 Fr may be equally effective at evacuating the blood [34]. More recently, a small randomized trial compared 14 Fr percutaneous pigtail catheter drainage to 28 Fr traditional chest tubes for traumatic pneumothorax; there were no differences in the rate of successful evacuation, duration of drainage, or complications; however, the pigtail catheters were associated with significantly less pain than the traditional tubes [35••].

Over the years, several studies have questioned whether pneumothorax seen on CCT but not on CXR needs treatment. Occult pneumothoraces are identified on CCT in 5–15 % of patients [36]. A recent meta-analysis of the three available randomized trials of observation versus drainage of "occult pneumothorax" identified on CCT showed no difference between drainage and observation with regard to progression of the pneumothorax, the risk of pneumonia, or the length of stay in the hospital or ICU [37]. A caveat of this analysis is that the included studies primarily examined blunt trauma patients. A recent study by Ball and colleagues of patients specifically looked at occult pneumothoraces in patients with penetrating thoracic injuries. They found the incidence of occult pneumothorax to be 17 %, with only 56 % of the occult pneumothoraces requiring chest tube drainage, compared to 95 % of the overt pneumothoraces [38]. Thus, it appears that a trial observation is safe with asymptomatic occult pneumothoraces, even in penetrating trauma.

Patients with so-called "asymptomatic" penetrating chest injuries, where there is no evidence of intrathoracic on their initial workup, have posed a quandry in the past. Out of concern for possible delayed presentation of a hemothorax or pneumothorax, the traditional approach has been to observe these patients and obtain repeat chest radiographs after 3–6 h [39]. However, in a recent study by Berg et al. of 88 such patients, no clinically significant findings were found on late delayed CXR (median delay 7 h 16 m) that were not also present on early delayed CXR (median delay 1 h 34 m), suggesting that earlier follow-up imaging and shorter periods of observation are likely safe [40•].

Resuscitation of the Unstable or Severely Injured Patient

Severely injured patients with penetrating chest trauma will generally present in one of two ways:

1. Profound hypotension due to:
   a. Tension pneumothorax or cardiac tamponade (obstructive shock)
   b. Exsanguination from great vessel injury, cardiac laceration, or intercostal artery laceration (hemorrhagic shock)
   c. Arrhythmia or heart failure from blunt cardiac injury or coronary artery laceration (cardiogenic shock)
2. Profound hypoxia due to:
   a. Major airway disruption (tracheobronchial injury)
   b. Loss of functional alveoli due to extrinsic compression or intrapulmonary hemorrhage (pulmonary injury)
   c. Disturbance of normal respiratory dynamics (chest wall injury)

Patients presenting in extremis or cardiac arrest after injury may be candidates for emergency department thoracotomy, depending on anatomic injury site, duration of pulselessness, cardiac rhythm, and ultrasound findings [41]. The absence of cardiac activity on ultrasonography has been shown to be a grave prognostic indicator in patients presenting with cardiac arrest [42, 43]. Ferrada and colleagues have shown that the use of ultrasonography in the evaluation of patients in traumatic cardiac arrest is associated with a decrease in nontherapeutic thoracotomy [44•].

Shock after penetrating thoracic injury is typically due to bleeding, tension pneumothorax, or pericardial tamponade. A small subset of patients may have neurogenic shock related to spinal injury, but it is dangerous to assume this as the etiology of shock until other sources have been ruled out.

Tamponade can be diagnosed clinically, but the accuracy of bedside exam in this setting is variable. Beck's Triad, consisting of profound hypotension, elevated central venous pressure (or jugular venous distention), and muffled heart sounds, has a sensitivity that is excellent in some studies [45] and poor in others [46]. Tension pneumothorax can also present similarly, except with decreased breath sounds and tracheal deviation on exam. In the often noisy environment of the trauma bay, the detection of muffled heart sounds or decreased breath sounds can be challenging, especially in the setting of bilateral tension pneumothorax. As discussed earlier, E-FAST allows for rapid, accurate detection of hemothoraces, pneumothoraces, and hemopericardium and thus should immediately follow the primary survey. Intravenous access and fluid resuscitation can be initiated by another member of the team in parallel with this survey.

In the secondary survey, care should be taken to note all sites of penetration with the patient fully exposed, while another member of the team obtains a history, if able. Although this article focuses on penetrating thoracic injuries, patients can often have multiple wounds or mechanisms that can cause both blunt and penetrating injury. When forced to prioritize interventions for multiple injuries, it is helpful to keep in mind "what will kill the patient first?"

Operative Indications in the Hypotensive Patient

Tension Pneumothorax

Needle thoracostomy with an angiocath in second intercostal space (ICS) at the midclavicular line (MCL) has long been taught as a component of ATLS for relief of tension pneumothorax. This can be used as an initial temporizing measure, particularly in the pre-hospital setting; however, several reports have raised significant concerns regarding the effectiveness of needle decompression at relieving tension physiology. In the trauma bay, insertion of a chest tube is the definitive approach and can be performed nearly as expeditiously.

Several recent studies have questioned the appropriate site and device for emergent decomptression of tension pneumothorax. Cadaver [47], animal [48–50], and clinical [51–54] studies have suggested that use of a small (3.2 cm) needle in the standard site (second intercostal space, midclavicular line) is not reliable, likely due to the thickness of the chest wall at this site and the small size of the needle or catheter. Even when proper placement is confirmed laparoscopically in animal models, Martin and colleagues showed that a 14-gauge angiocatheter fails to relieve tension physiology 64 % of the time [48]. The fourth or fifth intercostal space at the anterior axillary line is consistently thinner than the traditional site in multiple radiographic studies [52–54], which suggests that it may be a superior site for needle thoracostomy. Additionally, two groups have recently suggested borrowing techniques from laparoscopic abdominal surgery to avoid visceral injury as well as any problems with catheter kinking; Hatch and colleagues used 5-mm blunt laparoscopic trocars [49], while Lubin et al. suggest the use of a Veress needle with similar effect [50].

Cardiac Tamponade

Although cardiac tamponade is rapidly fatal when left untreated, prompt recognition and treatment can be lifesaving. In fact, in patients with stab wounds that present with cardiac tamponade, survival can be as high as 92 % [27]. If tamponade is suspected, emergent surgical intervention is needed. In a spontaneously breathing patient with tamponade, intubation should be avoided until drainage is imminent, as positive pressure ventilation can further impair venous return and provoke cardiac arrest [55].

Pericardiocentesis is still taught in ATLS as a temporizing measure in situations where there may be a delay in definitive surgical care. Nonetheless, it appears to have fallen out of favor in recent years. Lee et al. recently published a meta-analysis showing that the use of pericardiocentesis in patients with suspected cardiac tamponade has decreased between 2000 and 2010, from 45.9 to 6.4 % [56]. Intriguingly, Jones and colleagues have just reported a case series that raises the question of whether this procedure is underutilized. They looked retrospectively at a group of patients with tamponade who did or did not undergo ultrasound-guided percutaneous pericardial drain placement in the trauma bay prior to definitive surgical care. Insertion of the drain was not associated with any delay operative care, and in 59 % of the patients, hypotension improved after drainage [57••]. While their study was underpowered to show a difference in mortality, there was a trend toward improved survival in the patients who underwent drain placement, which suggests an area for further research.

