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Thoracic Vascular Trauma

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1. Introduction

Traumatic injuries to the thoracic vasculature – the aorta and its brachiocephalic branches, the pulmonary arteries and veins, the superior vena cava and intrathoracic inferior vena cava, and the innominate and thoracic veins – occurs following both blunt and penetrating trauma. The primary cause of mortality remains acute exsanguinating hemorrhage. A high clinical index of suspicion along with prompt recognition and resuscitation are necessary components in the surgeon's armamentarium for dealing effectively with thoracic vascular trauma.

Thoracic injury is directly responsible for 25% of trauma deaths. Penetrating trauma accounts for the vast majority of thoracic great vessel injuries - over 90% - and is generally secondary to projectile missiles such as bullets and shrapnel as well as mechanical disruption by stab wounds and even therapeutic interventions. In fact, iatrogenic lacerations of the great vessels by rapid placement of percutaneous central venous catheter in the emergency department are frequently reported complications. Intercostal vessels and major pulmonary and mediastinal vasculature can be injured by the placement of smaller bore tube thoracostomies. More recently, self-expanding metal stents have been noted to produce perforations of the aorta and innominate artery following placement into the esophagus and trachea, respectively [1].

The sudden forceful deceleration following motor vehicle collisions is the primary mechanism regarding blunt trauma to the thoracic great vessels. The pulmonary veins, innominate artery, vena cava, and most commonly, the thoracic aorta are most susceptible to this kind of injury [2,3]. Thoracic aortic injuries generally involve the descending thoracic aorta in 54-65% of cases, the ascending aorta or transverse arch in 12% or multiple segments in 13-18% [4]. Mattox and colleagues hypothesized several mechanisms for blunt great vessel injury: (1) shear mechanical forces onto a relatively mobile segment of a vessel adjacent to a fixed portion – this is the postulated method for descending aortic tears due to its attachment at the ligamentum arteriosum distal to the left subclavian artery and the distal attachment at the diaphragm; (2) compression of a vessel between bony structures –

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i.e. "the osseus pinch", such as that of the innominate artery between the sternum anteriorly and the vertebrae posteriorly during an anterior sternal impact; and (3) dramatic intraluminal hypertension during a profound traumatic event [4].

Importantly, isolated injury to the thorax and great vessels is the exception rather than the norm, particularly in blunt trauma. Patients with great vessel injury commonly have concomitant head, spine, abdominal, pelvic and extremity injury. It is imperative that the primary threat to the patient be rapidly analyzed and managed. Three distinctly different groups of patients with thoracic aortic trauma exist according to Mattox and Wall (Table 1).

Group	Description	Diagnostic Interval	Location of Death	Mortality	Cause of Death
1	Dead/dying at scene	<60min	Scene/EMS transport	100%	Hemorrhage/ exsanguinations
2	Unstable during transport	1-6hours	EMS/ED	>96%	Multisystem trauma
3	Stable	4-18hours	ICU	5-30%	CNS injury

Table 1. Mattox and Wall Patient Classification with Blunt Aortic Injury

The first group represents those with severe thoracic trauma. This is generally unsalvageable and patients are usually dead at the scene or die during transport from uncontrollable hemorrhage and exsanguination. Those that actually make it to the trauma center alive are divided into the second and third group. Unstable patients during transport that die in the emergency department, operating room, or intensive care unit usually succumb to hemorrhage from other sites secondary to multisystem trauma in the first few hours. The third group of patients that arrive in a relatively stable condition are usually found to have a thoracic aortic injury during trauma workup that is not immediately life-threatening; these patients usually suffer from a protracted course secondary to a major insult to the central nervous system.

2. Initial evaluation

2.1. Prehospital management

The initial evaluation of any trauma patient, whether with great vessel injury or not, should proceed along the Advanced Trauma Life Support (ATLS) protocol created by the American College of Surgeon's Committee on Trauma. The primary survey should be conducted with the priorities of airway, breathing and circulation, and basic life support interventions are usually already underway by paramedics who have responded to the scene.

Severe shock should be treated with blood transfusion; however, appropriate initial fluid management continues to be an ongoing debate. In general, judicious use of either blood or crystalloid fluids is the norm, especially in great vessel thoracic injury. The goal of increasing blood pressure to normal values has been shown to increase the incidence of acute respiratory distress syndrome (ARDS), postoperative complications, and mortality [5]. Permissive hypotension with mean arterial pressures of 65 mm Hg are an acceptable initial goal as aggressive fluid administration would be expected to increase ongoing hemorrhage by dislodging a soft perivascular clot if definitive surgical vascular control is not already achieved.

2.2. Clinical history

There is no substitution to a clear and comprehensive history of the event. Clearly, the mechanism of injury will yield the greatest amount of necessary data. Whenever possible, as much information should be gathered from the patient surrounding the events having had occurred. Many times, however, the patient has already been intubated in order to protect the airway and for analgesic control of traumatic injuries. Emergency Medical Service (EMS) personnel as well as law enforcement officers are trained in gathering and relaying the necessary information to medical providers. Noting the amount of external hemorrhage at the scene as well as hemodynamic instability during transport is imperative.

In cases of penetrating trauma, the type of firearm used as well as the number and caliber of the projectiles fired in addition to the distance the victim was from the weapon is important. If a knife is used, the length of the instrument and its design (e.g. serrated edges) should be noted.

Although blunt trauma to the thoracic great vessels has been reported with crush and blast injuries as well as falls from height (usually over 30 feet or more), overwhelmingly, the primary culprit is motor-vehicle collisions. Particular detail to the automobile damage, length of vehicular intrusion, starred or shattered windshields, bent steering wheels, front- or side-impact, airbag deployment, the number of passengers in the vehicle, and whether the passenger or others were wearing a seatbelt is important to ascertain.

2.3. Physical examination

A rapid comprehensive assessment should be performed as noted previously following ATLS protocol. Obvious external hemorrhage and other signs of blunt or penetrating trauma should be noted by inspection. Evidence of paradoxical thoracic wall movement can determine evidence of flail chest segments. Attention to the neck veins can help demonstrate concern of an intravascular pericardial injury with stigmata of pericardial tamponade or tension pneumothorax. Palpation of the chest wall can reveal disconnected rib segments. Although difficult to hear in a busy trauma bay, percussion of the thorax can reveal a classic "stony dullness" indicative of fluid, primarily a hemothorax.

