Thomas M. Scalea *Editor*

# The Shock Trauma Manual of Operative Techniques

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# Preface

Operative therapy for trauma is at the center of the care of a badly injured patient. Hemorrhage can stem from a number of body cavities, the chest, abdomen, retroperitoneum, muscle compartments, and the street. Consultative aid can be extremely helpful in caring for multiply injured patients. However, the initial resuscitation and lifesaving operative therapy is almost always within the purview of the general surgeon. This generally involves operating in the neck, chest, abdomen, retroperitoneum, and on the vasculature.

Operative therapy for trauma has become much less commonly needed. Nonoperative management of solid visceral injuries has become the norm, not the exception. Newer therapies for primary or adjunctive hemostasis such as catheter techniques have become very much more commonly used. Penetrating injury in some American cities has dropped considerably. Thus, a general surgery resident and/or faculty member may do a relatively small number of operations for trauma in a given period of time.

However, when it is necessary, there is no substitute. This book will attempt to provide a refresher for surgeons who may be called on to provide lifesaving care in the middle of the night. Our intention is that this book fits into a pocket of a white coat and will be an immediately available reference.

The Shock Trauma Center has been providing large-volume trauma care for over 50 years. Authors are current faculty at Shock Trauma who were primarily trained there and/or have been recruited from high-volume trauma centers. We have developed a very uniform practice. This will be depicted in this book. While there are many ways to approach any given problem, this book will illustrate our approach.

## The History of Care

Operative exploration was the norm for many years. In fact, within the abdomen, it was thought that the only diagnostics necessary was to prove intra-abdominal injury existed. The dogma at the time said that all injuries required exploration, visualization, and then therapy depending on its appearance [1].

For many years, physical examination was the only diagnostic test available. While careful physical examination can be quite helpful, even in good hands, it was only approximately 85 % accurate [2]. Newer diagnostic tests emerged. In 1965, H. David Root described diagnostic peritoneal lavage [3]. Surgeons now had a test to augment physical findings. However, DPL, while missing very few injuries, was overly sensitive, and we soon realized that a number of injures with a small amount of blood in the abdomen did not require real surgical therapy.

In the early 1980s, CT scan emerged and revolutionized the care of injured patients. As CT improved, we realized that we could explore with a scan [4, 5]. Operative therapy was reserved for those with proven injury and/or those who presented in shock.

Finally, catheter therapy proved to be a valuable adjunct to the non-operative management, particularly of solid visceral injuries. Splenic artery embolization, first described in 1995, has been extremely useful in sparing patients the need for operation [6]. Catheter therapy for liver injuries can be primary hemostasis and is also quite helpful as an adjunct to operative therapy [7].

## Operative Technique with Personal Tips

A systematic approach to the operative therapy of the patient with injuries is extremely important. While the need for this has decreased, nothing substitutes for it when it is necessary. No matter where one trains or practices, it is hard to experience the full gamut of injury, particularly serious injury over a short period of time. To date, we have very poor simulated models; thus, the only real training is clinical experience. The American College of Surgeons Committee on Trauma has several courses which can be quite helpful. The Advanced Trauma Operative Management course (ATOM) provides students with real-life scenarios requiring operative therapy [8]. ATOM requires a large animal model and is quite costly, thereby limiting its utility. Advanced Surgical Skills for Exposure in Trauma (ASSET) is a cadaver-based course, which allows students to become facile with operative exposures over the entirety of the body. As four students share a cadaver, ASSET can be efficient. However, it is unclear how long the lessons learned in ASSET or ATOM remain in the front of the surgeon's minds. Finally, newer techniques such as Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) provide new options to the surgeons. There are several courses that teach this technique. Both the ESTARS and BEST course run by the United States Military and the Shock Trauma Center are options for practitioners who wish to become facile with this technique [9, 10]. Early experience in both courses suggests that these are easily learned by surgeons who have some experience with guide wires and catheters.

Regardless of training, there is still need for a readily available reference to which surgeons can refer to at the time of need for operation. The reference should be portable and easy to understand. There should be sufficient number of illustrations, as these most likely will make reviewing procedures easier than simply reading text. Ideally, a surgical trainee or faculty member should be able to review procedures during down time between patient encounters. In addition, a surgeon should be able to rapidly review a particular facet of operative care on the way to the operating room.

*The Shock Trauma Manual of Operative Techniques* seeks to help fill the void that currently exists in training of surgeons. We recognize that no single book will be the answer. We hope this will provide some help in caring for injury around the world.

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# Part I
# Indication and Techniques for Trauma Exploration

# 1. Neck

*Laura S. Buchanan, M.D.*

## Introduction of the Problem

Neck injury has the potential to involve critical vascular, respiratory, and digestive structures. More than 15,000 neck injuries were documented in the National Trauma Data Bank for 2013 with an overall mortality of 1.87 % [1]. However, mortality for more severe injury (AIS ≥3) is almost 20 % greater than any other body region [1]. Neck injuries are combined with head in Centers for Disease Control (CDC) reporting and cumulatively account for 17 % of injuries requiring hospitalization and 20 % of injuries treated in an emergency department [2].

## History

Early management with expectant observation led to delayed diagnosis of injuries and high mortality. Mandatory explorations of traumatic neck wounds gained favor after World War II and resulted in decreased mortality from injury but were associated with significant rates of negative exploration with risk of surgical site morbidity. Improvement in imaging techniques and improved understanding of neck trauma have resulted in a gradual shift to selective exploration.

Treatment of neck injuries is best understood by dividing patients first by mechanism (blunt vs. penetrating) and by anatomic zones. Blunt injury most commonly results from motor vehicle collisions but may occur with strangulation, assault, and sport injuries. Seat belts and dashboards can result in injury to cerebral vessels or larynx. Cervical spine

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injury and spinal cord injury requiring stabilization are much more common in blunt neck trauma than in penetrating. Blunt trauma requires cervical immobilization until spine injury has been ruled out. Blunt cerebrovascular injury is rarely operative, while identified injury to aerodigestive structures typically require repair.

Penetrating neck injury was historically treated nonoperatively until shortly after World War II. Fogelman and Steward reported the first large civilian series on penetrating neck injury and advocated mandatory exploration citing a significant improvement in mortality (6 % vs. 35 % with expectant management) [3]. Violation of the platysma was used to determine potential for injury. During the remainder of the twentieth century, mandatory exploration was widely accepted for penetrating injury to Zone II, with a more selective approach to Zone I and Zone III injuries. Diagnostic modalities for Zones I and III included arteriogram for diagnosis of vascular injuries, laryngoscopy and bronchoscopy for airway injuries, and contrast esophagram and esophagoscopy for digestive injuries. This combination of testing is costly and low yield and has potential complications. Improvement in multidetector computed tomography (CT) allowed for more selective approach to operative and diagnostic procedures.

The transition from mandatory neck exploration to selective operation was studied prospectively by Inaba and colleagues [4]. Including 453 patients over 3 years, they identified 9 % with hard signs of injury mandating exploration. Forty-two percent had no signs of injury and were followed clinically and discharged with no missed injury. The remaining 49 % of patients underwent multidetector computed tomography, which had a sensitivity of 100 % and specificity of 97 % in detecting injuries [4], confirming that a selective approach to exploration in neck trauma is safe and appropriate.

The Eastern Association for the Surgery of Trauma (EAST) guidelines for clinical practice (2008) advise selective management is equally safe and effective to mandatory exploration despite a paucity of prospective trials [5]. The Western Trauma Association (WTA) algorithm for penetrating trauma (2013) also advocates a selective approach [6]. Patients with hard signs (Table 1.1) of vascular or aerodigestive tract injury should undergo airway stabilization and tamponade and proceed to operative exploration. Similarly, patients who are symptomatic with Zone II injuries should undergo early operative exploration. In the absence of the hard signs of major injury, all Zone I and III injuries and asymptomatic Zone II injuries should undergo diagnostic evaluation.

Table 1.1. Hard signs of neck injury as defined in the Western Trauma Association's algorithm [6].

| Hard signs of neck injury |
| --- |
| Airway compromise |
| Massive subcutaneous emphysema |
| Air bubbling through the wound |
| Expanding/pulsatile hematoma |
| Active bleeding |
| Shock |
| Neurologic deficit |
| Hematemesis |

## Surgical Technique

Wise operative planning for injury to the neck involves understanding of specific anatomic landmarks. The neck is divided into three zones. Zone I extends from the sternal notch to the cricoid cartilage and includes the thoracic outlet vasculature, proximal carotids, and vertebral arteries, as well as the trachea, esophagus, spinal cord, thoracic duct, and cervical nerve trunks. Zone II extends from the cricoid cartilage to the angle of the mandible. The carotid arteries, internal jugular vein, vagus nerve, and upper trachea, as well as the larynx, are included in Zone II. Zone III is superior to the angle of the mandible.

Proximal and distal vascular control in Zone II can be relatively easily accomplished via a standard neck incision. This makes injuries in Zone II the most surgically accessible. Distal control in Zone I injuries can be obtained in Zone II; however, proximal control requires a thoracic incision, either a sternotomy, thoracotomy, or peri-clavicular incision. Proximal control of Zone III injuries can be obtained in Zone II; however, distal control—particularly distal vascular control—involves controlling the vascular structures within the skull.

Certainly, patients who present in shock with Zone II injuries are best treated with diagnostic exploration. Even stable patients in Zone II can be treated with operative exploration, though most prefer imaging. Unstable patients with Zone I injuries also undergo operative exploration. The thoracic incision is determined by best guess. If the incision does not provide adequate exposure, a second incision and/or third incision can be made. Incisions can be extended with attempts to gain control. Given the invasive nature of thoracic exposure, stable patients with

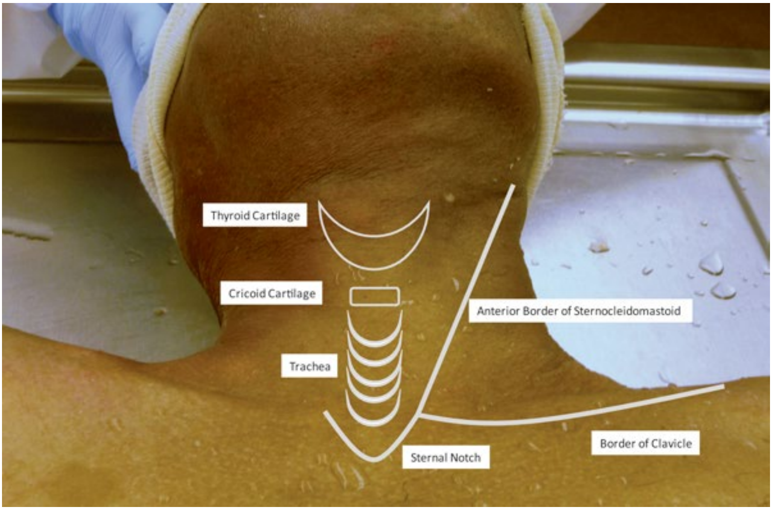


Fig. 1.1. Anatomic landmarks.

Zone I injuries are best served by diagnostic testing. Given the same issues of difficult vascular control in Zone III, stable patients should undergo diagnostic testing. While surgical dogma advocates operative exploration for Zone III injuries with hypotension, operative exploration can be quite time consuming. If a catheter option is immediately available, that may be wiser, particularly in selected cases.

The relevant surface anatomy of the neck is illustrated in Fig. 1.1.

## *Preparation*

The operative field should include the lower jaw, the bilateral neck, and entire anterior chest. If the cervical spine is cleared preoperatively, a shoulder roll will improve neck extension. The head should be slightly turned to the contralateral side for the standard anterior sternocleidomastoid incision and midline for a collar incision.

Selection of incision is determined by location of suspected injuries. Typical incisions are depicted in Fig. 1.2. Neck exploration is typically done through an incision on the anterior border of the sternocleidomastoid. This incision allows rapid exposure and control of the vasculature and can be extended into a sternotomy. Bilateral exploration can be

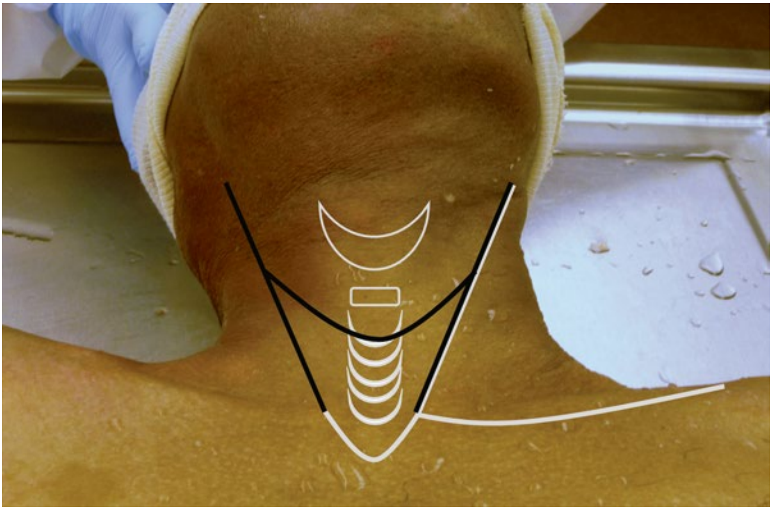

Fig. 1.2. Typical incisions (*solid black lines*).

performed using bilateral standard anterior incisions or via a collar incision. A collar incision gives the best exposure for the anterior trachea. A supraclavicular incision may be indicated for exposure of Zone I and can be combined with resection of the head of the clavicle or a trap door sternotomy to extend exposure toward the mediastinum.

## *Anterior Sternocleidomastoid Neck Exploration*

This standard approach starts with an incision on the side of the penetrating injury. An incision is made along the anterior border of the sternocleidomastoid extending from the clavicular head to the retromandibular area as needed. If extension is needed at the superior portion of the wound, the incision should curve posteriorly toward the mastoid process to avoid damage to the mandibular branch of the facial nerve exiting at the angle of the mandible. The platysma is divided along the same plane as the skin incision exposing the sternocleidomastoid (Fig. 1.3). The vascular sheath underlies the medial border of the sternocleidomastoid. The sternocleidomastoid is retracted laterally exposing the vascular sheath. The omohyoid muscle and facial vein cross the carotid. Dividing them will allow exposure of the common carotid and its bifurcation. The internal jugular vein, vagus nerve, and carotid artery

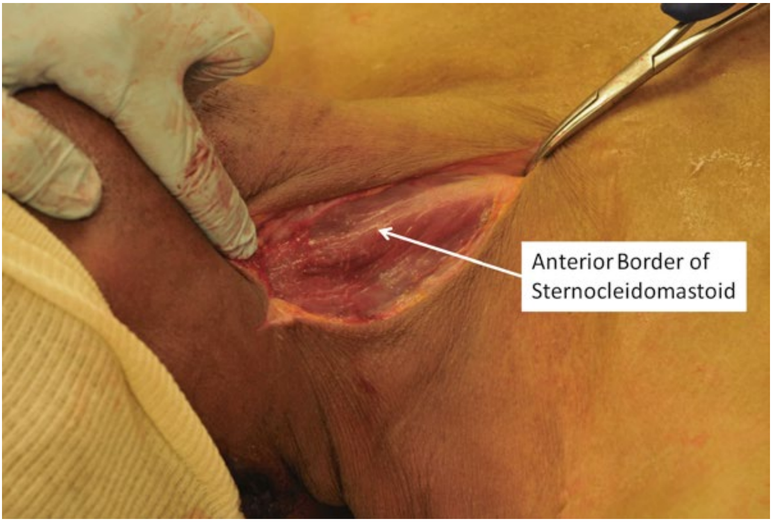


Fig. 1.3. Exposure after incision of skin and platysma.

are all exposed with this technique (Fig. 1.4). The hypoglossal nerve runs perpendicular to the carotid near the level of the bifurcation and should be preserved. Damage to the hypoglossal nerve will result in deviation of the tongue toward the ipsilateral side. Unilateral hypoglossal nerve injury may be asymptomatic but can result in difficulty with mastication, speech articulation, and swallowing. Visualization of vascular structures may be difficult in cases of ongoing hemorrhage, and proximal control may require access in the chest.

The esophagus and trachea can be accessed via this same incision medial to the vascular structures (Fig. 1.5). The access shown is right sided. The esophagus can be accessed via a left- or right-side standard incision. The esophagus is a left-sided structure in Zone II so it is best approached from the left side. The trachea and thyroid should be mobilized medially to expose the upper esophagus. Surrounding hematoma can obscure structures and anatomic planes. Placement of an enteric tube can provide tactile guidance to assist in identification of the esophagus. The esophagus can be mobilized if necessary to explore and repair injuries, as blood supply was in the wall, mobilization is safe. Mobilization should start on the posterior surface elevating the esophagus off the anterior spine. Once the esophagus is circumferentially mobile, placement of a penrose drain will aid in retraction and exposure during

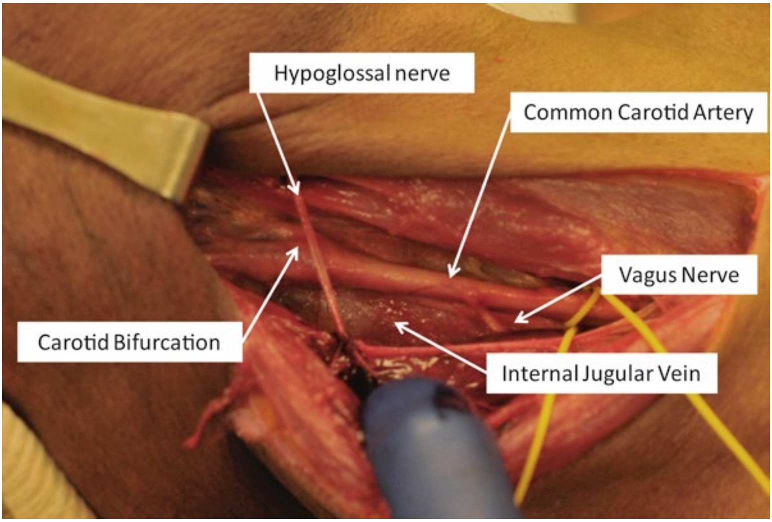


Fig. 1.4. Structures within the carotid sheath.

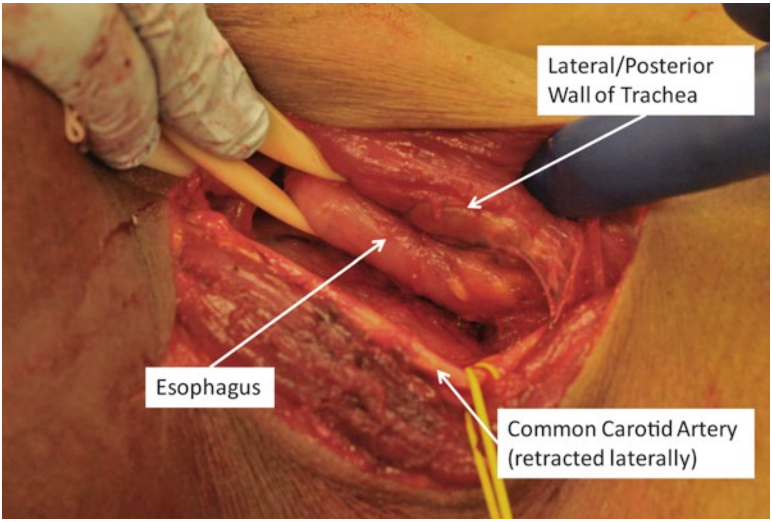


Fig. 1.5. Lateral exposure of trachea and esophagus.

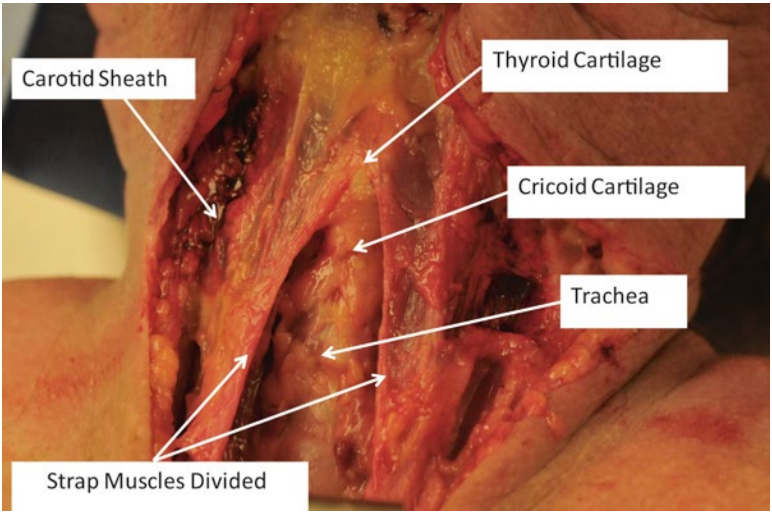


Fig. 1.6. Exposure via collar incision.

any subsequent repair. Tracheal exposure via this incision gives access to the anterior and lateral tracheal wall with limited exposure to the posterior trachea.

The trachea is best accessed via a collar incision. The patient should be positioned as previously described with the head in a neutral position. The incision is placed 1–2 cm above the sternal notch and extends laterally to the medial border of the sternocleidomastoid. The platysma is divided in the same orientation and flaps are raised superiorly and inferiorly (Fig. 1.6). Take care to ligate the anterior jugular veins. The strap muscles are divided. The thyroid isthmus is clamped and divided. This will expose the larynx and cervical trachea (Fig. 1.7). Access to the lower trachea may require partial sternotomy. Circumferential mobilization of the trachea will result in devascularization and should not be performed. The anterior and lateral surfaces can be easily reached through this incision. The posterior trachea may be easier to repair through an existing anterior tracheal wound or even opening the anterior trachea. After the posterior trachea is repaired, the anterior opening can be closed. It can also be exposed via a lateral exposure as described in the standard anterior sternocleidomastoid incision.

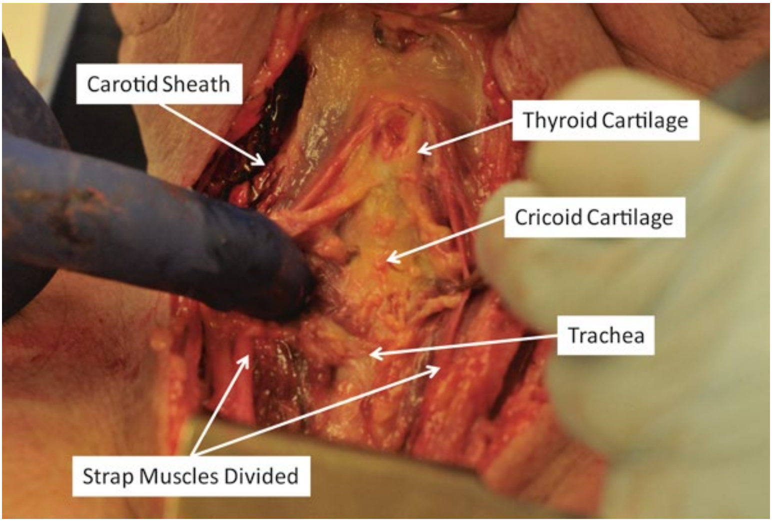


Fig. 1.7. Exposure of trachea and larynx.