Hemorrhagic Shock

The indications for surgical management of noncardiac chest trauma have not changed in some time. While various volume cutoffs for chest tube drainage have been proposed, numbers are no substitute for sound clinical judgement. In hemodynamically unstable patients or those with evidence of massive hemorrhage (immediate drainage of 1000–1500 mL of blood through the tube, or large residual hemothorax on post-tube CXR), thoracotomy is indicated. Autotransfusion of blood drained by thoracostomy is practiced variably in a number of centers. This practice has been studied in the setting of postoperative cardiac surgery patients since the 1970s as a means to possibly limit allogenic blood transfusion by reinfusion of shed mediastinal blood. There has been renewed interest in autotransfusion in trauma based on recent military experience suggesting a survival benefit to the transfusion of fresh whole blood [58–60]. Autotransfused blood has been shown to be safe, even in the presence of hollow viscus injury [61]. However, questions remain regarding the effectiveness of this practice at decreasing the need allogenic transfusion as well as the safety of autotransfusion of salvaged blood relative to allogenic transfusion of donor blood, particularly when directly reinfused without washing using a cell-saver device.

In trauma patients with hemothoraces, Salhanick et al. have shown that evacuated hemothorax differs significantly from whole blood; it is completely defibrinated, with high levels of fibrin degredation products, as well as decreased levels of coagulation factors, platelets, and red blood cells relative to venous blood [62]. In their study, it took 726 ml of evacuated hemothorax to approximate the red cell content of 1 U of packed red blood cells. Based on this finding, it appears likely that autotransfusion is clinically irrelevant in patients with less than 750–1000 ml of drainage, particularly if washing is performed prior to reinfusion.

Due to the lack of fibrinogen in evacuated hemothorax, it does not form clot in traditional coagulation assays such as the prothrombin time or partial thromboplastin time [62]. However, Smith and colleagues published the interesting observation that, when mixed with normal pooled plasma, the evacuated hemothorax fluid paradoxically induces a hypercoagulable state [63]; this was attributed to the presence of activated clotting factors within the hemothorax fluid. When the same group repeated this experiment using the patient's own plasma, the degree of induced hypercoagulability was even more pronounced [64].

Despite this hypercoagulopathy on traditional clotting assays, Konig and associates have shown that, on thromboelastography (TEG), salvaged blood actually induces a mixed state of factor hypercoagulability and platelet hypocoagulability when combined with the patient's own blood [65], with a 61 % decrease in R-time and a 26 % decrease in MA [65]. The platelet inhibition was attributed to competitive inhibition of platelet aggregation due to the high levels of fibrin degredation products in the salvaged blood. Unsurprisingly, both of these effects were reduced when the salvaged blood was washed first [65].

The relevance of these in vitro clotting abnormalities to the realm of patient care is unclear, as no existing studies have shown any clear benefit or harm to the practice of autotransfusion in trauma. While the above coagulation studies are intriguing, any theoretical risk also needs to be balanced against the real risks of autologous blood transfusion.

Cardiogenic Shock

Only rarely will patients with penetrating chest trauma present with life-threatening arrhythmias secondary to a cardiac contusion. Nonetheless, blunt cardiac injury (BCI) after penetrating injuries to the chest has been described, particularly with high-velocity gunshot wounds [66]. This is possible due to the large amount of energy transferred into the tissues surrounding the bullet tract. Isolated injuries to the coronary arteries leading to acute myocardial infarction (AMI) without cardiac perforation or tamponade have also been reported [67, 68]. The evaluation and management of BCI have been recently reviewed in depth [69].

Operative Indications in the Hypoxic Patient

Many patients with profound hypoxia after penetrating chest trauma will require an airway; most will require tube thoracostomy [70]. Profound hypoxia immediately after penetrating chest trauma is most frequently due to pneumothorax or hemothorax, for which closed tube thoracostomy is lifesaving. Following chest tube insertion, a large or continuous air leak is suggestive of tracheobronchial injury. This is rare injury, occurring in only 1–2 % of patients with penetrating thoracic injuries [71]. In addition, due to the proximity of the trachea and bronchi to other mediastinal structures, tracheobronchial injuries after penetrating chest trauma have a high incidence of associated injuries to the esophagus, spinal cord, heart, and great vessels. These associated injuries are frequently fatal (i.e., exsanguination from great vessel or cardiac injury) and often determine the ultimate outcome after injury.

In general, tracheobronchial injuries mandate early thoracotomy for repair due to inability to adequately ventilate the patient. Two recent case series have shown that selective conservative management of traumatic tracheobronchial injuries is possible with comparable outcomes to surgical repair [72, 73]. Patients amenable to conservative management include those with stable vital signs, effective ventilation if intubated or absence of respiratory distress if breathing spontaneously, nonprogressive mediastinal and/or subcutaneous emphysema, and absence of associated esophageal or major vascular injury. In these patients, management includes chest tube drainage, prophylactic antibiotics, and observation. Efforts should be made to characterize the nature of the injury using rigid or flexible bronchoscopy, prior to committing to a course conservative management, as large communication with the mediastinum may place the patient at risk for mediastinitis and should be considered an indication for surgical repair [73]; some authors are using CT virtual bronchoscopy for this purpose [72].

Traditionally, open pneumothorax was managed with application of a three-sided occlusive dressing that functioned as a flutter valve to vent any ongoing air leakage [74]. This is still taught in ATLS and until recently was recommended by the US Military Trauma Combat Casualty Care (TCCC) course [75]. There is little evidence of the effectiveness of these improvised dressings, and in recent years, numerous commercially available vented chest seals have been developed (Bolin, Asherman, HyFin, Russell, SAM, Sentinel), all of which incorporate some form of one-way valve to prevent development of tension pneumothorax. Several recent studies, including one from the US Army Institute of Surgical Research (USAISR), have demonstrated the effectiveness of vented chest seals at preventing the development of tension pneumothorax in animal models [76–78]. As such, recently published guidelines have endorsed the effectiveness of these products [74, 75, 79]. While these devices are an effective temporizing measure in the prehospital setting, such patients will ultimately require tube thoracostomy and reconstruction of the defect in the operating room.

Once the patient is intubated, if there is ongoing massive hemorrhage into the tracheobronchial tree, it is important to keep in mind that the immediate threat to life in this situation is typically due to asphyxia, not exsanguination. In these cases, emergency department or operating room thoracotomy will allow for pulmonary hilar cross-clamping to protect against further hemorrhage into the airway and prevent air embolism [80]. Direct surgical management of the pulmonary injury can then be undertaken.

The Challenge of Thoracoabdominal Wounds

Multiple authors have noted that incorrect sequencing in patients requiring dual-cavitary interventions is associated with large increases in mortality [81–83]; however, in most of these cases, death results from delayed recognition of a cardiac injury [81]. It is important to seek out evidence of PCI early. With thoracoabdominal wounds, it is easy to be mislead by chest tube output, either due to intraabdominal bleeding exiting the tube via a diaphragmatic defect or due to chest tubes clotting, thus concealing evidence of ongoing thoracic hemorrhage. In an older study, misleading chest tube output was found to be a frequent contributor to incorrect sequencing [82]. In the unstable patient with a thoracoabdominal wound, the determination of which cavity to explore first depends on the relative evidence of injury within the pericardium, thoracic cavity, and abdomen. When cardiac injury is present, most surgeons start with pericardial exploration. In the absence of cardiac injury, the choice between chest and abdomen is based on clinical exam and ultrasound findings. However, picking the initial site is less important than a rapid and flexible approach, wherein the first cavity is quickly evaluated and—if no source of massive hemorrhage is found—abandoned quickly in favor of exploration of the other cavity.