Classic findings associated with great vessel injury include:

- External hemorrhage
- Hypotension
- Radio-radial pulse inequality secondary to innominate or subclavian injury
- Unequal blood pressure measurements between upper and lower limbs secondary to pseudocoarctation syndrome

- Expanding or pulsatile hematoma at the thoracic outlet
- Intrascapular murmur
- Palpable thoracic spine fractures or instability
- Palpable sternal fracture
- Left flail chest

3. Assessment and imaging modalities

3.1. Chest radiography

Although the formal "erect" postero-anterior chest radiograph has been shown to be much more valuable in detecting true-negative instances in patients suspected of aortic injury, it cannot be safely obtained in a patient with hemodynamic instability or suspected spinal injury[6]. As such, the supine antero-posterior chest radiograph is the initial screening imaging of choice in the trauma patient. Several findings seen on the chest x-ray should raise suspicion of thoracic great vessel injury although none are necessarily diagnostic.

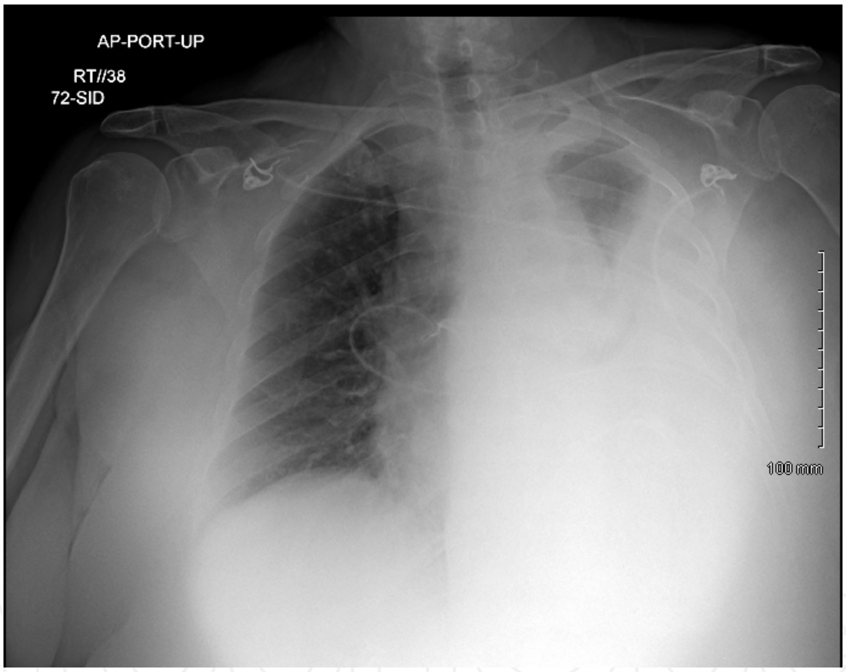

Figure 1. Left hemothorax secondary to significant blunt aortic injury

For blunt trauma, particular attention to the contour of the thoracic aorta is necessary. Evidence of mediastinal widening is the classic finding that represents a peri-aortic hematoma. Selective analysis of 16 radiographic signs by Mirvis and colleagues demonstrated that the most discriminating signs for traumatic aortic injury were loss of the aortopulmonary window, rightward deviation of the trachea, loss of the left paraspinal line without associated fracture, and abnormality in the contour of the aortic arch [6]. Other findings include an apical aortic or pleural cap, downward deviation of the left mainstem bronchus, and deviation of a nasogastric tube successfully placed in the esophagus. Of course, one needs to note any evidence of bony fractures such as the first rib, scapula and sternum, which generally require a large amount of force to cause such injury and should raise concern for underlying tissue and vascular structure damage.

In instances of penetrating trauma, radiographic findings that are suggestive of great vessel injury include a large hemothorax or a hemithoracic "white-out" (especially on the left), foreign bodies or missiles such as shrapnel or bullets, and an "out-of-focus" foreign body, which may indicate its intra-cardiac location.

3.2. Echocardiography and ultrasonography

As part of the Focused Assessment Sonography for Trauma (FAST) scan, a transthoracic approach with ultrasound should be routinely performed in both blunt and penetrating trauma to evaluate the pericardial space. In fact, FAST in rapidly becoming commonplace imaging in the initial assessment of trauma patients, expanding imaging to even assess the pleural space for hemothorax and pneumothorax following blunt and penetrating injury. There is an emerging role for the use of trans-esophageal echocardiography (TEE) and its application in acute and sub-acute trauma with suspicion of great vessel injury. Category 1 indications, or indications supported by strong evidence or expert opinion for the use of TEE in the trauma patient, include acute hemodynamic instability and the immediate evaluation of a patient suspected of thoracic aortic pathology such as a dissection, aneurysm or disruption [7]. TEE can rapidly diagnose such injuries by direct visualization of the aorta and a dissection, aortic wall thickening and the presence of a mural hematoma, evidence of an intimal or medial flap, and any intraluminal debris at the site of vessel injury [8].

In an evaluation of 101 trauma patients suspected of having aortic injury, Smith and colleagues conducted a prospective blinded study comparing conventional aortography and TEE. Imaging was performed sequentially by echocardiographic and angiographic personnel with the operators having had been blinded to the results of the previous evaluation. The sensitivity and specificity of TEE was calculated based on the results of aortography of the arch, surgery, and autopsy. The results demonstrated that TEE had a sensitivity of 100% and a specificity of 98%, with one false-positive TEE [9].

Although the use of TEE is safe, it is not without its risks and limitations [10]. Furthermore, as with most ultrasonography, it is operator dependent. TEE is not currently routine in the evaluation of a trauma patient suspected of great vessel injury, however, it remains a very useful adjunct in experienced hands.

3.3. Computed tomography

Contrasted, dynamic spiral computed tomography (CT) angiography is evolving into the imaging modality of choice in stable patients suspected of thoracic great vessel injury. It is of particular help in screening for great vessel injury in blunt trauma patients with a rapid deceleration mechanism. In addition to an evaluation of the aortic lumen and contour, it adds much information about the surrounding tissues and the presence of a mediastinal hematoma. It is also helpful for evaluating the trajectory of a missile in transmediastinal penetrating trauma.

Traditionally, the use of conventional CT was viewed as adding little extra knowledge to the clinical scenario. Surgeons, and even some radiologists, felt that obtaining a CT scan wastes valuable time, contrast administration would interfere and confound aortography, and that arteriography would still be necessary in a substantial number of cases [11,12]. However, with the use of helical CT technology, the aorta can be evaluated directly so that confusion of mediastinal hematomas and normal structures can be avoided. In addition, imaging of the aortic root with electrocardiographic gating can help minimize the pulsation and motion artifact that can leave concern about proximal aortic root injury that would traditionally require catheter-based angiography for definitive evaluation [13]. A study by Gavant and colleagues used helical scanning exclusively to screen over 1,500 patients with nontrivial blunt chest trauma. Those with abnormal CTs then underwent conventional aortography. Their evaluation yielded 100% sensitivity and 81.7% specificity for aortic injury [14].

