Western Trauma Association Critical Decisions in Trauma: Penetrating chest trauma

Riyad Karmy-Jones, MD, Nicholas Namias, MD, Raul Coimbra, MD, Ernest E. Moore, MD, Martin Schreiber, MD, Robert McIntyre, Jr., MD, Martin Croce, MD, David H. Livingston, MD, Jason L. Sperry, MD, Ajai K. Malhotra, MD, *and* **Walter L. Biffl, MD,** *Portland, Oregon*

This is a recommended algorithm of the Western Trauma Association for the acute management of penetrating chest injury. Because of the paucity of recent prospective randomized trials on the evaluation and management of penetrating chest injury, the current algorithms and recommendations are based on available published cohort, observational and retrospective studies, and the expert opinion of the Western Trauma Association members. The two algorithms should be reviewed in the following sequence: Figure 1 for the management and damage-control strategies in the unstable patient and Figure 2 for the management and definitive repair strategies in the stable patient. Figure 1 will discuss damage-control techniques; Figure 2 will focus on more definitive repairs. Because of the variety of possible mechanisms, presentation, injury sites, and operative approaches, we recognize that there will be variability in decision making, local resources, institutional consensus, and patient-specific factors that may require deviation from the algorithms presented. The algorithms and accompanying text represent our consensus for a safe and reasonable approach in these complex cases and attempts to incorporate historically validated approaches with the advent of newer imaging, interventional, resuscitative, operative, and selective/expectant management approaches.

Submitted: April 4, 2014, Accepted: June 30, 2014.
From the Department of Surgery (R.K.-J.), Legacy Emanuel; and Oregon Health and Sciences University (M.S.), Portland, Oregon; University of Miami School of Medicine (N.N.), Miami, Florida; University of California-San Diego Medical Center (R.C.), San Diego, California; Denver Health Medical Center (E.E.M. W.L.B.); and University of Colorado School of Medicine (R.M.), Denver, Colorado; University of Tennessee-Memphis Health Science Center (M.C.), Memphis, Tennessee; University Hospital (D.H.L.), Newark, New Jersey; University of Pittsburgh (J.L.S.), Pittsburg, Pennsylvania; Virginia Commonwealth University (A.K.M.), Richmond, Virginia.
This algorithm was presented at the annual meeting of the Western Trauma Association, March 2–7, 2014, in Steamboat Springs, Colorado.
The Western Trauma Association (WTA) develops algorithms to provide guidance and recommendations for particular areas but does not establish the standard of care. The WTA develops algorithms based on the evidence available in the literature and the expert opinion of the task force in the recent time frame of the publication. The WTA considers the use of the algorithm to be voluntary. The ultimate determination regarding its application is to be made by the treating physician and health care professionals with full consideration of the individual patient's clinical status as well as available institutional resources and is not intended to take the place of health care provider's judgment in diagnosing and treating particular patients.
Address for reprints: Riyad Karmy-Jones, MD, Legacy Emanuel Medical Center, 2801 N. Gantenbein Ave, Suite 130, Portland, OR 98774; email: rkarmy@lhs.org.

DOI: 10.1097/TA.0000000000000426

Historical Perspective

The precise incidence of penetrating chest injury, varies depending on the urban environment and the nature of the review. Overall, penetrating chest injuries account for 1% to 13% of trauma admissions, and acute exploration is required in 5% to 15% of cases; exploration is required in 15% to 30% of patients who are unstable or in whom active hemorrhage is suspected. Among patients managed by tube thoracostomy alone, complications including retained hemothorax, empyema, persistent air leak, and/or occult diaphragmatic injuries range from 25% to 30%.[1–6] In civilian practice, this low incidence has been generally attributed to "low-kinetic energy" mechanisms. In zones of conflict, among properly outfitted soldiers, body armor also results in a lower requirement for operation and incidence of complications.[1,5,6]

The reported incidence of specific injuries also varies, depending on site and characterization of the patient population. Demetriades[7] reported an overall incidence of great vessel injury of 5.3% following gunshot wounds and 2% after stab wounds to the chest. Rhee et al.[8] described an overall incidence of penetrating cardiac injuries as 1 per 210 admissions. Sixty-five percent of the patients admitted to the University of Louisville with peristernal penetrating injuries sustained a cardiac injury.[9] In patients requiring urgent (non–emergency department) thoracotomy, cardiac injuries are found in approximately 16% to 52% following stab wounds and 10% to 37% following gunshot wounds, and lung injuries are found in 30% to 59% of stab wounds and 65% to 86% of gunshot wounds.[10–12]

It is clear that mortality is significantly impacted by preadmission hypotension, the ability to perform aggressive resuscitation and operative intervention, and appropriate imaging in stable patients.[13,14] Focusing on blood products rather than crystalloids and in some settings "hypotensive" resuscitation seems to have a survival benefit.[6]

Anatomy

The simplest anatomic classification is based on the likelihood of specific organ injury. Classically, penetrating injuries between the nipple lines anteriorly or the scapula posteriorly have the potential for cardiac or great vessel injury. The "danger zone" has been described as the region between the epigastrium to the sternal notch and laterally within 3 cm of the sternum.[9,15] Injuries below the level of the tip of the scapula posteriorly or the inframammary crease/nipple anteriorly have the potential to traverse the diaphragm, particularly left lower