Conclusions

With penetrating injuries to the thorax, more than 85 % of patients who present to the hospital alive can be successfully treated with attention to the ABCs of trauma care and tube thoracostomy when needed to evacuate hemothorax or pneumothorax. Nonetheless, injuries to the heart and lung have the potential to rapidly result in patient demise if not promptly recognized and treated appropriately. Ultrasonography is playing an increasing role in the evaluation of patients after thoracic injury to improve recognition of both pneumothorax and penetrating cardiac injuries.

Compliance with Ethics Guidelines

Conflict of Interest Drs. Scott and Sava declare that they have no 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.

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•• Of major importance

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Early and Persistent Hemothorax and Pneumothorax

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Abstract The incidence of traumatic injury to the thorax is estimated at up to 40 % of patients that require hospitalization. The vast majority of these injuries can be managed with observation. However, the presence of pneumothorax or hemothorax has traditionally mandated tube thoracostomy placement and the inherent morbidities that may arise. Persistent pneumothorax is typically defined as the presence of pneumothorax and/or air leak for 5–7 days after tube placement. This morbidity may be managed expectantly or with video-assisted thoracoscopic surgery (VATS). The most feared complication after hemothorax is the presence of retained blood and the risk of infection that follows. Most authorities support the early use of VATS to resolve retained hemothoraces with the hopes of avoiding more invasive procedures aimed at the treatment of fibrothorax and empyema.

Keywords Hemothorax · Pneumothorax · Traumatic · Persistent · Traumatic hemothorax · Traumatic pneumothorax

Introduction

Thoracic trauma is a primary cause of morbidity and mortality in the multiply injured patient and accounts for approximately 25 % of trauma-related deaths annually [1, 2]. Pneumothorax and hemothorax are common findings in patients with thoracic injury and therefore demand mention.

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Pneumothorax

Identification and Diagnosis

History and Physical Examination

Initial evaluation of the traumatically injured patient consists of a systematic evaluation of the patient utilizing the principles of Advanced Trauma Life Support (ATLS). Tachypnea and respiratory distress are potential findings that may alert the astute clinician to the presence of a pneumothorax or other pulmonary pathology. Examination of the lungs can reveal decreased breath sounds or tympany on percussion. Although, these findings lack the sensitivity to be solely relied upon and can be difficult to observe in a bustling trauma center. The diagnosis of tension pneumothorax remains a clinical, not a radiographic diagnosis. A late diagnostic finding is tracheal deviation away from the side of injury. Additionally, a hyper-expanded and asymmetric chest wall may be detected. Hemodynamic instability secondary to decreased venous return to the heart is a late and potentially lethal sign of tension pneumothorax.

Initial imaging has traditionally consisted of supine chest radiography in the traumatically injured patient. Pneumothorax is diagnosed when pleural markings are not visualized projecting to the chest wall, but instead, gas has escaped from the lung parenchyma and created a space between the lung and the pleura. Additional findings suggestive of pneumothorax on chest radiography include the "deep sulcus sign" and the presence of subcutaneous gas within the tissues of the chest wall or

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neck. If an excessive amount of gas escaped into the subcutaneous tissues, crepitus may be palpated.

The rationale behind routine chest radiography in blunt trauma has recently been questioned. A study performed at a level I trauma center illustrated that of 484 blunt trauma patients evaluated, 16 (3.3 %) had significant intra-thoracic injuries. In assessing the providers pretest probability for injury, they found that a low suspicion for injury was associated with an extremely low rate of significant intra-thoracic trauma [3]. With that said, it is still our practice to perform initial chest radiograph on the vast majority of traumatically injured patients.

In an effort to identify blunt trauma patients most likely to benefit from chest radiograph, the NEXUS Chest Study has identified seven clinical criteria predictive of major chest trauma: age greater than 60 years, rapid deceleration mechanism, chest pain, intoxication, altered mental status, distracting injury, and tenderness to the chest wall on palpation [4]. Investigators report a sensitivity of 99.7 % and a negative predictive value of 99.9 % when evaluating blunt trauma patients older than 14 years [5] (Table 1).

Recent studies have shown ultrasonography to be a non-invasive and non-radiation requiring study that can accurately diagnose pneumothorax in the bluntly injured trauma patient [6, 7]. Ultrasound has consistently been shown to have better sensitivity and specificity than chest radiography in the detection of pneumothorax, with chest radiography having varying sensitivity from 28 to 75 %, but with specificity of 100 % [8, 9]. The apposition of the parietal and visceral pleura creates a "sliding" that is not present when air infiltrates this space (Fig. 1). Ultrasound has many features making it an attractive initial imaging option including its portability, repeatability, and the ability to obtain real-time and dynamic images by a member of the treatment team.

Computed tomography (CT) imaging of the chest has become commonplace in the current era and is invaluable in the diagnosis of blunt aortic injury and other life-threatening conditions [10–12]. However, the practice of obtaining chest CT after normal chest radiograph is controversial. In patients with a normal chest x-ray who then underwent chest CT, a 2013 study showed 82 % of patients proceeded to have a normal CT, 13.2 % had clinically minor injuries, 2.7 % clinically insignificant injuries, and only 2 % of patients had clinically major injuries on CT after normal chest x-ray [13].

Some pneumothoraces are not visible on initial chest x-ray, instead initially being visualized on computed tomography (CT) of the chest; these are labeled as occult pneumothoraces. Utilization of ultrasound as an adjunct to chest x-ray has been illustrated to accurately diagnose occult pneumothorax with an accuracy that approaches that of CT [14, 15]. These occult findings are of uncertain clinical significance, but concerns for tension pneumothorax with the application of positive pressure ventilation, such as is required during operative therapy, have been voiced. Some have suggested oblique chest x-ray as an adjunctive measure to identify occult pneumothorax in the unstable patient [16].

Table 1 NEXUS chest proposed criteria for safely reducing thoracic imaging in blunt trauma patients over 14 years of age. In the absence of the above signs, the incidence of significant chest injury is exceedingly low [4, 5]

Nexus chest
Blunt trauma patients greater than 14 years of age
Age greater than 60 years
Mechanism of injury—RAPID deceleration
Pain in chest
Presence of intoxicants
Altered mental status or level of consciousness
Distracting injury
Tenderness to palpation of the chest wall

Initial Treatment

Classic teaching has mandated placement of tube thoracostomy once the diagnosis of pneumothorax has been made. Recent evidence has illustrated that the placement of 14-Fr pigtail catheter is sufficient to evacuate traumatic pneumothorax [17]. In a subsequent randomized control trial, 40 patients were randomized to either a 28-Fr chest tube or a 14-Fr pigtail catheter for traumatic pneumothorax, with the 14-Fr pigtail catheter group having less pain and similar success rates compared to those receiving larger chest tubes [18•].