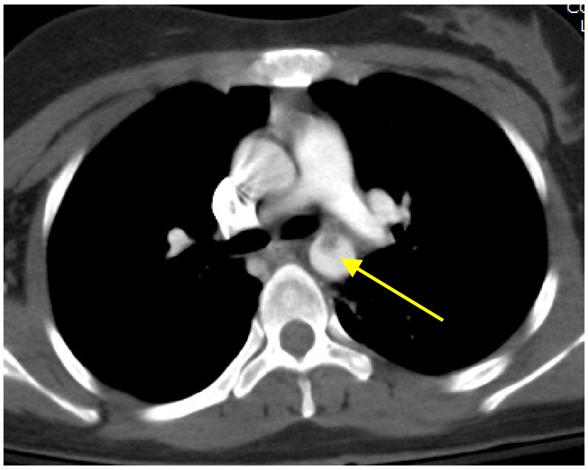

Figure 2. CT scan in axial section with aortic injury and intramural hematoma

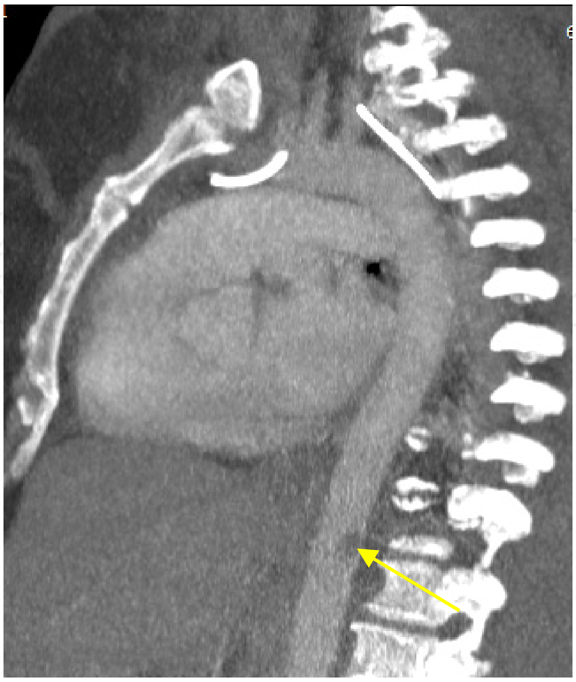

Figure 3. CT scan in sagittal section with intramural hematoma

Previously, the conventional CT scan was used as screening tool to guide further options. If no mediastinal blood is detected on CT, the probability of significant aortic injury is quite low and aortography is usually not needed [15]; efforts should be directed at the management of other injuries in the trauma patient. However, if the CT scan were positive for vascular injury, most surgeons would still proceed with aortography to help better delineate the exact location of the injury and possibly employ endovascular therapeutic options. With the advent of helical technology, however, CT angiography is considered a definitive diagnostic procedure that recognizes aortic injury and rupture.

3.4. Catheter-based thoracic angiography

Traditional teaching has placed conventional catheter-based angiography as the "gold standard" imaging modality when there is clinical or radiographic suspicion of a thoracic major vascular injury in the trauma patient. The information obtained from these studies help localize the injury and aid the surgeon in pre-operative planning and choice of incision as different thoracic approaches are needed for satisfactory anatomic exposure to obtain proximal and distal control of the affected vessels. Newer technology and better imaging resolution and capabilities are challenging this belief however.

In penetrating trauma, catheter arteriography is indicated for suspected aortic, innominate, carotid, or subclavian arterial injuries. Various film sequences have been used, including antero-posterior, lateral and oblique views. It is imperative that multiple views be obtained as more than one projection may be necessary to detect an aortic injury, especially if a small laceration has closed off or if a column of arterial contrast obscures a small extravasation in one view.

Indications for conventional angiography in patients presenting with blunt trauma include those with a rapid deceleration mechanism of injury, those with suggestive signs on chest radiograph – namely an obscure aortic knob or abnormal descending thoracic contour, a widened mediastinum – and those with a positive screening CT scan.

Angiography does have its limitations as well. It lacks spatial resolution, often requiring multiple injections in various different planes to demonstrate even minor lesions. In addition, it only provides luminal imaging and does not provide information on nearby parenchymal lesions and trauma as well as the integrity of adjacent venous structures. Furthermore, most institutions do not have an angiography team that remains "in-house" and as such, there is a time delay in assembling the necessary personnel to perform the imaging. Both false-positive and false-negative results have been reported [16]. These procedures are invasive and iatrogenic complications from catheter use such as arterial dissections, pseudoaneurysms, aortic lacerations, retroperitoneal hemorrhage as well as mortality have been reported [17]. Regardless, catheter-based thoracic angiography currently remains the frame of reference for the definitive diagnosis of thoracic vascular trauma.

3.5. Magnetic resonance angiography

For completeness, a note on magnetic resonance angiography is warranted. Although this modality can demonstrate evidence of acute or subacute mediastinal hemorrhage, its use in the acute trauma setting is not practical. Restricted access to a critically ill trauma patient while in the scanner is unsafe and the strong magnetic field can be severely limiting to those individuals requiring intensive monitoring and mechanical ventilator support.

4. Anatomy of the thoracic great vessels

Although a complete anatomic description of the thoracic vasculature is beyond the scope of this chapter, the relevant great vessel anatomy is described in the following subsections.

4.1. The aorta and its segments

The aorta is described in three different portions within the thoracic cavity; the ascending aorta, aortic arch and descending aorta.

The *ascending aorta* originates from the base of the left ventricle at the aortic orifice. Its origin and proximal aspect are contained within the pericardium. It courses anterosuperiorly and to the right where it becomes the aortic arch. Its total length is about 5 cm. Its only branches are the two coronary arteries, which arise immediately distal to the origin of the aorta just above the attached margins of the semilunar valves. Its location is central with respect to the other vascular structures. On the right side, it is in relation with the superior vena cava and right atrium. On the left side, it is in relation with the pulmonary artery. Posteriorly, it rests upon the right pulmonary artery and left atrium. It is separated from the sternum by the pericardium, the right pleura, the right lung anterior margin, some loose areolar tissue and the remains of the thymus.

The *aortic arch* runs at first posterosuperiorly and to the left, anterior to the right pulmonary artery and the carina of the trachea with its apex on the left of the distal trachea. It then courses downward posterior to the left hilum and becomes the descending aorta at the level of the lower border of the fourth thoracic vertebral body. Its branches, in order from right to left, include the brachiocephalic artery, the left common carotid artery and the left subclavian artery. All three branches arise from the convexity of the arch and are crossed close to their origins by the left brachiocephalic vein. Anteriorly, the vessel is covered by the lung pleura and the remains of the thymus. On the right side, it is in relation with the esophagus, the thoracic duct, the left recurrent laryngeal nerve and the deep part of the cardiac plexus. The trachea is also found on the right but posteriorly to the vessel. On the left side, the vessel is in contact with the left lung and pleura superiorly, and as it passes downward four nerves are encountered; the left phrenic, the lower of the superior cardiac branches of the left vagus, the superior cardiac branch of the left sympathetic, and the trunk of the left vagus. As the trunk of the vagus nerve crosses the aortic arch, it gives off its recurrent branch that wraps around the arch and then travels superiorly and to the right. Below the vessel are also the bifurcation of the pulmonary artery, the left bronchus, the superficial part of the cardiac plexus and the ligamentum arteriosum. The ligamentum arteriosum represents the remnant of the ductus arteriosus, connecting the inferior aspect of the aortic arch to the superior aspect of the pulmonary trunk.

