Thoracic Trauma: When and How to Intervene

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Trauma continues to be a significant source of patient morbidity and mortality, accounting for 140,000 deaths annually, and it is the leading cause of death in patients younger than 40 years of age [1]. Thoracic injuries are present after penetrating and blunt injury and are the primary or a contributing factor in up to 75% of all trauma-related deaths [2,3]. Most thoracic injuries can be managed with simple maneuvers such as tube thoracostomy [4]; however, 10% to 15% of patients who present with thoracic trauma require definitive operative repair [5].

The timing of intervention is oft debated but essentially takes place in one of three time periods mainly dictated by the patient’s physiologic status upon arrival to the emergency room: immediate (emergency room thoracotomy), urgent (in the operating room, within 1–4 hours of arrival), and delayed (24 hours after admission) [6–8]. Once the need for intervention is apparent, the critical decision for an appropriate surgical approach is based on the location and nature of the injury. In this article, we review the common algorithm that applies to managing thoracic trauma patients. We discuss considerations and variables that enter into the decision-making process and describe various scenarios in which they are applicable.

Emergency department thoracotomy

Emergency department thoracotomy (EDT) is a drastic procedure with limited utility. Its primary use is in the management of patients in extremis after penetrating injury and, to a lesser extent, after blunt injury. The
therapeutic goals of EDT include control of hemorrhage, effective cardiac compression, cross-clamping the pulmonary hilum in the case of air embolism or massive bronchopleural fistula, relief of cardiac tamponade, and cross-clamping of the descending aorta for lower torso hemorrhage control [9]. Whenever possible, the patient should be stabilized and transported to the operating room where superior facilities are available for definitive care. The survival rate after EDT is approximately 7% [10,11,12].

When making a decision to perform an EDT, three factors must be taken into consideration: mechanism of injury, location of major injury, and signs of life. Better outcomes are seen when performed for penetrating (8%-10%) injuries rather than blunt injuries (approximately 1%), with greatest survival occurring when EDT is performed for stab wounds (18%-24%) rather than gunshot wounds (4%-5%) [12–16]. Likewise, patients with isolated penetrating chest injuries have the greatest chance of survival rather than patients with multi-cavity injuries [17,18]. The use of EDT in patients with isolated abdominal trauma or extremity trauma is controversial but has been demonstrated to be of some limited value [19,20]. Finally, the absence of signs of life (palpable pulse, pupillary or gag reflex, demonstrable blood pressure) must be considered. In general, patients most likely to respond favorably to EDT include victims of penetrating trauma with signs of life upon presentation to the emergency room or patients who lose signs of life within 10 minutes of arrival. Victims of blunt trauma with no signs of life upon arrival to the emergency room have poor survival rates, and EDT should not be performed in these patients. Current guidelines provided by the American College of Surgeons Advanced Trauma Life Support advocate the use of EDT in patients with penetrating chest trauma and cardiac electrical activity but not with pulseless blunt trauma or penetrating trauma without cardiac electrical activity [21]. It should be emphasized that EDT is a procedure for surgeons, and in the authors’ experience there is no role for pericardiocentesis in these patients. Pericardiocentesis often is not effective in removing clotted blood from the pericardial space, it is not a risk-free procedure, it potentially delays the surgical procedure, and with the application of focused assessment with sonography for trauma (FAST) examination, the diagnostic use of this procedure is negligible.

Once the decision has been made to intervene, the standard incision is a left anterolateral thoracotomy that extends from the sternum below the nipple to the midaxillary line. After entering the pleural space, the hand is used to protect the lung, and scissors are used to open the intercostal space along the length of the incision. A chest retractor is then placed and opened. If required, additional exposure may be gained by using the scalpel to divide the costochondral junctions of the fifth, fourth, and third ribs, or alternatively, a Lebske knife or trauma shears may be used to divide the sternum transversely. After evacuating blood from the chest, attention is directed to the injury. If a great vessel is injured and bleeding,
pressure is used to staunch hemorrhage. If air embolism is encountered, the pulmonary hilum is clamped or the affected lung may be twisted 180° and air in the aorta evacuated.

When hemopericardium is present, the pericardium may be divided longitudinally from the aortic root to the apex of the heart. At this point, care must be taken to identify and preserve the phrenic nerve. Once the hemopericardium is evacuated, the heart is delivered from the pericardial sac and digital pressure is applied to control hemorrhage. A temporary repair is performed using suture or staples. Alternatively, the hole may be “plugged” with a Foley catheter balloon held under tension [22]. After the cause of arrest has been addressed, a cross-clamp may be applied to the descending thoracic aorta after sweeping the lung anteromedially and exposing the posterior mediastinum. Momentarily arresting mechanical ventilation and nasogastric tube placement are helpful adjuncts to visualize and localize a flaccid descending aorta. The pleura along the posterior mediastinum is opened and the cross-clamp is applied. Intravascular volume is restored, and if the patient responds, he or she is transported to the operating room for definitive repair of injuries.

Urgent thoracotomy

For the purposes of this article, thoracotomy within the first few hours of injury is considered an urgent thoracotomy. Included in this category are compensated cardiac injuries, non-exsanguinating injuries to the great vessels of the aorta, tracheobronchial injuries, esophageal injuries, and, in some cases, traumatic rupture of the thoracic aorta. Indications for urgent thoracotomy include the presence of cardiac tamponade, high chest tube output, persistent air leak, and air embolism.