## *Surgical Exposure of the Vertebral Artery*

The majority of the vertebral artery is protected by the bony canal of the cervical spine, and as a result, most intervention for injury is performed by interventional radiology. If necessary the origin can be exposed from the subclavian artery to the transverse process of the 6th cervical vertebra. The standard anterior sternocleidomastoid incision can be used. The carotid sheath is retracted medially, and the scalene fat pad retracted laterally. This exposes the anterior scalene muscle and inferior thyroid artery. The artery is divided, and the muscle retracted laterally to expose the vertebral artery. Alternatively, a supraclavicular incision with division of the sternocleidomastoid provides access to the proximal common carotid and the origin of the vertebral artery. Exposure of the distal vertebral artery requires subspecialty expertise.

# Tips

Control of airway remains primary and should be secured before any other intervention. The preferred airway control remains endotracheal intubation followed by a standard surgical airway. Only in very rare cases when the airway is violated and easily visible in the wound should one intubate the trachea through the existing wound. When possible, obtain at a minimum a preoperative chest X-ray to evaluate for mediastinal widening suggesting proximal vascular injury and pneumothorax as these may change operative planning in an unstable patient.

Plan for the unexpected, such as the need for emergent, proximal, or distal exposure by including the chest and jaw in the surgical field. Avoid pressure dressings as a means of temporary vascular control. Temporary vascular control is better achieved with direct digital pressure or balloon tamponade. Consider catheter therapy as adjunctive treatment, especially for injuries extending into Zone III. Techniques such as jaw dislocation, clavicular head resection, and surgical access to the distal segments of the vertebral arteries require significant time and expertise and are unlikely to benefit an unstable, actively hemorrhaging patient. A hybrid approach may be the best solution for vascular injury in these difficult-to-expose areas and may combine operative or balloon tamponade followed with catheter therapy.

Complications after treatment can relate to hematoma, pneumothorax resulting from violation of the apical pleural, infection, and iatrogenic injury to the cranial nerves in the neck. Operative drains should remain in place until output decreases. Series evaluating a mandatory exploration strategy result in 50–68 % negative exploration, suggesting avoidable perioperative morbidity.

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# 2. The Chest

*Margaret H. Lauerman, M.D. and Jose J. Diaz, M.D.*

## History of Interventions for Thoracic Trauma

In the contemporary era, operative therapy for thoracic trauma is considered routine. However, operative cardiac intervention was previously thought impossible [1], and until World War II, it was believed that reinflating the lung would cause bleeding [2], thus initially limiting operative intervention for both cardiac and thoracic injury.

Intervention for thoracic pathology has been described since Hippocrates, and over many centuries operative treatment of thoracic trauma has evolved. Drainage of both pneumothoraces and hemothoraces was described in the 1700s [2]. Cardiac intervention for trauma was first performed in the late 1800s, when Daniel Hale Williams III repaired a pericardial defect [3]. By the 1900s, our current chest tube drainage system had come into practice [2, 4], and despite concerns about performing thoracic surgery, operative intervention for exsanguinating hemorrhage was the primary therapy [5].

As minimally invasive surgical techniques were honed, they were applied to thoracic trauma as well. Minimally invasive operative techniques in thoracic trauma were first described in 1946, with the use of a thoracoscope to avoid a thoracotomy [6]. Thoracoscopic techniques have evolved from simple suction placement through an existing chest tube site [7] and diaphragmatic injury evaluation [8] to the currently used video-assisted thoracic surgery (VATS) [9–15].

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## Introduction

Thoracic trauma is common and potentially deadly. Injuries from thoracic trauma range from rib fractures requiring only pain control to cardiac lacerations with tamponade or exsanguinating hemorrhage. Given the range of injuries, acuity and clinical presentation, multiple diagnostic modalities, and treatment options, exist for thoracic trauma.

Within the overall trauma patient population, 30.6 % will sustain thoracic injuries [16]. Only 34 % of thoracic injuries are due to penetrating trauma, the remainder the result of blunt injury.

Knowledge of injury patterns can assist with patient evaluation and treatment. Thoracic injuries such as sternal, scapular, and first rib fractures may be associated with severe underlying injury. Sternal fractures are associated with mediastinal pathology, such as cardiac and great vessel injuries [17], while scapular fractures are associated with underlying thoracic cavity injuries, such as pneumothoraces and pulmonary injuries [18]. Concomitant pneumothoraces, hemothoraces, and cardiac injuries can be related to the presence of a first rib fracture [19].

Concurrent injuries are not limited to the thoracic cavity. Only 20 % of thoracic trauma patients have isolated thoracic injuries, with extremity, abdominal, and pelvic injuries often associated with thoracic pathology [16]. Presence of extrathoracic injuries can complicate the initial evaluation, especially in hemodynamically unstable patients, whose evaluation includes thoracic and extrathoracic pathology [16].

## Primary and Secondary Surveys

Thoracic injuries may affect oxygenation, ventilation, and maintenance of circulation. Life-threatening injuries seen during the primary survey should be treated before advancing to the secondary survey. Failure to address underlying pathology can result in decompensation or death, especially in the unstable patient. Thoracic trauma can cause significant respiratory distress, as with painful rib fractures restricting chest wall movement or pneumothoraces limiting oxygenation and ventilation. Patients in respiratory distress from thoracic injury require emergent intubation.

Next, the chest is inspected and auscultated. Hemodynamically unstable patients with signs of hemothorax or pneumothorax on exam require urgent chest tube insertion at this step in the primary survey. If an open chest wound is present, a three-sided dressing should be placed to prevent air from entering the thoracic cavity. Flail chest may be seen on inspection and palpation, although no acute interventions are necessary for flail chest other than supportive respiratory care. Patients with flail chest may require urgent endotracheal intubation for respiratory insufficiency. The chest is inspected to note location of wounds, with heightened attention paid to wound proximity to major vascular structures or potential mediastinal violation. Injuries entering “the box” (bordered by the clavicles, midclavicular lines, and costal margins) [20] may portend an underlying mediastinal injury (Fig. 2.1).

When assessing circulation, unequal upper-extremity pulses suggest a possible subclavian arterial injury. Heart sounds are auscultated to evaluate for pericardial effusion and underlying cardiac injury. Beck’s triad occurs in only 10 % of cardiac injuries [21] and is not relied upon for diagnosis in trauma. If there is bleeding from a chest wall wound, this should be controlled with direct pressure.

A minority of thoracic trauma results in isolated chest pathology [16]. The secondary survey is especially important in hemodynamically unstable patients. Hemodynamically unstable thoracic trauma patients may have concurrent extrathoracic injuries requiring emergent intervention.

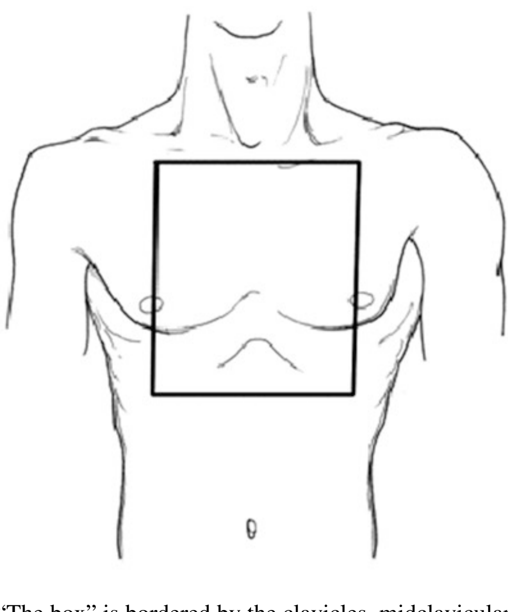

Fig. 2.1. “The box” is bordered by the clavicles, midclavicular lines, and costal margins.

Indications for operative intervention encountered during the primary and secondary survey include those for an ED thoracotomy, initial chest tube output greater than 1,500 cc, a chest tube with a massive air leak, concern for airway injury, and an open chest wall wound with instability. In all other patients, further radiologic evaluation should be undertaken as hemodynamic stability allows.

## Diagnostic Tests

Focused assessment with sonography for trauma (FAST) and chest X-ray (CXR) are both rapid and repeatable bedside tests and can help determine if indications for immediate operative intervention are present. CXR and FAST are performed in all thoracic trauma patients. After CXR and FAST, subsequent diagnostic evaluation of thoracic trauma patients may include a variety of noninvasive and invasive testing to determine the need for operative intervention.

### *Chest X-ray*

CXR displays a global image of the chest, with imaging of the mediastinum, bony structures, soft tissues, and both thoracic cavities. While ongoing research continues to develop the ideal targeted thoracic imaging algorithm [22, 23], an initial CXR should be obtained in all thoracic trauma patients. Radiographic evidence of a hemothorax or pneumothorax should prompt chest tube placement and subsequent monitoring of the chest tube for operative indications. An abnormally wide mediastinum or pneumomediastinum should prompt further imaging with computed tomography (CT). Massive pneumothorax with significant subcutaneous emphysema may be a sign of a bronchial injury.

### *Ultrasound*

In the chest, FAST allows visualization of the pericardial sac. FAST has also been extended to evaluate for pneumothorax through the "EFAST" [24]. In combination with CXR, FAST is helpful in the multiply injured, hemodynamically unstable patient, to determine the need for abdominal or thoracic exploration, or both, for hemorrhage control. Early reports evaluating pericardial FAST in penetrating cardiac wounds had a 0 % false-negative rate [25]. However, false-negative pericardial FAST exams have now been reported, potentially due to hemopericardium decompressing into the pleural space through a disrupted pericardium. Mortality is 40 % for cardiac injuries missed with FAST [26]. FAST is routinely used in blunt trauma despite the rarity of underlying cardiac injury [27], as mortality of undiagnosed hemopericardium is high [26]. EFAST may be an excellent test for pneumothorax detection for both blunt and penetrating trauma [28] and is often helpful in unstable patients to evaluate for pneumothorax when CXR is not rapidly available.

A positive pericardial FAST is an indication for exploration, either with a pericardial window or sternotomy, depending on patient stability. In penetrating trauma with concern for cardiac injury, a negative FAST for pericardial fluid does not negate the need for operative exploration of the pericardium, especially with a concurrent hemothorax. A positive EFAST in a hemodynamically unstable patient should prompt immediate chest tube insertion.

### *Computed Tomography (CT)*

In blunt and penetrating thoracic trauma, CT can add vital information to initial imaging. In one review, 14 % of patients had an occult hemothorax or pneumothorax seen on CT but not CXR; 62.8 % required intervention [29]. Missed injury on CXR included aortic injuries as well [30, 31]. CT angiogram is beneficial in penetrating thoracic trauma to evaluate for transmediastinal trajectory and potential mediastinal injuries. Traditional work-up for transmediastinal gunshot wounds included angiography, bronchoscopy, and esophagoscopy to evaluate the major mediastinal structures [32]. These have been replaced by CT angiogram without evidence of missed injuries [33].

It is imperative to understand that a patient with penetrating thoracic trauma resulting in hemodynamic instability requires a rapid evaluation, including CXR and FAST, followed by operative intervention. There is no role for additional imaging.

## Thoracic Intervention

### *Preoperative Preparation*

Success of thoracic exploration can be optimized with preoperative preparation. A major risk with thoracic exploration is bleeding, as most thoracotomies are performed for hemorrhage control [34]. Preoperative preparation should include availability of blood products, and a Cell Saver® (Haemonetics Corp., Braintree, MA) can be a useful adjunct. If there is concern for intrathoracic vascular injury, the infusion catheter should be placed on the contralateral side to the vascular injury so as to not infuse through the injured vessel. An arterial line should be placed for continuous blood pressure monitoring. The line should be placed in the upper extremity as femoral waveforms will be lost if the aorta is cross-clamped.

If pericardial tamponade is present or a possibility, the patient should be prepped and draped prior to intubation if possible. These patients are preload dependent, and loss of vasomotor tone can occur on induction resulting in cardiovascular collapse. An emergency exploration is then required to release the tamponade.

In the acute setting, intubation should be performed with a single-lumen endotracheal tube. For more chronic pathology, such as empyema or retained hemothorax, a double-lumen tube improves operative exposure by allowing single-lung ventilation. A bronchoscope should be available and can be used preoperatively or intraoperatively to assess tracheobronchial injury and provide airway clearance of secretions and blood.

Specific instruments should be available for every thoracic exploration. A sternal saw should be accessible for all cases should a sternotomy be required. A Lebsche knife should also be available, as it can be used to perform a sternotomy if the sternal saw malfunctions or to extend an anterolateral thoracotomy across the sternum into a clamshell thoracotomy. A Finochietto retractor can be used for either an anterolateral thoracotomy or sternotomy, but a specialized sternal retractor is preferred for a sternotomy. Internal paddles should be on the field and attached to a defibrillator.

## *Indications for Operation*

There are multiple indications for acute thoracic exploration. In patients with FAST or CT evidence of a pericardial effusion, cardiac exploration is always indicated, regardless of clinical stability. Initial chest tube output greater than 1,500 cc or 150–200 cc/h over several hours is an indication for exploration [35]. Other markers for acute exploration include: persistent bloody chest tube output despite not meeting initial chest tube output requirement for thoracotomy; large air leak with concern for airway injury; and known airway, esophageal, or vascular injury (Table 2.1). In stable patients, operative intervention is targeted to specific injuries as seen on radiologic evaluation.

Table 2.1. Indications for acute operative intervention in the thoracic trauma patient.

| Indications for acute thoracic operative intervention |
|---|
| 1. Cardiac arrest meeting ED thoracotomy guidelines |
| 2. Greater than 1,500 cc of initial chest tube output or 150–200 cc/h over 2–4 h after chest tube placement [35] |
| 3. Persistent bloody chest tube output |
| 4. Unresolving hemothorax with chest tube placement |
| 5. Large air leak with concern for airway injury |
| 6. Known esophageal, airway, or vascular injury |
| 7. FAST or CT with pericardial effusion |

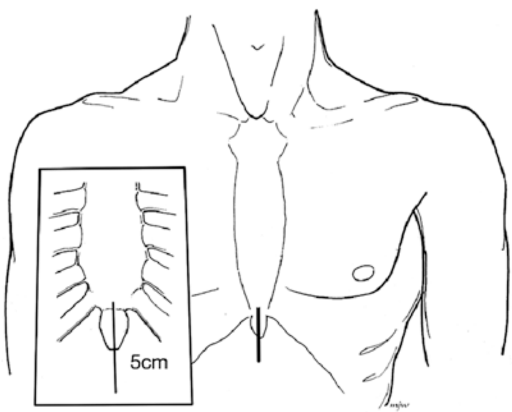


Fig. 2.2. A pericardial window incision extends from the lower sternal border to below the xiphoid process.

## *Pericardial Window*

Pericardial window is the gold standard to diagnosis hemopericardium. It is used in stable patients when pericardial FAST is indeterminate or not available. It is performed under general anesthesia with the patient supine. A 5-cm vertical midline incision is made from the lower sternal border and carried inferior to the xiphoid process (Fig. 2.2). Excising the xiphoid will improve exposure. Dissection is carried down through the fascia, and the peritoneum is left intact. The heart should be evident on palpation, and blunt dissection is undertaken through the substernal connective tissue. Hemostasis must be meticulous to avoid a false-positive result. The pericardium is grasped between clamps and sharply incised. A negative pericardial window has return of clear fluid, and the myocardium should be visible. Return of bloody fluid or no fluid return should prompt further investigation. The pericardium can be closed if desired. The fascia, subcutaneous tissues, and skin are closed.

If a laparotomy is performed and a pericardial window is indicated, the pericardium can be approached through the central tendon of the diaphragm. To perform a transdiaphragmatic pericardial window, the diaphragm is first grasped with clamps and sharply divided. The pericardium is then grasped with clamps, elevated, and divided. Inspection of the heart and pericardial fluid proceeds as in a subxiphoid window. When evaluation is complete, the diaphragm is closed in 2 layers. Thoracoscopic pericardial evaluation has also been reported in stable patients [36] but has not gained widespread use. This is likely due to the low rate of complications seen with subxiphoid pericardial window [37] and modern use of FAST in the initial cardiac evaluation.

Although pericardiocentesis is often used in the management of medical pericardial effusions, it has almost no role in trauma. In trauma, pericardiocentesis has been associated with an 80 % false-negative rate, as the pericardium is often filled with clot [38]. Unless there are extenuating circumstances, such as the inability to perform a pericardial window, pericardiocentesis should not be performed.

## *Operative Exposure*

The thoracic cavity can be approached through various incisions. Whichever one is chosen must provide adequate exposure, be performed rapidly, and be versatile. The presence of hemodynamic instability will also influence the choice of incision. Finally, the operative approach will depend if the operation is being performed for exploration or definitive organ repair.

The combination of mechanism, location of wounds, physical exam, hemodynamics, CXR, and FAST results will dictate the operative approach. Hemodynamically unstable patients require rapid access to the chest and mediastinum. Anterolateral thoracotomy and extension into the contralateral chest with a clamshell incision are rapid and afford adequate exposure. Trauma surgeons and most general surgeons are familiar with this incision. Surgeons familiar with sternotomy can perform it quickly in the unstable patients; however, in most emergent circumstances, the clamshell will be the incision of choice [39].

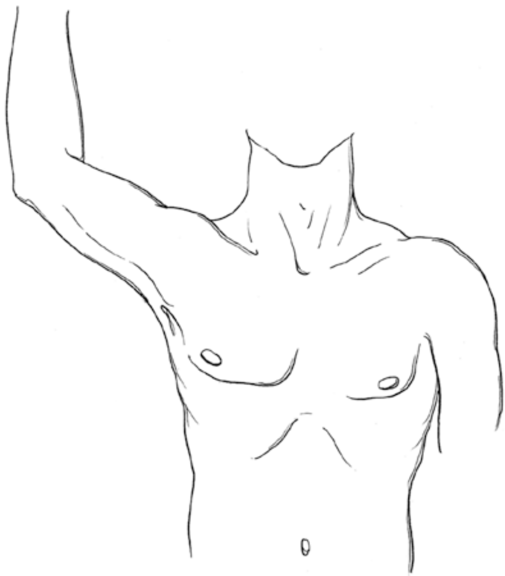

Fig. 2.3. The "hailing cab" position is used for thoracoabdominal injuries.

With trauma, more than one body cavity may be involved and require exploration, most commonly the abdomen. A sternotomy can be easily extended or, if an anterolateral approach was initially chosen, a separate abdominal incision is made. If there is concern for thoracoabdominal injury, the patient is positioned in a "hailing cab" position, exposing the anterolateral aspect of the chest and abdomen on the side of the thoracic injury (Fig. 2.3). The chest and abdomen can then be exposed by either a midline laparotomy combined with a median sternotomy or with a thoracoabdominal incision (Fig. 2.4).

When operating in an urgent, not emergent, setting, on a stable patient for a specific, well-defined injury, the choice of incision depends on preoperative imaging and optimal exposure of the injury (Table 2.2). Tracheal and right pulmonary injuries are approached using a posterolateral thoracotomy. Similarly, left-sided injuries are approached through a left posterolateral thoracotomy. Exposure of esophageal injuries depends on the location of the injury; cervical injuries are exposed through the left neck, mid-esophageal injuries through a right posterolateral thoracotomy, and distal injuries through a left posterolateral thoracotomy. A posterolateral thoracotomy is the preferred incision for

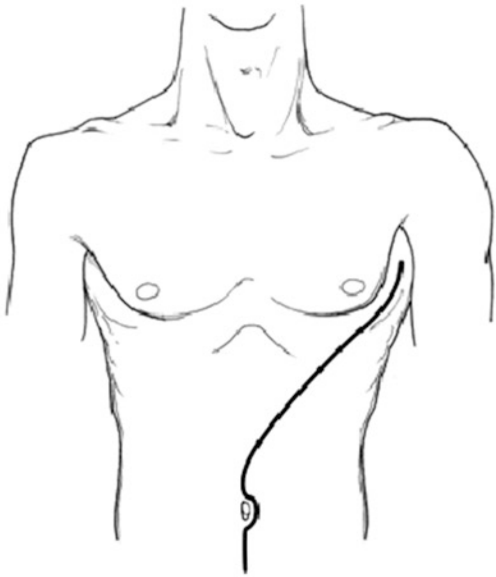

Fig. 2.4. A thoracoabdominal incision can be used for combined thoracic and abdominal injuries.

elective thoracic surgery; however, it is not suitable in unstable patients as hemodynamic decompensation may occur with lateral positioning. Also, a posterolateral thoracotomy is not a versatile incision since it cannot be extended. If additional exposure is needed, the chest must be temporarily closed, and the patient placed supine. Finally, the lateral decubitus position risks aspiration into the "good" lung that is now in the dependent position and an increased risk of atelectasis.

## *Anterolateral Thoracotomy*

The anterolateral thoracotomy is frequently used in unstable patients and is the most common incision in penetrating trauma [40]. A left anterolateral thoracotomy allows access to the lung, pulmonary hilum, and pericardium but allows limited cardiac exposure. It does not provide ideal access to the great vessels, mediastinal structures, or the entire heart. The right anterolateral thoracotomy allows access to the right lung and pulmonary hilum but has the same disadvantages as a left anterolateral thoracotomy.

Table 2.2. Choice of incision for thoracic intervention in the hemodynamically stable patient.

| Incision choice in the hemodynamically stable patient |
|---|
| Sternotomy |
| 1. Cardiac injury |
| 2. Great vessel and ascending aorta injury |
| Right posterolateral thoracotomy |
| 1. Azygos vein injury |
| 2. Tracheal injury |
| 3. Mid-esophageal injury |
| 4. Isolated pulmonary injury, hilar injury, retained hemothorax, or persistent pneumothorax |
| Left posterolateral thoracotomy |
| 1. Descending aorta injury not amenable to endovascular therapy |
| 2. Distal esophageal injury |
| 3. Isolated pulmonary injury, hilar injury, retained hemothorax, or persistent pneumothorax |
| VATS |
| 1. Evaluation for diaphragmatic injury |
| 2. Drainage of retained hemothorax |

The anterolateral thoracotomy is versatile, however, and can be extended as a clamshell incision for increased exposure. An anterolateral thoracotomy can also be extended as a trap-door thoracotomy, created by adding a sternotomy and a supraclavicular incision (Fig. 2.5). A trap-door thoracotomy can be used for access to the proximal left subclavian artery, though we and others favor using a sternotomy.

When performing an anterolateral thoracotomy, enhanced exposure is achieved by placing a 20–30° bump under the back, extending the ipsilateral arm, and carrying the incision to the axilla. The incision is placed in the inframammary fold and follows the curve of the ribs (Fig. 2.6). The subcutaneous tissue is incised, and the muscles are divided. The intercostal muscles should be incised on the superior border of the rib to avoid intercostal vessel injury. A Finochietto rib retractor is placed with the retractor handle toward the floor so as to not block the exposure. If additional exposure is necessary, the anterolateral thoracotomy can be extended to the contralateral side as a clamshell incision.