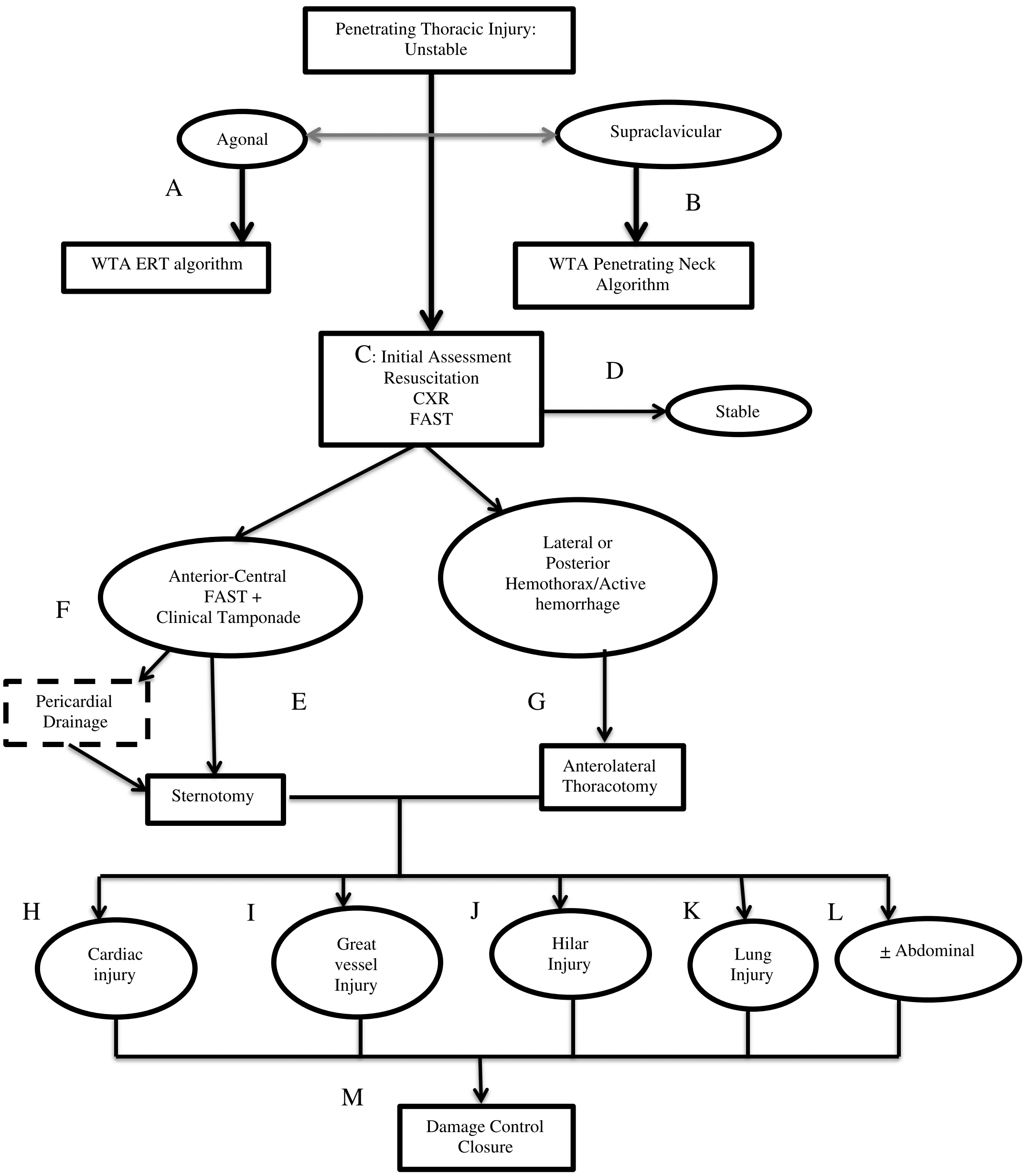

Figure 1. Management of the stable patient.

thoracic injuries.[1] As many as 20% of patients with penetrating injuries will have associated abdominal injuries.[14] Unfortunately, particularly with gunshot wounds, any region of the chest may be affected, and these anatomic relationships should only be considered as generalizations.

Presentation

The presentation and management of a patient of penetrating trauma depends on three interrelated factors: stability, mechanism, and location of the wound. For the purposes of this discussion, stability requires that the airway be secure (with or without intubation), that the patient is both oxygenating and ventilating at an acceptable level, and that continued hemodynamic stability is documented. Patients with evidence of shock or impending collapse (systolic blood pressure < 90 mm Hg and/or persistent tachycardia > 120 beats per minute, not explained by pain or anxiety and/or persistent hypoxemia) should be managed by airway control combined with aggressive blood product resuscitation. In essence, a stable patient is one in whom there is time to consider different diagnostic and therapeutic options; the unstable patient is one in whom the approach is predicated on getting to the operating room as soon as possible with minimal delay for extraneous testing. This excludes the agonal patient. Clearly, there are times when the

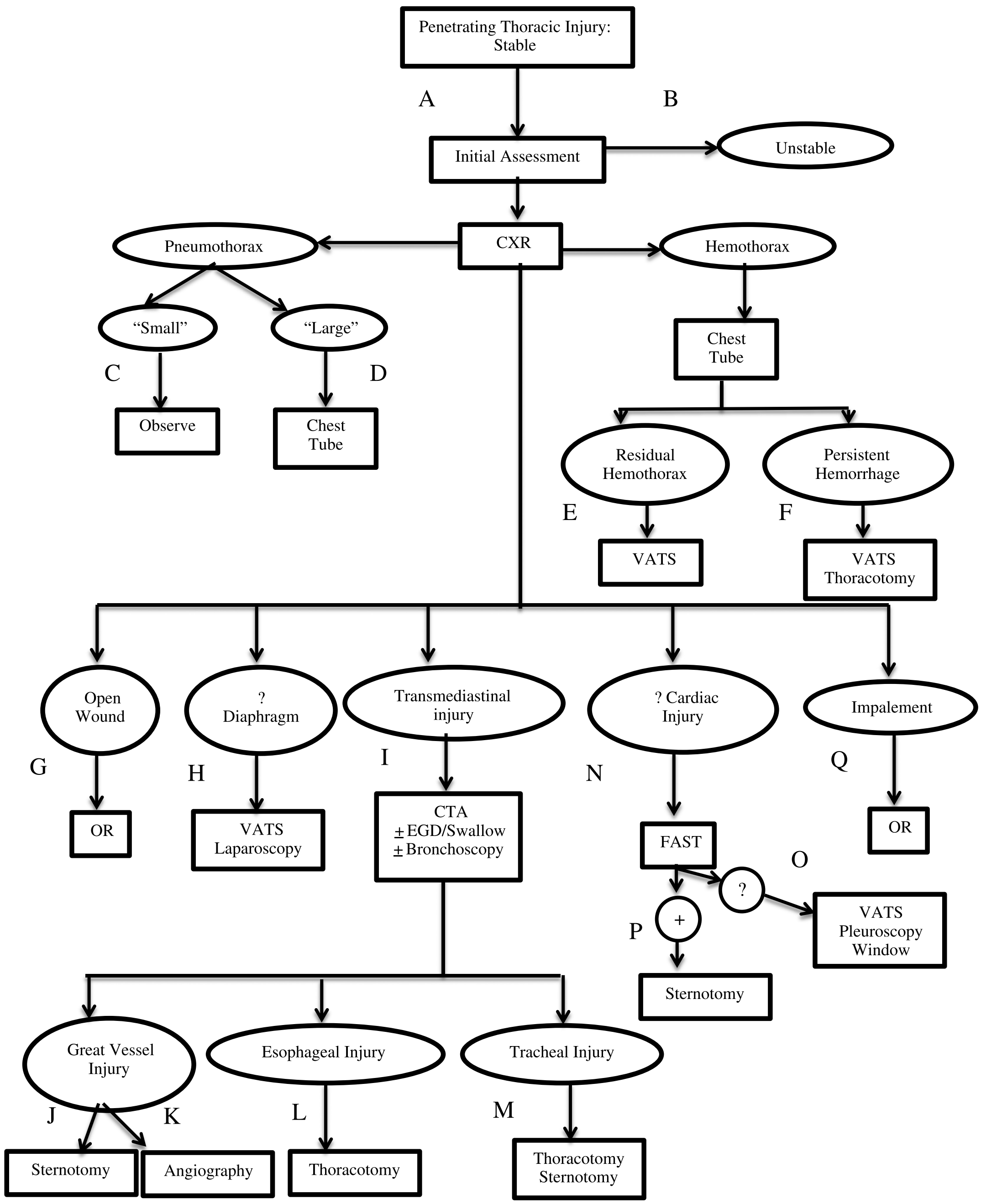

Figure 2. Management of the unstable patient.