When deliberating whether a patient requires chest exploration based on chest tube output, the fundamental question is, “Will the bleeding stop?” If a hemothorax is suggested on physical examination or initial chest radiograph, a chest tube should be placed. The drainage of a massive amount of blood suggests the presence of major vascular injury that is unlikely to stop without surgical intervention. Many authors use 1500 mL of initial chest tube drainage as a trigger at which chest exploration becomes mandatory; however, we routinely use 1000 mL of chest tube drainage as an indication to consider chest exploration [23–25]. Ongoing bleeding after chest tube placement at a rate of 200 to 300 mL/h is also proposed to be an indication for chest exploration [6,24,25].

There are some caveats to these general guidelines. In some patients, however, this rule of thumb is not applicable. Some caveats to chest tube drainage as an indicator for chest exploration are (1) pulmonary parenchymal bleeding, (2) blunt chest trauma with delayed presentation, and (3) presence of a coagulopathy (medications in elderly patients or closed head injuries). In cases of pulmonary parenchymal bleeding, it is important to
understand that the pulmonary circulation is a low pressure system, and complete expansion of the lung usually tamponades any parenchymal source of bleeding. Another scenario that is especially common in the setting of rural trauma is a patient presenting with blunt chest trauma in a delayed fashion. These patients may have a significant hemothorax that has accumulated in the time it has taken the patient to arrive in the emergency department. In these situations, evidence of ongoing bleeding rather than initial chest tube drainage may be a more reliable indication for chest exploration. This is in contradistinction to victims of penetrating trauma or blunt trauma occurring in close proximity to the trauma center. In these patients, 1000 to 1500 mL of chest tube drainage remains a reliable indicator for chest exploration. Another group of patients in whom caution should be exercised when considering thoracotomy are individuals with a coagulopathy and chest wall injury. Two common scenarios for this involve elderly patients on anticoagulant medications and coagulopathy in the presence of a closed head injury. In the authors’ experience, operation in this setting is often not therapeutic and may add to the already present chest wall bleeding.

A second indicator for urgent chest exploration after injury is the presence of massive air leak defined as being present during all phases of respiration that is associated with an inability to fully expand the affected lung or impairing ventilation through the loss of effective tidal volume. These findings suggest major tracheobronchial injuries. The presence of cardiac tamponade, demonstrated using a combination of findings on physical examination (Beck’s triad: muffled heart tones, distended neck veins, and hypotension) and, more recently, by the presence of a pericardial effusion on FAST examination, demands further evaluation with pericardial window or median sternotomy. Finally, air embolism, a rare entity associated with penetrating injury, occurs when a fistula develops between a bronchus and pulmonary vein; it requires urgent thoracotomy. Typically, the patient is stable until intubated and placed on positive pressure ventilation, when sudden cardiovascular collapse or the onset of lateralizing neurologic symptoms occurs [26]. To summarize, the major indicators for urgent thoracotomy include (1) chest tube output $>1000$ mL (with noted exceptions as described above) (2) evidence of ongoing bleeding at a rate of 200 to 300 mL/h, (3) massive air leak, (4) cardiac tamponade, and (5) air embolism.

Given the indications for chest exploration, selecting the appropriate chest incision is critically important. What makes this decision difficult is that four different compartments must be considered: the right chest, left chest, mediastinum, and, in the case of concomitant abdominal injury, the peritoneal cavity. Several factors should be measured carefully before making a decision. Information regarding missile or injury trajectory, a thorough working knowledge of thoracic/mediastinal anatomy, and the exposures offered by each different incision are vital to choosing the appropriate incision. Surgical approaches for common traumatic injuries to thoracic viscera are summarized in Table 1. For example, a left parasternal
### Table 1
Surgical approaches for traumatic injuries to thoracic viscera

<table>
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<tr>
<th>Site</th>
<th>Sternotomy</th>
<th>Right thoracotomy</th>
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<td>Right ventricle</td>
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<td>CPB</td>
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**Abbreviations:** CPB, cardiopulmonary bypass; IMA, internal mammary artery; IVC, inferior vena cava; LL, lower lobe; ML, middle lobe; PA, pulmonary artery; SVC, superior vena cava; UL, upper lobe.

+++., preferred; ++., acceptable; +., with difficulty; 0, not accessible.

gunshot wound may injure the anterior and posterior walls of the left ventricle. Of these two injuries, although the anterior injury is easily exposed and repaired through a median sternotomy or anterior thoracotomy, the posterior injury is more difficult to repair and is best approached with a left posterolateral thoracotomy.