If the patient is hemodynamically unstable, severely acidotic, hypothermic, or coagulopathic, damage control thoracotomy can be performed [41]. Closure is carried out in a similar manner to abdominal

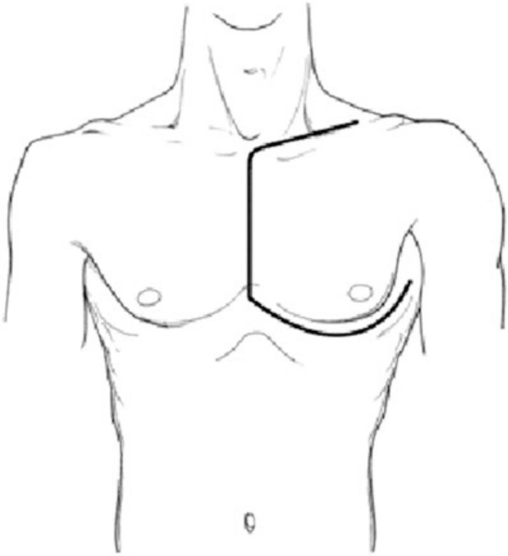

Fig. 2.5. The trap-door thoracotomy can be created for left subclavian artery access.

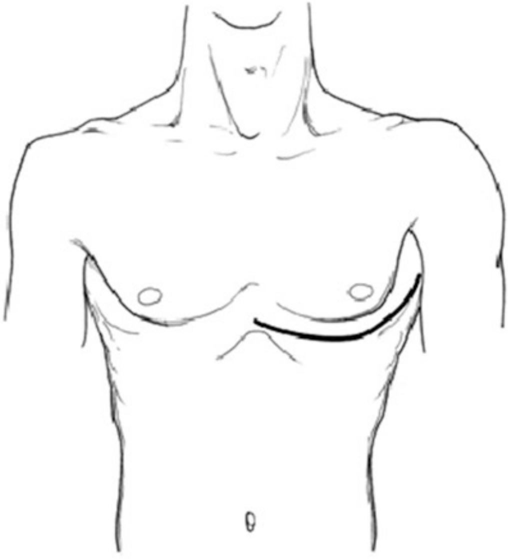

Fig. 2.6. The anterolateral thoracotomy is used for rapid access to the chest in unstable patients.

damage control closure with a negative pressure dressing but should include placement of chest tubes. With standard closure of the incision, two chest tubes are positioned at the posterior base and apex. The ribs are reapproximated with interrupted pericostal sutures with each encircling two ribs. A rib approximator can assist with closure by taking tension off the chest wall. The muscles are closed in layers incorporating the fascia. The subcutaneous tissue and skin are then closed.

## *Posterolateral Thoracotomy*

A posterolateral thoracotomy should be performed in hemodynamically stable patients for definitive repair, rather than for exploration. A double-lumen endotracheal tube provides lung isolation, thus improving exposure. A left posterolateral thoracotomy provides exposure to the pulmonary hilum, lung, distal esophagus, and descending aorta. The trachea, mid-esophagus, lung, pulmonary hilum, and azygos vein are best approached from the right. While providing excellent exposure, a posterolateral thoracotomy is not versatile. The incision is made two fingerbreadths below the scapula tip and follows the curved rib contour (Fig. 2.7). The muscles are divided as in an anterolateral thoracotomy, but muscle-sparing techniques can be used. The latissimus dorsi can be retracted posteriorly or divided for increased exposure if needed. The pleura is entered, and the Finochietto retractor is placed. Occasionally, a rib is transected to improve exposure. Chest wall closure is performed in a similar manner as that of an anterolateral thoracotomy.

## *Clamshell Thoracotomy*

The clamshell thoracotomy provides enhanced exposure and access to the pleural spaces, heart, and mediastinum. A clamshell thoracotomy can be rapidly performed, which is a significant advantage in an unstable patient. Despite its advantages for surgical exposure, a clamshell thoracotomy is a morbid incision, with more wound complications, potential for sternal overriding, and chronic pain when compared with sternotomy [42].

A clamshell thoracotomy incision is started as an anterolateral thoracotomy and extended across the midline to the contralateral thorax (Fig. 2.8). Care should be taken to extend over the midportion of the bony sternum, rather than the costal margin inferiorly. The sternum is

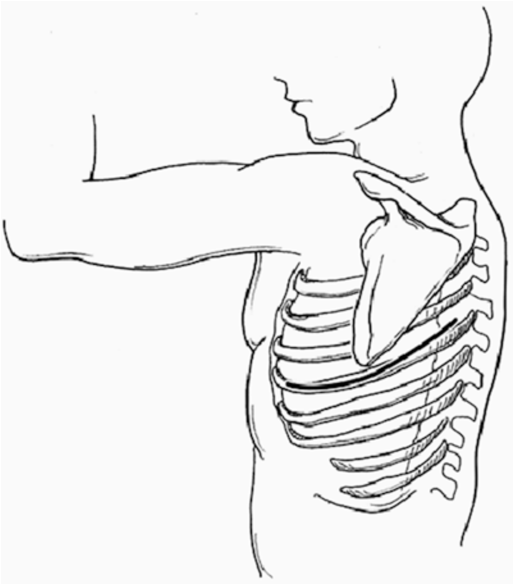

Fig. 2.7. The posterolateral thoracotomy provides excellent access to the lung, hilum, trachea, and esophagus.

divided transversely using a Lebsche knife, both internal mammary arteries are ligated, and a chest retractor is positioned. In the hypotensive patient, the internal mammary arteries may not initially bleed but will once normal blood pressure is achieved. If the incision was placed correctly, excellent exposure of the heart, great vessels, and bilateral pleural spaces will be obtained. Closure of the clamshell is performed in a similar fashion to an anterolateral thoracotomy, with sternal wires used to reapproximate the sternum.

## *Sternotomy*

Sternotomy is the incision of choice for cardiac surgery, as it provides optimal exposure of the heart and great vessels. It has an underappreciated role in thoracic trauma. It can be rapidly performed by surgeons familiar with it, is versatile, and provides outstanding mediastinal exposure. Access to the lung parenchyma is achieved by widely

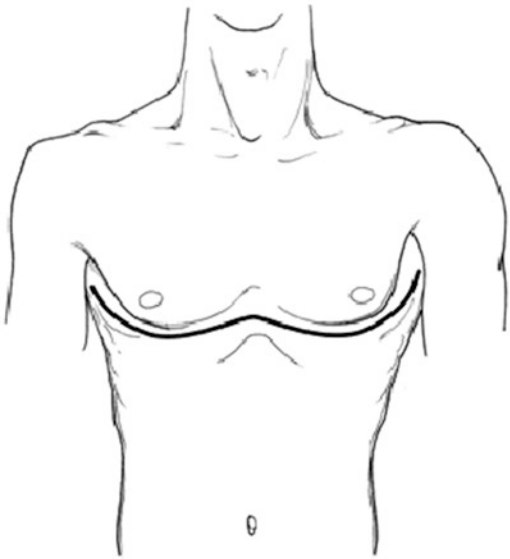

Fig. 2.8. The clamshell thoracotomy provides rapid exposure to both thoracic cavities and the mediastinum.

excising the pleura. Exposure of the subclavian or carotid vessels can be achieved by extending the sternotomy as a pericostal or neck incision (Fig. 2.9). The neck extension is performed along the anterior border of the sternocleidomastoid. The clavicular extension is performed along the superior border of the clavicle, with resection of the clavicle if needed.

To perform a sternotomy, the patient is placed supine with arms extended. A skin incision is made from the sternal notch to the xiphoid, which is excised. Blunt dissection is performed posterior the sternum, superiorly and inferiorly, ensuring a free retrosternal plane. The sternum is divided in the midline using a sternal saw, applying upward tension on the sternum to minimize injury to underlying structures. A sternal retractor is then placed. If needed, the pericardium is incised, and a pericardial sling is constructed. At closure, mediastinal drains are placed, the pericardium is generally left open, and the sternum is closed with wires. If the pleura was opened, a chest tube is placed in that hemithorax. The subcutaneous tissue and skin are closed in the usual fashion.

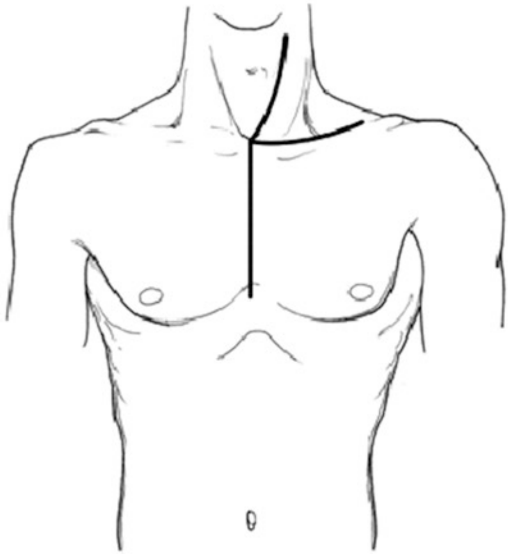

Fig. 2.9. A neck or clavicular extension can be added to the median sternotomy for increased access to the great vessels.

## Video-Assisted Thoracic Surgery (VATS)

The role of video-assisted thoracic surgery (VATS) in trauma is expanding; as more are performed the number of thoracotomies is decreasing [43]. For retained hemothoraces, the rate of utilization of VATS was 33.5 %, compared to 22.2 % for thoracotomy [44]. In trauma, VATS is generally performed as an elective procedure for a retained hemothorax. Early experience with VATS suggested the procedure be performed within 7 days of injury [45]. More recent studies report successful evacuation of retained hemothoraces beyond this time frame [14, 43, 46]. VATS has been successful in the acute post-injury setting as well [13].

VATS has been traditionally used for retained hemothorax, persistent pneumothorax or air leak, and empyema [12, 14, 47]. As technology and surgical skills have evolved, so have the possible uses of VATS. Expanded uses of VATS include: control of intercostal arterial bleeding, pulmonary resection, bronchoplasty, thoracic duct ligation, pericardial window creation, foreign body removal, evaluation and repair of diaphragmatic injury, evaluation of esophageal injury, and chest wall repair [13, 43].

Despite the broad spectrum of interventions reported with VATS, underlying thoracic pathology often influences the decision to perform a thoracotomy as opposed to a VATS [44]. At out institution, VATS is most often used in the non-acute setting for retained hemothoraces. The diaphragm is acutely evaluated using laparoscopy, which allows assessment for other intra-abdominal injuries.

VATS is performed in the full lateral position as for a posterolateral thoracotomy. Single-lung ventilation is achieved with a double-lumen endotracheal tube. Appropriately positioned ports are essential to thoroughly examine the pleural space and perform an uncomplicated procedure. Once the optimal site for the first port is chosen, the skin is incised, and dissection to the chest wall carried out in a similar fashion to chest tube placement. The tract should be superior to the rib avoiding injury to the intercostal vessels. The VATS port is then passed through the tract. The camera port is placed first, and subsequent ports are placed under direct visualization. The camera port is placed in the midaxillary line in approximately the seventh intercostal interspace. In general, the remaining two working ports are placed on the posterior axillary line adjacent to the scapular tip and on the anterior axillary line (Fig. 2.10). The working ports are placed on the potential posterolateral thoracotomy incision,

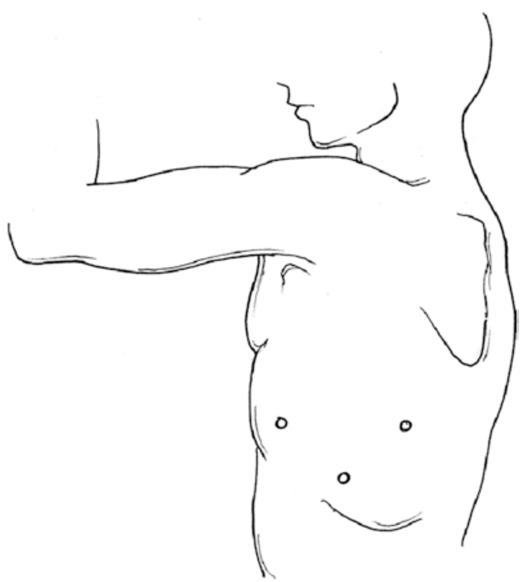

Fig. 2.10. Initial port placement for VATS in trauma utilizes three ports.

as these port incisions can be included in the incision if conversion to thoracotomy is required. At VATS completion, the port sites can be used for chest tube placement.

## Outcomes

Overwhelmingly, thoracic trauma is treated with nonoperative management, which is successful in 85 % of patients [16]. However, procedural or operative intervention is sometimes required, often for severe or complicated injuries in hemodynamically unstable patients. Intervention is more often required in penetrating as opposed to blunt trauma [34]. Multiple procedures are occasionally necessary, as some patients will fail initial chest tube management and require subsequent operative intervention for hemothorax, empyema, or air leak [14].

Overall quantification of outcomes for patients with thoracic trauma can be difficult, given the frequency of polytrauma in this population. Specifically for operative thoracic interventions, chest tubes are typically removed in 3–5 days depending on the operative approach [48] and drain output (<200 cc/day). Overall length of stay varies widely from 6 to 30 days [48–50] and is longer in patients with concurrent injuries and associated morbidities [49]. The majority of patients have a good long-term functional outcome, with 60 % of thoracotomy patients and 81 % of VATS patients returning to usual activities after 2 years [48].

Technical success of VATS likely depends on the underlying injury. Overall failure rate of VATS ranges from 3.4 to 73 % [14, 48, 50, 51]. The implications of technical failure of VATS extend beyond the need to convert to an open thoracotomy; it is also associated with empyema development [14]. Multiple factors predict a successful VATS, such as administration of antibiotics with first chest tube insertion, VATS done after 5 days [14], and smaller retained hemothorax volume [44]. Specifically for diaphragm evaluation, success with VATS has been excellent, with some reports of no missed injuries [52].

## Complications

Thoracic trauma has an overall morbidity of 25.2 %. The most common complication is atelectasis, occurring in 14.6 % of patients. The more deadly pulmonary complications are less frequent, with respiratory failure occurring in 5.5 % of patients, acute respiratory distress syndrome

(ARDS) in 3.2 %, and bronchopleural fistula in 0.3 % [34]. Empyema is a common complication in thoracic trauma [53]. Specifically for patients with retained hemothoraces, empyema develops in 26.8 % [47]. Overall mortality with thoracic trauma is high, ranging from 9.3 to 20 % [16, 34], and increases with associated injuries [34].

Morbidity varies by surgical approach and underlying pathology. Morbidity ranged from 14.6 % for thoracotomy within the first day after injury [49], to 33 % with evacuation of empyema, and to 11 % with VATS evacuation of empyema [51]. Reoperation is common, with 2.5–12 % of patients requiring reoperation [49, 50]. Similar to morbidity, mortality varied by surgical approach, with no mortality after VATS in many series [12, 13, 48, 50] versus 10.8–29 % mortality after thoracotomy [40, 49, 54]. This difference in mortality between the operative approaches is likely due to a discrepancy in underlying injury severity, with the more seriously injured, unstable patients undergoing thoracotomy. Extent of resection was also associated with mortality, with pulmonary repair having the lowest mortality, and lobectomy and pneumonectomy the highest [40, 49, 54]. Thoracic bleeding was the cause of 48–54 % mortality after thoracotomy [40], and 70 % of patients who died had an intraoperative death [49].

## Conclusion

Overall, thoracic trauma is a morbid and mortal condition. Evaluation and operative options for thoracic trauma continue to evolve, especially as our ability to identify injury burden preoperatively improves. Unstable patients should proceed emergently to the operating room for exploration. Stable patients can undergo a more detailed work-up, with identification of the injuries preoperatively, allowing for a more targeted intervention. Choice of incision depends on the injury pattern, patient hemodynamics, concurrent injuries, and surgeon preference.

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# 3. Emergency Department Thoracotomy

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## Introduction

Emergency department thoracotomy (EDT) is perhaps the most dramatic procedure performed on injured patients. Thus, there is great interest in attaining the skills necessary to perform it. It is also among the most controversial, as there are no clear indications for its use. Even if applied to the patients most likely to live, survival is far less than 50 %. It is imperative to have all equipment needed for EDT readily available in the ED. Rapid decision making and skilled performance are essential to maximize survival.

## History

Thoracotomy as a resuscitative procedure was first suggested in 1874 by Schiff as a way to perform open cardiac massage [1]. The concept of suture repair of the heart dates back to 1882 when Block performed experiments on rabbits [2]. Although initially shunned by his colleagues [3, 4], the practice continued and in 1897 Rehn reported the first successful left thoracotomy for a cardiac injury in a human [5]. Over the next 75 years, there was widespread use of EDT until 1960 when Kouwenhoven and colleagues introduced the practice of closed cardiac massage for cardiac arrest [6], essentially eliminating the need for open cardiac massage. During the next 10 years, Beall and colleagues renewed the interest in EDT with multiple publications supporting its use for patients in extremis following penetrating chest trauma [7–9].

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As interest in performing a resuscitative thoracotomy increased, so did the controversy surrounding it. On the one hand, the ability to perform a lifesaving bedside procedure must be balanced against the potential abuse and in inappropriate patient selection. However, as most hospitals do not see adequate number of patients who are candidates for EDT, the concern for adequate training for both emergency medicine and surgical residents arises. As a result, ethical issues of performing an EDT on patients that are clearly non-survivable in order to "practice" have arisen.

## Indications

Two issues need to be mentioned prior to discussing indications for EDT. The first is to define terms, specifically "signs of life" and "vital signs," which are used in the decision-making algorithm in performing an EDT. "Signs of life" (SOL) include cardiac electric activity, respiratory effort, motor effort, and pupillary response, while "vital signs" specifically include a palpable pulse, measureable blood pressure, and spontaneous respiratory activity [10].

The second is defining the goals of the procedure, which can help one apply it to the appropriate patient. Generally, the goals of an EDT are evacuation of pericardial blood, direct control of intrathoracic hemorrhage (pulmonary or cardiac origin), open cardiac massage, and temporarily cross-clamping the descending aorta to improve cerebral and cardiac blood flow while minimizing systemic hemorrhage. Other indications include vascular control for intra-abdominal hemorrhage and managing acute bronchovenous air embolism.

One of the challenges of creating an algorithm for EDT is that almost all the published reports are retrospective. Obviously, prospective randomized trials are not feasible. The Advanced Trauma Life Support (ATLS) course states that patients with penetrating thoracic injuries arriving pulseless with myocardial activity should undergo immediate EDT, while those sustaining blunt trauma are not candidate for EDT based on extremely low survival rates [11].

In 2000, Rhee and colleagues reviewed the literature on EDT from the previous 25 years [12]. The authors made three general recommendations for performing an EDT:

1. *Indications*—"patients with penetrating thoracic injuries with SOL in the field who do not respond to fluids and are losing vital signs in the resuscitation bay"

2. *Relative indications*—"patients with penetrating abdominal injury with at least one clear SOL in the field. Blunt trauma patients who lose SOL in the hospital or immediately before"
3. *Contraindications*—"patients without any SOL in the field either from penetrating or blunt trauma" [12]

In 2001, the American College of Surgeons—Committee on Trauma established guidelines for performing an EDT [13]. The committee stated that an EDT is best applied to those with penetrating cardiac injuries arriving to the hospital with SOL. Additionally, they recommend that EDT should be performed for noncardiac thoracic and ensanguining abdominal vascular injuries; however, both these patient populations have low survival rates. Furthermore, blunt trauma patients who suffer a cardiac arrest should rarely have an EDT performed due to low survivability and poor neurological outcome. Only patients who arrive to the hospital with vital signs and then have a witnessed cardiac arrest should have an EDT after blunt trauma.

In 2004 Powell and colleagues published indications for EDT based on 26 years of consecutive data [14]. The authors concluded the following: EDT is *indicated* when there is witnessed penetrating chest trauma and <15 min of prehospital cardiopulmonary resuscitation (CPR); witnessed non-penetrating chest trauma and <5 min of prehospital CPR; or witnessed blunt trauma and <5 min of prehospital CPR. EDT should also be performed for severe hypotension (systolic blood pressure <60 mmHG) due to cardiac tamponade, intrathoracic hemorrhage, air embolism, or active intra-abdominal hemorrhage. Furthermore, they concluded that *contraindications* to an EDT include penetrating trauma and >15 min of CPR and no SOL, and blunt trauma with >5 min of CPR and no SOL or asystole [14, 15]. Some authors have liberalized the times originally established by Powell et al. [10, 16]. For example, some recommendations extend the time of prehospital CPR in the blunt trauma patient to 10 min [16]. Others extend the prehospital CPR time in penetrating non-thoracic (specifically abdominal) to <15 min [10].

## Procedural Technique

EDT should be performed as part of the initial resuscitation process. It should occur at the same time as securing the airway, establishing adequate intravenous access and volume resuscitation. For patients with vital signs and/or SOL, a quick cardiac view ultrasound can evaluate for pericardial fluid (tamponade). If hemopericardium is identified, the patient's vital signs should be reevaluated. Patients with stable hemodynamics should be immediately transported to the OR prior to intubation. In the presence of cardiac tamponade, there is a substantial risk of cardiovascular collapse on induction of anesthesia. The loss of vasomotor tone in preload-dependent patients can result in cardiac arrest. It is preferable to intubate in the OR after the patient is prepped and draped. However, if the patient is marginal and/or the OR is a distance away, intubation and EDT are probably wisest.

Prior to performing an EDT, the clinician should if possible notify the operating room, anesthesia staff, and the blood bank to initiate a possible massive transfusion. Additionally, universal precautions including protective eyewear for all team members are essential. It is recommended that the emergency department/resuscitation bay has an established EDT tray that is always available with all necessary equipment (Fig. 3.1). A left anterolateral thoracotomy is the incision of choice for

Fig. 3.1. Basic components of an emergency thorocotomy tray: *Bottom left*: Lebsche knife and mallet for crossing sternum. *Bottom center*: Finochietto retractor. *Bottom right*: atraumatic vascular clamps, a Satinsky clamp on the *left*, and a DeBakey aortic occlusion clamp on the *right*. *Top center*: long-handled needle driver, tissue forceps, and Metzenbaum scissors. Not illustrated: scalpel with #10 or #20 blade and Mayo scissors.

Fig. 3.2. A *left* anterolateral thoracotomy is the incision of choice for an EDT.

an EDT (Fig. 3.2). The advantages of the incision include rapid access, ability to perform in a supine patient, and ability to be extended to the right hemithorax (clamshell) or laparotomy if clinically warranted.