The *descending thoracic aorta* is found in the posterior mediastinal cavity. It begins at the level of the fourth thoracic vertebra and descends on the left of the midline exiting the thorax through the aortic hiatus posterior to the diaphragm at the level of the twelfth thoracic vertebra. Its branches include the bronchial arteries, the posterior intercostal arteries as well as the pericardial, esophageal, mediastinal, superior phrenic and subcostal branches. On the anterior surface of the vessel, from above downward, are the root of the left lung, the pericardium, the esophagus and the diaphragm. Posteriorly, it is in relation with the hemiazygos veins and the vertebral column. On the left side of the vessel are the left pleura and lung, and on the right side are the azygos vein and thoracic duct. The esophagus lies on the right side of the descending aorta superiorly, then courses anteriorly and eventually to the left side of the vessel just above the diaphragm.

4.2. The great veins

The *brachiocephalic veins* are located on either side of the root of the neck and are devoid of valves. The right brachiocephalic vein is a short, about 2.5 cm long vessel and is formed by the confluence of the right subclavian and right jugular veins. Its origin is posterior to the medial aspect of the right clavicle. It runs vertically downwards and joins the left brachiocephalic vein just below the cartilage of the right first rib to form the superior vena cava. Its tributaries are the right vertebral vein, the right internal thoracic vein, the first posterior intercostal vein, the right inferior thyroid and thymic veins. The left brachiocephalic vein is about 6 cm long and is formed by the confluence of the left subclavian and left jugular veins. It begins behind the medial aspect of the left clavicle and travels obliquely downward and to the right posterior to the sternum to anastomose with the right brachiocephalic vein just below the cartilage of the right first rib. Its tributaries include the left vertebral vein, , the left internal thoracic vein, the left superior intercostal vein, the left inferior thyroid vein, and some thymic and pericardiac veins.

The *superior vena cava* is formed by the confluence of the right and left brachiocephalic veins. It has no valves. It measures about 7 cm in length and runs vertically downward posterior to the first two intercostal spaces to drain into the upper part of the right atrium The distal portion of the vessel is partially invested by pericardium. Its only tributary is the azygous vein. The inferior vena cava begins in the abdomen and enters the thorax through the caval hiatus in the diaphragm at the level of the eighth thoracic vertebra and immediately drains into the inferior aspect of the right atrium. It is partially invested by pericardium. It has no tributaries in the thorax.

The *azygous vein* begins in the abdomen and enters the thorax through the aortic hiatus in the diaphragm . It runs upward to the right side of the bodies of the thoracic vertebrae to the fourth thoracic vertebra, where it arches anteriorly over the right main bronchus and drains into the posterior aspect of the superior vena cava. It is found in the posterior mediastinum to the right of the esophagus and aorta, and to the left of the pleura and lung. Posteriorly, it is in relation to the lower right intercostal arteries and the thoracic vertebral bodies; anteriorly, to the root of the right lung and the pleura. Its tributaries include the hemiazygous vein, the right subcostal vein, some of the left intercostal veins and the nine lower intercostal veins on the right, the lower right superior intercostal vein, the right bronchial vein and several esophageal, mediastinal, and pericardial veins. The tributaries have complete valves, but the azygous vein itself only has a few imperfect valves.

5. Management options

With increases in technology and research, there are three mainstay treatments of blunt aortic injury: non-operative management, endovascular stent-graft methods, and traditional open repair (either immediate or delayed).

Azizzadeh and colleagues [18] initially proposed a classification system for blunt aortic injury based on the presence of an external aortic contour abnormality on computed tomography and/or the presence of free rupture noted on laparotomy.

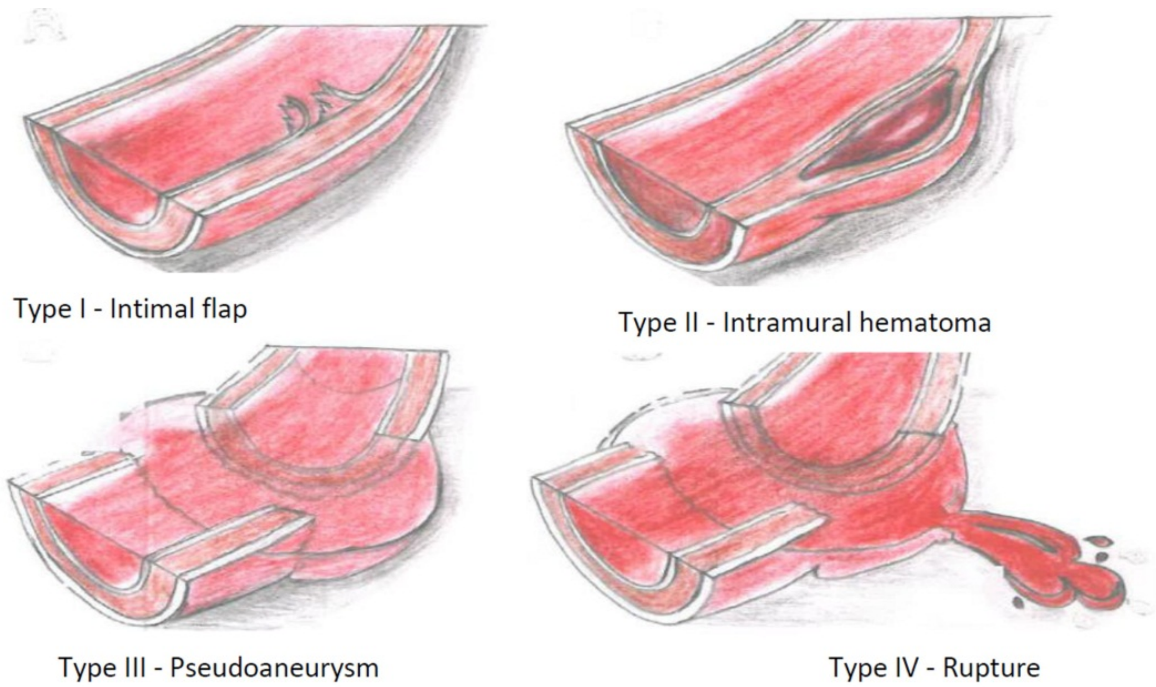

Figure 4. Schematic representation of blunt thoracic injury with implications for management

This classification system was further modified by Starnes and colleagues [19], as follows:

- Intimal tear: absence of aortic external contour abnormality and intimal defect and/or thrombus of <10mm in length or width
- Large intimal flap: absence of aortic external contour abnormality and intimal defect and/or thrombus of ≥10mm in length or width
- Pseudoaneurysm: external aortic contour abnormality and contained rupture
- Rupture: external aortic contour abnormality with free contrast extravasation noted on computed tomography or hemoperitoneum found on exploratory laparotomy

The Society for Vascular Surgery in 2011 has determined clinical practice guidelines for the repair of traumatic thoracic aortic injury [20]. Type I injuries can be managed expectantly with serial imaging; however, types II to IV should be repaired. Endovascular approaches are becoming the standard option in this regard if amenable.