Median sternotomy offers adequate exposure for most parasternal stab wounds because these injuries do not typically penetrate deeply and primarily involve the anterior mediastinum. Likewise, in the instance of right parasternal gunshot wound, a median sternotomy provides good exposure of structures that are likely to be injured, including the right atrium and ventricle, the superior vena cava, atrial appendage, right pulmonary artery, and lung. The incision for a sternotomy may be extended into the neck or supraclavicular fossa to enhance exposure of the great vessels (Fig. 1, see inset). Posterolateral thoracotomy provides superior exposure of the posterior

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**Fig. 1.** Median sternotomy with optional extension. A median sternotomy provides excellent exposure for the right atrium and ventricle, the superior vena cava, atrial appendage, right pulmonary artery, and lung. If necessary, the incision may be extended into the neck or supraclavicular fossa (inset) to enhance exposure of the great vessels. Ao, aorta; LCCA, left common carotid artery; PA, pulmonary artery; RA, right atrium; RCCA, right common carotid artery; RSV, right subclavian vein; RV, right ventricle; SVC, superior vena cava.
heart and should be used in instances of left parasternal gunshot wound. For lateral wounds, depending on the side involved, a right or left posterolateral thoracotomy provides the best exposure because these injuries are more likely to be posterior. In cases of massive hemothorax, a posterolateral thoracotomy on the affected side offers excellent visualization of the great vessels, such as the subclavian artery or aorta. A left posterolateral thoracotomy (Fig. 2) is the incision of choice in instances of air embolism and massive air leak.

Right thoracotomy is an excellent approach for right lung, tracheal, and proximal left main stem bronchial injuries (a point that is often forgotten). Most esophageal injuries are best approached through a right thoracotomy, except in cases of distal esophageal injuries that are best accessed through the left chest. Right heart structures, such as the right atrium, right ventricle, atrial appendage, and left atrium, are also easily exposed with a right thoracotomy. Left thoracotomy provides adequate exposure of the left lung, left pulmonary hilum, aorta, proximal left subclavian artery, left heart chambers, distal esophagus, and distal left main stem bronchus. A "clam shell" incision, formed by extending a thoracotomy incision transversely across the sternum using the Lebske knife, a pair of trauma shears, or a saw,

![Diagram](image)

Fig. 2. Left posterolateral thoracotomy. A left posterolateral thoracotomy (inset) provides excellent exposure of the left pulmonary hilum, left lung, proximal left subclavian artery, descending aorta, distal esophagus, and left diaphragm. LCCA, left common carotid artery; LPA, left pulmonary artery; LSA, left subclavian artery.)
provides excellent access but suboptimal exposure of every intrathoracic or mediastinal structure except the right ventricle and right atrium. When using this approach, the internal mammary arteries are divided and often do not bleed in the poorly perfused patient. Once blood pressure is restored, however, significant hemorrhage from these vessels may result. A more stable closure of the transverse sternotomy is achieved with sternal plates rather than wires.

**Urgent exploratory thoracotomy**

If the diagnosis is uncertain, then a posterior lateral thoracotomy along the fifth intercostal space on the injured side is the incision of choice. If time and circumstances permit, placement of a dual lumen endotracheal tube so that the lung may be collapsed is beneficial, but this is often not practical in a trauma setting. With a known diagnosis, the incision should be chosen to provide optimal exposure for the injury. Efforts to spare the latissimus dorsi, although commendable, rarely are practical in a trauma setting, although preservation of an intercostal flap is simple and advisable. The surgeon’s thinking must remain flexible and insist on good exposure of the injury. Often an inexperienced surgeon attempts to repair an injury with less-than-optimal exposure. In most cases, after the immediately life-threatening issue has been addressed, even in a temporary fashion, the patient is better served by extending the initial incision or making a second incision so that definitive repair of the injury can be performed under optimal exposure. Finally, a damage control thoracotomy with packing of lung, bone, venous, or chest wall bleeding is a valid and commonly overlooked option.

The order of an exploratory thoracotomy should proceed in a logical and orderly fashion. If the diagnosis is uncertain, a posterolateral thoracotomy fashioned along the fifth intercostal space is the incision of choice. First, the thoracic cavity should be evacuated of clotted blood and then the lung packed out of the field, which may be facilitated by division of the inferior pulmonary ligament. Upon clearing the field, the mediastinum and pericardium should be evaluated carefully for bleeding. It is surprisingly difficult to detect the presence of blood in the pericardium by simple visual inspection. A small pericardiotomy that can be expanded as necessary is useful to exclude or confirm the presence of hemopericardium. Major vascular injuries require prompt proximal and distal control, which can be achieved effectively with hilar control in cases of pulmonary parenchymal bleeding. After hemorrhage is controlled, formal repair of injured vascular structures may proceed.

**Cardiac injuries**

Cardiac injuries may involve the myocardium, coronary arteries, valves, or septum or result in the late presentation of a ventricular aneurysm. Mortality rates range from 10% to 70%, reflecting various presentations and
injury mechanisms [27–30]. Cardiac injuries usually cause either cardiac tamponade or hemorrhagic shock, depending on the nature of the pericardial injury and whether pericardial blood can escape into the pleural space [31]. Pericardial tamponade results from the accumulation of fluid within the pericardial space that compresses the heart and prevents cardiac filling. The sac-like pericardium has poor compliance, and as little as 50 mL of blood can effectively cause tamponade. Many patients with this condition die before arrival at the hospital. The presence of cardiac tamponade is usually made based on clinical findings of a distinctive dusky, plerotic facial complexion associated with distended neck veins, hypotension, and evidence of pericardial effusion on FAST examination [5]. It should be noted however, that the sensitivity of FAST in the detection of hemopericardium is markedly diminished in the presence of a massive hemothorax, in which blood may be escaping from the injured heart directly into the thoracic cavity, leaving only small amounts in the pericardium [32]. Muffled heart sounds are classically described with cardiac tamponade but are difficult to discern in the usually noisy emergency department. In patients who are in extremis, bilateral chest tubes should be placed, and if the patient’s condition does not improve, immediate thoracotomy is warranted. In this situation, pericardiocentesis is ineffective in removing blood that is clotted in the pericardial space. Patients who are not in extremis should be taken to the operating room urgently for subxiphoid pericardial window or formal chest exploration, typically through a median sternotomy.