Suggested initial treatment of presumptive tension pneumothorax has been the placement of a 16-gauge angiocatheter in the second intercostal space at the mid-clavicular line [19]. However, recent evidence suggests that the second intercostal space may be inadequate in a significant number of patients. At the University of Southern California, Inaba and colleagues utilized a fresh cadaveric model and were able to show the standard 5-mm angiocatheter suggested for needle decompression was of inadequate length to reach the pleural space in 57.5 % of cadavers' second intercostal space. However, when placed in the fifth intercostal space, they would adequately decompress 100 % of the cadavers studied [20]. In contradistinction, an investigation in blunt trauma patients undergoing CT imaging of the chest showed that commonly employed angiocatheters are of insufficient length to reach the pleural space laterally, and many are too short to reach in the second intercostal space [21].

Treatment of occult pneumothorax is often debated, as CT imaging has the ability to detect small pneumothoraces of unknown clinical significance. Single institution studies have suggested that observation of occult pneumothoraces is safe

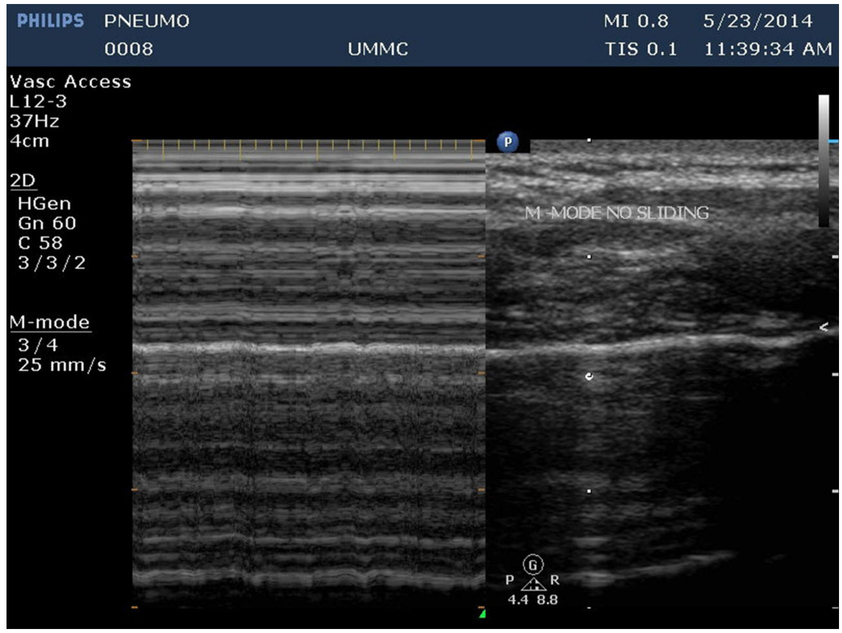


Fig. 1 The *left panel* shows the characteristic "sliding" image present when the parietal and visceral pleura are well opposed, whereas the *right panel* shows a characteristic still image when air infiltrates the space (pneumothorax)

and does not lead to tension pneumothorax with the application of positive pressure ventilation. Additionally, the authors show that patients managed without chest tube placement have shorter hospital lengths of stay [22]. A 2011 American Association for the Surgery of Trauma (AAST)-sponsored multi-institutional prospective study showed similar findings, concluding that the majority of bluntly injured patients with occult pneumothoraces can be safely observed. The authors found that worsening respiratory distress and progression of pneumothorax were associated with failure of observation, with no influence provided by the application of positive pressure ventilation [23•].

Treatment for Persistent Pneumothorax

The definition of persistent pneumothorax varies throughout the literature, but we typically view a pneumothorax as persistent if an air leak is present for greater than 5–7 days after placement of thoracostomy tube. In the vast majority of traumatically injured patients with persistent pneumothorax and air leak secondary to pulmonary parenchymal injury, the air leak will resolve without treatment as the lung heals. However, studies have shown decreased length of hospitalization and fewer chest tube days with early video-assisted thoracoscopic surgery (VATS) therapy and application of a topical sealant, pleurodesis, or pulmonary parenchymal resection or repair [24–26].

Alternatively, a technique which we occasionally utilize is the placement of a Heimlich valve at the distal aspect of the thoracostomy tube. The Heimlich valve acts as a one-way valve for gas and fluid, thus the patient can safely be managed without the cumbersome underwater drainage system [27]. We tend to employ this technique in patient's likely to have a hostile thoracic cavity or who carry a high operative risk of morbidity, for example those with emphysematous lung disease.

Complications and Outcomes

Overall, when compared to a penetrating mechanism of injury, patients with a blunt mechanism of injury tend to have longer intensive care unit stays, more ventilator days, and more tube thoracostomy days [28]. Some suggest that the utilization of a clinical practice algorithm, especially in patients with an elevated chest Abbreviated Injury Score (AIS), can decrease the morbidity associated with tube thoracostomy management and eventual removal [29, 30]. Though our current practice is to obtain a chest radiograph on removal of thoracostomy tubes, others have proposed the utility of such a film is low in the absence of clinical signs exhibited by the patient [31].

Hemothorax

Identification and Diagnosis

Similar diagnostic principles exist for both hemothorax and pneumothorax. Physical examination may reveal decreased breath sounds or dullness to percussion on the affected side, though this finding is exceedingly variable and difficult to detect in a noisy trauma environment. Chest radiography is most commonly utilized for definitive diagnosis and will illustrate blunting of the costophrenic angle with varying amounts of opacification within the hemithorax. However, ultrasound is also a widely accepted diagnostic adjunct and has been shown to be more sensitive than, and at least as specific, as plain film radiography [32, 33]. In consideration of which diagnostic technique to utilize, the clinician must consider the physiologic state of the patient and always remember, in the hemodynamically abnormal patient, the ideal maneuver is likely the placement of bilateral chest tubes to both diagnose and treat pneumothorax and hemothorax.

Initial Treatment

Traditionally, traumatic hemothorax has been managed with the placement of a large-bore tube thoracostomy into the affected hemithorax. A small prospective study of 227 patients has suggested that placement of a 14-Fr pigtail catheter for traumatic hemothorax is adequate to evacuate blood with equivalent tube durations, insertion complications, and rate of failure [17]. In the majority of cases, we utilize tube thoracostomy for hemothorax drainage, though we have had success with image-guided placement of pigtail catheters into hemorrhagic collections. This option is especially appealing in the elderly population and those patients with anatomically inaccessible collections.

A 2012 American Association for the Surgery of Trauma (AAST) multicenter trial highlights the importance of early evacuation of retained hemothorax. Investigators found a 26.8 % incidence of empyema among patients with a post-traumatic retained hemothorax. They identified rib fractures, Injury Severity Score (ISS) greater than 25, and additional procedures to evacuate retained hemothorax as independent predictors of empyema formation [34•]. This underscores the importance of obtaining adequate drainage with the fewest number of thoracic manipulations possible.

Treatment for Persistent Hemothorax

The management of persistent hemothorax has garnered much attention over the past 5–10 years, with a focus on early evacuation via video-assisted thoracoscopic surgery (VATS). Many investigators have shown and advocate for early thoracoscopic exploration in an effort to evacuate any retained blood products and prevent formation of fibrothorax and empyema [35–38]. Early evacuation and decreased incidence of empyema formation should lead to a decreased need thoracotomy, a more invasive and painful procedure.