scenarios overlap (e.g., transmediastinal gunshot wound with suspicion of tamponade), and the pathways described are not mutually exclusive.

Incisions and Approaches

There are a number of different approaches that can be used involving variations in incision, airway management, and positioning. The choice is dictated by stability, mechanism, and surgeon preference/experience. A brief review of these is presented in Table 1. In an unstable patient, the optimal positioning is supine in the crucifix position, with the patient draped to include the neck, supraclavicular area, entire thorax, abdomen, and proximal thighs. A single-lumen tube is the optimal initial airway tool in chest trauma. The tube can be advanced into the left main stem bronchus to isolate the right lung, or an endobronchial blocker can be placed to isolate the left. Advancing a single-lumen tube into the right often causes obstruction of the right upper lobe bronchus. This rapid isolation can be particularly useful in patients with massive unilateral air leak and/or hemorrhage. A double-lumen tube can be used in stable patients who require lung isolation or in centers that are facile with emergent placement. In patients who present

TABLE 1. Description of Thoracic Interventions

Technique	Description/Definition	Pros	Cons
Pleuroscopy	Usually using a mediastioscope	Simple; does not require lung isolation; can explore pleura and pericardium; large working port	Limited visualization; requires good experience with intrathoracic anatomy; limited to simple interventions such as pleural drainage
Thoracoscopy	Generally refers to videothoracoscopy, without an accessory incision	Simple; excellent visualization; can be used for simple repairs of injuries	Requires lung isolation and absence of pleural symphisis, as well as patient stability
VATS	Video-assisted thoracic surgery; implies intrathoracic procedures often accompanied by an accessory incision that can be of any size but does not use rib spreading	Less morbid approach for repair of simple injuries; excellent visualization	Requires lung isolation and absence of pleural symphisis, as well as patient stability
Anterolateral thoracotomy	Anterior approach, minimal muscle division, can "bump" patient up	Rapid, easy, quick access to cardiac structures; can be combined with laparotomy	Limited apical and posterior exposure
Posterolateral thoracotomy	Posterior approach with various degrees of "muscle sparing" possible	Excellent exposure to all parts of the hemothorax; can be performed without lung isolation although not ideal. Used in stable patients with unilateral injuries.	Poor exposure of the repair injuries at the apex of the hemothorax; requires repositioning if laparotomy or contralateral exposure needed; most painful incision; can lead to contamination of contralateral airway if not controlled; should not be used in a hypotensive patient[14]
Sternotomy		Excellent exposure to heart and great vessels and anterior hila	Limited exposure to lateral and posterior injuries

in severe shock and/or require massive volume resuscitation, it may not be possible to "switch out" the double-lumen tube at the end of the case because of tenuous oxygenation/ventilation status. When possible, antibiotics with gram-positive coverage should be administered, although there has been conflicting data regarding the efficacy of "prophylactic" antibiotics.[16,17] Ideally, this should be administered before tube thoracostomy, but practically, it happens soon after. There are various recommendations regarding duration, but in general, duration of greater than 24 hours is not recommended.[18]

Figure 1: Approach to the Unstable Patient

A. Patients in arrest are approached using the Western Trauma Association resuscitative thoracotomy algorithm.[19]

B. Supraclavicular injuries can be managed according to the Western Trauma Association penetrating neck trauma algorithm.[20]

C. Resuscitation and assessment follow standard guidelines. If not intubated, the airway is secured, usually with a single-lumen tube. If intubated, placement must be confirmed. Direct visualization of the tube placement by laryngoscopy, auscultation, and confirmation of end-tidal CO_2 are simple initial measures. If there are absent breath sounds, indicative of pneumothorax and/or hemothorax, chest tubes are placed on the affected side(s). If there is any doubt, it is safer to place chest tubes on the affected side(s) rather than waiting for confirmatory imaging. Ultrasonography can be used to document pneumothorax/hemothorax if the operator is trained to do so.[21] Ultrasonography is now accepted as a tool to rapidly assess for pericardial fluid, although in the presence of hemothorax, a negative study result does not rule out a cardiac injury.[22] Needle decompression can be used as an initial step, but in most dedicated trauma centers, it is almost as expedient to place a chest tube. Circulation is supported by product resuscitation. In the setting of significant hemorrhage from a chest tube, autotransfusion can be used, although in conjunction with ongoing product resuscitation. A quick chest x-ray (CXR) can confirm laterality of injury, rule out transmediastinal/multiple injuries, and confirm endotracheal tube placement.

D. A number of patients will respond to simple initial maneuvers and become stable.[14] These patients can then be managed according to the "stable" algorithm (Fig. 2).

E. Central injuries (between the midclavicular lines) and those associated with possible great vessel or cardiac injuries are best approached by sternotomy. This seems to be particularly salient in the setting of gunshot wounds.[10] Supraclavicular extension will allow exposure of the great vessels.[13] If the surgeon is not facile with sternotomy or if other findings (such as multiple different wounds, etc.) affect planning, an anterolateral thoracotomy with extension across the midline is perfectly acceptable and is the preferred approach for many surgeons. It is difficult to control the left inferior pulmonary vein from a transsternal approach without causing cardiac decompensation. Whichever approach is used, there should be no hesitation to extend the incision in any way needed.