5.1. Non-operative management

The advent of multi-detector CT and TEE has resulted in the identification of subtle injuries that were previously beyond the resolution of traditional imaging techniques. This has resulted in a dilemma of which particular injuries require immediate treatment and which ones can be safely observed. Some practitioners withhold intervention for minor aortic injuries such as minor intimal defects of 1 cm with no or minimal periaortic hematoma [21]. Complete resolution of such injuries has been noted but complications have also been documented from such non-operative management, even many years later. The natural history of these injuries is unknown but such complications include delayed rupture of pseudoaneurysms or even fistulization with profound hemorrhage [22]. Those patients that are treated non-operatively for blunt aortic injuries should undergo careful follow-up with imaging to observe and document injury resolution.

Patients that should not undergo immediate repair of blunt aortic injury include:

- Severe hemodynamic instability from concomitant injuries within the abdomen or pelvis
- Severe head injury
- Prohibitive medical co-morbidities
- Severe pulmonary injury
- Patients with progressive coagulopathy, acidosis and hypothermia
- Severe burns
- Profoundly contaminated wounds
- Severe sepsis
- Patients not in a trauma center capable of definitive repair

The mainstay of non-operative management involves aggressive pharmacological control of blood pressure with beta-blockers and critical care in an effort to delay the physiological insult of surgical intervention until the patient is adequately resuscitated and optimized. Avoiding hypertension is recommended to minimize intraluminal stress on the injured vessel from increased systolic blood pressure.

5.2. Endovascular stent-graft interventions

The advancement of endovascular techniques and device technology has truly revolutionized the treatment of blunt aortic injury over the last few years. In fact, at many centers, the use of thoracic endovascular repair (TEVAR) has become an attractive approach whereas initially it was only used in highly selected patients deemed too high risk for conventional open repair.

There are multiple advantages to the use of TEVAR, especially in the high-risk patient population. By nature, endovascular treatment is less invasive than open surgery, and if successful, averts the need for a traditional thoracotomy. It is associated with decreased morbidity and mortality, as has been noted in several studies [23-25]. Blood loss is minimal. Placement of a stent-graft does not require aortic cross clamping, which reduces the risk of distal visceral and spinal ischemia. In addition, such cross-clamping and unclamping complicate resuscitation and anesthesiologist management in patients with circulatory collapse and hemodynamic instability. Respiratory compromise from lung and thoracic wall injuries is magnified by thoracotomy, and single ventilation in such patients may be quite problematic. Furthermore, appropriate positioning for open surgery may compound neurologic deficits in patients with spinal fractures. Although systemic heparinization is usually employed during routine stent-grafting procedures, in cases of polytrauma with concomitant visceral organ injuries and fractures of the pelvis and long bones, heparin is withheld. Importantly with TEVAR, the absence of circulatory assistance with bypass and the need for high systemic doses of heparin, limit the feared hemorrhagic complications. Xenos et al. performed a meta-analysis of seventeen retrospective cohort studies evaluating 589 patients, and indicated that endovascular management of descending thoracic aortic injuries is a viable alternative to traditional open repair; it is associated with decreased ischemic spinal cord complication rates and lower postoperative mortality [23].

Successful use of endovascular stents in this patient population requires a sophisticated multidisciplinary and experienced team approach. Strict evaluation of the patient's anatomy is imperative. Current devices were primarily designed to treat aneurysmal disease, which is more prevalent in an aging population. Trauma patients have a considerable young demographic. As such, appropriate "fitting" of commercial devices is not always possible, rendering the use of stent-grafts difficult. Some young patients have aortic diameters less than 20 mm, which are too small for standard devices, even if oversizing the device diameter by the recommended 10-15% is employed. Adolescents and young teens also commonly have an aortic arch with a tight radius of curvature making sufficient apposition suboptimal due to inflexibility of devices. Most importantly, most reports of the use of stent-grafts demonstrate great short- and mid-term results. However, the data is lacking on long-term results, a concern for young patients expected to have a considerable life expectancy following the incident. Such patients will need close follow-up and continued surveillance imaging; the associated cost for the continued evaluation and the radiation burden is a concern [26].

It should be noted that endovascular options such a balloon occlusion, arterial embolization, and stenting or stent-grafting are viable endovascular options for the management of other great vessel trauma, such as the carotid, vertebral, subclavian, and axillary arteries.

5.3. Surgical repair

The standard of care for treating blunt aortic trauma has been emergent thoracotomy with interposition prosthetic graft or direct aortic repair with either a "clamp and sew" technique or with some variation of circulatory assistance and bypass. The rationale for treating blunt aortic injury is to essentially prevent early rupture from the acute injury and to prevent late aneurysm formation and subsequent rupture. The traditional approach is through a left thoracotomy with single lung ventilation, however, as noted previously, patients with pulmonary injuries and thoracic wall trauma may not tolerate single-lung ventilation [26-28].

Despite the many advances in peri-operative management and operative techniques, there continues to be a high morbidity and mortality with these injuries. The risk of paraplegia varies from 2.3% with active distal aortic perfusion to over 19% with the "clamp and sew" approach [26]. Mortality rates have been reported between 5% and 28% [28].

The indications for urgent thoracotomy remain hemodynamic instability, continued and significant hemorrhage from an adequately place tube thoracostomy, and rapidly expanding mediastinal hematoma noted on imaging. Certain pre-operative considerations are necessary prior to operative intervention, and include adequate pre-operative preparation, pharmacologic control, choice of incisions, availability of prosthetic material, and surgical repair techniques.

5.3.1. Pre-operative preparation

After confirmation of great vessel injury, the patient should expeditiously be prepared for immediate transport to the operating room for definitive surgical vascular control. While in the trauma bay, however, intravenous access should be obtained and cross-matched blood should be sent for; O negative blood should be used for immediate resuscitation efforts along with crystalloid fluids in the judicious manner described previously. Large bore central venous catheters should be placed on the side contralateral to the injury, above and below the diaphragm. It should be noted again, however, that no efforts should delay transport.