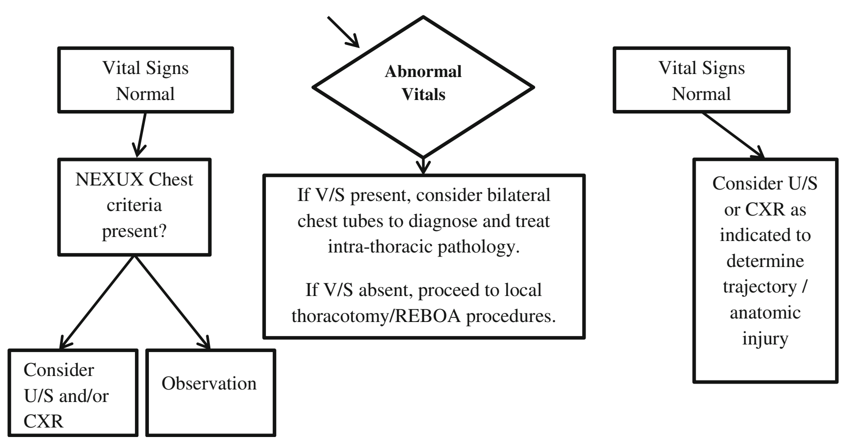
In a 2011 AAST multi-institutional prospective trial, DuBose and colleagues enrolled 328 patients with retained hemothorax at 20 individual trauma centers. VATS was performed in 33.5 % of those patients with 22.2 % of patients requiring thoracotomy. The authors stress that 25 % of the patients required at least two procedures to adequately clear their hemothorax [39]. Investigators have also shown that implementation of a clinical pathway for management of retained hemothorax leads to VATS in more patients, in addition to decreasing hospital cost and improving outcomes [40].

Complications and Outcomes

Retained hemothorax is reported to occur in approximately 20 % of patients with thoracic trauma and hemothoax [41]. Because of the concern for bacterial contamination and subsequent empyema formation, great emphasis is placed on early evacuation of any retained clot. Our institutional guideline is to perform a chest radiograph on the day following tube thoracostomy placement. If opacity obscures the costophrenic angle, a chest CT scan is performed, as studies have illustrated that plain film radiography is insufficient to predict the need for thoracoscopic intervention [42]. Retained blood estimated at greater than 500 mL or opacification of 1/3 of the hemithorax are indications to proceed with VATS.

Additionally, pneumonia exists as a very real concern after thoracic trauma and hemothorax formation. Issues surrounding pre-procedural administration of antibiotics to prevent pneumonia, and possibly empyema, are still undergoing debate. In 2012, the Eastern Association for the Surgery of Trauma published a practice management guideline stating

Fig. 2 Proposed algorithm for the management of suspected intra-thoracic trauma in both blunt and penetrating mechanisms of injury [4, 5]



"there is insufficient published evidence to support any recommendation either for or against this practice" [43]. However, in 2013, Bradley and colleagues utilized the AAST Post-Traumatic Retained Hemothorax database and found that lack of pre-procedure antibiotics was an independent risk factor pneumonia formation [44]. Current institutional protocol at our institution leaves the administration of antibiotics at the discretion of the practitioner.

Conclusions

The management of hemothorax and pneumothorax continues to evolve towards a more minimally invasive and thoughtful approach, while at the same time obviating the physiologic instability that often accompanies both conditions. However, the clinician must not forget or lose the ability to perform urgent and facile invasive maneuvers in the hemodynamically unstable patient (Fig. 2).

Compliance with Ethics Guidelines

Conflict of Interest Brandon R. Bruns and Jose J. Diaz declare no 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.

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Emergency Department Thoracotomy: an Update

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Abstract Emergency department thoracotomy (EDT) has been considered a heroic, high-risk procedure for patients in extremis since its introduction in 1967, and over the last four decades, the technique has been used with increasing selectivity. Patients with isolated stab wounds to the chest stand the best chance of survival. Most institutions agree that EDT should be performed in patients with penetrating mechanisms of injury who have lost signs of life, but controversy surrounds its use in patients who undergo prehospital CPR or in cases involving blunt mechanisms of traumatic arrest. Dismal outcomes have been reported for patients with penetrating injuries and prehospital CPR >15 min and blunt trauma victims who undergo prehospital CPR. Despite the low survival, the Western Trauma Association advocates EDT in cases of blunt traumatic arrest with CPR <10 min. Biochemical profiles during EDT and outcomes beyond neurologic recovery are currently being investigated, and alternatives such as resuscitative endovascular balloon occlusion of the aorta (REBOA) are emerging.

Keywords Resuscitative thoracotomy · EDT · Emergency thoracotomy

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Introduction

Since its introduction in 1967, emergency department thoracotomy (EDT, also known as resuscitative thoracotomy (RT)) has been a topic of energetic debate. Initial enthusiasm was curbed by guidelines intended to minimize futility and save hospital resources. The challenge for today's surgeon lies in determining whether a patient would benefit from EDT, a radical procedure that offers a chance of survival for patients who present in extremis. This is a state of profound neurological, respiratory, and cardiovascular collapse, and for which standard Advanced Trauma Life Support (ATLS) protocols are inadequate. EDT may be used for a variety of purposes depending on the initial cause of distress, including to relieve cardiac tamponade and control of bleeding from cardiac, pulmonary, and great vessel sources; to initiate open cardiac massage to preferentially divert blood flow to the cerebral and coronary circulation; to provide intravenous access through the right atrium for intracardiac administration of medications; and to reduce significant bleeding from abdominal or pelvic sources until control of these areas is regained. This clinical update will outline trends in EDT indications and procedures to help guide the practicing surgeon.

Indications

The major benefit of EDT is to patients in profound shock who are not yet dead, and the debate over EDT use does not center around this patient population. However, the degree of shock and the definition of dead have been brought into question, and indiscriminate use yields poor outcomes at high cost [1•]. When is the patient salvageable? Although the terms "no signs of life," "no vital signs," "lifeless," and "agonal" have been used in the literature to describe the physiologic state of the patient before surgery, all of these terms are vague. The

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disagreement in terminology and indications for EDT are illustrated in a survey commissioned by the American Association for the Surgery of Trauma [2], in which the 304 members surveyed widely disagreed on clinical scenarios for RT and the definition of "signs of life."

The survey reflects the limitations of the literature when describing indications for performing EDT. However, some definitive conclusions may be drawn from level II and level III evidence. The first is that EDT is supported in patients with any sign of life (SOL) or who deteriorate shortly after arrival, particularly in trauma patients with thoracic stab wounds and subsequent cardiac tamponade, where survival rates may reach 40 % [3]. The second conclusion is that EDT is not indicated for either penetrating or blunt trauma patients who never exhibited SOL.