F. Patients who have documented pericardial tamponade can (rarely) be temporized by ultrasound-guided placement of a pericardial catheter. This is most beneficial in a patient with clinically obvious tamponade, who is not yet intubated, to avoid acute decompensation on induction.[23] Pericardial drainage should never be performed as a "diagnostic" maneuver and mandates operative exploration, as does the presence of clinical tamponade.[15]

G. Injuries lateral to the midclavicular line or deemed to be outside the "peristernal" area are best approached by anterolateral thoracotomy. The decision of what constitutes a "lateral" injury varies between surgeons, and both of the criteria mentioned earlier are acceptable. If bilateral injuries are present and there is one surgeon, the anterolateral thoracotomy should be on the side where the most blood loss is suspected or documented. This can be converted to a clamshell thoracotomy as needed. The incision should be at approximately the third or fourth intercostal space. This is best found by making the incision in the true inframammary crease. A common error is to start an anterolateral incision that does not curl up sufficiently, resulting in crossing the sternum inferiorly. This inhibits exposure and healing.

H. If pericardial tamponade is encountered on entering the chest, the pericardium is opened. From the sternotomy approach, "T-ing" the pericardium along the diaphragmatic reflections increases exposure. From an anterolateral or posterolateral approach, extending the incision anteriorly to the opposite side and in a craniocaudal manner anterior to the phrenic nerve is optimal. Penetrating injuries affect the ventricles more than the atria and the right more often than the left. Most injuries can be controlled with digital pressure then repaired with sutures (3-0 or 4-0, surgeon's choice) often with pledgets (can be pericardial). If significant bleeding is encountered, temporizing measures include the use of Foley catheter for tamponade, staples on the left ventricle, and/or caval occlusion.[15,19] A Foley catheter can actually lead to more damage, especially if pulled out inadvertently, and should be used primarily for left ventricular injuries if direct pressure is not an option. Staples can be used on the right ventricle, but this thinner walled chamber is more prone to damage and generally has lower pressure, and finger pressure usually suffices. Caval occlusion is simple and quick and reduces blood loss. If there is evidence of myocardial compromise after repair, insertion of an intra-aortic balloon pump can support the patient.[24] Cardiopulmonary bypass has been used rarely to resuscitate patients who have sustained cardiac injury that is repaired and are experiencing severe myocardial compromise or malignant arrhythmias. However, this is only applicable if all the bleeding sources have been controlled.

I. If superior mediastinal hematoma is encountered, the root of the great vessels, the ascending aorta, and arch can be exposed by extending the pericardial incision superiorly in the midline. This often allows for proximal intrapericardial control before inadvertently decompressing the hematoma.[25] If, on entering the chest, major apical bleeding is encountered, packing the apex and holding hand pressure can temporize the bleeding. Ascending arch injuries can be controlled digitally, but caval occlusion can be helpful as well.[25,26] Distal exposure of the great vessels can be obtained by simple supraclavicular or lateral neck extensions. Repair can be performed by simple suture, end-to-end reconstruction, interposition graft, or bypass graft. Temporary shunts may be used if available and if there is enough exposure. In the persistently unstable patient, this is usually not practical, and the proximal and distal exposure is not sufficient. Ligation is generally limited to the left subclavian artery and in patients with devastating injuries who manifest coagulopathy.

J. Central hilar injuries are managed first by hilar control.[27] This can take the form of "hilar twist," snare or simple hand control, followed by clamping. The hilar twist requires division of the inferior pulmonary ligament, and results in severe hilar injury and obscures operative exposure. Therefore, it is really of historical interest. Clamping inferiorly also requires division of the inferior pulmonary ligament, while this is not needed if clamping from superior to inferior. This reduces the risk of fatal hemorrhage and air embolism.[28] Massive central injuries may require pneumonectomy. A central tractotomy can lead the surgeon to the injured area, permitting control and avoiding pneumonectomy. If performing a "stapled" pneumonectomy, fluid should be restricted when possible, and bronchial stump reinforcement should be performed acutely or, if the patient is too unstable, at a later date.[29] The mortality rate following trauma pneumonectomy ranges from 50% to 100%, and commonly, the cause is acute cor pulmonale. Once bleeding is controlled, fluids should be restricted.

K. Lung injuries that are bleeding massively may also require rapid hilar control. Tractotomy is preferred to expose the depth of a bleeding wound, permits ligation of injured pulmonary vessels, and is particularly appropriate as a damage-control technique.[30,31] In general, the lesser the parenchymal resection, the better the outcome.[3] Deep parenchymal tracts should not be managed by oversewing the entry and exit sites. This will lead to intraparenchymal hemorrhage, respiratory failure, and air embolism. It is far better to leave the tract open. Biologic glues may be tried if it is clear that there is no open communication with major airways or vasculature. The technique (anatomic vs. stapled) is determined by the experience of the surgeon and comfort level, but what works quickest is generally associated with improved outcomes. Air embolism results in acute instability and can manifest with cardiac (arrhythmia, arrest) and/or neurologic (sudden stroke) complications. It may occur with intubation and positive-pressure ventilation or at thoracotomy when the lung injury is decompressed. Cardiac air embolism may be evident as air is usually seen in the coronary arteries. Management includes clamping the airway to the affected parenchyma or hilar control. In patients who are acutely decompensating, cross-clamping the aorta (to increase coronary perfusion pressure), cardiac massage, and venting the left ventricle are required.[19,32] Rarely, cardiopulmonary bypass may be an option in patients without contraindications. Neurologic air embolism is similarly addressed by controlling the site of lung injury, maintaining cerebral perfusion pressure, and hyperbaric oxygenation in select patients.

L. If penetrating injury involves the lower third of the thorax and there is evidence of abdominal injury, laparotomy may be the appropriate initial maneuver. The decision to perform thoracotomy or laparotomy first is determined by clinical findings, chest tube output, chest radiograph, and/or Focused Assessment with Sonography in Trauma (FAST). As a practical manner, it does not really matter which is performed first, as long as the goal is rapid exposure and damage control. In essence, exploration should start where the majority of the hemorrhage is originating.[33]

M. Delayed closure is appropriate in patients who manifest thoracic compartment syndrome and/or who have diffuse bleeding and are persistently unstable. It will be readily apparent when attempting to close the chest and manifests as a drop in blood pressure and/or sudden rise in airway pressure. Retractors can be left in place, or the skin can be loosely closed. Persistent cardiac dysfunction can be managed with an intra-aortic balloon pump.

Figure 2: Approach to the Stable Patient

A. Patients who are hemodynamically stable, maintaining a patent airway, or have a secure airway with evidence of good oxygenation, without obvious ongoing air leak or bleeding are initially assessed according to Figure 2 with adherence to Advanced Trauma Life Support guidelines. Clinical examination can be incorrect in up to one third of cases when assessing for hemothorax and/or pneumothorax, although it is still the criterion standard for initial assessment.[34] In stable patients, it is reasonable to obtain a CXR before performing tube drainage. Marking entrance and exit sites can be helpful, and in gunshot wounds, abdominal films may be required to define the trajectory of missiles. Centers with expertise in ultrasonography may choose to use this technique as a screening tool to detect pneumothorax and/or hemothorax.[21]

B. If at any time during the evaluation the patient becomes unstable or exhibits active hemorrhage requiring blood product resuscitation, management should shift to the unstable algorithm, with the emphasis on rapid transport to the operating room without additional imaging.