In the operating suite, close collaboration with the anesthesiologists is imperative. A double-lumen endotracheal tube should be placed (or converted to from the single-lumen endotracheal tube), if possible. Induction anesthetic agents can cause a precipitous decline in blood pressure that should be avoided, and artificial elevation of the blood pressure with vaso-active agents is also undesirable, especially when vascular control is not yet achieved. A nasogastric tube should also be inserted if not already done so. An arterial radial line will help with real-time hemodynamic monitoring. Perfusionists and full cardio-pulmonary bypass capabilities and circulatory assistance must be readily available in addition to an auto-transfusion device. A urinary catheter should also be placed. Prophylactic antibiotics are administered and tetanus prophylaxis should be ensured.

Although all efforts are moving at a fast pace to transport the patient to the operating room, it is essential that the surgeon be forthcoming about the seriousness of the situation and the high potential for post-operative complications with the patient and family whenever possible. The possibility of neurological damage, paraplegia, myocardial infarction, cerebrovascular accidents, renal failure and death must be discussed.

5.3.2. Pharmacologic control

Use of beta-blockers has become quite commonplace. The goal is to reduce the pressure on the injured aortic wall in order to avoid fatal rupture while maintaining cerebral perfusion.

Pate and colleagues demonstrated that the use of antihypertensive strategies in the management of acute traumatic aortic injuries eliminated in-hospital rupture of blunt aortic trauma when a delay in operative intervention was necessary [29]. In fact, the EAST Practice Management Guidelines Work Group recommends the use of vasodilators such as sodium nitroprusside or beta-blockade when non-operative or delayed management of blunt aortic injuries is considered [30].

5.3.3. *Choice of incision*

Adequate anatomic exposure is clearly imperative to visualize the injury and achieve appropriate proximal and distal vascular control. Injury detection through imaging greatly aids the surgeon in selecting the best incision to manage thoracic great vessel injuries.

Injured Vessel	Recommended Incision
Unidentified vessel in hemodynamically unstable patient	Left anterolateral thoracotomy ± transverse sternotomy ± right anterolateral thoracotomy (clamshell incision)
Ascending aorta	Median sternotomy
Transverse aortic arch	Median sternotomy
Descending thoracic aorta	Left posterolateral thoractomy
Brachiocephalic (innominate) artery	Median sternotomy with right cervical extension
Right subclavian artery or vein	Median sternotomy with right cervical extension
Right common carotid artery	Right cervical incision
Left common carotid artery	Median sternotomy with left cervical extension
Left subclavian artery or vein	Left anterolateral thoracotomy and separate left supraclavicular incision ±vertical sternotomy (book thoracotomy)
Pulmonary artery (main segment)	Median sternotomy
Pulmonary artery (intrapericardial segment)	Median sternotomy
Pulmonary artery (right or left hilar segment)	Ipsilateral posterolateral thoracotomy
Superior vena cava	Median sternotomy
Intrathoracic inferior vena cava	Median sternotomy
Innominate vein	Median sternotomy
Pulmonary vein	Ipsilateral posterolateral thoracotomy

Table 2. Recommended incisions for thoracic vascular injuries. Adapted from Feliciano, Mattox, and Moore, Thoracic Great Vessel Injury, 2008, p. 597.

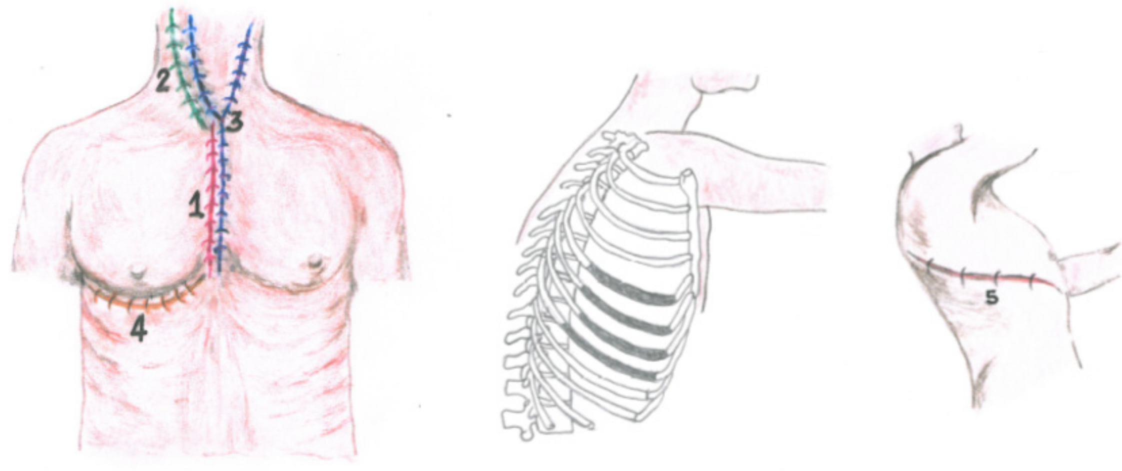

Figure 5. Incisional choices to approach the thoracic great vessels. (1) Median sternotomy; (2) Right cervical extension; (3) Median sternotomy with left cervical extension; (4) Ipsilateral anterolateral thoracotomy; (5) Ipsilateral posterolateral thoracotomy

In the unstable patient, the classic left anterolateral thoracotomy is performed with appropriate extensions as needed for adequate vascular control. It is important that the patient be prepped and draped from the neck down to the knee to allow for any and all possibilities. In stable patients, pre-operative radiography will allow specific identification of injuries and the incisions are tailored to the particular site.

5.3.4. Prosthetic materials

Availability of appropriate prosthetic material is important in emergency situations where aortic reconstruction is necessary. For vessels larger than 5 mm, a prosthetic material (either Dacron or PTFE) is generally used. For smaller thoracic vessels that are injured, some would advocate the use of autogenous conduits, such as the saphenous vein, for concerns of long-term patency. Prosthetic graft material soaked in antibiotic solution may theoretically prevent infection and bacterial seeding.

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6. Great vessel injuries

6.1. Arterial injuries

6.1.1. Ascending aorta

Blunt trauma to the ascending aorta is relatively rare and patients rarely survive transportation to the hospital. Open repair is indicated and usually involves placement of an interposition prosthetic Dacron graft with total cardiopulmonary bypass. The injury is approached through a median sternotomy.

Penetrating injuries are equally uncommon secondary to protection from the sternum. If anterior injuries are encountered, they may be repaired directly without cardiopulmonary bypass, however, circulatory assistance is usually necessary if concomitant posterior injuries are noted.