Practical Aspects

The decision-making analysis for EDT begins with the patient characteristics upon presentation to the ED. Signs of life include detectable blood pressure, respiratory or motor effort, cardiac electrical activity, or pupillary activity. The time from initiation of CPR is determined directly from prehospital personnel. Blunt trauma patients undergoing prehospital CPR have a low chance of survival following EDT, and many trauma centers use this scenario as a contraindication for performing EDT. However, guidelines published by the Western Trauma Association (WTA) in 2012 argue against this practice [4••], stating that patients undergoing CPR on presentation to the hospital should be stratified based on injury and transport time to ascertain whether EDT is advisable. Specifically, resuscitative efforts should be directed toward patients in extremis with electrical cardiac activity that are intubated, supported with cardiac compressions, and have been rapidly transported to the hospital. Because field salvageability is highly variable, the WTA guidelines support resuscitative efforts in this population but offer the qualification that blunt trauma patients with greater than 10 minutes of prehospital CPR and no SOL should be pronounced dead [5, 6].

The use of EDT in blunt or penetrating trauma patients who undergo prehospital CPR for less than 10 or 15 minutes, respectively, is supported by two studies separated by a considerable amount of time but conducted by the same group. These studies were critiqued by Rabinovici and Bugaev in their update on RT [7•]. In the first study by Powell et al. (2004), 959 patients underwent EDT over 26 years. There were 65 survivors, 26 of which received prehospital CPR. Six of the 26 sustained stab wounds to the heart with tamponade and had asystole on arrival to the ED. Four of the 6 were discharged with either mild or severe neurologic deficit. The CPR time for survivors varied from 3 to 15 min, but the CPR time for patients without electrical activity upon admission was not reported. No blunt trauma patients with asystole survived. A 2011 multicenter study by the same group examined 56 EDT survivors, 37 % of which underwent prehospital CPR. The upper limit of CPR was 9 min in trauma patients with blunt torso injuries and up to 15 min in patients with penetrating torso injuries. There was only 1 survivor with a cardiac laceration and tamponade who survived with 15 min of CPR. Ten of the 56 survivors had moderate to severe anoxic brain injury. These studies are intriguing but generate several concerns. The studies report small numbers of survivors presenting without SOL. Most survivors sustained cardiac stab wounds with laceration and tamponade; there were no gunshot wound patients and only 1 blunt trauma patient. The multicenter study did not provide patient CPR time, the total number of patients undergoing EDT, or an analysis of nonsurvivors. Finally, as in all studies, the completeness and accuracy of the prehospital information is in question. In summarizing this data, EDT should be offered to patients who arrive in asystole to the hospital and are suspected to have a cardiac injury and tamponade.

In an editorial critique of the WTA 2012 algorithm on RT, withholding EDT in blunt trauma patients was supported by several organizations including the National Association of EMS Physicians Standards and Clinical Practice Committee as well as the American College of Surgeons' Committee on Trauma (ACS COT).

Another focus of the debate over EDT indications involves a moribund patient with extrathoracic exsanguination. Performance of EDT on patients exsanguinating from abdominal vascular injuries is supported by the ACS 2001 guidelines [3], although they acknowledge the low survival in these patients and qualify this recommendation by stating that "judicious selection of patients should be exercised." The ACS guidelines are supported in a more recent retrospective review by Seamon et al. in 2008 [8] of 50 patients with abdominal exsanguination who underwent EDT. In these patients, 98 % sustained gunshot wounds (GSWs), 84 % had SOL in the field, and 78 % in the ED. There were 8 (16 %) neurologically intact survivors, whose cardiac rhythm on presentation was categorized as asystole (1), pulseless electrical activity (PEA) (2), or some form of organized rhythm in the remaining 5. This data supports EDT as having a survival advantage before laparotomy in patients with exsanguinating abdominal hemorrhage.

The WTA 2012 algorithm also supports thoracic aortic occlusion for massive hemorrhage via EDT. The rationale for aortic cross-clamping is based on several physiologic findings. The first is that the limited volume of blood remaining during hemorrhagic shock is redistributed to the heart and brain during aortic cross-clamping [9]. Second, if there is an abdominal source of hemorrhage, aortic cross-clamping reduces blood loss below the diaphragm [10]. Third, coronary filling is increased from the diverted blood flow associated with the return of spontaneous circulation following CPR [11, 12].

An additional controversy over indications for EDT presents in patients with thoracic GSWs. Seamon et al. analyzed data from two urban level I trauma centers [13]. The majority of the 283 patients suffered from GSWs to the heart and great vessels (n=250, 88 %). Survival was 9.5 % from a single GSW and 1.4 % from multiple GSWs. There was 1 patient (0.8 %) with multiple GSWs who survived EDT. In summary, EDT may benefit the patient with a single GSW to the chest with SOL, but should not be performed in the moribund patient with multiple GSWs to the chest.

Physiologic Profile

The electrolyte, coagulation, and acid–base profiles of patients subjected to EDT are poorly understood. Schnuriger et al. prospectively sampled intracardiac blood from trauma patients undergoing open CPR [14•]. A total of 22 patients were included in the study. Although all ultimately died, 10 patients experienced a transient return of circulation (mean 51±69 min). The majority of patients (91 %, 20/22) presented with severe acidosis (pH<7.20) from hypoperfusion following cardiac arrest or profound shock. Not surprisingly, patients who never regained cardiac activity had higher lactate, sodium, and potassium levels than their counterparts who did (Table 1). Severe hyperkalemia (potassium>5.5 mmol/L) (p=0.030) was more common in the group who never regained a rhythm. In addition, 96 % of patients were coagulopathic and thrombocytopenic (INR>1.2 and/or prothrombin time >15 s and/or platelet count <100,000/µL). This mechanism may be secondary to hemodilution as well as activation of the protein C pathway.

Interestingly, the patients had normal blood gas levels (pCO_2 <45 mmHg in 68 % (15/22) and pO_2 >75 mmHg in 77 % (17/22)). This finding was unexpected since cardiopulmonary arrest and acidosis shift the oxygen-hemoglobin dissociation curve, worsening blood gas levels. Calcium and magnesium levels were also not significantly different between the two groups, calling into question the role of these two electrolytes in cardiac arrest.

Additional evidence for severe acidosis comes from a multi-institutional prospective study by Moore et al. [15•] that included 56 EDT survivors of both blunt and penetrating mechanisms. Prehospital CPR was reported in 34 % of survivors. The physiologic status of these patients included a mean base deficit (BD) of 23.3 mequiv/L (range, 14–32 mequiv/L) for patients undergoing CPR >5 min. Four of 7 patients who survived asystole upon ED arrival had a BD>25 mequiv/L.

Table 1 Biochemical profile during open cardiopulmonary resuscitation [14•]

	Transient cardiac activity	No cardiac activity	p value
Lactate (mmol/L)	10.6+4.9	17.1+2.6	0.018
Sodium (mmol/L)	147+9	155+14	0.094
Potassium (mmol/L)	4.6+1.0	6.0+1.1	0.014

Another study examining the value of preclinical blood gas analysis in the management of prehospital cardiac arrest found that the majority of patients had severe acidosis (pH range <6.9 to 7.31), 1 had alkalosis (pH 7.51), and only 2 patients had an arterial pH within normal range [16]. In this study, the pCO_2 was variable (range 24–97 mmHg) and there was no correlation between pH and BD (r=0.267) or pH and pCO_2 (r=0.016).