The patient should be positioned supine with the left arm extended above the head (Fig. 3.3). The entire region should be prepped with antiseptic solution prior to the incision. The incision should begin to the right of the sternal border (Fig. 3.4) and progress along the fifth intercostal space toward the left axilla in a curved lined (Fig. 3.5). Beginning the incision to the right of the sternum will facilitate sternal transection and extension to a clamshell thoracotomy if needed. Anatomically, the fifth intercostal space corresponds to the inferior border of the pectoralis major and is just below the patient's nipple. In women, the inframammary fold should be the anatomical landmark. The breast may need to be retracted superiorly in order to allow better access to the proper landmarks. A curvilinear incision is made following the course of the rib, rather than transversely. In general, once at the level of the nipple, begin to curve toward the left axilla and follow the rib cage (Fig. 3.6).

The skin, subcutaneous tissue, and chest wall muscle are rapidly divided. Intercostal muscles can then be cut with a scalpel or curved

Fig. 3.3. Patient should in a supine position with *left* arm above head.

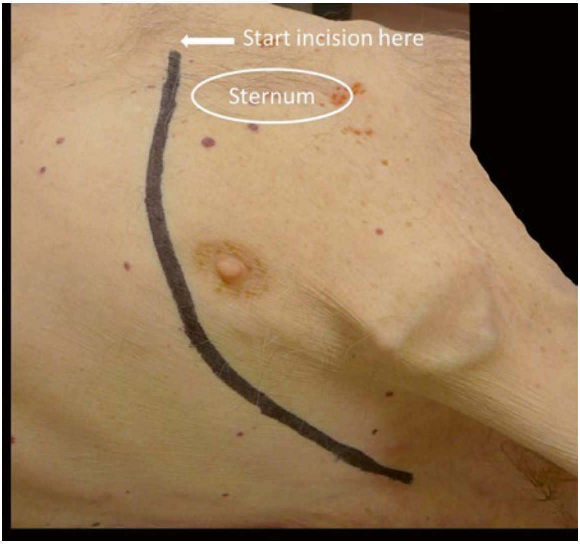


Fig. 3.4. Begin incision to the *right* of the sternum.

Fig. 3.5. Incision along the fifth intercostal rib space toward the *left* axilla in a curved lined.


Fig. 3.6. Begin curving incision at the level of the nipple.

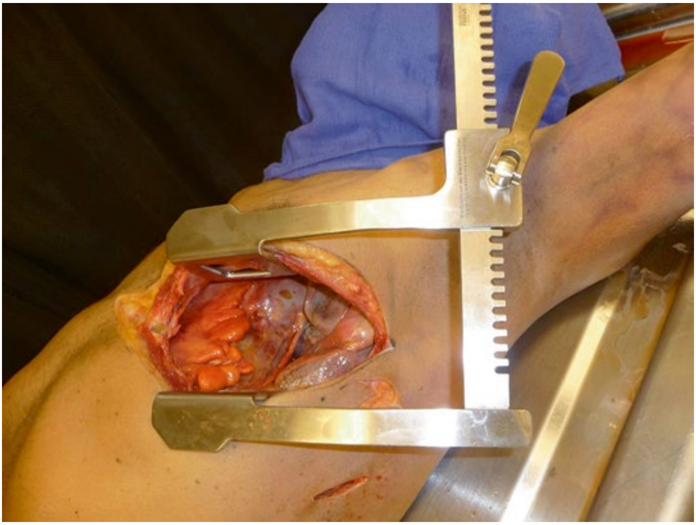

Fig. 3.7. Retractor with handle down (away from midline).

scissors. One should try to incise the intercostal muscle on the superior side of the rib in order to avoid injuring the intercostal neurovascular bundle. Although the procedure should be rapidly performed, one must be careful and avoid injuring the heart or lungs. Once the chest cavity has been entered, a Finochietto retractor is placed, with the handle toward the axilla (Fig. 3.7), and the ribs are spread. To facilitate exploring the mediastinum and right chest, the incision can be extended as a clamshell. This is accomplished by dividing the sternum transversely using a Lebsche knife (Fig. 3.8) and extending the incision as a right anterolateral thoracotomy (Fig. 3.9). If the sternum is divided and perfusion is restored, the internal mammary arteries will need to be ligated.

## *Pericardiotomy*

The pericardium should routinely be opened following traumatic arrest. It is the belief of this author that cardiac tamponade cannot be ruled out visually, and wide incision of the pericardium is required. If the pericardial sac is not tense, one may pick up the pericardium with toothed forceps and make an incision from the apex to the aortic root.

Fig. 3.8. Lebsche knife to extend into *right* hemithorax.

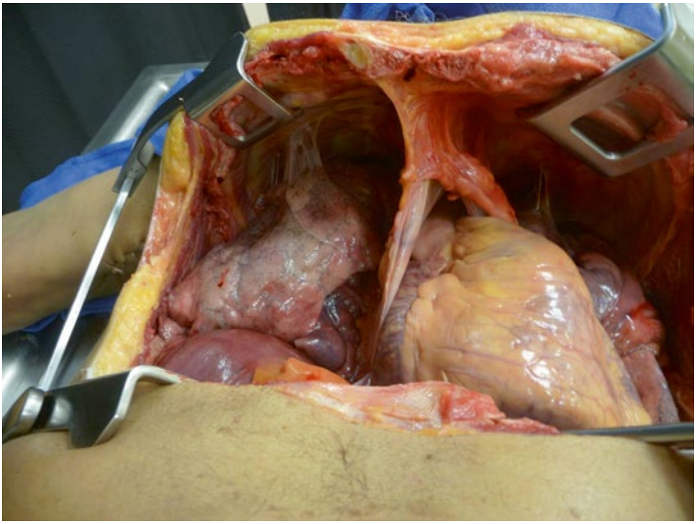

Fig. 3.9. Clamshell thoracotomy.

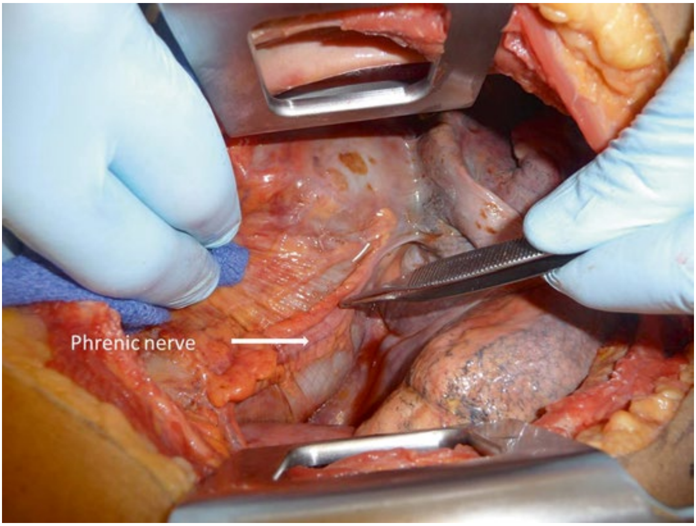


Fig. 3.10. Pericardiotomy should be medial to phrenic nerve.

The incision should be parallel and anterior to the phrenic nerve (Fig. 3.10). If the pericardial sac is filled with blood, a knife may be needed to make the initial incision, and then the pericardium incised as described previously. Once the pericardium is widely opened, the heart should be delivered, and all blood clots are removed allowing full inspection of the myocardium. Any bleeding should initially be controlled with digital pressure while preparing for a more definitive repair. Any injury should be rapidly repaired by using either temporary sutures or staples. Although once thought to be a valuable tool, the use of a Foley catheter as a temporizing measure for cardiac injuries may actually worsen the injury, and the practice should be avoided. Other options for repair include using sequentially stacked intestinal Allis clamps, similar to what has been described for retroperitoneal venous injury [17]. Atrial and great vessel injuries may be controlled with a partial occlusion (side-biting) vascular clamp. One should be careful when suturing the ventricle not to include any of the coronary vessels in the repair causing ischemia (see Chap. 10).

## *Aortic Cross-Clamping*

Aortic cross-clamping is often described as a simple procedure, but in reality accessing the aorta is sometimes challenging. This is particularly true in the hypovolemic, hypotensive patient in whom the aorta is collapsed. The aorta, which lies anterior to the vertebrae, is best exposed by retracting the lung anteriorly and superiorly. At this point the inferior pulmonary ligament can be taken down for better exposure, although this step may not be necessary and may pose unnecessary risk of injury to the inferior pulmonary veins [15]. Ideally one should dissect under direct vision; however, this is often not possible. When one cannot directly incise the mediastinal pleura and bluntly separate the aorta and esophagus, blinded blunt dissection with one's thumb and fingertips can be used. Once the aorta is separated from the esophagus, the clinician's left hand encircles the aorta, and a clamp is placed with the right hand (Fig. 3.11). Placing a nasogastric tube may help differentiate the aorta from the esophagus and facilitate proper clamp placement. If isolating the aorta still remains a challenge, then simply providing digital pressure against the spine can be performed as a temporizing measure.

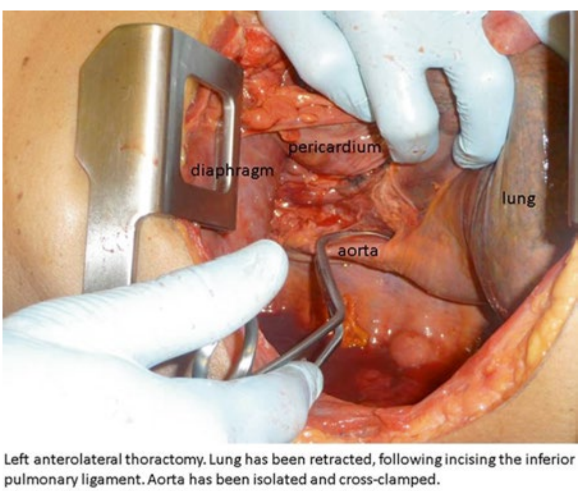


Fig. 3.11. Cross-clamping the aorta.

The rationale of aortic cross-clamping is to increase blood flow to the brain and coronary arteries. However, total aortic occlusion can have significant detrimental effects as well. Distal ischemia can exacerbate tissue acidosis and oxygen debt, both of which may affect multiple organ failure [15, 18]. The safe duration of aortic cross-clamping remains unknown. Extrapolating data from traumatic aortic injuries, more 30 min of cross-clamp time increases complication rates significantly [19, 20]. Additionally, when the cross-clamp is removed, rapid reperfusion of the previously ischemic tissue occurs with resultant worsening acidosis. This "de-clamp shock" can cause hemodynamic instability and even cardiac arrest [15, 21, 22].

Although taught as a vital component of the EDT, cross-clamping of the aorta is not routinely performed at this author's institution. Even though increased cardiac and brain perfusion is desired, placing an aortic cross-clamp significantly increases the afterload on an already failing heart. It is hard to understand how this added strain can help overall cardiac function and perfusion. Additionally, when the aorta is crossed-clamped, aggressive volume resuscitation can lead to further cardiac failure due to acute ventricular dilatation.

## *Cardiac Massage*

When cardiac arrest has occurred, bimanual internal cardiac massage should begin immediately (Fig. 3.12). The bimanual technique is preferred to a one-hand technique (Fig. 3.13) because it is not only more effective but also has less potential for causing damage to the heart [10, 15]. A "hinged clapping" motion from the palms to the fingertips compressing the heart from the apex to the aortic root is preferred [10, 15].

## *Controlling Noncardiac Hemorrhage*

Injuries to the great vessels, lung parenchyma, or central pulmonary vessels are other potential causes of massive hemorrhage. Great vessel injuries are typically lethal; however, if patients arrive to the ED in a timely manner and an EDT is performed quickly, these injuries are best initially managed with digital pressure, while resuscitation continues and the patient is transported to the OR. Adequate repair of a mediastinal great vessel is very difficult in the emergency department/resuscitation bay and is best achieved in the operating room.

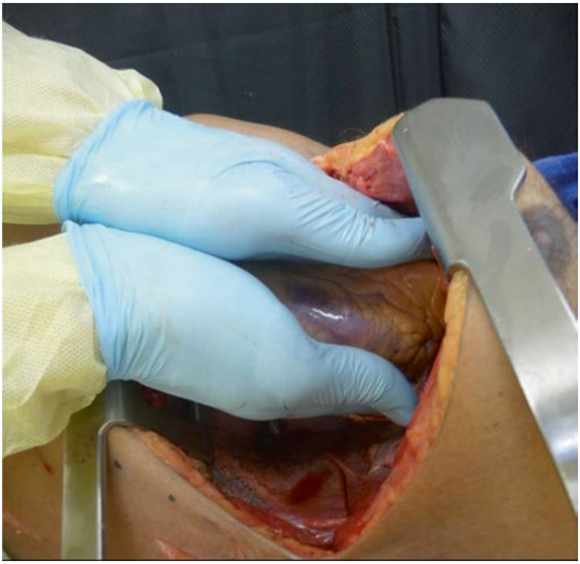

Fig. 3.12. Two-hand internal cardiac massage.

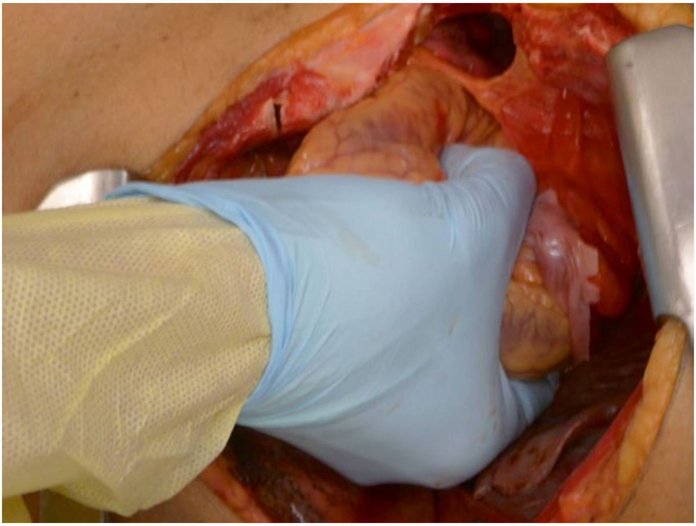

Fig. 3.13. One-hand internal cardiac massage.

Lung parenchyma injuries are usually managed with tube thoracostomy alone, and an EDT is typically not needed. In cases of massive pulmonary parenchymal bleeding, simply applying a vascular clamp proximal to the source of bleeding should be sufficient. More extensive dissection and definitive hemorrhage control should be performed in the OR. In contrast to parenchymal injuries, pulmonary hilar injuries often present with massive hemorrhage requiring rapid control. Options for hemorrhage control include digital pressure, placing a vascular clamp over the hilum, or twisting the lung on its hilum.

### *Evacuate Bronchovenous Air Embolism*

Although not thought as one of the traditional indications, patients who have been diagnosed with acute bronchovenous air embolism may benefit from an EDT. It occurs when either the bronchial tree or lung parenchyma and blood vessels are injured in continuity. Clinically, patients with a chest injury will decompensate after intubation and initiation of positive pressure ventilation. When an EDT is performed in this situation, the hilum of the affected lung should be clamped. This may necessitate a clamshell thoracotomy or a right-sided thoracotomy if the right lung is the suspected source. Once the hilum is controlled, cardiac massage can help propagate the air through the coronary vessels. This can be followed by needle aspiration of the left ventricle and possibly the aortic root [10, 15].

## Outcomes

Much of the debate over the utility of the EDT centers on the patient selection and outcome of the procedure. Simply measuring "survival" may not be the best endpoint. Survival with significant neurologic deficit should not be considered a success. Outcomes reported in the literature vary widely but in general are associated with mechanism of injury, pattern of injury, and the presence of SOL. Very simply, an isolated stab wound has better survival than multiple stab wounds. Stab wounds tend to have better outcomes than gunshot wounds, and blunt injuries typically have the lowest survival.

A 2000 review by Rhee and colleagues looked at 25 years of EDT and survival rates [12]. It remains the most comprehensive and referenced literature when discussing survival after EDT. The authors only included thoracotomies performed in the ED or resuscitation bay and excluded those performed in the OR. More than 4,600 patients were included in the study. The overall survival following EDT was 7.4 %, ranging from 1.8 to 27.5 %. When survival was analyzed by mechanism of injury, penetrating injuries had a rate of 8.8 % while blunt trauma just 1.4 %. When stratifying penetrating injuries, the authors showed survival rate for stab wounds was 16.8 % and while that for gunshot wounds was 4.3 %. When analyzed from the perspective of the major site of injury, "cardiac" had the highest the survival rate, 19.4 %, as compared to noncardiac thoracic, abdominal, or multiple sites of injury (10.7 %, 4.5 %, 0.7 %, respectively). Those with SOL in the hospital had an almost fivefold increase in survival rates as compared to those with no SOL on arrival (11.5 % vs. 2.6 %). Those with SOL during transport had a sevenfold increased rate of survival than those with no SOL in the field (8.9 % vs. 1.2 %). Finally, 92.4 % of patients discharged from the hospital were reported to have normal neurological outcome.

In 2001, The American College of Surgeons—Committee of Trauma published a practice management guideline on EDT [13]. They analyzed 42 studies for outcome following EDT. These studies included all but one of the studies in Rhee and colleagues 2000 review. The results were essentially identical. Overall survival following EDT was 7.83 % [13] (7.4 % Rhee [12]). Following penetrating injury the survival rate was 11.16 % [13] (8.8 % Rhee [12]), while that for blunt was 1.6 % [13] (1.4 % Rhee [12]).

## Complications

As is with any surgical or invasive procedure, there exist numerous potential inherent complications to performing an EDT. First and foremost, injury to a member of the care provider team is possible. That is why universal precautions including protective gown, mask, and eyewear are imperative for all team members. If there is any question regarding possible needle stick, body fluid exposure, or any break in skin barrier, the hospital's infection control or "STIK" hotline (may vary from one hospital to another) should be contacted immediately.

Technically, there is potential for damage to other structures while performing an EDT including the ribs, intercostal vessels, lacerating the lung parenchyma, phrenic nerve, and even the heart including the coronary arteries. If a clamshell thoracotomy is performed, one must remember to ligate the internal mammary arteries if circulation/perfusion is restored. Post-procedural complications include infection, bleeding, and postpericardiotomy syndrome.

## Conclusion

The emergency department thoracotomy remains an important procedure, and when rapidly performed in the appropriate patient population, it saves lives. A number of EDT guidelines for indications exist helping the clinician to decide when to or not to do an EDT. Patients with a stab wound to the heart have the highest rates of survival, while those with blunt trauma have the lowest. But as with any surgical procedure, complications are possible and need to be recognized and managed appropriately.

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# 4. Indications and Techniques for Trauma Laparotomy

*Paulesh K. Shah, M.D.*

## History of Care

Prior to World War I, penetrating abdominal trauma was managed nonoperatively, with accompanying high mortality rates. Toward the end of World War I and afterwards, a policy of routine abdominal exploration for penetrating trauma was adopted. Mortality decreased over the following decades with earlier operative intervention, faster transport times, better understanding of fluid resuscitation, use of blood transfusion, and the advent of antibiotics. The concept of selective nonoperative management of penetrating abdominal trauma was revisited in the 1960s and later. Several investigators observed that many patients who sustained abdominal stab wounds ultimately were diagnosed with no significant injury at laparotomy [1–4]. These findings were later extended to gunshot wounds as well, although the incidence of intra-abdominal injury requiring surgical repair is higher with gunshot wounds than with stab wounds [5–7]. As advanced imaging including ultrasonography and CT scanning was integrated into the trauma workup, management algorithms incorporating these diagnostic techniques began to be developed. However, through all of this, a few principles remained constant. The physical examination remains a necessary component of the trauma workup. The presence of peritonitis on physical examination or the presence of hemodynamic instability referable to intra-abdominal bleeding almost always mandates operative exploration.

Within the last 20 years, it has been appreciated that, for the most severely injured patients, correction of the physiologic derangements

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associated with trauma is more important than definitive anatomic reconstruction, especially in the setting of profound hemorrhagic shock complicated by hypothermia, acidosis, and coagulopathy. This realization gave rise to the concept of trauma damage control, which employs a staged approach to treating injuries [8]. Damage control begins with limited surgery to address sources of major hemorrhage and GI contamination, followed by rewarming, resuscitation, and correction of metabolic abnormalities in the ICU, and subsequent definitive operative management when the patient is not as physiologically compromised and in better shape to tolerate surgery. While these principles have changed the care of the most critically injured patients, and have been extended to other settings besides trauma, they are also associated with their own set of challenges and complications.

# Techniques

## *Preoperative Evaluation*

The critical points to be addressed during the evaluation of an injured patient include presence of abdominal injuries and whether those injuries require operative management. The mainstay of the evaluation is physical examination. The presence of peritonitis in the setting of blunt or penetrating trauma is an indication for operative exploration. Likewise, hemodynamic instability, in the absence of another explanation for it, is generally an indication for laparotomy. Adjuncts to the physical exam, such as chest and pelvis X-rays and FAST, can be very helpful to narrow down the potential location of bleeding, particularly in blunt trauma, and can guide operative decisions. In general, hemodynamic instability and a positive FAST is an indication for laparotomy. For the hemodynamically stable penetrating trauma patient, CT scan may be a helpful adjunct to physical exam, particularly for selected gunshot wounds or back/flank stab wounds [9, 10]. For blunt trauma patients, CT scan is often performed. While CT scan is very good at accurately characterizing solid organ injuries, and guiding decisions for observation versus angiographic and/or operative intervention [11, 12], it is notably less helpful with respect to hollow viscus injuries. The most frequent finding with hollow viscus injuries is unexplained free fluid, but this is quite nonspecific [13, 14]. If this is found, then further observation, examination, lab studies, and/or imaging may be warranted. Of course, physical examination may be limited by intoxication, severe head injury, and/or need for intubation and sedation. The decision on whether or not to operate must take into account the ability of the physician to obtain accurate serial abdominal exams.

## *Operative Techniques*

The optimum operative care of the critically injured patient begins prior to incision. The surgeon must utilize all information gleaned in the workup in order to anticipate the suspected injuries, establish operative priorities and contingency plans, and guide the intraoperative resuscitative effort. Communication between the operative team and the anesthesia team is critical. The patient should generally be positioned supine, unless there is a plan to perform sigmoidoscopy or other procedure requiring perineal or perianal access in which case lithotomy may be chosen. Generally, prep should extend from nipples to mid-thigh, extending higher if thoracoabdominal injury is suspected, and from table to table laterally (Fig. 4.1). Preventing hypothermia with forced air blankets and by keeping the room warm is important as well.

## *Exploring the Abdomen*

The abdomen is explored almost always via a midline laparotomy incision (Fig. 4.2). This provides adequate exposure to most of the abdomen and may easily be extended if necessary. The incision should be long enough to provide the exposure required without struggling, but does not necessarily have to involve the entire length of the abdomen. In fact there are several circumstances where excessive inferior extension of the incision may ultimately prove troublesome. For example, if the abdomen is to be left open at the end of the case, as in a damage control procedure (more on that later), it may be difficult to secure the vacuum dressing if the incision terminates very low. Also, a midline incision that extends very low may interfere with placement of a low transverse incision for preperitoneal pelvic packing, if that is being considered in the setting of pelvic fracture bleeding. Finally, if a pelvic vascular injury is suspected, usually by absence of one femoral pulse, leaving a soft tissue envelope for a femoral-femoral bypass is wise.