The incision for a subxiphoid pericardial window is made over the lower midsternum and upper abdomen, extending approximately 10 cm. The xiphoid process can be grasped with a clamp and either elevated out of the field, divided, or removed. A substernal plane is created using blunt dissection in the plane anterior to the peritoneum, detaching the muscle fibers between the diaphragm and the sternum. Once the pericardium is encountered and grasped with two Kocher clamps, a small incision is made between the clamps while lifting the pericardium so as to prevent injury to the underlying epicardium. An efflux of blood indicates cardiac injury and is an indication to proceed with definitive operation (most commonly through a sternotomy). When necessary, the pericardiotomy may be enlarged to relieve the tamponade. If no blood is encountered, then the incision should be enlarged sufficiently to visualize the epicardial surface of the heart and ensure that the pericardial sac truly has been entered. If negative, the incision may be closed with absorbable sutures [5].

Cardiac injuries that require immediate repair include wall defects, coronary artery injuries, and injuries to the great vessels. Injuries that can be repaired in a delayed fashion with the use of cardiopulmonary bypass include intracardiac lesions, such as septal defects, valve injuries, and ventricular aneurysms. If profound heart failure is present, however, cardiopulmonary bypass should be instituted and repair performed at the time of initial operation.
Atrial wounds are controlled by simple digital pressure or by exclusion with a curved vascular clamp and simple oversewing. Right or left ventricle free wall injuries that are remote from the coronary arteries are controlled with digital pressure. After hemostasis is restored, the injury is repaired using horizontal mattress polypropylene sutures (3.0 or 4.0) under the wound and reinforced with an epicardial running suture along the site of injury. Pledgeted sutures are an absolute requirement for repair of left ventricle wounds because they allow for compression and prevent the suture from tearing through the myocardium. Simple right ventricle wounds often may be closed without pledgets if the sutures are placed accurately. Injuries near the coronary arteries must be closed without encompassing the coronary artery. Horizontal mattress sutures are placed deep and lateral to the coronary artery across the injury and out the opposite side. This must be performed with awareness of the function of the myocardium distal to the repair and monitoring of the intraoperative electrocardiogram to prevent coronary artery occlusion and ischemia.

The possibility of coexistent intracardiac injury always must be considered by the surgeon [33–35]. Palpation of the pulmonary outflow tract or left ventricle for a thrill discloses the presence of a traumatic ventricular septal defect or aortic insufficiency, respectively. Digital palpation of the atrium or through atrial wounds should be used routinely to identify atrioventricular valvular insufficiency. Intraoperative transesophageal echocardiography is a useful adjunct and can facilitate diagnosis of intracardiac injuries. Postoperatively, chest auscultation should be used to exclude murmurs; if they are found, echocardiography is required.

**Injuries to the great vessels**

The great vessels of the aorta include the left subclavian, the left common carotid, and the innominate arteries. Great vessel injuries are rarely encountered after penetrating chest trauma, with a reported incidence of approximately 4% [36]. The principal reason for this low incidence is that victims typically exsanguinate into the chest or externally before arrival at the hospital; however, with improved prehospital care and decreased transit times, these injuries are increasingly encountered at trauma centers [28].

The detection of the presence of a great vessel injury can be overt or subtle in presentation, depending on multiple factors, including the mechanism and the vessel involved. The presence of a wound at the base of the neck or transmediastinal gunshot wound should alert the clinician to the possibility of great vessel injury. The patient may be pulseless or moribund at presentation, and diagnosis is confirmed at the time of EDT or urgent thoracotomy. In a stable patient or one who easily stabilizes with resuscitation, the diagnosis can be confirmed with angiography or CT angiography, if available [37]. Patients with proximal injuries may present with a massive hemothorax, pericardial tamponade or external bleeding. Pulse deficits in
the affected vessel’s distribution, brachial plexus injuries, stroke or coma, and the presence of a thrill or bruit in the base of the neck also support the diagnosis of a great vessel injury. Chest radiography may demonstrate the presence of an apical cap or widened mediastinum.

After a diagnosis has been made, the patient should be taken to the operating room for exploration. If possible, although frequently not feasible, the placement of a dual lumen endotracheal tube greatly facilitates exposure of the injuries. Many incisions have been described as providing adequate exposure for repair of great vessel injuries. For right subclavian injuries or right parasternal injuries, a median sternotomy with extension into the neck or a supraclavicular extension is recommended [38]. A median sternotomy provides excellent exposure of the ascending aorta and the proximal right subclavian, innominate, and common carotid arteries. A left thoracotomy provides optimal exposure of the descending aorta and adequate exposure of the proximal left subclavian and proximal left common carotid arteries. For distal control when dealing with left subclavian or left common carotid artery injuries, classically a supraclavicular or neck counter-incision is required. Alternatively, a median sternotomy can be used to connect the incisions (trapdoor incision); however, this type of incision provides poor exposure and is associated with significant morbidity. It should be used only when necessary [39]. Comprehensive knowledge of chest and neck anatomy is required when exposing these vessels to prevent injury to the phrenic, vagus, and recurrent laryngeal nerves, which lie in close proximity to these vessels, and to protect the thoracic duct when approaching the left subclavian artery.