C. Patients with no evidence of intrathoracic penetration and no significant chest wall injuries can be discharged. Those with small pneumothoraces and/or hemothoraces can be observed for up to 24 hours. Most small pneumothoraces do not require evacuation. Even in otherwise stable ventilated patients, the trend has been for observation.[35–37]

D. Larger pneumothoraces (classically those that are immediately apparent on the first plain CXR) generally are drained. In the absence of other indications, small-bore tubes or a range of pleural catheters (8.5–16 Fr) are acceptable.[14,38] The catheter tubes are easy to place, less painful, and as effective as the more traditional tubes in one series.[39] Stable patients who have had previous thoracotomy, chronic lung disease (such as emphysema), and/or pleural inflammation (e.g., chronic bronchitis) may be better managed by image-directed catheter drainage to avoid areas of adhesions.

E. Traditionally, when hemothorax is suspected or diagnosed, large-bore chest tubes (36–40 Fr) have been advocated. These tubes may actually be too big for smaller patients and are associated with increased pain. Smaller-bore (28–32 Fr) chest tubes or a range of pleural catheters (11–16 Fr) may be as effective in stable patients with less pain associated with placement.[14,38,39] Whatever the size of the initial drainage tube, residual hemothorax is a significant risk factor for the development of empyema. The primary risk factor for empyema is the need for a chest tube. Thus, this does not apply to the residual small untapped or drained hemothorax.[40] Patients with a hemothorax still apparent after tube drainage in the trauma bay on plain CXR or large collections noted on chest computed tomography (CT) have up to a 25% incidence of empyema, particularly with a residual hemothorax of greater than 300 cc.[35,41] CT scan is much more accurate in predicting the volume of retained hemothorax than plain CXR. Early washout and evacuation within 72 hours is optimal. Techniques can include pleuroscopy, video thoracoscopy (VATS), or thoracotomy. VATS has been favored over placing more chest tubes, the former being associated with quicker resolution and with fewer complications.[35] Instillation of thrombolytic agents has been described and is associated with a delay in resolution, increased cost, and possibly increased complications in the trauma setting.[42]The majority of organisms associated with posttraumatic empyema are gram positive, but it is not clear whether "prophylactic" antibiotics independently reduce the risk.[16,43] Nevertheless, most centers administer at least one dose of antibiotics that covers gram-positive organisms as soon as practical.

F. Mansour et al.[12] found that the most common indication for urgent thoracotomy following penetrating injury was excessive chest tube output (28% following stab and 50% following gunshot wounds). An acute evacuation of blood on tube placement exceeding 1,500 cc should prompt consideration for operative exploration. Persistent bleeding has been defined as 200 cc/h for four or more hours. Practically, a limit of 1,500 cc over a 24-hour period as an indication to consider operation results in less delay and perhaps less complications.[35] Large retained hemothorax, transient instability, or other clinical indicators (e.g., acidosis with no other explanation, air leak, suspicion of relevant injuries such as diaphragm) may prompt exploration with less blood output than the classic "1,500" cc.[35] Relying exclusively on chest tube output can lead to an underestimation of the injury severity.[33] In stable patients in whom the blood loss seems to be "slowing," VATS may be an option. Intercostal bleeding can be controlled with clips, lung bleeding with wedge resection, and diaphragm laceration with suture repair. Thoracotomy is advisable if the bleeding is persistent or if there is any doubt of the origin or of patient stability. The choice of approach (posterolateral vs. anterolateral vs. sternotomy) is dictated by whether the hemorrhage is unilateral and what structures are suspected to be involved. In general, a posterolateral approach (VATS or thoracotomy) affords the greatest exposure in stable patients with unilateral injuries.

G. Open chest wounds can lead to immediate ventilatory compromise. Initial management in the emergency department is to occlude the defect and place a chest tube. Depending on the size and degree of tissue damage, management can range from simple debridement and closure to complex, staged coverage using bio prosthetics and muscle/cutaneous flaps. Devastating chest wall injuries, such as those related to close range shot gun blasts, may be approached in a similar fashion, even if a sucking wound is not present. In complex destructive chest wall injuries, it is important to debride devitalized tissue and remove all foreign material as soon as practical to prevent necrotizing infections.

H. Diaphragmatic injury may be suspected by location of the wound, path of the missile, or clinical findings. Left thoracoabdominal wounds have up to 17% incidence of diaphragmatic penetration.[44] When diaphragm injury is suspected but there are no clinical or other findings that mandate laparotomy or thoracotomy, laparoscopy and thoracoscopy are both reasonable options.[44] In patients with pneumothorax or retained hemothorax, thoracoscopy is a reasonable option. Left diaphragm injuries mandate abdominal exploration. Right-sided injuries, in stable patients, when it is felt that there is only an injury to the liver that does not require operation, do not always mandate abdominal exploration.[45] The diaphragmatic injury itself can be repaired thoracoscopically or by thoracotomy, depending on surgeon's preference, or can be followed up to see if repair is needed at all. Repairs via laparoscopy or laparotomy are also acceptable approaches.

I. In the stable patient, transmediastinal gunshot wounds may not be immediately clinically apparent. In a number of cases, the patient has experienced multiple gunshot wounds. However, the diagnosis can be made with clinical examination and CXR in 90% of cases in nonagonal patients.[14] After assuring stability, managing hemothorax/pneumothorax, and using FAST to exclude obvious cardiac injury, computed tomography angiography (CTA) should be the next evaluation. CTA may show that the transmediastinal tract is extrathoracic and can exclude major vascular injury.[14] Occasionally, metallic artifact precludes an accurate assessment of the arterial wall, and elective angiography may be required. If there is evidence that suggests aerodigestive injuries, bronchoscopy and flexible exophagoscopy should be performed, with or without gastrograffin or thin barium esophagogram as the scenario dictates.