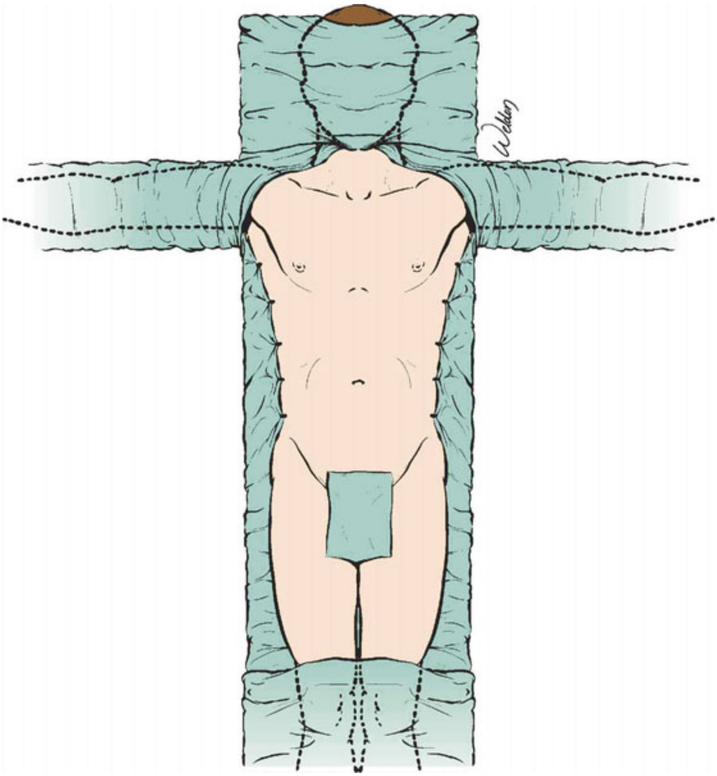

Fig. 4.1. Positioning and prep area for standard trauma laparotomy (from Hirshberg A. Trauma Laparotomy: Principles and Techniques, in Mattox KL, Moore EE, Feliciano DV eds. Trauma, 7th edition, McGraw-Hill 2013).

Once the abdomen is entered, the immediate priority is rapid temporary hemostasis. The hemoperitoneum is evacuated quickly (having two suctions set up is handy), the small bowel is eviscerated, and the abdomen is packed in all four quadrants. Packing may also be guided by imaging results if available. I spend a few seconds and divide the falciform ligament routinely to facilitate exploring and if necessary packing the right upper quadrant. Effective packing relies on mechanical compression of bleeding sources; merely placing sponges on top of blood is insufficient (Fig. 4.3). Packs should utilize the abdominal wall to provide the necessary compression. Manual compression or clamping of a vessel may also be necessary, such as with a large liver laceration or shattered spleen.

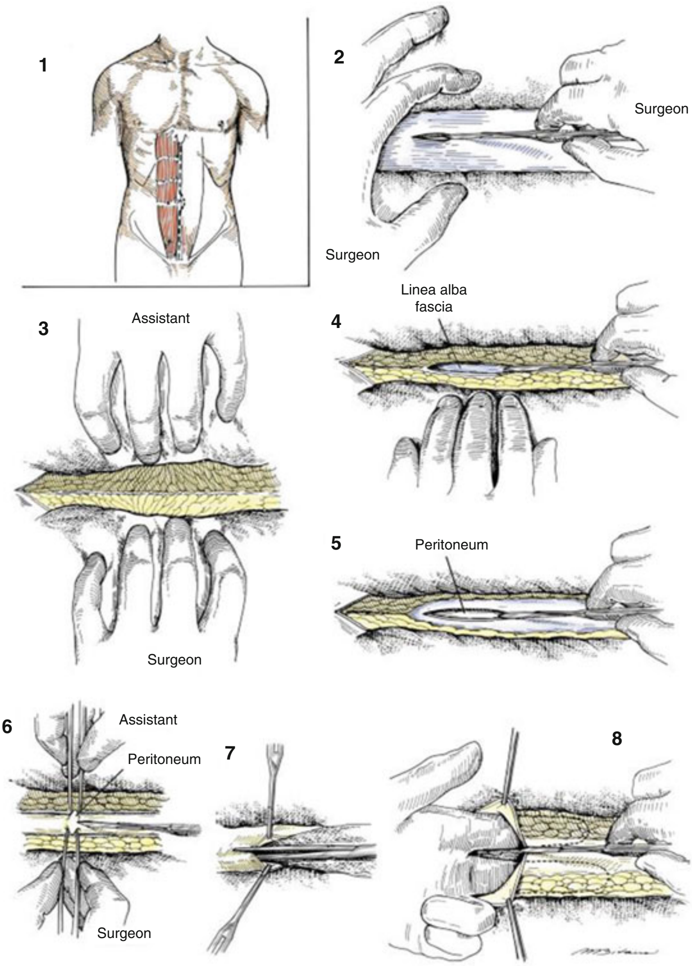


Fig. 4.2. Technique for midline laparotomy (from Zollinger RM, Ellison EC. Zollinger's Atlas of Surgical Operations, 9th edition, McGraw-Hill 2011).

Once temporary hemostasis has been achieved, allow some time for the anesthesia team to catch up on volume resuscitation, replacement of blood, and correction of coagulopathy and metabolic derangements.

Systematically exploring the abdomen is necessary to avoid missing injury. The most common method is used to explore the area of least suspicion first, working ones way back to the area where injury is most

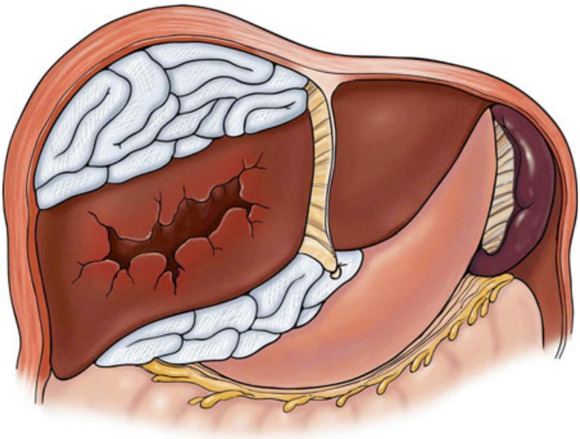

Fig. 4.3. Technique of liver packing (from Mattox KL, Moore EE, Feliciano DV eds. Trauma, 7th edition, McGraw-Hill 2013).

likely to be found. This is certainly a reasonable way to proceed, but not the only way. However, it is vitally important to utilize the same method every time. This avoids forgetting to do a thorough exploration and potentially missing an injury.

Hemorrhage from the abdomen and/or retroperitoneum comes from one of four sources, the liver, the spleen, the mesentery, or the retroperitoneal vasculature. Rapid exploration of the liver or spleen with the hand should identify major injury. The mesentery can be fanned out quickly to allow visual inspection. Finally, with the small bowel lifted up cephalad, the surgeon can get a good look at all zones of the retroperitoneum.

The injured liver and spleen must be completely mobilized in order to fully explore them and to make further decision about further operative therapy. The spleen is mobilized by releasing all of the lateral ligament attachments. The spleen should be mobilized up onto the anterior abdominal wall to allow full visualization and operative therapy. The liver must be mobilized by completely taking the falciform ligament down to the vena cava. The triangular ligaments must be completely divided as well. This allows for mobilization of the right lobe onto the anterior abdominal wall, similarly to the spleen. The liver is then suspended only on its vasculature.

The mesentery of the small bowel should be carefully inspected for injury. Similarly, the mesentery of the right colon, transverse colon, and the left colon should be examined. Major hemorrhage from any of these sources should be controlled before further exploration is undertaken.

The aorta can also be approached by incising the lesser omentum and entering the lesser sac. The left lobe of the liver can be mobilized to give better visualization. The esophagus is mobilized providing access to the aorta. We still believe it is prudent to completely encircle the aorta prior to applying the clamp. It is often necessary to divide the lower diaphragmatic crura using this approach too. More recently, the aorta may be controlled with a transfemoral balloon. The REBOA is described elsewhere in detail, but is an internal cross clamp which can be very helpful.

The next priority is temporary control of ongoing contamination from hollow viscus injury. The entire GI tract should be quickly and thoroughly inspected, with particular attention paid to those areas at highest risk of injury, for example, based on evaluation of the trajectory of a penetrating injury. Injuries should be controlled with atraumatic clamps, such as Babcock's, rather than being definitively repaired at this time. Care should be taken to completely evaluate for through-and-through injuries by appropriate mobilization and exploration, e.g., opening the lesser sac and evaluating the posterior wall of the stomach when there is an anterior penetrating wound.

Once bleeding and contamination have at least been temporarily controlled, the abdomen and retroperitoneum can be assessed for contained injuries, such as hematomas, and decisions made about exploring or observing those injuries. This is also the time at which a decision needs to be made about whether the current operation is to be the definitive one or whether the abdomen is to be managed via a damage control approach. If the patient does not have serous metabolic derangements, definitive repair is the best. Repair and/or resection of bleeding solid organs proceed as appropriate, followed by repair and/or resection of the hollow viscus injuries. Once all identified injuries have been definitively managed and hemostasis is satisfactory, the abdomen is irrigated and the fascia is closed if there is no significant tension. If there is significant bowel edema precluding fascial closure without undue tension and concern for abdominal compartment syndrome, then the abdomen may be left open and managed with a negative pressure wound dressing.

## *Exploring the Retroperitoneum*

The retroperitoneum is generally divided into three zones (Fig. 4.4). Zone 1 is the central portion. Zone 2 is the perinephric spaces and Zone 3 is the pelvis. Conventional teaching is that all Zone 1 hematomas must be surgically explored to evaluate the central vasculature. Zone 2 hematomas are explored for penetrating trauma, but are observed for blunt trauma unless there is pulsatile hemorrhage or they are rapidly expanding. Another indication for exploring a Zone 2 hematoma would be proven injury within the kidney or ureter requiring surgical therapy.

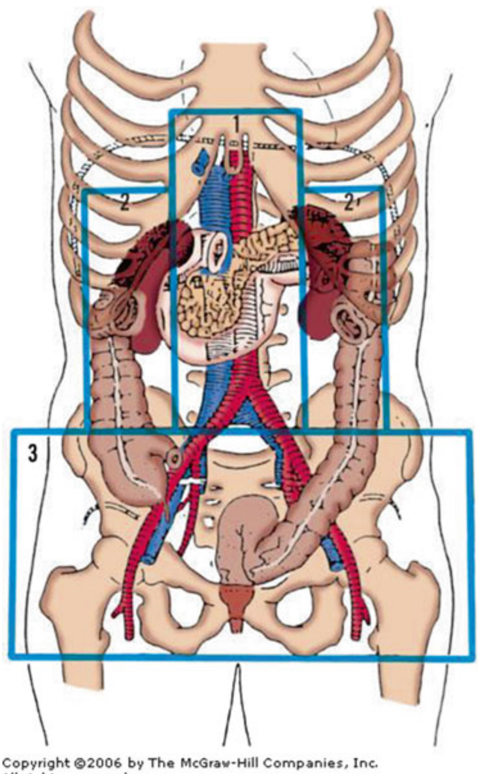


Fig. 4.4. Vascular zones of the retroperitoneum (from Skandalakis JE ed. Surgical Anatomy: The Embryologic and Anatomic Basis of Modern Surgery, McGraw-Hill 2004).

Zone 3 hematomas are generally explored for penetrating injury but observed in blunt trauma.

This conventional dogma however has more recently been questioned. The average general surgeon spends little time in the retroperitoneum, thus may not be experienced with exploration in Zone 1. If there is significant suspicion of injury, calling a more senior colleague may be prudent. For small hematomas, further exploration with a combination of CT and/or angiography may be preferable to surgical exploration.

Preoperative imaging is now fairly common in stable patients, even those with penetrating trauma. Thus, patients who have had preoperative imaging and who either have no injury or minor injury in Zone 2, likely do not require full exploration. Finally, extraperitoneal pelvic packing is now used relatively commonly to obtain hemostasis following pelvic fractures. Thus, the dictum of never opening a pelvic hematoma after blunt trauma no longer holds true.

Full exploration of the retroperitoneum is generally accomplished with a medial visceral rotation. This is done similarly whether on the right side, termed the Cattell-Braasch maneuver, or on the left side, often called the Mattox maneuver. Regardless of the side mobilized, it is wise to fully divide the white line of Toldt. In order to be complete, the mobilization should be brought around either the splenic or hepatic flexure onto the transverse colon. If the colon is grasped in one hand, and pressure put at the base of the mesentery with a lap pad, the colon can be rapidly mobilized. This gives wonderful exposure to the vena cava on the right side, as well as all of its branch vessels. On the left side, the aorta will be encountered at the base of the mesentery. All branch vessels of the aorta come out either at 12:00 or 3:00. The plane between them is open; thus, dissection can come up the aorta relatively rapidly.

On the right side, fully mobilizing the duodenum using a Kocher maneuver gives visualization of the vena cava up to the level of the retrohepatic vena cava. The duodenum should be completely mobilized up off of the cava. Superiorly, the dissection should go to the level of the porta. The second and third portion of the duodenum should be completely mobilized (Fig. 4.5). This gives access to the vasculature, particularly the kidney on the right side.

A full left-sided medial visceral rotation often involves mobilizing the kidney. Our preference is to virtually always leave the kidney in situ, believing that full mobilization of the kidney is only necessary if there is high suspicion of injury to the kidney requiring surgical therapy (Fig. 4.6). The spleen and tail of the pancreas can be mobilized, giving access to the aorta at the level of the diaphragm.

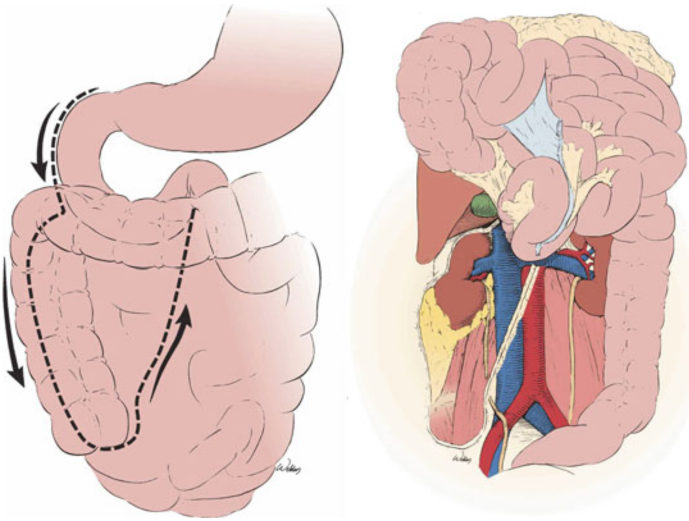

Fig. 4.5. Right medial visceral rotation for wide retroperitoneal exposure (from Hirshberg A. Trauma Laparotomy: Principles and Techniques, in Mattox KL, Moore EE, Feliciano DV eds. Trauma, 7th edition, McGraw-Hill 2013).

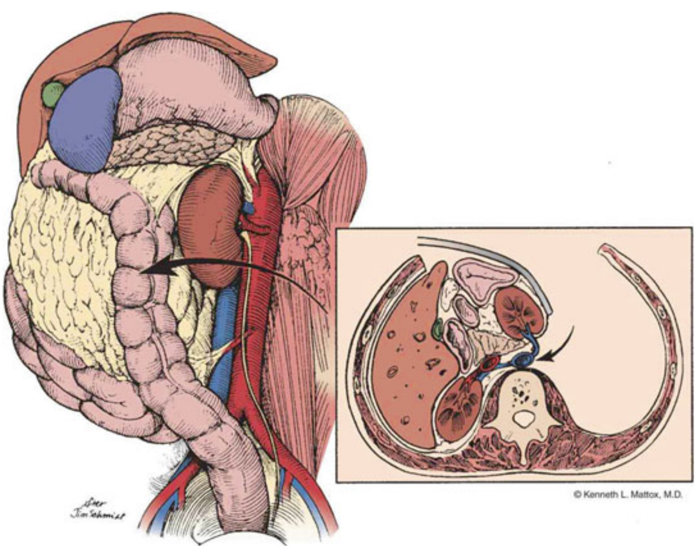


Fig. 4.6. Left medial visceral rotation for exposure of the aorta, especially the suprarenal segment. In the modified version, the kidney is left in place (from Hirshberg A. Trauma Laparotomy: Principles and Techniques, in Mattox KL, Moore EE, Feliciano DV eds. Trauma, 7th edition, McGraw-Hill 2013).

When a central retroperitoneal hematoma is encountered, one question is whether a right- or left-sided approach is the best option. In those cases, we generally utilize a right-sided approach. The small bowel mesentery can be mobilized up off of the aorta, giving access to the infrarenal aorta and vena cava. Visualization from the left side may not be ideal, particularly in the pelvis, as the mesentery of the sigmoid colon will be in the way.

Exposure of the superior mesenteric artery and celiac axis can be problematic. In fact, there is no good way to expose the very proximal portion of either of those blood vessels. Widely opening the lesser sac by dividing the gastrocolic omentum gives access to the body of the pancreas. The superior mesenteric artery is often best exposed through a combination of a left-sided medial visceral rotation and opening the lesser sac (Fig. 4.7). Widely opening the lesser omentum, combined with a left-sided medial visceral rotation, often gives the best access to the proximal celiac axis (Fig. 4.8).

Absolute inflow control for abdominal or retroperitoneal injury can be obtained by controlling the aorta at the level of the diaphragm. An aorta occluder or sponge stick may provide temporary control until more definitive steps are taken. Several approaches exist to control the aorta at the diaphragm. The most common is a full left-sided medial visceral rotation. The spleen and tail of the pancreas must be mobilized. The esophagus can be differentiated from a flaccid aorta if a nasogastric tube is placed. The lower diaphragmatic crura generally have to be divided to get access to the supraceliac aorta. The aorta must be fully mobilized dividing the posterior retroperitoneal tissues. We encircle it from the patient's left side using the index finger of the left hand. The posterior attachments are bluntly dissected and the aorta completely encircled prior to placing the clamp. Blindly placing a clamp without full mobilization usually results in the clamp falling off.

## Damage Control

Damage control is a philosophy where operative therapy is staged, with emphasis on control of major physiologic insults early and definitive anatomic reconstruction at a later time when the patient has been stabilized. This came out of experience in the late 1980s and early 1990s. Penetrating trauma with high-velocity weapons became much more common in the United States that patients did not tolerate prolonged operative therapy, particularly when they presented with hypotension. Damage

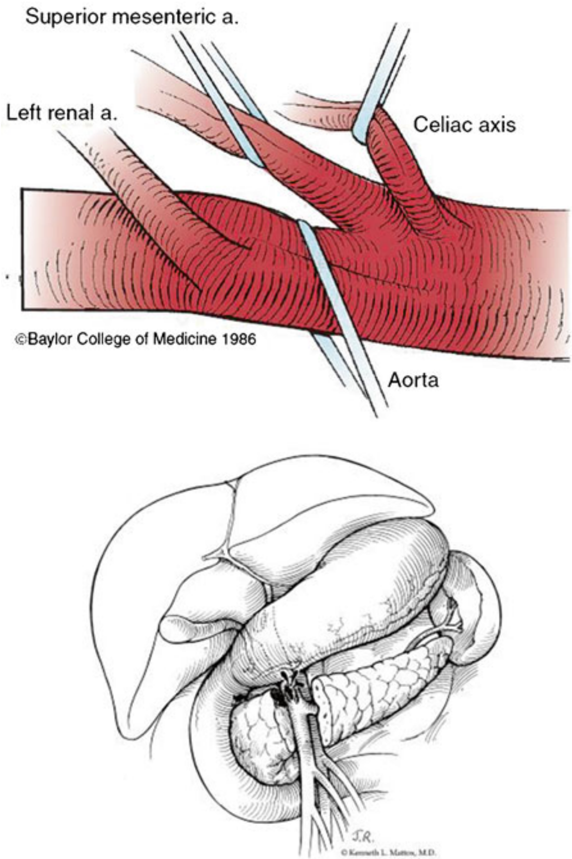


Fig. 4.7. Exposure of celiac axis and superior mesenteric artery via left-sided medial visceral rotation (*top*) and via entry to the lesser sac (*bottom*). Note that exposure of proximal portal venous injuries may be facilitated by dividing the pancreas (*top* from Dente CJ, Feliciano DV, in Mattox KL, Moore EE, Feliciano DV eds. Trauma, 7th edition, McGraw-Hill 2013; *bottom* from Mattox KL, Hirshberg A in Vascular Trauma, 2nd edition, Elsevier 2004).

control allows for control of immediately life-threatening injuries only on the night of admission. Injuries not requiring immediate therapy, such as gastrointestinal injuries, are temporarily controlled. Definitive care is deferred until the patient is physiologically more stable.

Damage control should be used early in appropriate patients. If one waits until the patient has developed the lethal triad of coagulopathy, acidosis, and hypothermia, patients are likely to die, regardless of therapy selected. Thus, early use of damage control is wise. However, one must control all means of bleeding. Packing major vascular injuries is doomed to failure. The judgment as to when to "bail out" often requires senior consultation. Junior surgeons should ask for consultative help early on.

The principles of damage control laparotomy include first control of major sources of hemorrhage. In such patients, no thoughts should be given to organ preservation. Injured spleens and even kidneys should be resected, not repaired. Major vascular injuries must of course be controlled. Complex repair should be deferred. Intraluminal shunting can be a very valuable technique to preserve distal perfusion. Any conduit suffices. It need only be a good size match to the vessel. The aorta can be shunted with a chest tube. The superior mesenteric artery can be shunted with IV tubing. As patients are often coagulopathic, no anticoagulation is necessary to preserve flow. Virtually all veins in the abdomen or retroperitoneum can be ligated. While ligation of the superior mesentery vein can be done, these patients virtually all develop serious mesenteric venous hypertension and intestinal ischemia. Thus, we prefer to shunt the SMV, rather than ligate it. In addition, the suprarenal vena cava cannot be ligated. One must at least obtain temporary control, preferably by direct suture repair of these injuries. The location makes shunting problematic.

One should also recognize that direct surgical therapy may not be the best idea for a number of injuries such as retroperitoneal vascular injuries located deep in the pelvis or deep injuries to the right lobe of the liver. Temporary packing and catheter therapy can be lifesaving in these types of injuries. In the past, this has required transfer of the patient to the angiography suite. However, the advent of the hybrid operating room is ideal for these patients, as catheter therapy and direct surgical therapy can occur at the same time.

One should consider use of the REBOA as a means of temporary inflow occlusion for such critically injured patients. The REBOA can provide inflow control and keep patients alive while catheter therapy is planned. We have had great success using it for serious liver injuries, as well as exsanguinating hemorrhage from pelvic fracture bleeding.