We would like to offer one recommendation regarding the approach used when a left infraclavicular stab wound with left subclavian artery injury is encountered. Anterior thoracotomy to expose the proximal subclavian artery for proximal control followed by a supraclavicular incision for distal control is the classical approach described for this type of injury. In the authors’ experience, however, proximal control of the subclavian artery through this incision is difficult, and back bleeding from the vertebral and mammary arteries often can be profuse despite control of the proximal subclavian artery. We prefer preparing the entire chest, neck, and arm into the field followed by a posterolateral thoracotomy with the patient’s arm extended and gaining exposure of the proximal subclavian artery. The subclavian artery may be followed distally from within the chest, exposing and controlling the vertebral and internal mammary arteries. After control is obtained, the arm may be dropped to the patient’s side and a supraclavicular incision made to expose the distal subclavian artery. Repositioning of the operating room table after thoracotomy facilitates this approach.

Once proximal and distal control is obtained, many of these injuries lend themselves to lateral repair or end-to-end primary anastomosis. Interposition grafts composed of polytetrafluoroethylene or knitted Dacron are the conduits of choice. Caution must be exercised when subclavian arteries
are repaired. In the authors’ experience, these vessels are friable because of the lack of elastic fibers in the tunica media. End-to-end anastomosis is rarely possible because the anastomosis must be under no tension or the repair will fail. Interposition graft is desired when repairing these injuries. Associated venous injuries (superior vena cava, internal jugular, innominate) are common; if possible, they should be treated by lateral repair or patch venography. Internal jugular or innominate injuries can be ligated with little ill effect except in patients with closed head injury. Vena cava injuries can be shunted if repair is not feasible and ligated only as a measure of last resort.

**Lung injuries**

Lung injury that requires operative intervention is more common after penetrating rather than blunt injury [7,8]. Most cases of pneumothorax or hemothorax can be treated adequately with accurate chest tube placement and full re-expansion of the lung. It is estimated, however, that 20% to 40% of patients after penetrating injury and 15% to 20% of patients after blunt injury who require thoracotomy need some form of lung resection [7,40,41]. It must be noted that anatomic lung resection after blunt injury is distinctly uncommon but required in 0.5% of patients [7]. Trauma surgeons should remain familiar with the technique of anatomic lung resection, although most lung injuries that require thoracotomy can be dealt with successfully using lung-sparing techniques, such as nonanatomic stapled resections or tractotomies [42].

Operative indications for lung injury tend to fall into one of two categories: hemorrhage or persistent air leak impairing ventilation. The incision of choice for lung injury is a fifth intercostal space posterolateral thoracotomy on the involved side. The most common procedures performed are simple suture repair of superficial lung lacerations and wedge resection of the injured lung using a stapling device. In penetrating injuries, tractotomy is used as a definitive form of treatment for nonhilar injuries [43,44]. The principle of tractotomy is to open the tract of the bullet or knife wound (Fig. 3A) so that larger interior vessels may be identified and ligated individually. 3-0 polypropylene suture may be used to ligate the vessels individually or may be run along the length of the tractotomy (Fig. 3B). The practice of simply oversewing penetrating lung injuries should be discouraged. Oversewing entrance and exit sites may stop bleeding into the pleural cavity, but it does not stop intraparenchymal bleeding. Blood can be forced into the tracheobronchial tree and result in aspiration, pneumonia, acute respiratory distress syndrome, and further worsening of the functional lung injury. Simple maneuvers, such as tractotomy, wedge resection, and simple suturing, are more commonly performed after penetrating lung injury because more proximal lung injuries are often associated with concurrent fatal mediastinal injuries. Anatomic resections, such as lobectomy and
pneumonectomy, are more commonly performed if resection in needed after blunt injury. Blunt trauma often results in a more severe and diffuse lung injury that is typically more difficult to treat surgically and has worse outcomes when compared with penetrating trauma [39,45,46].

More extensive deep lobar and perihilar lung injuries frequently require anatomic lobectomy. Deep lobar injuries in patients with hemodynamic instability should be approached initially with tractotomy to expose the deep bleeding vessels. Simple oversewing may not suffice, in which case the edges of the tractotomy may be stapled or large, pledgeted mattress sutures may be used. If lung-sparing techniques fail or are not applicable, most of these patients require lobectomy.

Patients with perihilar injuries are typically in shock or have extensive parenchymal injury (as seen commonly after blunt injury). Hilar control should be the initial maneuver upon entering the chest if profuse lung bleeding is encountered. This procedure can involve placing a large clamp across the pulmonary hilum or dividing the pulmonary ligament to the level of the inferior pulmonary vein and twisting the mobilized lung. Occasionally, intrapericardial control of the pulmonary artery is required in cases of proximal injuries. If the artery and vein are injured, pneumonectomy is indicated. At this point, lung amputation can be performed using a stapler or, alternatively, the hilum may be oversewn. Animal models have demonstrated that each technique has similar bursting strength [47]. Traumatic pneumonectomy is associated with mortality rates of 50% to 100% and should be considered only if there is no alternative [41,48,49]. Sudden right heart failure contributes to the acute mortality after this procedure. If it occurs immediately, extracorporeal membrane oxygenation is an option, but it usually

Fig. 3. Tractotomy for nonhilar injuries. (A) The principle of tractotomy is to open the tract of the bullet or knife wound (inset) so that larger interior vessels may be identified and ligated individually. (B) 3-0 polypropylene suture may be used to individually ligate the vessels or may be run along the length of the tractotomy. Oversewing penetrating lung injury is discouraged.
proves to be fatal. More insidious onsets that occur days after operation may be treated medically with oxygen and pulmonary vasodilators.