J. When performing operative repair, the ascending aorta, innominate, left common carotid, and origin of the left subclavian can be approached by sternotomy or dedicated clamshell. It is best to open the pericardium and dissect along the ascending aorta. This allows proximal control with a decreased risk of inadvertently decompressing the injury. Distal control can be obtained by neck or supraclavicular extensions. Injuries to the descending aorta are best approached via left thoracotomy, the level of incision being determined by the site of injury. As described previously, caval occlusion can permit repair of ascending aortic injuries (even through and through). If the patient has no other exsanguinating injuries, cardiopulmonary bypass (including circulatory arrest) can permit repair of injuries that would be otherwise difficult to control. [25,46] In general, simple suture repair with or without pledgets is sufficient. If repair results in significant narrowing or there is extensive loss of vessel wall, resection and end-to-end anastomosis can be performed if there is no tension. Repair with synthetic graft material is required if there is significant tissue loss.[13] If anticipated, the use of temporary shunts to bypass injuries before entering the hematoma has been described.[25] Injuries at the origin of the great vessels are often best approached by side clamping at the origin, division of the vessel, mattress closure of the aortic wall, and then ascending aortic end-to-end graft to the distal vessel. Others prefer to start with an ascending aortic end-to-side graft to the affected vessel and then to ligate the origin at the injury site, but we have seen issues with late embolism from the arterial stump.

K. The emergence of endovascular technologies has allowed for more options for the management of intrathoracic great vessel injury detected by CTA. The majority of endovascular repairs that have been described have been used following blunt trauma. To use an endovascular approach, the patient must be clinically stable. There are two settings in which an endovascular approach may be considered, both requiring that the interventional and operative skill set is available for the patient. In the more common scenario, a branch of the vessel has been injured, and embolization is a less morbid procedure than open repair. Rarely, anatomically appropriate areas of the thoracic aorta or great vessels have been injured, and the team feels that an endovascular approach is safer. The planning and technique are beyond the scope of this article. In short, rapid consideration of possible impairment of critical branch vessels, appropriate sizing for degree of shock, and determination of true landing zones are required. As true "hybrid' operating suites become more commonplace, the role of endovascular approaches may expand, although the basic principles stated earlier will remain valid.

L. The upper two third of the intrathoracic esophagus is approached via a right sixth intercostal space incision and the lower one third via a left seventh posterolateral thoracotomy. Because the mechanism is usually stab wound or small caliber gunshot, simple debridement, primary repair, and pleural wrap are sufficient in most cases.[47] If endoscopy and/or esophagogram determine that the airway or esophageal injury is minor and without loss of significant tissue and without active leak, nonoperative management usually suffices.

M. Isolated intrathoracic tracheobronchial injuries are uncommon. When they occur, it is usually in the setting of stab wounds. Small injuries without tissue loss and in the absence of ongoing air leak can be managed nonoperatively. Most thoracic tracheal injuries are approached via right posterolateral fourth intercostal thoracotomy, and generally simple repair is sufficient. Usually, simple interrupted absorbable 4-0 sutures are sufficient. Occasionally, the presence of combined great vessel and tracheal injury mandates a transsternal approach.

N. Cardiac injury may be suspected by location of the entry wound (between the midclavicular lines anteriorly), clinical examination (jugular venous distension, muffled heart sounds, and/or pulsus paradoxus), or plain CXR (widened shadow or path of the missile). Unfortunately Beck's triad of clinical findings (hypotension, muffled heart sounds, and distended neck veins) is present in at most 10% of patients subsequently documented to have sustained a cardiac injury.[48] Thus, a degree of clinical suspicion is often required. As noted previously, FAST is an effective screening tool, although it cannot reliably rule out pericardial fluid in the setting of a hemothorax. In an entirely stable patient, it may be reasonable to consider a CT scan to evaluate the mediastinum.

O. If the diagnosis is still in question, exploration by subxiphoid pericardial window, pleuroscopy, or VATS will rule out injury. Most commonly, this occurs in the setting of a residual hemothorax.[22] FAST has diminished the role of subxiphoid window to diagnose cardiac injuries, but this approach can still be appropriate based on the setting and the team's comfort level.[49,50] In stable patients, particularly after stab wounds, there has been increasing experience in *not* performing sternotomy if the window is "mildly" positive. This implies that there is no ongoing hemorrhage. Recent work has suggested that in this setting, injuries are superficial, do not involve the heart, and/or have closed.[51] This requires a great deal of confidence and close observation. Options include direct observation by lifting on the xiphoid, exploration with mediastinoscope or thoracoscope to inspect the surface of the heart, and/or application of biologic glues over possible injury sites.

P. Sternotomy is the optimal approach to manage cardiac injuries. Splitting the pericardium anteriorly, up to the origin of the ascending aorta, and dividing laterally along the diaphragmatic reflection obtain maximal exposure. Pericardial retraction stiches will elevate the heart. If there are posterior wounds, gently packing a sponge along the diaphragmatic surface will elevate the posterior surface of the heart. Most cardiac injuries can be repaired with simple 3-0 mattress sutures using pledgets (pericardium is an easy substitute). If the injury is close to a major coronary artery, placing horizontal sutures deep to either side of the artery will reduce the chance of coronary occlusion.[52] Direct injuries to the coronary artery can be repaired primarily with 6-0 or 7-0 sutures, usually in an interrupted fashion. As a rule, proximal left anterior descending coronary arteries require repair, while more distal injuries, right coronary, and/or circumflex injuries in the absence of obvious major cardiac compromise are managed by ligation.[24] If the patient is stable and has a critical coronary injury, such that it is evident that a major myocardial injury will result, repair with vein or internal mammary bypass has been reported.[24] This can be performed "on or off pump." Injuries close to the coronary ostia or ascending aorta can be managed with primary repair using caval occlusion or mechanical circulatory support.[24,53] After procedure, a formal transesophageal echocardiogram should be performed to rule out septal or valve defects. Persistent evidence of myocardial ischemia should prompt coronary angiogram when possible to exclude rare coronary fistula or occlusions that might be amenable to stenting. Septal or valvular defects that are not associated with major hemodynamic compromise can be repaired when the patient is more stable.[24] Stable patients with major septal or valvular defects with no other major injuries can be evaluated by transesophageal echo and may undergo immediate repair.[54]

Impalement injuries are generally approached by stabilizing the object and positioning the patient in a manner that will not dislodge the object. If the physical findings, often in conjunction with CXR, suggest that the object does not penetrate the chest, then it may be removed, although larger objects (fence posts, steel bars) may require anesthesia and surgical debridement. Injuries that are anterior, in the region of the heart or great vessels, may be evaluated by CXR, FAST, or occasionally CT to determine the depth and tract of the object. If the patient is entirely stable, the object can be removed in the operating suite. The impaled object can be removed under thoracoscopic guidance to determine if there are injuries that require repair. Any findings that suggest the object may involve a cardiac or great vessel injury (pulsating, CT suggests injury, etc.) mandates that the object should be removed at the time of the operative exposure.