Hyperkalemia in the noncrush trauma patient is thought to be secondary to transfusion of cell- or plasma-based products. The reported prevalence of hyperkalemia is 29 % [17]. Independent risk factors for hyperkalemia include an ED plasma potassium level of 4.0 mmol/L or higher (relative risk 3.40; 95 % confidence interval 1.17 to 9.84; p=0.024 vs. baseline potassium level <4.0 mmol/L) and transfusion (relative risk 10.56; 95 % confidence interval 3.62 to 30.78; p<0.001). The authors concluded that aggressive support is required for those patients with plasma potassium levels >4.0 mmol/L to prevent additional cardiac risks in the periresuscitative period.

Outcome

One of the strongest predictors of survival post-EDT is the mechanism of injury [18]. In general, patients who require EDT after penetrating trauma mechanisms have better outcomes than those who have suffered blunt trauma. Both the National Association of EMS Physicians Standards and Clinical Practice Committee and the ACSCOT guidelines state "patients sustaining blunt injuries that arrive pulseless but with myocardial electrical activity are not candidates for resuscitative thoracotomy" [19, 20]. These guidelines support the concept that injury mechanism is usually the first decision point for initiating resuscitation in the ED. However, more recent multicenter data refute the assertion that injury mechanism alone is a predictor of futility. The 2011 WTA perspective defining the limits of resuscitative EDT provide evidence that in the absence of a devastating head injury, blunt trauma does not preclude meaningful survival after EDT, and duration of prehospital CPR is a more reliable predictor to establish futility, although the precise time limit is still disputed [15•]. In summary, they suggest survival is unlikely when patients sustain blunt trauma and require >10 minutes of prehospital CPR without response.

The clinical bottom line of Khorsandi et al., using EDT as a best evidence topic, is that survival rates after EDT for blunt trauma are very low in the vast majority of available case series, particularly when no vital signs are present. This point of view is further supported by the fact that in the few survivors sustaining a blunt mechanism, the neurologic sequelae are frequent and severe [21•]. The ultimate positive outcome of EDT is survival without neurological deficits. A systematic review performed by ACSCOT included 42 cohort studies reporting on survival and 14 studies reporting on neurologic sequelae in survivors of EDT [3]. The survival rate was 1.6 % among 2193 patients who suffered blunt trauma, 15 % of the survivors from both blunt and penetrating mechanisms suffered from neurologic impairment. Rhee et al. reviewed the neurologic outcomes of all trauma survivors (both blunt and penetrating) and found no neurologic effects in 92.4 % of these cases [22].

The seemingly conflicting data on performing EDT in the blunt trauma population is unlikely to be resolved. The only consensus may be derived from a patient's point of view. Because patients requiring EDT are in cardiac arrest and have a 100 % predicted mortality, this is the only procedure that has the potential to save their lives.

Although most survival studies of EDT focus on neurologic outcome, a novel study by Keller et al. examined the long-term social, cognitive, functional, and psychological consequences [23•], reviewing 37 survivors (98 % penetrating trauma) from an urban level 1 trauma center. A total of 16 of the 37 patients were available for comprehensive evaluation using several functional scoring systems at a median 59-month follow-up period. Most of the patients (75 %) had normal cognition and returned to normal activity, 81 % were freely mobile and functional, and 75 % had no evidence of posttraumatic stress disorder. Even so, unemployment (75 %), daily alcohol (50 %), and drug use (38 %) were common. This study has several limitations, including the small population of patients with only penetrating mechanisms of trauma at a single institution, nonuniform study participation (16/37), and no control group, although interviewing a control group would be impractical given the inevitably fatal alternative outcome. Despite the limitations, the results of this study contradict the prevailing belief that EDT leads to significant emotional, physical, and social impairment in survivors.

International Perspectives

Several papers describe EDT protocols overseas. The majority of these papers originate in Europe and report higher survival than North American studies, with authors from Switzerland, Austria, and Denmark reporting survival rates from 12.5 % to as high as 59 % [24–26]. However, direct comparison is difficult for several reasons. First, European indications tend to be more liberal, and EDT may be performed on patients who would have survived without it. The corollary is that these centers may avoid performing the procedure on some severely injured patients who may have met US qualifications. Second, in the USA, EDT almost always entails a left anterolateral thoracotomy with open cardiac massage and clamping of the descending aorta. In Europe, the procedure has included a right anterolateral thoracotomy or midsternotomy alone or in combination with a left anterolateral thoracotomy. Finally, many of the European results describe the procedure frequently being performed in the operating room, whereas in North America, it is done in the ED. The consensus is that EDT is performed globally, and the procedure is challenging for everyone.

Military Perspectives

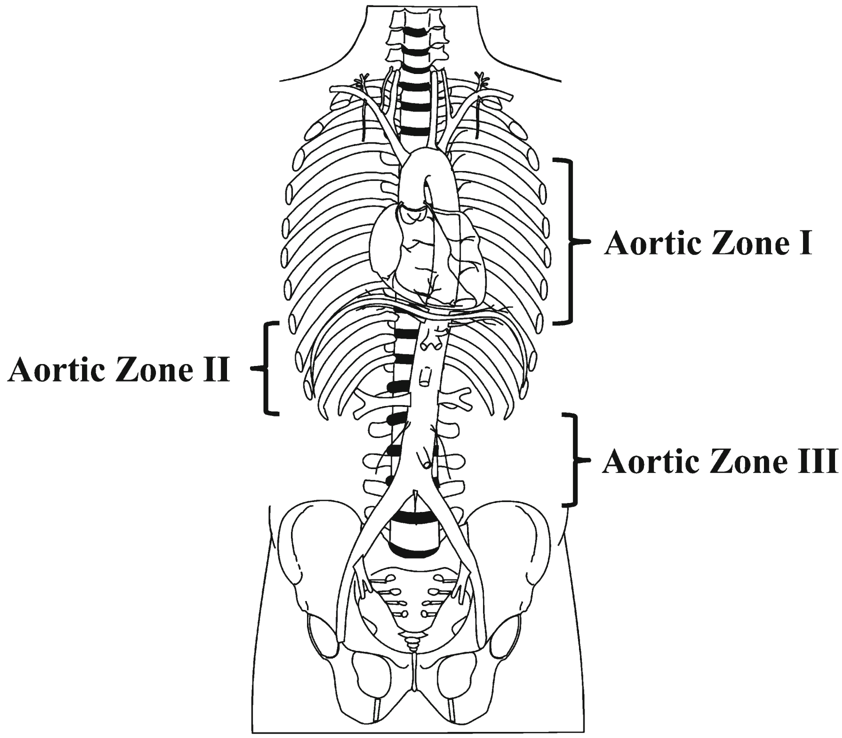
The Joint Theater Trauma System Clinical Practice Guideline 2012 summarizes the military's stance on emergent resuscitative thoracotomy on the battlefield [27]. The guidelines state that this procedure is warranted only in patients with penetrating injuries who present to a forward surgical facility with critical care capacity. They acknowledge that the majority of casualties will not survive, but that the small percentage that do will have normal neurological function. Edens et al. reported a 12.7 % survival for penetrating trauma and 0 % for blunt mechanisms [28]. The distribution included thoracic (40 %), abdominal (30 %), and extremity (22 %) injuries. All patients presented with SOL and 92 % underwent CPR. In military casualties, the guidelines state that emergency thoracotomy be used in the rare case of a blunt trauma victim losing SOL while in a military training facility.