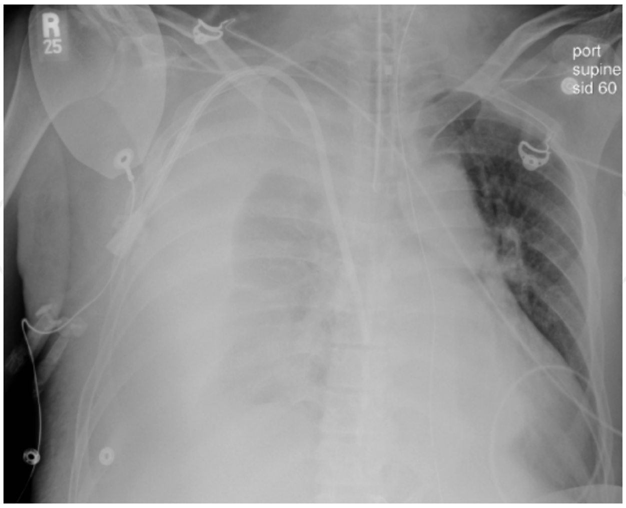

Figure 6. Unusual presentation of a patient with a right hemothorax after a retrograde dissection of the descending thoracic aorta into the transverse aortic arch and ascending aorta

6.1.2. *Transverse aortic arch*

Injuries to the transverse aortic arch pose a challenge as control of initial massive hemorrhage is difficult and usually the cause of surgical failure. Such injuries are exposed with a median sternotomy and commonly with a neck extension to allow for satisfactory distal control of the arch vessels. A variety of surgical methods such as tangential incomplete or intermittent complete aortic occlusion, vena caval occlusion, the use of temporary shunts, and even ventricular fibrillation have been used to help control hemorrhage during repair [31-33].

Deep hypothermia and circulatory arrest are recommended during the repair of these injuries to allow for optimal exposure, especially when posterior arch injuries are detected or suspected. Anterior injuries can be directly repaired.

6.1.3. *Descending thoracic aorta*

The descending thoracic aorta is the most commonly affected segment of the great vessel. In blunt mechanisms, it is usually just distal to the ligamentum arteriousum that the aorta is injured. Evaluation of the aorta at the aortic hiatus in the diaphragm should also be conducted because the vessel is tethered at this location and therefore susceptible to rapid deceleration forces.

It is important to note that trauma patients presenting to the hospital with blunt aortic injury usually have multiple other injuries. If the aortic injury is stable without evidence of an expanding hematoma and the patient continues to demonstrate hemodynamic instability, an expeditious search for other major trauma, primarily to the abdomen or pelvis, should be performed and addressed first. This may in fact necessitate laparotomy and control of intraabdominal hemorrhage prior to managing the great vessel injury, which can be conducted in a delayed fashion. Contemporarily, the use of intraluminal stents and TEVAR can be performed immediately following laparotomy.

Open surgical repair methods include either a primary direct repair of the aortic injury with either the "clamp and sew" approach or via circulatory assistance, or with placement of an interposition graft. The descending thoracic aorta is approached through a posterolateral thoracotomy, usually through the 4th intercostal space.

With the so called "clamp and sew" technique, the aorta is clamped distal to the left subclavian artery take-off, if possible, in order to allow cephalad perfusion; if not, the transverse aortic arch is clamped just distal to the left common carotid artery take-off with a second clamp placed on the left subclavian artery. A distal clamp is then placed as proximal as possible on the descending thoracic aorta to allow spinal cord perfusion while maximizing anatomic exposure for repair. If feasible, the clamps should be moved closer to the injury when identified. Care should be taken to not debride the aorta. This technique is particularly useful in the polytrauma patient as the additional risks of systemic heparinization are avoided as circulatory assistance is generally not used; however, this comes with the increased risk of paraplegia. This most feared complication – paraplegia – has an incidence of 0% to 19% [34] and is thought to be directly due to spinal cord ischemia from aortic cross clamping. The lowest reported rates of paraplegia have been noted with cross-clamp times less than 30 minutes [34]. Eighty-five percent of blunt aortic injuries are repaired with a soft interposition graft, however, if less than 50% of the aortic diameter is injured, primary repair may be employed. In addition, care should be taken not to sacrifice intercostals vessels – only those that compromise exposure due to continued bleeding should be ligated.

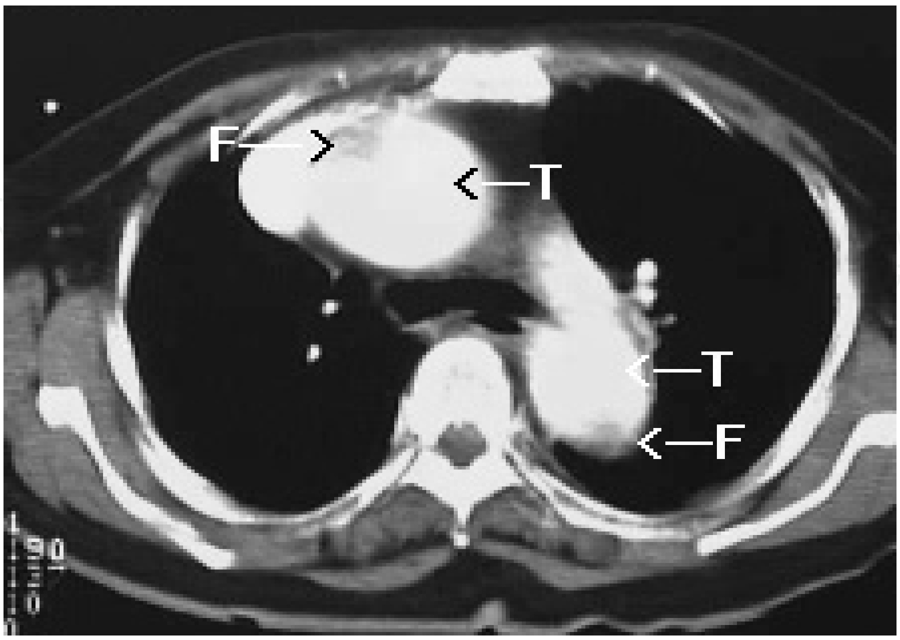

Figure 7. Aortic injury with secondary dissection from an intimal flap. (T) – true lumen; (F) – false lumen

The other alternative is to perform the repair while the distal thoracic aorta is perfused with extracorporeal circulation. This can be either via temporary, passive bypass shunts such as left ventricle to aorta or ascending to descending aortic shunts, or with active pump assisted left atrial to femoral bypass in a traditional format which requires heparin or a centrifugal pump mechanism. This method has been associated with decreased rates of paraplegia due to continued perfusion of the distal thoracic aorta, and as such, the spinal cord, during aortic repair. Some series even note no post-operative paraplegia with this technique [36].

Clearly, it is important to note that endovascular stent-grafts offer a particular advantage in these patients, if the anatomy is favorable, as morbidity and mortality are decreased.The paraplegia rate with this method is essentially close to zero. These interventional techniques have become quite commonplace in many trauma centers with such capabilities, and when possible should be considered.