DISCLOSURE

The authors declare no conflicts of interest.

REFERENCES

1. Calhoon JH, Trinkle JK. Pathophysiology of chest trauma. *Chest Surg Clin N Am*. 1997;7(2):199–211.
2. Paci M, Ferrari G, Annessi V, de Franco S, Guasti G, Sgarbi G. The role of diagnostic VATS in penetrating thoracic injuries. *World J Emerg Surg*. 2006;1:30.
3. Karmy-Jones R, Jurkovich GJ, Shatz DV, Brundage S, Wall MJ Jr, Engelhardt S, Hoyt DB, Holcroft J, Knudson MM. Management of traumatic lung injury: a Western Trauma Association multicenter review. *J Trauma*. 2001;51(6):1049–1053.
4. Thompson DA, Rowlands BJ, Walker WE, Kuykendall RC, Miller PW, Fischer RP. Urgent thoracotomy for pulmonary or tracheobronchial injury. *J Trauma*. 1988;28(3):276–280.
5. Robison PD, Harman PK, Trinkle JK, Grover FL. Management of penetrating lung injuries in civilian practice. *J Thorac Cardiovasc Surg*. 1988;95(2):184–190.
6. Ivey KM, White CE, Wallum TE, Aden JK, Cannon JW, Chung KK, McNeil JD, Cohn SM, Blackbourne LH. Thoracic injuries in US combat casualties: a 10-year review of Operation Enduring Freedom and Iraqi Freedom. *J Trauma Acute Care Surg*. 2012;73(6 Suppl 5):S514–A519.
7. Demetriades D. Penetrating injuries to the thoracic great vessels. *J Card Surg*. 1997;12(2 Suppl):173–179; discussion 179–180.
8. Rhee PM, Foy H, Kaufmann C, Areola C, Boyle E, Maier RV, Jurkovich G. Penetrating cardiac injuries: a population-based study. *J Trauma*. 1998; 45(2):366–370.
9. Siemens R, Polk HC Jr, Gray LA Jr, Fulton RL. Indications for thoracotomy following penetrating thoracic injury. *J Trauma*. 1977;17(7):493–500.
10. Karmy-Jones R, Nathens A, Jurkovich GJ, Shatz DV, Brundage S, Wall MJ Jr, Engelhardt S, Hoyt DB, Holcroft J, Knudson MM, et al. Urgent and emergent thoracotomy for penetrating chest trauma. *J Trauma*. 2004; 56(3):664–668; discussion 668–669.
11. Karmy-Jones R, Jurkovich GJ, Nathens AB, Shatz DV, Brundage S, Wall MJ Jr, Engelhardt S, Hoyt DB, Holcroft J, Knudson MM. Timing of urgent thoracotomy for hemorrhage after trauma: a multicenter study. *Arch Surg*. 2001;136(5):513–518.
12. Mansour MA, Moore EE, Moore FA, Read RR. Exigent postinjury thoracotomy analysis of blunt versus penetrating trauma. *Surg Gynecol Obstet*. 1992;175(2):97–101.
13. O'Connor JV, Scalea TM. Penetrating thoracic great vessel injury: impact of admission hemodynamics and preoperative imaging. *J Trauma*. 2010; 68(4):834–837.
14. Renz BM, Cava RA, Feliciano DV, Rozycki GS. Transmediastinal gunshot wounds: a prospective study. *J Trauma*. 2000;48(3):416–421; discussion 421–422.
15. Brown J, Grover FL. Trauma to the heart. *Chest Surg Clin N Am*. 1997;7(2):325–341.
16. Richardson JD, Carrillo E. Thoracic infection after trauma. *Chest Surg Clin N Am*. 1997;7(2):401–427.
17. Fallon WF Jr, Wears RL. Prophylactic antibiotics for the prevention of infectious complications including empyema following tube thoracostomy