**Tracheobronchial injuries**

Injuries to the trachea or main stem bronchi are uncommon in patients who survive to reach the hospital and may occur after blunt trauma or, less commonly, after penetrating injury with an estimated incidence of 0.2% to 8% [50–53]. Blunt injuries typically occur as a result of a direct blow to the neck, shear forces on the trachea at its fixed points (i.e., the cricoid and carina), or sudden increases in intratracheal pressure secondary to compression of the chest against a closed glottis. Gunshot wounds may occur at any point along the tracheobronchial tree; however, stab wounds almost exclusively involve the cervical trachea in patients who reach medical attention. Regardless of mechanism, most of these injuries occur within 2.5 cm of the carina, with main stem bronchial injuries present in 86%, distal bronchial injuries in 9.3%, and complex injuries in 8% [54]. Associated intrathoracic or mediastinal injuries are common [54].

Symptoms depend on the location of the injury and whether the injury communicates with the pleural cavity. Cervical injuries may present with stridor, hemoptysis, cervical subcutaneous emphysema, hoarseness, or respiratory distress secondary to an obstructed airway. Thoracic injuries with pleural communication present with pneumothorax that may or may not be under tension. A pneumothorax that persists after chest tube placement or has a continuous air leak indicates tracheobronchial damage. The “fallen lung sign” is a radiographic feature that is highly specific for tracheobronchial injury. On chest radiographs, the lung is falling away from rather than toward the hilum, as is the case with a simple pneumothorax [55]. In injuries with extrapleural communication, massive pneumomediastinum is typically encountered, occasionally without pneumothorax [55–57]. In this case, the diagnosis is more difficult to make on clinical grounds alone and often requires bronchoscopy. The injury may be initially missed and present later as tracheal or bronchial stenosis. Nonspecific symptoms of tracheobronchial injury can include subcutaneous emphysema and hemoptysis; however, most subcutaneous emphysema is a result of subpleural rupture of alveoli, not tracheobronchial injury, and hemoptysis is more often a result of aspiration of blood from facial and pharyngeal injuries. It has been reported that as many as two thirds of tracheobronchial injuries go unrecognized for more than 24 hours, and approximately 10% of patients may present weeks or months later, after stricture occurs [53,58,59]. The diagnosis of tracheobronchial injury is made based on clinical findings and radiographic findings (chest radiography and CT) and is confirmed with bronchoscopy [60,61]. Rigid or flexible bronchoscopy is essential to exclude reliably the diagnosis of tracheobronchial injury.
As with any trauma patient, the first priority is securing an adequate airway. Treatment of tracheobronchial injuries is directed at ensuring or establishing adequate ventilation. When safe, avoidance of positive pressure ventilation is recommended during the initial evaluation, but if necessary, bronchoscopic-guided intubation is suggested. Blind intubation in these patients is hazardous. In cases of small, well-contained tracheal injuries with minimal tissue loss, bronchoscopic guidance allows placement of the endotracheal tube safely past the injury with the cuff placed beyond the site of injury. Intubation past the site of injury alone for 48 to 72 hours occasionally may result in complete resolution of the injury in selected cases [54]. Nonoperative management is reserved only for highly selected patients who have lesions that involve less than one third of the bronchial wall with well-opposed edges and minimal tissue loss [61–64]. The lung must fully re-expand with chest tube placement, the air leak should stop soon after chest tube insertion, and positive pressure ventilation is not required [61]. These patients should be treated with prophylactic antibiotics, humidified air, frequent suctioning, and regular bronchoscopy and should be monitored for sepsis and airway obstruction.

Because most intrathoracic injuries occur within 2 cm of the carina, we recommend a right thoracotomy to approach virtually all of these injuries except in cases of distal left main stem bronchial injuries > 3 cm from the carina, where a left posterolateral thoracotomy is preferable. The incision should be placed over the fifth rib space, because we have found that resection of the fifth rib provides for optimal exposure and permits the intercostal muscle in this interspace to be saved for later use as a muscle flap to buttress the repair. Primary emphasis should be placed on maintaining an adequate airway, which may require advancing the endotracheal tube under direct vision beyond the level of injury or passing a sterile endotracheal tube through the operative field into one or both lungs. Tracheobronchial injuries should be repaired primarily using interrupted or running monofilament suture with the knots placed on the outside of the lumen to reduce granuloma or stricture formation. When limited tracheal resection is required, up to 2 cm of trachea can be excised easily and safely and primary repair performed. If needed, additional tracheal length may be gained by performing a pericardial release or by flexing the patient’s neck intraoperatively and for a short period of time after operation, provided the cervical spine is without injury. Repairs should be buttressed with viable vascularized tissue, usually an intercostal muscle flap (as previously suggested), pericardium, omentum, or, rarely, rhomboid or latissimus muscle flaps.