6.1.4. Brachiocephalic artery

The brachiocephalic (or innominate) artery is approached via a median sternotomy to achieve proximal control at its origin from the aortic arch, with the incision extending into the right neck depending on how distal control is necessary. Exclusion and bypass via the "bypass principle" is the most common method of repairing a brachiocephalic injury, which occurs mostly at its origin.

The areas for bypass are from the ascending aorta to the distal brachiocephalic artery, just proximal to its bifurcation into the right common carotid and right subclavian. The brachiocephalic artery is clamped proximal to the injury while allowing continuous perfusion to the remainder of the body through the aorta. Distally, the brachiocephalic artery is clamped proximal to its bifurcation. A prosthetic Dacron graft is used for bypass. A side-biting clamp is placed onto the ascending aorta at the point for the proximal anastomosis, and an end-to-end anastomosis is performed distally. The native brachiocephalic origin is oversewn to complete the repair. Circulatory arrest and cardiopulmonary bypass is not necessary [36].

6.1.5. Subclavian artery

The right subclavian artery can be approached through a median sternotomy and right cervical extension. The left is approached through a left anterolateral thoracotomy for proximal control and a separate left neck incision for distal control. Pre-operative imaging with computed tomography or angiography is extremely helpful in delineating the exact location of the injury. The relation to the scalene muscles is also beneficial – if the injury is medial to the muscle, then a mid-sternotomy alone with extension should suffice, however, a supraclavicular approach will generally be satisfactory with a lateral injury.

Injuries are usually repaired either by lateral arteriorraphy or by placement of an interposition graft. When a graft is employed, the anastomosis is usually created in an end-to-side fashion as end-to-end can be quite difficult. Clearly, it is important to avoid the brachial plexus roots and the phrenic nerve during exposure.

The use of endovascular options is attractive for these injuries in particular. White et al. have noted one year primary patency and exclusion rates of 86% and 90%, respectively [37]. Complications are much less severe than with open surgical repair with stenoses and occlusions predominating however.

6.1.6. Left common carotid artery

The approach to the left common carotid artery mirrors that of its contralateral companion. A median sternotomy is employed with a left neck cervical extension when necessary. Small injuries can be repaired with primary arteriorraphy or with a patch; however, more severe injuries are preferentially repaired with bypass grafts.

6.1.7. Internal mammary artery

Internal mammary artery (IMA) injuries are more common with penetrating injuries rather than blunt injuries, however, the disruption of the IMA during latter has been described. It may follow relatively minor trauma resulting in a self-limited hematoma either in an extra-pleural setting or in between parietal pleura and the transversus thoracic muscle, or worse leading to a mediastinal hematoma with cardiac compression and/or hemodynamic instability.

The standard approach to repair involves a thoracotomy for adequate exposure. Small injuries in this setting may be repaired with primary arteriorraphy or via a patch. As with other thoracic injuries, more severe vessel trauma will require a bypass graft. It should also be noted that an endovascular approach with selective embolization using coils has been reported.

6.1.8. Pulmonary artery

Pulmonary artery injuries are very lethal and fortunately quite uncommon. Their management depends on where along the course the trauma has occurred. Proximal pulmonary and intrapericardial portions are approached through a median sternotomy. As with most other thoracic great vessel trauma, anterior injuries can usually be repaired directly, however, posterior injuries usually require total cardiopulmonary bypass to allow for satisfactory exposure.

The repair of distal or hilar pulmonary artery injuries is made difficult by the presence of the lung. These injuries are approached via an ipsilateral posterolateral thoracotomy. The need to perform a trauma pneumonectomy should be in the surgeon's armamentarium in cases of rapid hemorrhage so as to facilitate the necessary exposure to a major distal hilar injury.

6.2. Venous injuries

6.2.1. Thoracic vena cavae

Injury to the superior vena cava or intrathoracic inferior vena cava is infrequent due to the short length of these vessels within the thorax. Hemopericardium with pericardial tamponade physiology is usually found with such injuries. The surgical approach is through a median sternotomy. Superior vena cava injuries can usually be repaired via lateral venorrhaphy. The main difficulty with repair of caval injuries, however, is obtaining adequate exposure because of hemorrhage. Vascular isolation techniques such as atrio-caval shunting have been proposed to limit bleeding in pursuit of the strategy of direct repair of these venous injuries. However, mortality rates are fairly high, which has made many surgeons question the reliability of these approaches. As such, total cardiopulmonary bypass can be used as an alternative technique in order to decrease the blood return to the surgical field while maintaining perfusion of the body. Using circulatory assistance, an abdominal inferior vena caval to right atrial cannulation circuit should be used. The vena cava is repaired from within the lumen via access through a right atriotomy. Short inflow occlusion can be used if necessary.

Several surgical techniques have been used for reconstruction of the IVC including patch angioplasty and saphenous vein grafting. For extensive injuries, however, PTFE interposition grafts are preferred based on their superior patency rates and rapidity of the repair [38,39]. It is also important to exclude any other injuries that may preclude the use of systemic anticoagulation prior to total cardiopulmonary bypass.

Of note, thoracic inferior vena cava injuries that extend into the abdominal segment or that even include the retrohepatic veins can be repaired in a manner similar to the above description of cardiopulmonary bypass and total hypothermic circulatory arrest, if a completely bloodless surgical field is required. [40].

6.2.2. Pulmonary veins

Approach to the pulmonary veins is employed through an ipsilateral posterolateral thoracotomy. Repair with lateral venorraphy is preferred but technically difficult. If ligation is necessary, the respective lobe must also be resected.

6.2.3. Subclavian veins

Exposure for subclavian vein injuries is similar to the exposure necessary for subclavian artery injuries. Repair is either performed via a lateral venorraphy or suture ligation of the vessel.

7. Post-operative considerations and critical care

Patients suffering from thoracic great vessel injury clearly require critical care management in an intensive care unit setting. Hemodynamic monitoring and strict measurement of fluid inputs and outputs is necessary. Measures should be taken to avoid significant variability in blood pressure by judicious use of fluids and pharmacologic agents.

A tertiary survey will be required to evaluate for any further suspicion of injuries and commonly, repeat imaging is employed. Patients with multi-trauma will have an exaggerated systemic inflammatory response syndrome and hemodynamic support should be carefully instituted. Care must be taken to avoid attributing hypotension due to this exaggerated response – continued hemorrhage from unrecognized injuries or technical surgical failure must be excluded immediately.

Although the operation, revascularization, and reconstruction may be successful, patients are still susceptible to the many postoperative complications following major surgery, including pneumonia, urinary tract infections, wound disruption, adult respiratory distress syndrome, transfusion reactions, and coagulopathy. Management of these patients should be performed in an interdisciplinary approach with critical care physicians and the trauma surgeon playing a lead role in directing care.

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