for trauma: results of meta-analysis. *J Trauma*. 1992;33(1):110–116; discussion 116–117.
18. Luchette FA, Barrie PS, Oswanski MF, Spain DA, Mullins CD, Palumbo F, Pasquale MD. Practice management guidelines for prophylactic antibiotic use in tube thoracostomy for traumatic hemopneumothorax: the EAST Practice Management Guidelines Work Group. Eastern Association for Trauma. *J Trauma*. 2000;48(4):753–757.
19. Burlew CC, Moore EE, Moore FA, Coimbra R, McIntyre RC Jr, Davis JW, Sperry J, Biffl WL. Western Trauma Association critical decisions in trauma: resuscitative thoracotomy. *J Trauma Acute Care Surg*. 2012;73(6):1359–1363; discussion 1363–1364.
20. Sperry JL, Moore EE, Coimbra R, Croce M, Davis JW, Karmy-Jones R, McIntyre RC Jr, Moore FA, Malhotra A, Shatz DV, Biffl WL. Western Trauma Association critical decisions in trauma: penetrating neck trauma. *J Trauma Acute Care Surg*. 2013;75(6):936–940.
21. Dulchavsky SA, Schwarz KL, Kirkpatrick AW, Billica RD, Williams DR, Diebel LN, Campbell MR, Sargysan AE, Hamilton DR. Prospective evaluation of thoracic ultrasound in the detection of pneumothorax. *J Trauma*. 2001;50(2):201–205.
22. Ball CG, Williams BH, Wyrzykowski AD, Nicholas JM, Rozycki GS, Feliciano DV. A caveat to the performance of pericardial ultrasound in patients with penetrating cardiac wounds. *J Trauma*. 2009;67(5):1123–1124.
23. Breaux EP, Dupont JB Jr, Albert HM, Bryant LR, Schechter FG. Cardiac tamponade following penetrating mediastinal injuries: improved survival with early pericardiocentesis. *J Trauma*. 1979;19(6):461–466.
24. Wall MJ Jr, Mattox KL, Chen CD, Baldwin JC. Acute management of complex cardiac injuries. *J Trauma*. 1997;42(5):905–912.
25. Pate JW, Cole FH Jr, Walker WA, Fabian TC. Penetrating injuries of the aortic arch and its branches. *Ann Thorac Surg*. 1993;55(3):586–592.
26. Vosloo SM, Reichart BA. Inflow occlusion in the surgical management of a penetrating aortic arch injury: case report. *J Trauma*. 1990;30(4): 514–515.
27. Van Natta TL, Smith BR, Bricker SD, Putnam BA. Hilar control in penetrating chest trauma: a simplified approach to an underutilized maneuver. *J Trauma*. 2009;66(6):1564–1569.
28. Wiencek RG Jr, Wilson RF. Central lung injuries: a need for early vascular control. *J Trauma*. 1988;28(10):1418–1424.
29. Wagner JW, Obeid FN, Karmy-Jones RC, Casey GD, Sorensen VJ, Horst HM. Trauma pneumonectomy revisited: the role of simultaneously stapled pneumonectomy. *J Trauma*. 1996;40(4):590–594.
30. Wall MJ Jr, Villavicencio RT, Miller CC 3rd, Aucar JA, Granchi TA, Liscum KR, Shin D, Mattox KL. Pulmonary tractotomy as an abbreviated thoracotomy technique. *J Trauma*. 1998;45(6):1015–1023.
31. Asensio JA, Demetriades D, Berne JD, Velmahos G, Cornwell EE 3rd, Murray J, Gomez H, Falabella A, Chahwan S, Shoemaker W, Berne TV. Stapled pulmonary tractotomy: a rapid way to control hemorrhage in penetrating pulmonary injuries. *J Am Coll Surg*. 1997;185(5):486–487.
32. Boyd AD, Glassman LR. Trauma to the lung. *Chest Surg Clin N Am*. 1997; 7(2):263–284.
33. Hirshberg A, Wall MJ Jr, Allen MK, Mattox KL. Double jeopardy: thoracoabdominal injuries requiring surgical intervention in both chest and abdomen. *J Trauma*. 1995;39(2):225–229; discussion 229–231.
34. Chen SC, Markmann JF, Kauder DR, Schwab CW. Hemopneumothorax missed by auscultation in penetrating chest injury. *J Trauma*. 1997;42(1):86–89.
35. Mowery NT, Gunter OL, Collier BR, Diaz JJ Jr, Haut E, Hildreth A, Holevar M, Mayberry J, Streid E. Practice management guidelines for management of hemothorax and occult pneumothorax. *J Trauma*. 2011; 70(2):510–518.
36. Conrad MF, Patton JH Jr, Parikshak M, Kralovich KA. Selective management of penetrating truncal injuries: is emergency department discharge a reasonable goal? *Am Surg*. 2003;69(3):266–272; discussion 273.
37. Kirkpatrick AW1, Rizoli S, Ouellet JF, Roberts DJ, Sirois M, Ball CG, Xiao ZJ, Tiruta C, Meade M, Trottier V, et al. Occult pneumothoraces in critical care: a prospective multicenter randomized controlled trial of pleural drainage for mechanically ventilated trauma patients with occult pneumothoraces. *J Trauma Acute Care Surg*. 2013;74(3):747–754; discussion 754–755.
38. Kulvatunyou N, Vijayasekaran A, Hansen A, Wynne JL, O'Keeffe T, Friese RS, Joseph B, Tang A, Rhee P. Two-year experience of using pigtail catheters to treat traumatic pneumothorax: a changing trend. *J Trauma*. 2011;71(5):1104–1107; discussion 1007.
39. Rivera L, O'Reilly EB, Sise MJ, Norton VC, Sise CB, Sack DI, Swanson SM, Iman RB, Paci GM, Antevil JL. Small catheter tube thoracostomy: effective in managing chest trauma in stable patients. *J Trauma*. 2009; 66(2):393–399.
40. Karmy-Jones R, Holevar M, Sullivan RJ, Fleisig A, Jurkovich GJ. Residual hemothorax after chest tube placement correlates with increased risk of empyema following traumatic injury. *Can Respir J*. 2008;15(5):255–258.
41. DuBose J, Inaba K, Demetriades D, Scalea TM, O'Connor J, Menaker J, Morales C, Konstantinidis A, Shiflett A, Copwood B; AAST Retained Hemothorax Study Group. Management of post-traumatic retained hemothorax: a prospective, observational, multicenter AAST study. *J Trauma Acute Care Surg*. 2012;72(1):11–22; discussion 22–24; quiz 316.
42. Meyer DM. Hemothorax related to trauma. *Thorac Surg Clin*. 2007;17(1): 47–55.
43. Maxwell RA, Campbell DJ, Fabian TC, Croce MA, Luchette FA, Kerwin AJ, Davis KA, Nagy K, Tisherman S. Use of presumptive antibiotics following tube thoracostomy for traumatic hemopneumothorax in the prevention of empyema and pneumonia–a multi-center trial. *J Trauma*. 2004;57(4):742–748; discussion 748–749.
44. Leppaniemi A, Haapiainen R. Occult diaphragmatic injuries caused by stab wounds. *J Trauma*. 2003;55(4):646–650.
45. Renz BM, Feliciano DV. Gunshot wounds to the right thoracoabdomen: a prospective study of nonoperative management. *J Trauma*. 1994;37(5): 737–744.
46. Samanidis G, Dimitriou S, Sakorafas A, Khoury M. Repair of a penetrating aortic arch injury using deep hypothermic circulatory arrest and retrograde cerebral perfusion. *Interact Cardiovasc Thorac Surg*. 2012;14(3):356–358.
47. Asensio JA, Chahwan S, Forno W, MacKersie R, Wall M, Lake J, Minard G, Kirton O, Nagy K, Karmy-Jones R, et al. Penetrating esophageal injuries: multicenter study of the American Association for the Surgery of Trauma. *J Trauma*. 2001;50(2):289–296.
48. Trinkle JK, Toon RS, Franz JL, Arom KV, Grover FL. Affairs of the wounded heart: penetrating cardiac wounds. *J Trauma*. 1979;19(6):467–472.
49. Mattox KL, Wall MJ Jr. Newer diagnostic measures and emergency management. *Chest Surg Clin N Am*. 1997;7(2):213–226.
50. Thorson CM, Namias N, Van Haren RM, Guarch GA, Ginzburg E, Salerno TA, Schulman CI, Livingstone AS, Proctor KG. Does hemopericardium after chest trauma mandate sternotomy? *J Trauma Acute Care Surg*. 2012;72(6):1518–1524; discussion 1524–1525.
51. Nicol AJ, Navsaria PH, Hommes M, Ball CG, Edu S, Kahn D. Sternotomy or drainage for a hemopericardium after penetrating trauma: a randomized controlled trial. *Ann Surg*. 2014;259(3):438–442.
52. Beall AC Jr, Bricker DL, Crawford HW, De Bakey ME. Surgical management of penetrating thoracic trauma. *Dis Chest*. 1966;49(6):568–577.
53. Feliciano DV. Trauma to the aorta and major vessels. *Chest Surg Clin N Am*. 1997;7(2):305–323.
54. Wong SS. Penetrating thoracic injuries: the use of transesophageal echocardiography to monitor for complications after intracardiac nail removal. *J Trauma*. 2008;64(5):E69–E70.