Postoperatively, barring other contraindications, a thoracic epidural catheter should be placed to assist with pain control and ensure adequate pulmonary toilet. Patients on the ventilator should be extubated as soon as possible, ideally immediately after the operation is complete. If ongoing positive pressure ventilation is required, positioning of the endotracheal tube distal to the repair, jet ventilation, or, occasionally, extracorporeal
membrane oxygenation may be necessary to allow the repair to heal. Routine postoperative use of proton pump inhibitors is recommended because acid and pepsin exposure promotes granuloma formation at the site of repair.

**Esophageal injuries**

Esophageal injuries are rare and primarily involve the cervical esophagus, typically as the result of gunshot wounds or iatrogenic trauma [65–68]. Intrathoracic esophageal injuries are present in approximately 1% of gunshot wounds to the chest [69]. Blunt esophageal injuries typically occur in the neck as a result of a direct blow or may occur in the chest just proximal to the esophagogastric junction. Blunt injuries are associated with increased intraluminal pressures against a closed glottis causing a bursting-type injury.

These wounds are usually diagnosed at the time of exploration for other injuries or on diagnostic studies that are obtained in stable patients because of the proximity of the wounding agent to the esophagus. Clinical manifestations may be present in 60% to 80% of patients depending on the location, size, amount of contamination, time to diagnosis, and presence of associated injuries [70]. Symptoms include odynophagia, dysphagia, and hematemesis. A small amount of mediastinal emphysema or small pleural effusion may be seen on chest radiograph. The presence of chest or back pain is also a clue to the presence of esophageal injuries [71,72]. Tracheal and vascular injuries are often found as associated injuries [73]. The diagnosis can be made definitively at the time of surgical exploration, on endoscopy, or with esophagoscopy. Our preference is to use CT to determine if the wound is in proximity to the esophagus followed by an esophagram. An esophagram with barium rather than water-soluble contrast is recommended for increased sensitivity, superior image quality, and decreased incidence of pneumonitis caused by aspiration [73,74]. Rapid diagnostic evaluation is desirable because the best surgical results are obtained when the duration of time between injury and repair is minimized [32,75].

Esophageal injuries should be treated early and aggressively. Cervical injuries should be approached through a neck incision along the anterior border of the left sternocleidomastoid muscle or with a collar incision. These injuries may be repaired primarily, whereas more complex wounds may require resection or combined tracheal repair. Upper and middle third thoracic injuries should be approached through a right posterolateral thoracotomy in the fourth or fifth interspace, depending on the level of the injury. Distal third esophageal injuries are best approached through left posterolateral thoracotomy through the sixth intercostal space. Once the wound is identified, the esophagus is mobilized sparingly but enough so that the injury can be defined completely. When diagnosed and operated on within 24 hours, most esophageal injuries lend themselves to primary repair with a single layer of absorbable monofilament suture [66,72,76].
Depending on the length of time before exploration, local inflammation, degree of contamination, and the severity of the injury, primary repair may not be feasible. Several techniques have been described in the literature, including esophageal diversion, esophageal exclusion, esophagectomy, and T tube drainage with later definitive repair. If the patient is in extremis, wide drainage with a chest tube and placement of a nasogastric tube above the injury is an option [77–79]. Regardless of the patient’s condition, all esophageal repairs should be drained widely with a chest tube and buttressed with viable, vascularized tissue (intercostal muscle flap, pericardial fat pad, gastric wrap, or thickened pleura) [80,81].

Traumatic rupture of the thoracic aorta

Acute blunt rupture of the thoracic aorta is associated with a high death rate. Eighty percent to 90% of these patients die before reaching the hospital. Historically, of the individuals who reach the hospital, 50% die within the first 24 hours and 90% die within the first month if the injury is not repaired [82,83]. Acute rupture of the thoracic aorta may occur after any form of severe deceleration injury. A shearing effect is caused by different degrees of mobility of the aorta above and below the fixation point of the aortic isthmus by the ligamentum arteriosus and the intercostal vessels. Most ruptures occur at the aortic isthmus, distal to the origin of the left subclavian artery. Less commonly, the ascending aorta just above the aortic valve can be affected, but this occurrence is exceedingly rare. No signs or symptoms on physical examination are the rule. Chest radiography may provide the surgeon with several clues to the presence of this injury: a left apical cap, wide mediastinum, obscurity of the contour of the aortic knob and aortopulmonary window, depression of the left main stem bronchus, and deviation of the nasogastric tube to the right. Diagnosis is confirmed on chest CT angiography or, if it remains in doubt, by angiography. Once the diagnosis is made, a critical component of initial management is beta blockade, not just antihypertensive therapy. Beta blockade decreases the systolic ejection slope of the left ventricle, which decreases the tearing force on the aortic wall. Vasodilators given alone widen the pulse pressure by dropping the diastolic pressure and actually may increase the likelihood of rupture. In suitable candidates for immediate repair, the injury is best approached through a left posterolateral thoracotomy. Given the unpredictable nature of the aortic injury, which often requires complex repair and the lower reported rates of paraplegia, the use of cardiopulmonary bypass is highly recommended by the authors [84]. Most cases require an interposition graft, although 15% to 20% may be treated with primary anastomosis [84]. Alternatively, endovascular treatment of acute thoracic aortic rupture is gaining in popularity. Immediate outcome data in patients who undergo endovascular stent grafting seem at least as good as after conventional surgical repair [85]. Size mismatch and possible collapse of current large stent grafts when used in the...
young trauma population remain concerns. The long-term effectiveness of this management is still not known, but in the future, this technique may represent a viable alternative to surgery in patients with significant coexisting injuries that would preclude immediate repair.