The British experience supports the American reports in combat environments. They recommend appropriate patient selection and suggest that this procedure has no role in the prehospital setting [29•,30].

Resuscitative Endovascular Balloon Occlusion

Resuscitative endovascular balloon occlusion (REBOA) is a relatively recent adjunct for hemorrhagic shock involving use of an intra-aortic balloon catheter tamponade for control of intra-abdominal hemorrhage (Fig. 1). A published protocol for REBOA is illustrated in Fig. 2. The use of REBOA as a supplement during EDT has been recently proposed. In comparison to thoracotomy and clamp occlusion in an animal model, patients who underwent REBOA were less acidotic (pH, 7.35 vs. 7.24, $p<0.05$) and had a lower serum lactate level (4.27 vs. 6.55, $p<0.05$) [31]. In addition, the REBOA group required less fluid (667 vs. 2166 mL, $p<0.05$) and norepinephrine (0 vs. 52.1 mcg, $p<0.05$) during resuscitation. The authors concluded REBOA increased central perfusion pressures with less physiologic disturbance than thoracotomy with aortic clamping [31, 32•]. REBOA is not yet used in all institutions caring for trauma patients, and not all trauma surgeons have acquired the skills required to perform this procedure. However, it is feasible to consider that REBOA may replace EDT in the future.

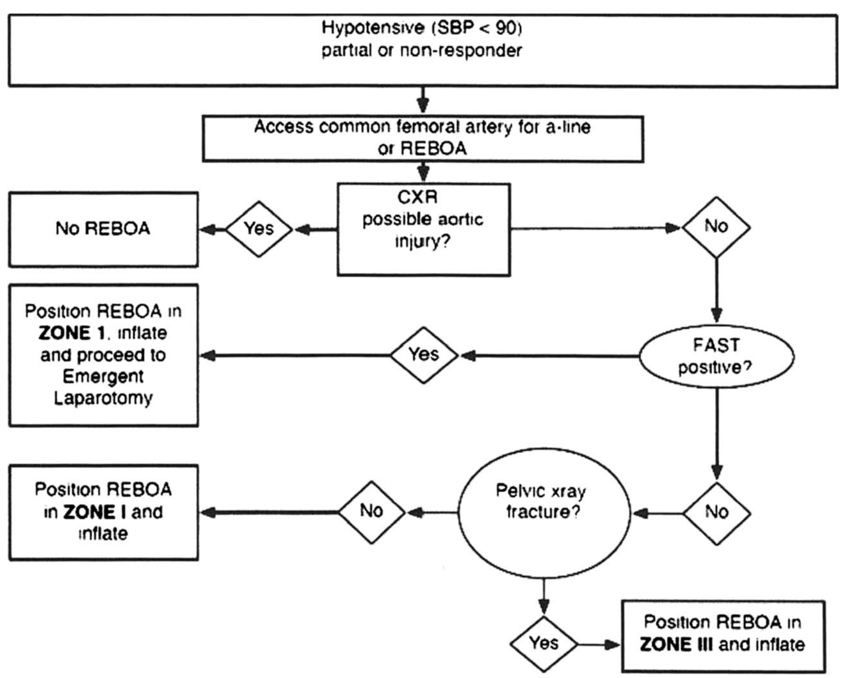
Fig. 1 Zones of aorta



Societal Perspectives

Performing an EDT is agreed to be a high-risk, low-yield procedure. Although lifesaving, it can also lead to waste of resources and increased exposure to blood-borne pathogens. In a recent study considering societal costs of inappropriate EDT, the authors found a substantial increase in costs and waste of resources in performing EDT for improper

Fig. 2 Shock trauma center protocol. Courtesy of Brenner M. J Trauma. 2014; 77(2):287



indications [1•]. They also concluded that healthcare providers had a possibly greater exposure to blood-borne infections, while poor patient selection offered no survival benefit.

Brown et al. performed a cost-utility analysis of EDT in 2007 [33]. The incremental cost-effectiveness ratio of EDT for penetrating trauma was $16,125 per quality-adjusted life year (QALY), and less than $50,000 per QALY with a 93.4 % probability. The incremental cost-effectiveness ratio for blunt trauma was $163, 136 per QALY, and less than $50,000 per QALY with a 37 % probability. Neither model was sensitive to provider exposure. Only the blunt model was sensitive to the probabilities of survival and of neurologic impairment. The authors concluded that EDT is cost-effective for penetrating but not blunt trauma. Occupational exposure did not significantly impact the cost-effectiveness of the procedure.

The incidence of anti-HIV, HBsAg, or anti-HCV in penetrating trauma victims at Temple University Hospital between 2008 and 2010 was greater than 9 %, and the majority of seropositive patients (75 %) were unaware of their status [34]. While it is commonly understood that HIV and hepatitis infection are widespread in the penetrating trauma population, serologic evidence of at least one of the three viruses (16.7 %), anti-HCV (14.5 %), and anti-HIV (5.6 %) antibodies was also common in patients 25 to 44 years old that were undergoing major surgery at a tertiary-care medical center located in New York [35]. Both studies strongly underscore the importance of universal precautions. The prevalence of undiagnosed HIV and hepatitis infections in penetrating trauma victims also provides an opportunity for education, screening, and earlier treatment of this high-risk population. A cost analysis based on provider exposure to human immunodeficiency virus (HIV) and hepatitis from percutaneous injury during EDT was reported by Sikka et al. [36]. They assumed a prevalence of 7.1 % for HIV and 18 % for hepatitis and a provider percutaneous injury rate of 10 %. The probability was 0.00004 for HIV and 0.0027 for chronic hepatitis C seroconversion. Exposure was associated with a cost of $1377 per thoracotomy.

Organ Donation

The potential for organ donation rescue after traumatic arrest and EDT was evaluated by Schnuriger et al. [37]. A total of 11 patients (4.2 %) out of 263 patients who underwent EDT became potential organ donors. Eleven organs (6 kidneys, 2 livers, 2 pancreases, and 1 small bowel) were harvested from three donors. Two of the three donors sustained blunt injury. The potential for organ donor rescue is one of the more tangible and important outcomes after traumatic arrest and EDT, and the authors maintained that donation has greater potential to alter survival and quality of life for organ recipients than for survivors of the procedure itself.

Conclusion

Analysis of the current literature on EDT supports a selective approach as the optimal treatment paradigm for this last-chance procedure for patients in extremis. One undisputed fact is that the best results are achieved in patients with thoracic stab wounds who present in the trauma bay with SOL. EDT should not be performed in patients who never exhibited SOL. Finally, although contested by the WTA data, EDT is futile in blunt trauma patients who arrive to the hospital without SOL.

New insights into biochemical changes during EDT are being reported. International and military perspectives are in line with North American civilian outcomes. REBOA is a new adjunct that may be considered for future applications. Finally, costs to society in terms of both healthcare personnel exposure and financial terms are high for inappropriate EDTs.

Compliance with Ethics Guidelines

Conflict of Interest Drs. Codner and Brasel declare that they have no 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.

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