## Complications

The specific complications following laparotomy depend greatly on what injuries were found at the time of the initial operation and accordingly what operative repairs were performed. However, general compli-

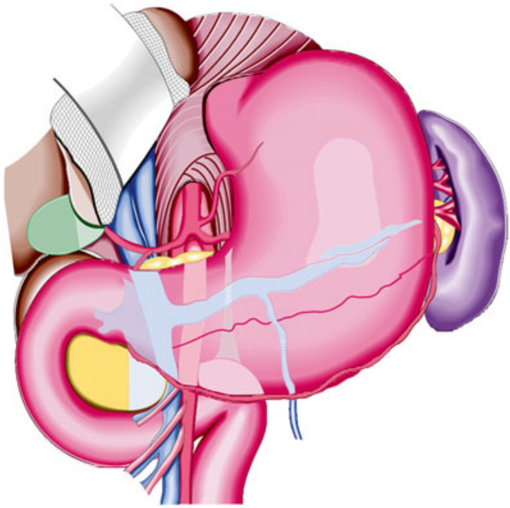

Fig. 4.8. Exposure of celiac axis via opening the lesser omentum (from Desai TR, Gewertz Bl in Lumley JSP and Hoballah JJ eds. Vascular Surgery, Springer 2009).

cations of laparotomy may be divided arbitrarily into early, median, and late categories. Early complications (<4–5 days after index operation) frequently require an unplanned return to the operating room for management and include postoperative hemorrhage, abdominal compartment syndrome, fascial dehiscence or evisceration, or early anastomotic leak. Median complications (7–14 days) include wound infections, fascial dehiscence, and fistula formation. During this phase, evolving intra-abdominal inflammation and increasing acute adhesions make formal operative exploration increasingly hazardous. Management of these complications at this stage frequently involves operative debridement, wound management, and external drainage of fistulas, with formal repair reserved for several months post-op to allow the intra-abdominal adhesions to mature. Late complications (>14 days) include standard long-term complications of laparotomy, including incisional hernia and bowel obstruction.

Inability to close the fascia is an unfortunate sequela of damage control surgery. Persistent visceral and/or retroperitoneal edema may render primary fascial closure impossible in the acute setting. Prompt recognition of the inability to close the abdomen and expedient visceral soft tissue coverage is the priority in this case, in order to reduce the risk of fistula formation [15]. Frequently, it is possible to close the skin over the bowel, and reconstruct the fascia several months later. In certain circumstances, neither the skin nor the fascia is able to be closed. My preference in this case is to cover the bowel with a double layer of woven Vicryl mesh sutured to the fascia or to the skin if the fascia is of extremely poor quality or tightly adherent to the underlying viscera. A negative pressure dressing is used to cover the wound and may usually be changed at the bedside. Once adequate granulation tissue forms, a split-thickness skin graft is applied to the granulation tissue overlying the abdominal viscera. As above, reconstruction of the abdominal wall is planned when the intra-abdominal adhesions have matured, usually several months later.

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# 5. Indication and Techniques for Vascular Exploration

*Jason David Pasley, D.O., F.A.C.S.*

## History of Care

Patients who present with hemorrhagic shock are assumed to have a vascular injury until proven otherwise. As with all patients, tenants of ATLS should be followed. Obvious external hemorrhage should be immediately controlled with direct pressure, tourniquets, or clamps.

Locations for hemorrhage include the chest, abdomen, pelvis, long bones, and external loss. Hard signs and symptoms that are highly diagnostic of vascular injury include active/pulsatile bleeding, shock not explained by other injuries, expanding or pulsatile hematoma, absent peripheral pulse, audible bruit, palpable thrill, or evidence of regional ischemia (pain, pallor, paresthesia, paralysis, pulselessness). While care must be individualized, in general, patients with hard signs of vascular injury require emergent operative control and repair. Soft signs and symptoms that are suggestive but not diagnostic of vascular trauma include mild shock, stable hematoma, slow bleeding, injury in proximity to a major neurovascular tract, peripheral nerve injury, and diminished pulses. Patients with soft signs or orthopedic injuries associated with potential vascular injuries should undergo diagnostic testing. Figure 5.1 shows the Western Trauma Association (WTA) algorithm for the workup of peripheral vascular injury.

For injured extremities, the injured extremity index should be obtained. Documentation of the Doppler determined arterial pressure in an injured extremity, divided by the pressure of an unaffected limb using a manual blood pressure cuff provides the value. An index above 0.9 excludes

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injury, while a value of less than 0.9 warrants further investigation such as CTA, angiogram, or exploration [2, 3].

Assessing distal pulses may be difficult in a patient in shock or who is hypothermic; therefore, these patients should be resuscitated in the usual fashion, and once improved, palpation and distal assessment with noninvasive testing should be performed [1].

In addition to CT angiogram and formal angiogram, both MR angiogram and duplex have been advocated for use. There is such an array of options, and some of these are operator dependent. The imaging modality of choice is currently site specific. The multicenter AAST prospective observational vascular injury trial (PROOVIT) is prospectively collecting data regarding imaging, for further guidance.

In combined long-bone fractures and vascular injury, immediate involvement of orthopedics should occur in conjunction with the trauma team. To maximize limb salvage, the interval between injury and reperfusion should be minimized to less than 6 h. Restoration of flow should take priority over skeletal injury management by shunting if there is an unstable fracture or dislocation or by definitive arterial repair if the skeletal injury is stable and not significantly displaced. If a shunt is used, after the extremity is stable, the formal repair can take place at that time or once the patient is clinicaly stable. Combined arterial and skeletal trauma pose a high risk for compartment syndrome so fasciotomies are strongly considered [4]. In patients who are unable to be examined, such as head injured patients or patients intubated for other reasons, I almost always perform fasciotomies since clinical exam can be inaccurate and you lose the subjective aspects for the diagnosis. Serial compartment pressures are time consuming and compartments can be missed on evaluation.

Venous injuries encountered during exploration for arterial injuries should be repaired if the patient is hemodynamically stable and the repair will not significantly delay the treatment of associated injuries, otherwise ligation is an option. Suprahepatic IVC, superior mesenteric vein, and portal vein injuries must all be repaired as ligation would be fatal. The highest patency rates are achieved with lateral venorrhaphies that do not significantly narrow the lumen of the repaired vein. For complex repairs, end-to-end or paneled repairs are likely the best options. Synthetic and interposition repairs have the worst reported patency rates. Regardless of the repair, lower extremity edema and thrombosis rates are high [4]. With artery and vein injury of the lower extremity, especially with vein ligation, fasciotomies should be performed.

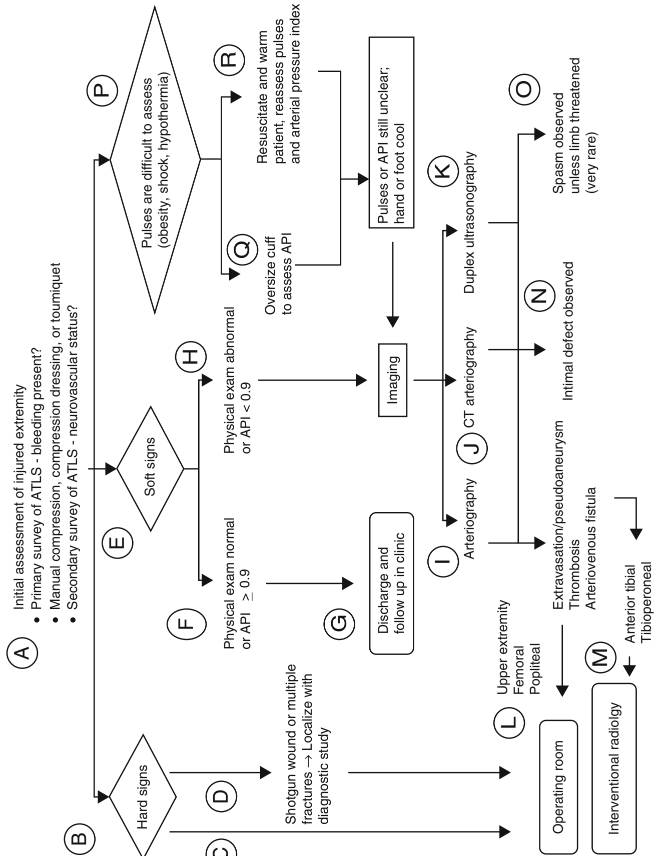


Fig. 5.1. The WTA developed an algorithm for the workup of peripheral vascular injury.

## Fasciotomies and Compartment Pressures

Patients that are "high risk" for developing early compartment syndrome after trauma include hypotension in the field; delay in treatment, especially without arterial inflow for 4–6 h; ongoing hypotension during resuscitation or operation; evidence of crush injury combination of arterial and venous injury, especially the popliteal artery and vein; and need for arterial or venous ligation or early thrombosis and repair of either [5]. Compartment pressures can be measured intraoperatively or postoperatively if a fasciotomy was not performed. Devices such as the Stryker Intra-Compartmental Pressure Monitor System (Stryker Instruments, Kalamazoo, MI) or arterial line with slit/side port catheter can be used. There is ongoing debate about absolute pressures versus delta P (compartment perfusion pressure (CPP) = mean arterial pressure – compartment pressure) on who needs a fasciotomy. Absolute pressures of 30–35 mmHg or delta P of less than 30 mmHg should warrant fasciotomy [5].

## Technique with Personal Tips

In the emergency department, foley balloon tamponade can be used in the neck/upper chest for noncompressible hemorrhage during transition to the OR. Saline is used to inflate the balloon and a clamp is placed on the other distal portion of the catheter so blood does not continue to flow out the catheter. In the operating room, an angiographic compatible bed is key for identifying an injury or for intraoperative imaging during the case. Loupe magnification and headlamps are also very helpful for taking care of these injuries.

The affected area should be widely prepped and draped for adequate exposure. This prep should include proximal areas outside of the zone of injury, in case vascular control must be gained at that location. With patients that have neck or upper extremity vascular injury, the chest should be included, in case a sternotomy, thoracotomy, or a clavicular incision is needed for more proximal control. With patients that have lower extremity injury, the abdomen should be included in the prep, in case access is needed to the external iliac arteries. If manual pressure is required to maintain hemostasis, the hand should be prepped into the field until another source of control can be obtained. The lower extremity, groin, and thigh should always be included, as saphenous vein from an uninjured leg may be needed as conduit.

Proximal and distal control of the injured vessel is the basic principle of vascular surgery. If the injury is to an extremity and it is distal to the groin or axilla, a sterile pneumatic tourniquet can serve as inflow control, until the vessel can be properly dissected out. Once identified, control can be obtained with vascular clamps, bulldogs, or vessel loops and the tourniquet taken down. For the upper extremity, proximal vascular control can be obtained on the brachial artery, axillary artery, subclavian artery, or great vessel control via sternotomy, depending on the location of the injury. For the lower extremity, superficial femoral artery, common femoral artery, or external iliac artery control may be needed, depending on the location of the injury. The external iliac can be accessed either transperitoneally or through a lower abdominal oblique incision into the preperitoneal space, like in transplant surgery. Distal control should also be performed outside the area of hematoma or hemorrhage. If this is difficult, direct control can be performed and internal balloon tamponade with a fogarty and a three-way stopcock can be used. Wherever the injury is located, using clamps far proximally and distally and then walking them in towards the wound can provide excellent control and avoid extra hemorrhage rather than trying to attack these wounds in close proximity to the injury.

Once the vessel is isolated both proximally and distally, vessel loops are used for inflow and outflow control. The injury should be assessed as to whether a simple or complex repair is needed. Additional injuries and the patient's hemodynamic status must be considered. In the case of complex injury and/or if the patient is unstable, damage control with shunting or ligation should be used (see shunt section).

The vessel should have the edges debrided to normal, healthy tissue. Inflow and back bleeding should be noted. A fogarty catheter can be run proximally and distally to clear the vessel of any thrombus. Distally, the catheter should be used until no thrombus is returned on two consecutive passes. Appropriate sizes for the catheter include a #6 for the common and external iliac arteries, a #4 to #5 for the common femoral artery, a #4 for the superficial femoral artery, a #3 to #4 for the popliteal artery, and a #3 for the other arteries of the leg. Balloon catheters are never passed in venous injuries because these will disrupt the veins [6].

Systemic heparinization should be considered in stable patients with isolated extremity/vascular injury. 5,000 (50–75 units/kg) units IV should be given. Systemic heparin should be avoided in patients with torso or head injuries. Local administration of heparinized saline should be injected both proximally and distally before any repair to aid in preventing local thrombosis using approximately 20–25 mL per site (50 U/mL).

If the injury to the artery only has minimal loss, a primary repair can be used depending on the luminal diameter. When closing, the last stitch or two is left loose until proximal and distal flushing are performed. Care is made not to cinch down the last knot or knots too tightly to avoid constricting the anastomosis. For partial arterial injuries of smaller vessels (brachial, SFA, popliteal), patch angioplasty can be used so the resulting luminal diameter is not too narrow.

For a complete transection, the injured vessel must be debrided to healthy tissue at both ends. Some length can be gained by sacrificing some of the branches of the vessel depending on its location. This maneuver may gain up to 3 cm of total advancement of both ends. If this is not feasible or the defect is too large, an interposition graft is necessary [6]. Choice of conduit will depend on size match and location of the injured vessel. Greater saphenous vein from the uninjured leg is typically the first choice for conduit. As the injured artery is typically vasoconstricted, consider a slightly larger conduit in what is visualized.

For suturing into the arterial wall, the key maneuver is perpendicular passes of the needle. Most vascular trauma is to young healthy arteries, so although formal vascular training teaches "inside out" on the artery to prevent intimal flaps, this is less worrisome in vascular trauma. For the repair, it is easier to perform the distal anastomosis first, especially if it is in a difficult location to allow for better visualization of the posterior suture line. Figure 5.2 shows the WTA algorithm for operative decison making in vascular injury.

## Saphenous Vein

The ideal conduit for extremity vascular injury is contralateral saphenous vein. The saphenous vein can be used as the primary conduit, patch, or spiraled for reconstruction of larger vessels. The amount of vein harvested should be longer than the defect as it may be trimmed down prior to anastomosis. During vein harvest, small branches should be ligated with 2-0 or 3-0 silk. After the vein is harvested, it should be reversed and an olive-tip catheter secured to the distal end with silk suture. Using heparinized saline, the vein should be dilated while closing the other end to look for any leaks. These leaks can be controlled with ties or small Prolene sutures. One side of the vein is marked using a sterile marker, so as to not twist the conduit when performing the anastomosis. Once the conduit is satisfactory, it is placed in a heparinized saline bath. If the greater saphenous vein is absent, diseased, has a poor diameter, or is the

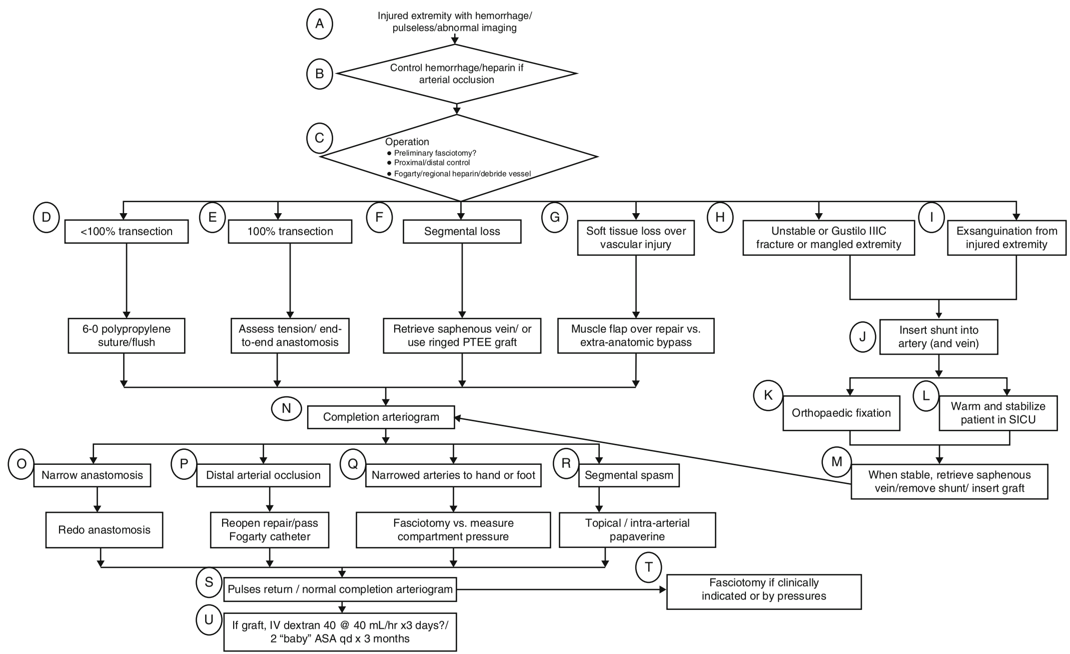


Fig. 5.2. The WTA II flow chart shows one algorithm for the operative decision making for vascular injury.

only venous outflow for an injured extremity, other options include the lesser saphenous or the cephalic or brachial vein [6].

## PTFE

Due to the size of injured vessels ideally, PTFE should only be placed proximally to the axilla and/or to the knee. If the injury is distal to this location, vein should be used because the diameter of the injured vessel is small and smaller PTFE will clot. PTFE has shown improved patency (70–90 % short term) and rare infection, even in contaminated wounds [7, 8]. It is clear that patency with PTFE is equivalent to that of a vein for injuries proximal to the popliteal artery; PTFE grafts smaller than 6 mm should not be used. 8 mm grafts are typically the smallest I would use. PTFE and vein grafts must be covered with soft tissue or there is a significant risk of hemorrhage from desiccation of the vein, with subsequent autolysis or breakdown of the anastomosis [9]. Patients with PTFE placed should be put on ASA of 162–325 mg daily × 3 months postoperatively [10]. The ASA recommendation is extrapolated from aortosaphenous bypass from CABG data as well as from bypass from peripheral vascular disease.

## Other Conduits

Other conduits for vascular repair include bovine pericardium as well as CryoVein. As these are tissue conduits, they may be better options than PTFE if there is poor autologous saphenous vein for conduit or a size mismatch. They can also be used in case of vascular graft infection. There is little published data on these techniques and none in the trauma literature.

As with PTFE, healthy tissue must be used to cover the repair. Local muscular flaps may be used. In an unstable patient without time for complicated coverage, porcine xenograft or other biologic can be placed under mesh gauze soaked with antibiotics [6].

## Shunts

Shunts are the primary damage control modality for vascular injury. In an unstable situation, a shunt can be placed to re-establish blood flow and the patient can be resuscitated in the OR or ICU. A formal repair can be performed when the patient is stable. Various commercial shunts are available in assorted sizes and configurations. If commercial shunts are not available, anything from IV tubing to pediatric feeding tubes all the way to chest tubes can be used for conduits, depending on the size of the injured vessel. We use Argyle shunts because they are straight, providing direct flow. The shunt size should be the largest diameter that will fit comfortably into the injured vessel. Other shunts can loop and become dislodged so we typically do not use them. Venous shunting can be considered depending on location; however, in true exsanguination, ligation may be used.

For arterial shunting, once proximal and distal control is obtained, fogarty catheters should be used to clear the thrombus. Local heparin (10 units/1 mL) can be instilled and the shunt can be inserted into the injured vessel. The distal end is inserted first with back bleeding appreciated. Heparinized saline is then instilled in the wound as it is inserted proximally, to prevent an air embolism. The shunt is then secured to the injured vessel with 2-0 silk suture as close to the edge of the injured vessel as possible, as this portion of the artery will need to be resected for the definitive repair (Fig. 5.3). We typically leave the vessel loops in place loosely, with the end secured by a clip. Patency of the shunt should be confirmed with palpation of a pulse or with

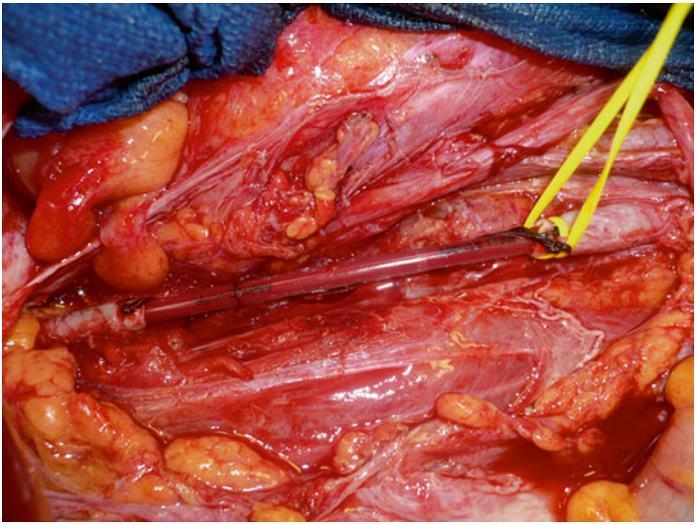

Fig. 5.3. Shunt in place.

Doppler wave flow. If possible, muscle is loosely approximated over this or a moist Kerlix/towel used. Dry dressings are then placed and covered with Ioban or another occlusive dressing. For venous shunting, larger tubes may be needed such as small chest tubes (16–24 F) depending on the site. Continued pulse checks should occur in the ICU and propt re-exploration performed if there is a loss of pulse or loss of doppler signal. Once the patient is more clinically stable, the shunt should be removed and a formal repair perfomed.

## Angiogram

At the completion of the anastomosis, goals should be a "pulse or picture," especially if the repair was more involved than a simple primary suture. If a palpable pulse is not appreciated, we obtain an angiogram to make sure there are proper distal flow and no other surgically correctable lesions. Angiographic imaging requires a butterfly needle, typically 18–20 G, two syringes, and a three-way stopcock. One syringe is filled with heparinized saline and the other with contrast. The butterfly needle is placed into the artery proximal to the injury or anastomosis and the contrast is injected prior to fluoroscopy.

Narrowing of either anastomosis requires revision. If a continuous suture was used initially, consideration should be made for interrupted or partially interrupted repair. Distal occlusion to the anastomosis mandates reheparinization replacement of clamps and an arteriotomy, typically 1 cm proximal to the distal anastomosis. Fogarty embolectomy should be attempted. If one artery in the leg is occluded but the foot has a palpable pulse and is clearly viable, this is an acceptable result [6].

If a beaded appearance is noted on the completion angiogram, this may be due to compartment syndrome or spasm. If there has been a delay in treatment or any suspicion for compartment syndrome, fasciotomies should be performed. If it is unclear, compartment pressures may be monitored [6].

## Lower Leg Fasciotomy

The most reliable technique is a two incision, four compartment fasciotomy. The lateral incision will release the anterior and lateral compartments, while the medial incision will release the seep and superficial posterior components. Both incisions should be generous in length to allow for adequate fascial opening from the level just below the tibial plateau (3–6 cm) to 3–6 cm above the medial and lateral malleolus, respectively.