**Delayed thoracotomy**

The indications for delayed thoracotomy (>24 hours) include missed tracheobronchial injuries, traumatic aortic rupture, intracardiac injuries, retained hemothorax, and posttraumatic empyema. Persistent air leak or tracheal/bronchial stenoses are typical manifestations of missed tracheobronchial injuries. The approach and principles of repair for these injuries are as previously described, although they are technically more demanding as a result of ensuing inflammation. The traditional management of acute traumatic rupture of the thoracic aorta endorses repair as quickly as possible. As we have gained a better understanding of the natural history of this injury and the role of pharmacologic treatment, however, the concept of delayed repair of this injury—often for hours or sometimes for days—has gained in popularity [54, 86–88]. The principal use of delayed repair is to allow the more life-threatening injuries to be addressed initially and avoid systemic heparinization in the immediate posttraumatic setting [89]. In patients with major intra-abdominal or intracranial injuries or significant pulmonary contusions, adopting the practice of early beta blockade allows elective repair of their aorta anywhere from 2 to 29 months later [90]. Likewise, delayed repair of intracardiac injuries (atrioventricular valvular insufficiency, ventricular septal defects) is advocated by the authors, unless the patient develops severe congestive heart failure, in which case immediate repair is warranted [5].

Inadequately drained posttraumatic hemothorax and contamination of the pleural space are often the result of improper chest tube placement by a member of the trauma team with the least experience in sterile technique or proper placement. An incompletely drained hemothorax essentially has one of three possible outcomes: resolution, infection (posttraumatic empyema), or fibrothorax/entrapped lung [91]. Prophylactic antibiotic use does not reduce infectious morbidity [92]. Retained blood in the pleural space is a risk factor for the development of posttraumatic empyema. As a result, every effort should be made to place chest tubes correctly under sterile conditions and remove the tube as soon as possible after insertion. If chest tube drainage fails to evacuate a hemothorax, especially after penetrating trauma, video-assisted thoracoscopy or thoracotomy should be considered. Additional chest tube placement is often not effective in evacuating clotted blood from the pleural space [93–95]. Diagnosis of a retained hemothorax using plain chest radiography can be misleading, often underestimating the amount of fluid in the chest. Chest CT provides information about location and size of the hemothorax that can be used intraoperatively to make the appropriate incision [96]. Video-assisted thoracoscopy is minimally
invasive, relatively easy to perform, and effective, especially when performed early after injury [97–99]. The best results are seen after penetrating injury [100]. Conversion to thoracotomy occurs in approximately 20% and is more common after blunt injury or when video-assisted thoracoscopy is performed later after injury [93–95]. A dual-lumen endotracheal tube and single lung ventilation are usually necessary. With the patient in decubitus position, typically two or three incisions approximately 2 cm in length are used as chest ports, and the clotted blood may be evacuated using suction catheters, ringed forceps, or a multitude of other instruments and techniques. The same ports then may be used for chest tube placement once the procedure is complete.

Thoracotomy is usually required in cases in which the hemothorax has been present for longer periods of time and dense adhesions have formed, which typically occurs after blunt trauma as continued oozing from rib fractures makes the timing of intervention in this group of patients more difficult to determine [100]. Often the hemothorax has become infected [91]. A posterolateral thoracotomy on the affected side through the fifth intercostal space typically provides adequate exposure. Often, the clotted hemothorax has a fibrous peel that necessitates decortication. Emphasis should be placed on completely removing the peel from the visceral surface of the pleural so that complete lung expansion may be obtained postoperatively. Ringed forceps or the scalpel may be required to remove the densely adherent peel from the lung, and moderate hemorrhage may be encountered during this part of procedure. Once decortication is complete and the retained hemothorax has been removed, wide drainage with chest tubes is required to prevent reaccumulation of blood and facilitate re-expansion of the involved lung. Postoperatively, a thoracic epidural greatly assists with pulmonary toilet. Chest tubes should be discontinued as soon as safely possible.

**Summary**

We have described the three windows of intervention in thoracic trauma dictated by the patient’s physiologic status upon arrival to the emergency room.

<table>
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<th>Thoracotomy in thoracic trauma</th>
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<th>Urgent</th>
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<td>Cardiac, lung esophagus, tracheobronchial, great vessel injuries, aortic rupture</td>
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room. As shown in Table 2, the time and setting of the thoracotomy primarily depend on the nature and site of the critical injuries. Many variables must be considered in this decision process, and each injury has unique issues to be addressed. We have characterized some of the most common injuries and scenarios that are likely to be encountered in thoracic trauma and report general methods for effective management. We also suggest and describe various surgical approaches that, in our collective experience, have proved useful for visualization, exposure, and repair of thoracic injuries. The thoracic trauma patient is at primary risk for trauma-related complications and, at worst, death. Thoughtful, effective, and timely surgical intervention is critical to favorable patient outcomes.

References