The lateral incision is made in a line one fingerbreadth (1–2 cm) anterior to the edge of the fibula. The incision is carried out through the skin and subcutaneous tissue until fascia is exposed. The intramuscular septum is identified. Perforating vessels can be followed into the fascia as they enter the septum, if it is difficult to identify. With a knife a transverse incision can be created to identify the anterior and lateral compartments as well as the septum. The compartments can then be opened in a cranial/caudal direction with scissors. The tips of the scissors should be pointed away from the septum. Identification of the septum and the deep peroneal nerve ensures decompression of both compartments.

The medial incision is made one fingerbreadth (2–3 cm) posterior to the medial edge of the tibia and carried out to the level of the fascia. Care should be taken to protect the saphenous vein. The fascia is opened, decompressing the superficial posterior compartment. The deep compartment is released by bluntly and sharply taking down the fibers of the soleus muscle from the edge of the tibia. Identification of the neurovascular bundle confirms entry into the deep compartment [11].

## Specific Access and Repair Options

### *Axillary Artery Exposure*

The subclavian artery becomes the axillary artery as it crosses beneath the first rib. The pectoralis minor muscle divides the artery into three sections. This artery becomes the brachial artery as it courses across the lower border of teres major.

The incision begins at the inferior edge of the center of the clavicle and runs in the deltopectoral groove (Fig. 5.4). A self-retaining retractor is placed. The pectoralis major can be retracted or split in the level of its fibers (if hemodynamically stable) or divided 2 cm from its insertion into the humeral head (if unstable). We reposition the self-retaining retractor and then divide the pectoralis minor by placing an army navy retractor underneath the pectoralis minor and divide the muscle using cautery (Fig. 5.5). This provides access to the second portion of the axillary artery. The brachial plexus is just inferior to the artery and the axillary vein typically runs with the artery, just inferior as well (Fig. 5.6) [11].

Fig. 5.4. Skin markings for axillary exposure. The sternal notch and clavicle should be delineated. At approximately proximal 1/3 mark of the clavicle, a lateral incision in the deltopectoral groove should be carried out. If the injury is to the distal axillary artery, the incision can be carried into the beginning of the confluence of the biceps and triceps for proximal brachial artery exposure.

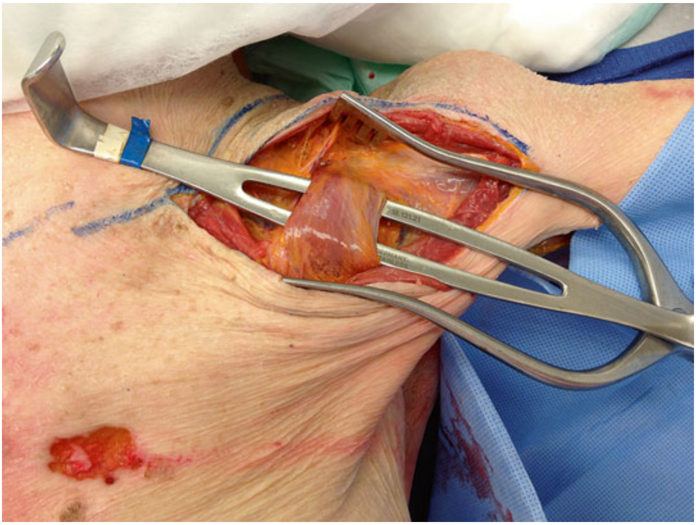

Fig. 5.5. Dissection of pectoralis minor prior to division.

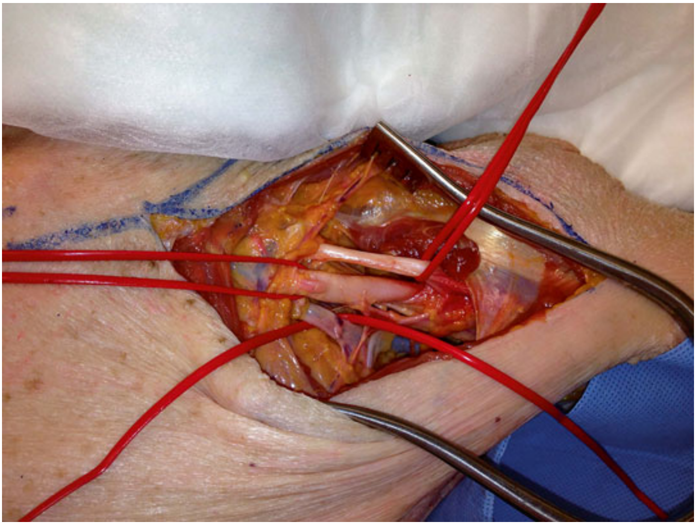

Fig. 5.6. Axillary artery (*middle*), vein (*inferior*), and associated nerve (*superior*) with vessel loops.

Options for repair include shunting or ligation with fasciotomy, if the patient is in extremis. Since there are abundant collaterals around the shoulder, ligation is an option. Reconstruction with vein or graft is preferred in the stable patient.

## Brachial Artery

The brachial artery is subcutaneous in its course as it runs between the biceps groove between the biceps and triceps of the medial arm. It veers laterally at the antecubital fossa and collaterals arise around the elbow. The artery is accompanied by two venae comitantes, typically on either side of the artery. The median nerve runs anteriorly and the ulnar nerve posteriorly. Halfway down the arm, the median nerve crosses the artery and runs along the posteromedial side of the artery (Fig. 5.7).

The incision is carried out in the groove between the triceps and biceps muscle bellies. It can be extended obliquely across the antecubital fossa laterally if exposure of the bifurcation is necessary. A self-retaining retractor is placed. Sometimes an injured brachial or basilic vein can be used as a conduit; therefore, care should be taken not to injure these in

Fig. 5.7. Brachial artery exposure. Median nerve anterior and inferior in *middle* of picture. Brachial artery is just posterior to this nerve.

dissection. If the bifurcation of the brachial artery needs to be exposed, the bicipital tendon must be divided. This tendon lies just beneath the median cubital vein [11]. Repair of these injuries are either simple repair, plus or minus vein patch, or interposition vein graft.

## Proximal Aorta and IVC

For aortic control, consideration should be made for an endovascular balloon for aortic occlusion versus open occlusion.

When the upper portion of zone 1 has a hematoma or hemorrhage, injury to the aorta, celiac axis, SMA, or renal arteries should be considered and proximal control should be performed. The lesser omentum should be incised vertically, creating a window between the distal esophagus and liver. The hepatophrenic ligament may need to be divided. The left crus can be split along its fibers or divided. A finger is used to bluntly dissect off loose tissue around the aorta. The aorta can be clamped or occluded with a sponge stick, "occluder" device, or clamp. This should be released when more specific control can be obtained. The tips of the clamp should contact the spine and paraspinous muscles to ensure complete control. If a clamp is used, it is helpful to invert the clamp so the handles are going up towards the thoracic cavity and not as much in the way. This can be tethered up with an umbilical tape and clamped to the drape. Another option can be intraluminal control with an aortic balloon occluder.

Injuries to the right retroperitoneum (zone 1/2) can be accessed by a medial visceral rotation (Cattell-Brasch maneuver). The IVC and renal vasculature can be visualized and controlled in this fashion. The parietal peritoneum at the white line of Toldt is taken down from the base of the cecum to the hepatic flexure. This can be started with cautery or scissors and extended in the same manner or bluntly. The colon is mobilized medially and superiorly, exposing the iliac vessels, IVC, and renal vessels. This can be accomplished by lifting the colon and pushing it away from the retroperitoneum with a lap pad. If more proximal exposure is needed, the duodenum can be mobilized using a standard Kocher maneuver.

For IVC injuries, sponge sticks provide great means for compression to obtain proximal and distal control. If a simple laceration is noted anteriorly, a Satinsky clamp can be used to clamp the injured side while it is repaired in a running fashion. Allis clamps can also be used to bring the edges together while repairing the vein. Depending on the injury mechanism and trajectory, a posterior injury should also be considered (Figs. 5.8, 5.9, 5.10, and 5.11). The IVC can be rotated carefully to inspect this area and repair any other injury, if identified. The posterior injury can also be fixed through the anterior injury, if necessary. If a larger wound is noted, attempts can be made for primary end-to-end repair. Otherwise, consideration can be used for a panel graft or ligation. If the infrarenal IVC is to be ligated, it is recommended to ligate it right next to the renal veins so that there is no excess IVC to form a clot infrarenally.

Our preferred method to control the IVC is using intestinal Allis clamps. The injury is first controlled with digital pressure. Proximal and distal control can be obtained with either vessel loops or from pressure from sponge sticks. The first clamp is applied in a controlled fashion. Adjacent clamps can then be placed to approximate the wound. When the injury is completely controlled, the clamps are lifted, thus improving venous return. The injury is then repaired under the clamps, sequentially removing them as the repair is completed. This control can also be performed with a Satinsky clamp and repaired in a similar fashion.

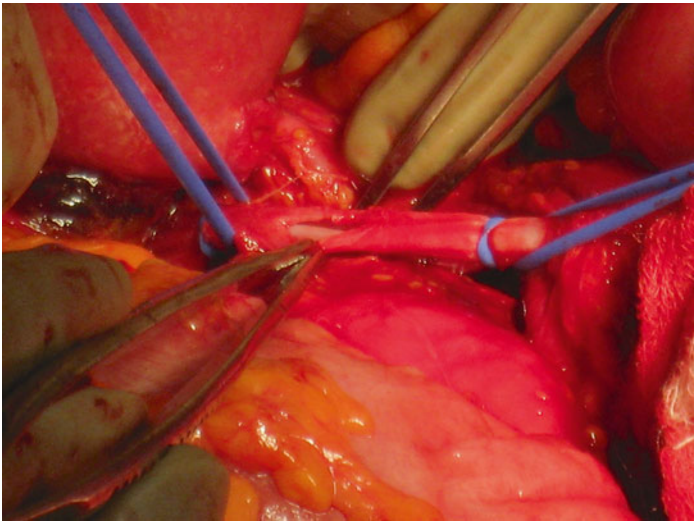

Fig. 5.8. Anterior IVC injury.

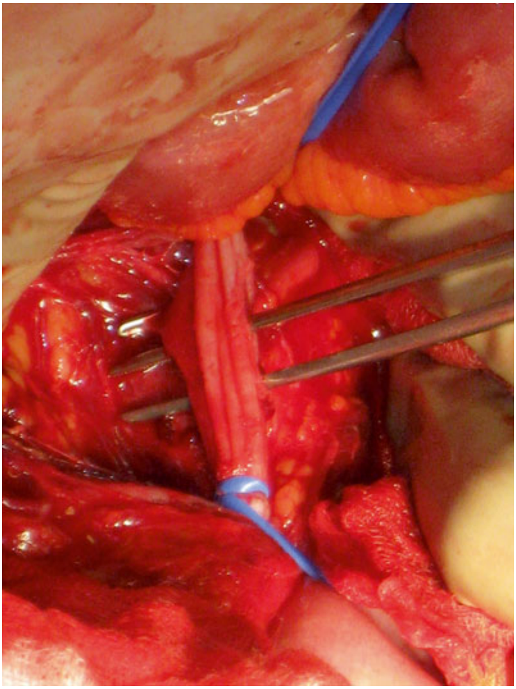

Fig. 5.9. Through-and-through IVC injury with forceps delineating the injury.

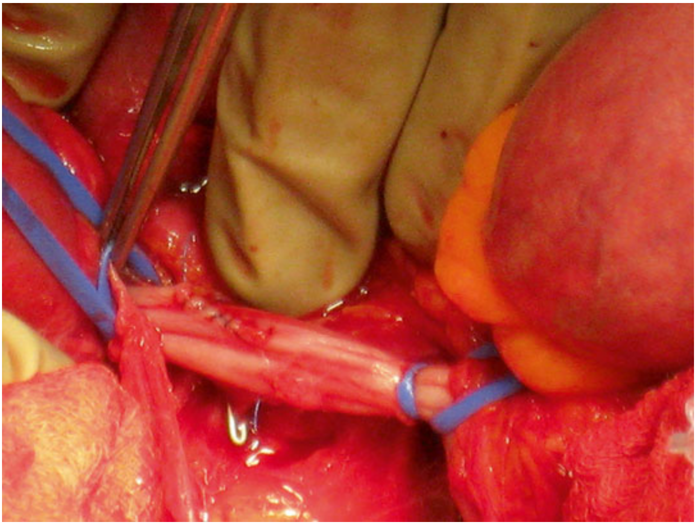

Fig. 5.10. IVC repair with proximal and distal flow controlled with vessel loops.

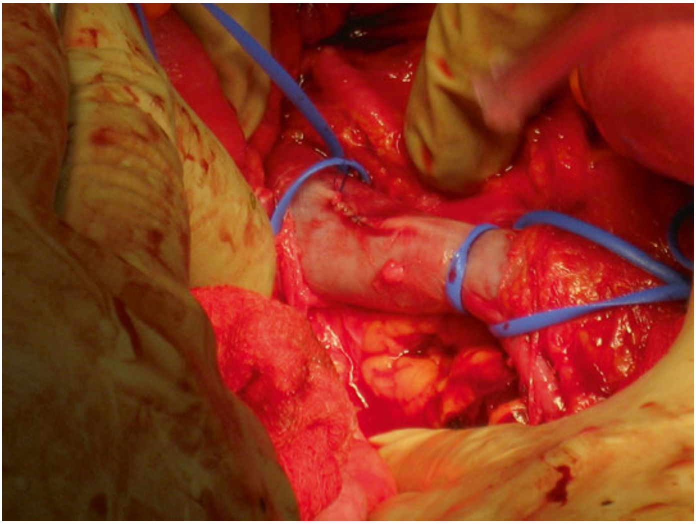

Fig. 5.11. IVC repair with vessel loops loose, assessing for venous flow.

## Distal Aorta and Iliac Vessels

With hemorrhage in zone 3, a vascular injury to the distal aorta or IVC or common/internal/external iliac artery or vein must be ruled out. Due to the proximity, the ureter should also be evaluated. A visceral medial rotation should be performed to expose this area. The common iliac veins are densely adherent to the back wall of the common iliac arteries; therefore, dissection should be done carefully. The right common iliac artery crosses over the distal bifurcation of the IVC and the confluence of iliac veins, so this may need to be divided to obtain control of underlying structures. The artery can be reanastomosed once the venous injury is handled. For a distal aortic injury, the proximal aorta should be controlled for inflow and the iliac arteries for outflow. Ideally, this is performed with vessel loops. Temporary maneuvers can include lap pads, sponge sticks, or digital compression.

The mid-aorta can be controlled via a left-sided medial visceral rotation. The IVC is best approached from the right side. If there is doubt, we prefer a right-sided approach. The mesentery of the small intestine can be lifted off the retroperitoneum, giving access to the IVC and infrarenal aorta, as well as the proximal iliac vasculature.

Iliac arterial injuries can be isolated by vessel looping the common iliac near the aortic bifurcation and the distal external iliac artery by the inguinal ligament. The internal iliac artery can be identified by lifting these vessel loops and placing one around the internal iliac artery.

Hypogastric venous injuries can be difficult to expose. The vein runs behind the artery and the main vessel is quite short. It then branches into many smaller vessels. Dividing the hypogastric artery aids in exposure. The artery may be dissected off the vein quickly, greatly improving exposure.

Iliac arterial repairs will depend on the extent of the injured vessel, degree of contamination, as well as the overall disease burden of the patient. If the patient is in extremis, shunting is a viable option. For extreme situations, the iliac artery can be ligated. A fasciotomy should be performed, and if the patient survives, a femoral-femoral bypass can be considered. Interpositions grafts can be used in a contaminated field; however, if it is severely contaminated, ligation with extra-anatomic bypass should be considered.

Fig. 5.12. External iliac artery control above the inguinal ligament. The vessel loop is around the distal external iliac artery above the inguinal ligament.

## External Iliac Artery

The external iliac can be exposed via a transperitoneal approach, but it is typically more expedient to approach it from a retroperitoneal approach above the ligament. A "hockey stick" incision can be carried out from the groin to above the inguinal ligament in a lateral direction above the iliac crest. The external and internal obliques are separated and the retroperitoneal space is entered. A self-retaining retractor can be placed and a lap pad used to rotate all of the peritoneum medially to expose the psoas muscle and vessels (Fig. 5.12). The inguinal ligament can be divided if the femoral artery needs to be accessed. Care must be taken not to injure the ureter that can be found at the common iliac bifurcation [11].

## Common Femoral Artery

The common femoral artery lies just distal to the inguinal ligament until it divides into the SFA and profunda. It is found between the anterior superior iliac spine and the pubic tubercle, typically about 2 fingerbreadths lateral to the pubic tubercle. The incision should be started just above the inguinal ligament and carried out longitudinally along the medial border of the Sartorius. A self-retaining retractor should be placed. Dissection should start laterally as the vein and lymph channels are more medial. The femoral sheath can be opened staying anterior to the artery. Occasionally bridging veins will be encountered and these can be ligated. Exposure can be carried out to the bifurcation [11]. If there is difficulty exposing the proximal artery due to bleeding, it is wise to divide the inguinal ligament or use an extra-peritonal approach to access the external iliac artery.

## Proximal SFA and Profunda

The profunda is typically found 4–6 cm inferior to the inguinal ligament coursing posterolaterally. Once dissection of the common femoral bifurcation is performed as above, typically the take-off of the profunda can be seen by a decrease in the diameter of the common femoral artery. Upward traction of the common femoral and superficial femoral artery can be obtained with vessel loops to aid in finding the origin of the profunda. Profunda control is performed by passing a vessel loop under the common femoral and then the SFA to avoid damaging the lateral circumflex vein [11].

## Distal SFA

The SFA is a continuation of the common femoral on the anterior aspect of the thigh, subsartorial, until it enters the popliteal (Hunter's) canal. The adductor hiatus (Hunter's canal) is fascial lined cleft located medially to the vastus muscles and lateral to the adductor muscles in the mid-thigh. Distal to the hiatus is the suprageniculate popliteal artery. Full exposure of the SFA is most easily achieved through an incision that parallels the lateral border of the sartorius. The sartorius is retracted medially to expose the roof of the canal to allow entry to the vessels.

In a large hematoma, more proximal control may be necessary as the anatomy may be distorted. The sartorius is a good coverage option for vascular repairs. Venous injury often accompanies arterial injury, so visualization with repair or ligation must occur if an injury is identified [11]. If soft tissue coverage is needed for your vascular repair, a sartorius flap can be mobilized in this position.

## Popliteal Artery

The popliteal artery is located between the adductor hiatus and the lower border of the popliteus muscle. Medially, the semitendinosus and its confluence with gracilis and sartorius and the semimembranosus cover the popliteal fossa and vessels. The veins are typically adherent to the artery. The tibial nerve is loosely attached to the vessel sheath within the popliteal fossa. The distal end of the popliteal artery is located at the hiatus by the origin of the soleus.

The knee should be flexed at 30° and laterally rotated. A bump or a rolled-up sheet can aid in this. The skin incision should be between vastus medialis and sartorius. The saphenous vein should be maintained and ideally left with the posterior skin flap. The incision can be carried distal to the knee, one cm posteriorly to the tibia. For full exposure, it is often necessary to divide the semimembranosus, semitendinosus, gracilis, and sartorius 2–3 cm from the insertion and tag each of these to reapproximate later. For the distal portion, the medial head of the gastrocnemius will need to be divided [11].

## Outcomes

### *Complications with Treatment*

Postoperatively, the patients should be monitored for frequent neurovascular and pulse checks. The most immediate complication of vascular repair is early thrombosis. This can be suspected with pulse changes and signs of distal ischemia. Prompt identification of thrombosis is critical and operative re-exploration with revision is needed to salvage the limb. If ischemic signs are not present, revascularization may be delayed or further evaluated by angiography [12]. Any changes in pulse examination or Doppler signals necessitate investigation, either with imaging or operative exploration [13].

Postoperative anticoagulation is not generally indicated following repair, unless previous condition exists such as hypercoagulable state, mechanical valve, etc. [12]. Antiplatelet therapy can be considered for below-knee bypasses, extrapolated from elective vascular disease.

Reperfusion injury may occur, producing hyperkalemia, hypoxia, and acidosis. These must be aggressively corrected. Any changes in pulse examination or Doppler signals necessitate investigation, either with imaging or operative exploration [13].

If a fasciotomy was not done at the initial operation, monitoring for signs of compartment syndrome is vital. If fasciotomy was performed, it is still critical to monitor vitals, pain, lab values, and renal function to assure that ongoing rhabdomyolysis is not present from a missed or inadequately released compartment. With worsening acidosis, CPK, or myoglobin, or worsening renal failure, re-exploration is needed to assure all compartments are fully released.

Infection at the site of vascular repair may lead to thrombosis, false aneurysm, or anastomotic disruption with hemorrhage. Close monitoring of the wounds must take place and appropriate antibiotics and drainage is indicated if infection is suspected. If the anastomosis is infected, the vessel must be ligated and resected and bypass through a clean field performed [12].

At discharge, a daily walking program should be encouraged to improve flow to the local extremity. Smoking cessation should also be advocated. Aspirin administration of 162 mg for 3 months is encouraged. Due to poor patient follow-up with trauma patients, it is unknown what the course of these vascular repairs is. Because of this lack of follow-up, recommendations for discharge surveillance modality and timing have not been established. We are currently prospectively collecting our data for the PROOVIT by obtaining imaging at 1, 3, 6, and 12 months with duplex ultrasound by a vascular tech.

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# Part II
# Techniques for Diagnosis and Resuscitation

# 6. Intubation, Cricothyrotomy, Tube Thoracostomy, Diagnostic Peritoneal Lavage, and Local Wound Exploration

*Kim Boswell, M.D., Kevin Jones, M.D., and Jeffrey Rea, M.D.*

## Intubation

### *Intro*

Airway is the first concern after injury. The Eastern Association for the Surgery of Trauma (EAST) defines endotracheal intubation (ETI) as necessary in patients with airway obstruction, severe hypoxemia, hypoventilation, Glasgow Coma Scale ≤8, severe hemorrhagic shock, and cardiac arrest. EAST also emphasized the need for ETI in patients with smoke inhalation with evidence of airway obstruction, major cutaneous burns (>40 % BSA), moderate to severe facial burns, or airway injury appreciated on endoscopy [1]. Other patient candidates for ETI include patients with facial or neck injury, persistent combativeness and concern for brain injury, and cervical spine injury with evidence of respiratory insufficiency.

### *Technique*

Rapid sequence intubation (RSI) is used for emergent intubation in the critically ill trauma population. RSI is the simultaneous administration of both an induction agent and a paralytic to facilitate ETI. The bag valve mask should be applied to the face, and the patient should be passively preoxygenated with 100 % oxygen using a jaw thrust or chin lift to open the airway. Active bagging should be avoided. When done properly,

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RSI decreases the risk of complications including vomiting and aspiration while increasing the rate of successful intubation to approximately 98 % [2].

The most common technique utilized in the trauma patient is direct laryngoscopy with cervical spine precautions. The laryngoscope is placed into the mouth, sweeping the tongue to the left of the oral cavity and inserting the tip of the laryngoscope blade into the posterior pharynx. The vocal cords and arytenoids should be seen. If the epiglottis is seen overhanging the larynx, the laryngoscope should be further advanced into the vallecula to reveal the vocal cords. The endotracheal tube is introduced, passing directly through the cords and advanced to approximately 21–24 cm from the teeth. The balloon should be inflated and the endotracheal tube secured. Color capnography should be attached to the endotracheal tube, and color change should be demonstrated on 6 successive breaths. The oxygen saturation probe should be properly attached to the patient and continuously monitored. If present, end-tidal $CO_2$ should be monitored. The intubator should auscultate breath sounds and should observe the chest wall to visualize chest rise and fall with ventilation. A chest radiograph should ensure proper location of the endotracheal tube in the trachea [3].

For patients in which there is concern for, or a known, unstable cervical spine fracture, intubation should be preferably performed by an anesthesiologist or other skilled operators using a fiber-optic scope to prevent fracture displacement and/or worsening spinal cord injury.

## *Outcomes*

Intubation is a well-tolerated and successful procedure if performed by an experienced individual.

## *Complications*

Peri-intubation emesis and aspiration are likely the most common complications of intubation. Patients who are properly medicated prior to intubation have decreased complications including vomiting, aspiration, airway trauma, and death [4].

The difficult airway can often be handled using adjunctive airway devices like the gum elastic bougie to facilitate endotracheal tube placement or a laryngeal mask airway (LMA). The LMA is not considered a definitive airway, but can oxygenate and ventilate patients, while a definitive or surgical airway can be established.

The difficult airway may require placement of an emergent surgical airway. Transtracheal jet ventilation, needle cricothyroidotomy, and other emergent, invasive airway rescue techniques can be used to rescue the difficult airway, but these methods require highly skilled and well-versed physicians to be successful. Cricothyroidotomy is the preferred intervention for failed endotracheal intubation [5].

## Cricothyrotomy

### *Intro*

Cricothyrotomy is the preferred procedure for establishing an emergent surgical airway. When attempts at orotracheal intubation fail, and a patient cannot be adequately ventilated by alternate means, the immediate solution is a cricothyrotomy. Emergent surgical airways are rarely needed, in one study accounting for 0.3 % of urgent and emergent airways [6].

The landmarks for cricothyrotomy are easily palpable in an adult, making the procedure one which can be performed entirely using tactile input. The risk of esophageal injury is minimal, as the posterior wall of the airway is completely encased by the cricoid cartilage. The risk of injury to blood vessels or the recurrent laryngeal nerve is also minimal, as the lateral aspects of the cricothyroid membrane are bounded by the inferior horns of the thyroid cartilage. The cricothyroid membrane is superior enough to be away from the thyroid isthmus or superior thyroid arteries and veins.

A number of prepackaged kits exist for the purpose of performing percutaneous cricothyrotomy. These kits utilize a Seldinger technique of first introducing a needle, then a wire, and then a series of dilators, ultimately followed by a kit-specific airway device, through the cricothyroid membrane. The open surgical technique has advantages over these percutaneous kits and has been demonstrated to be superior in the simulated environment [7].

## *Technique*

As time and patient stability allow, prep and drape the anterior neck. Grasp the patient's larynx between the thumb and middle finger of the nondominant hand. This "laryngeal handshake" will provide a continuous reference to midline, throughout the procedure. Identify the thyroid and cricoid cartilages, as well as the cricothyroid membrane between them. Make a vertical incision extending from over the mid-thyroid cartilage to over the mid-cricoid cartilage. In larger individuals, a larger incision may be required to define the anatomy. With the blade oriented horizontally, insert the scalpel blade straight through the middle of the cricothyroid ligament, penetrating 2–3 mm. Incise the membrane to the lateral margins where it is bounded by the cartilaginous structures of the thyroid cartilage (Fig. 6.1). Dilate the opening with a finger or the handle of the scalpel. Insert the tracheal hook, and retract the laryngeal cartilage, anterior, and cephalad (Fig. 6.2). Insert the airway (Fig. 6.3).

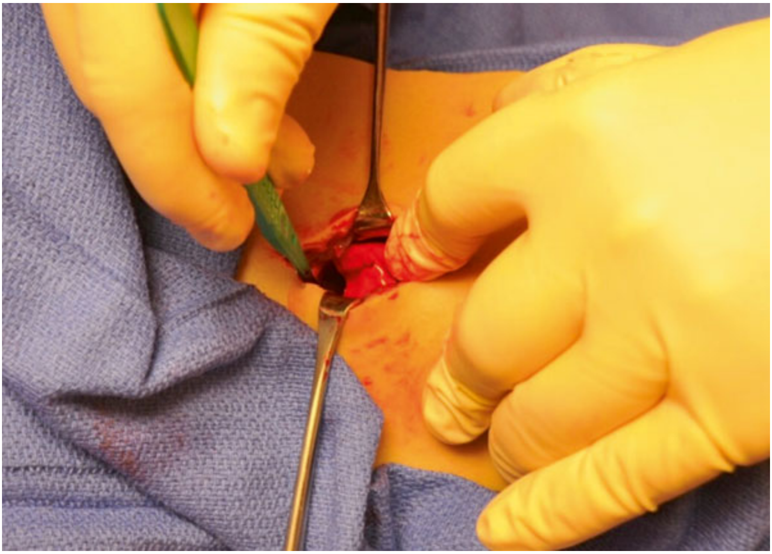

Fig. 6.1. Incise the cricothyroid membrane laterally in both directions to the margins defined by the thyroid cartilage, and then dilate the opening with the handle of the scalpel or with your finger.

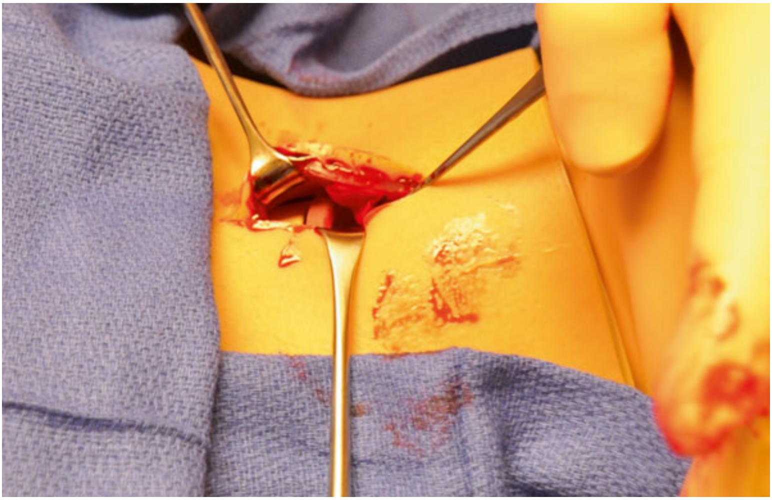

Fig. 6.2. Insert a tracheal hook and lift the thyroid cartilage cephalad and anterior.

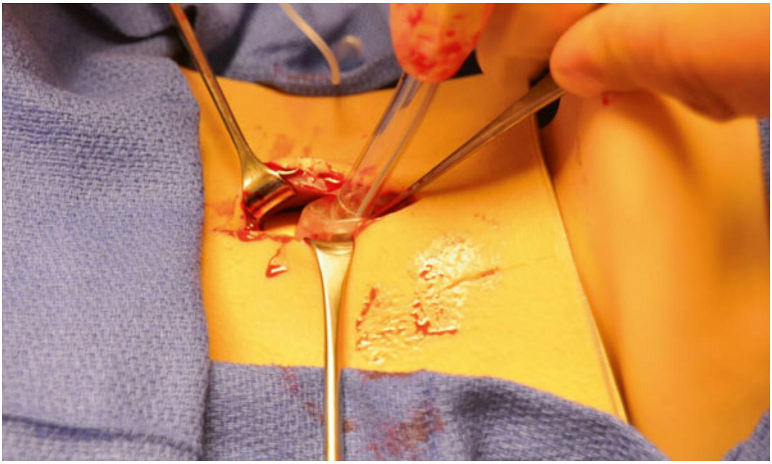

Fig. 6.3. Insert the airway.

Here we use a 6.0 ETT, but a 6.0 internal diameter Shiley or similar tracheostomy device will also work. Once the airway is through the cricoid cartilage into the trachea, remove the tracheal hook. Ventilate and confirm airway position with end-tidal $CO_2$.

### *Complications*

The worst complication of a cricothyrotomy is failure to appropriately cannulate the trachea, usually by creating a false tract when attempting to place the airway device. Immediate confirmation of airway position by the use of end-tidal $CO_2$ detection is imperative in order to immediately identify the mal-placed airway.

Bleeding is an inevitable complication to some degree. Practice performing the cricothyrotomy using only tactile input beforehand. It is rare, given the confines of the cricothyroid cartilaginous cage, to encounter hemodynamically significant hemorrhage if the midline and lateral margins of the operative field are defined with a firm "laryngeal handshake."

Because the cricoid ring is a closed circumferential ring around the airway, prolonged use of a cricothyrotomy may lead to scarring and stenosis at the cricoid level. Cricothyrotomies should be converted to tracheostomies in a controlled environment within 3 days of placement.

### *Critical Take-Home Points*

- Be decisive about recognizing the need and proceeding with a cricothyrotomy. The biggest risk is failing to perform it quickly when needed.
- Establish control of the larynx and define the midline using a "laryngeal handshake."
- Once the cricothyroid membrane is entered, always have something inserted in the tract to maintain it: the scalpel, your finger, a tracheal hook, etc.
- Practice this procedure so you will not hesitate to perform it when required.
- Practice performing this procedure using only tactile input, as visual references will rapidly disappear with even minimal incision bleeding in the trauma bay.

## Tube Thoracostomy

### *Intro*

After ensuring an adequate airway, correction of hemodynamic compromise, inadequate oxygenation, or inadequate ventilation due to hemothorax or pneumothorax is the most immediately correctable cause of trauma mortality during a primary survey. This is done in the resuscitation bay by means of placement of a tube thoracostomy (TT). TT is the procedure of choice for the initial management of traumatic hemothorax or pneumothorax.

Indications for tube thoracostomy in the trauma patient include clinical suspicion for a tension pneumothorax or massive hemothorax, any identified hemothorax on CXR or CT scan [8], and/or any pneumothorax visualized on CXR. While some debate exists, the current EAST Practice Management Guidelines states, "Occult pneumothorax, those not seen on chest radiograph, may be observed in a stable patient regardless of positive pressure ventilation (Level 3)" [8]. For the acute trauma patient in the resuscitation bay, there are no absolute contraindications to tube thoracostomy. Relative contraindications in the more stable patient include known pleural disease and coagulopathy.

## *History*

While the use of tubes to aspirate empyema goes back as far as Galenus and Celsus in the Roman age [9], the first modern published account of continuous pleural space drainage was published by Dr. F. Cresswell Hewett, A.M.D. in 1876 [10]. Significant reductions in the rate of posttraumatic empyema were shown during the Franco-Prussian War of 1870–1871 using Hewett's technique when applied to empyema [11] and were widely endorsed as the preferred alternative to open management after the US experience in World War I [9]. This approach was further cemented during World War II, where TT with an underwater seal became the standard of care for simple traumatic hemothorax and pneumothorax.

## *Technique*

### Patient Prep and Positioning

If possible, place the patient in a lateral recumbent position with the arm extended over their head. If this is not safe, placing the ipsilateral arm as far over the patient's head as possible will help expand the lateral chest wall and define anatomic landmarks, as well as provide a reasonable degree of exposure. Unless the patient is in extremis, the time should be taken to thoroughly prep widely around the site of insertion and place a maximal sterile barrier drape.

Make sure all requisite equipment is in place, including the following: the chest tube; two large clamps, one for occluding the chest tube and the other for guiding the tip of the tube during placement; a large pair of Kelly forceps for bluntly dissecting through the intercostals and parietal pleura; suture for securing the chest tube; and water-seal or equivalent suction apparatus setup and ready for use.

Tube thoracostomy with inadequate or, worse, no analgesia in a conscious patient is one of the more brutal procedures performed in the trauma bay. While the use of fentanyl or other systemic opioid analgesics is helpful, it is unlikely to be adequate except in large doses. Thorough regional anesthetic use is requisite. The ease of performing tube thoracostomy is inversely proportional to the degree of patient discomfort.

## Choice of Tube

Large chest tubes have traditionally been used for the drainage of hemothorax in trauma patients, having less the chance to clot and becoming occluded. No advantage is seen in the use of very large (36–40 Fr) chest tubes over the use of more moderate (28–32 Fr) tubes in the multitrauma patient [12]. Use of tubes smaller than 28 Fr is not wise.

## Incision and Finger Thoracostomy

A routine trauma chest tube should be placed in the fifth or sixth intercostal space (Fig. 6.4). This will roughly correspond to the intercostal space at or just superior to the level of the inframammary crease. Extending the ipsilateral arm of the patient over their head will often reveal a rectangular area of relatively accessible ribs lying along the fifth or sixth intercostal space posterolateral to the pectoral groove at the anterior axillary line and anterior to the soft tissue bulk associated with the latissimus dorsi, which often extends as far forward as the midaxillary line.

Place the incision immediately over the rib inferior to the intercostal space you plan to enter. Bluntly dissect through the subcutaneous tissue and intercostal muscles, spreading the tissue with the tips of a large pair of curved Kelly forceps (Fig. 6.5). Creating a tract through the subcutaneous tissue slightly cephalad and posterior from the skin incision will help direct the tube in the cephalad and posterior direction as it enters the chest.

Fig. 6.4. External landmarks. The *dashed lines* represent the anterior *axillary line* and the superior and inferior margins of the 6th rib. The solid line is the location for our incision.

Fig. 6.5. Blunt dissection through subcutaneous tissue.

Fig. 6.6. Entering the pleura. Note the Kelly forceps held firmly 1–2 cm from the skin to prevent over-insertion.

Place the tip of the closed Kelly clamp against the rib, grasp it approximately 2 cm from the skin surface, and firmly push the clamp over the rib and through the intercostal muscles just superior to the rib (Fig. 6.6). There should be a "pop" or give as the underlying parietal pleura is punctured. Spread the Kelly forceps, actively parting the intercostal muscles just superior to the rib until you can gain entry to the thoracic space with your index finger.

With your finger now in the thoracic space, hook your finger against the parietal pleura, and turn your finger completely around the thoracostomy, ensuring the lung and chest wall are separated and free of adhesions. If the lung is adhered to the chest wall, consider an alternate site for chest tube insertion [11].

## Tube Insertion

Clamp the end of the chest tube to prevent blood spilling on the floor. Slide the tube along the palmar aspect of the finger you are keeping in the thoracic cavity (Fig. 6.7). Pass the tube posterior and superior to the lung. Advance the tube to the depth far enough to ensure the most proximal side port of the tube is well within the thoracic space. Verify the tube is within the thoracic space by feel. Connect the tube to suction or water seal.

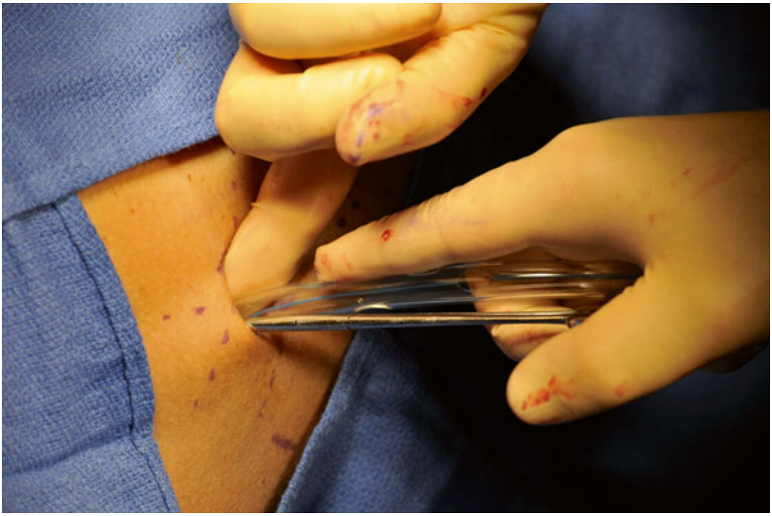

Fig. 6.7. Inserting the chest tube. Slide the tube along the palmar aspect of your index finger, replacing your finger with the tube in the pleural space.

Place a purse-string mattress suture around the tube, and close the skin snugly against the tube, leaving long trailing suture on either end of your knot. Then wrap each end of the suture two or three times around the tube in opposing directions and pull tight. The suture should be pulled tight enough to slightly indent the plastic of the tube; otherwise, the tube will be free to slide in and out of the suture "collar." We entwine the tube with Xeroform gauze and snug this up against the insertion site followed by gauze.

## *Complications*

Complication rates following tube thoracostomy have been reported as being as high as 25 %. By far the most common complication is malposition [13]. Tube malposition is common and has been reported to be as high as 20 % [14]. Incorrect placement can result in a lack of adequate or any drainage from the pleural space or damage to internal organs.

Intraparenchymal placement occurs when the tube is advanced toward a preexisting defect in the lung parenchyma. This can be avoided by fastidious efforts to direct the tube along the chest wall during insertion. Placement in the fissure occurs when the tube is advanced medially.

Over-inserted tubes are often found kinked or bent as the tip of the tube abuts either the apex of the pleural space or the mediastinum. Under-inserted tubes, unless recognized while an entire sterile field is still in place, must be replaced, as advancing a tube will track non-sterile tube into the chest cavity.

Empyema rates following TT for trauma have been reported as high as 10 %. Empyema following TT is almost always caused by skin flora introduced at the time of insertion. The best prevention of this complication is fastidious adherence to aseptic technique throughout tube insertion.

The most likely cause of new hemorrhage as a complication of tube thoracostomy is damage to the intercostal vessels. This can be best avoided by using a blunt dissection technique and by ensuring access is gained immediately over the top of the rib.

## Diagnostic Peritoneal Lavage

### *Intro*

Although falling out of practice in modern day trauma care secondary to the widespread use of ultrasound and CT scans, diagnostic peritoneal lavage (DPL) remains an important procedure. Ultrasound is insensitive to visceral organ injury, and it is within this population of patients which DPL may continue to have a role.

### *History*

DPL was first introduced by H. David Root in the mid-1960s to diagnose occult intra-abdominal hemorrhage in a small population of patients. In his paper, Root demonstrated 100 % accuracy among 28 patients in identifying intra-abdominal injuries [15]. Several important practices were also outlined in Root's paper that would improve the reliability of the procedure, namely, minimizing skin bleeding to prevent contamination of the intra-abdominal contents, peritoneal aspiration prior to lavage to evaluate the presence of gross blood, rocking the patient after lavage and prior to withdrawal to ensure good mixing of the fluid, and lavaging/removing as much as possible. It has been used ever since as a technique to determine the presence of intraperitoneal hemorrhage.

Within the past 10 years, bedside ultrasound has become prevalent in trauma resuscitation bays and has essentially supplanted the use of DPL in the diagnosis of potential hemoperitoneum. The Focused Assessment with Sonography for Trauma (FAST) exam can be done rapidly and safely identifying as little as 100 mL of blood in the abdomen when done by an experienced practitioner [16].

## *Technique*

Primarily used in the setting of hemodynamically unstable trauma patients with blunt abdominal trauma, DPL is a straightforward procedure. There are two primary approaches to DPL, percutaneous or open. Infraumbilical approaches are preferred in all patients except those with pelvic fractures and pregnant women in which the supraumbilical approach is safer to avoid injuring the gravid uterus. Regardless of the technique used, a Foley catheter and nasogastric tube should be placed to decompress the bladder and stomach, respectively, prior to starting the procedure. All supplies should be ready at the bedside.

For the percutaneous procedure: the abdomen is prepped and draped in a sterile fashion. A needle is passed in the midline through the abdominal wall into the peritoneal cavity (Fig. 6.8) in a caudad direction

Fig. 6.8. A needle is advanced through the abdominal wall into the peritoneum.

Fig. 6.9. Guidewire advanced through needle into the peritoneum.

through which a guidewire is advance (Fig. 6.9). The needle is removed and a small incision is made in the skin where the guidewire enter the abdomen. The catheter is then placed over the guidewire and inserted into the peritoneal cavity and the guidewire is removed (Fig. 6.10). A 10 mL syringe is attached to the catheter and aspirated (Fig. 6.11). A bloody aspiration of 10 mL is considered a positive result. If there is an absence of blood, or less than 10 mL of blood is aspirated, 1 L of lactated ringers or normal saline is infused into the peritoneal cavity. To improve the sensitivity, the patient can be tilted, rolled, or the abdomen otherwise maneuvered to encourage distribution of the fluid. Once the fluid is infused, the bag is placed on the ground, and the fluid is siphoned back into the IV fluid bag. The fluid is sent for laboratory analysis.

The open procedure: Again, the abdomen is prepped and draped in sterile fashion. Local anesthetic is used. A midline abdominal incision is made approximately one third of the way between the umbilicus and the symphysis pubis down to the fascia. The fascia is then incised exposing the peritoneal cavity. A catheter is then place through the fascia into the peritoneum, and the following steps are the same as in the percutaneous technique.

Fig. 6.10. A catheter is placed over the guidewire, and the wire is removed.

Fig. 6.11. Aspirate off the catheter with a 10 mL syringe.

Table 6.1. Diagnostic peritoneal lavage—red blood cell criteria.

| | Positive | Indeterminate |
|---|---|---|
| Stab wounds | | |
| Anterior abdomen | 100,000 | 20,000–100,000 |
| Flank | 100,000 | 20,000–100,000 |
| Back | 100,000 | 20,000–100,000 |
| Low chest | 5,000–10,000 | 1,000–5,000 |
| Blunt abdominal trauma | 100,000 | 20,000–100,000 |
| Gunshot wounds | 5,000–10,000 | 1,000–5,000 |

### *Outcomes*

Interpretation of the results is based on immediate return of 10 mL of gross blood upon initial aspiration or a threshold of red blood cells noted in the lavage fluid after laboratory evaluation (see Table 6.1 for laboratory result interpretation).

Currently, the only contraindication to DPL is a previously determined need for laparotomy. Relative contraindications exist, but in general, DPL is well tolerated with few complications. There is no difference in outcome or complications associated when comparing the percutaneous to open techniques [17].

### *Complications*

The most common complications that occur with DPL include local wound infections or dehiscence, bowel, bladder, or vascular injury. Bleeding from the incision can result in a false-positive lavage. Overall complications occur in less than 1 % of patients undergoing this procedure [18].

## Local Wound Exploration

### *Intro*

Severity of penetrating abdominal trauma can be difficult to evaluate. Specifically, determining if a hemodynamically stable patient with stab wounds to the anterior abdomen requires an exploratory laparotomy or CT scan can be difficult. Local wound exploration (LWE) at the bedside can help clarify the depth of injury and guide further management.

## *History*

In 1977 Erwin Thal published the first paper evaluating LWE in combination with DPL for anterior lower chest and abdominal stab wounds. His data was based on 123 patients who had a combination of physical exam, LWE, and DPL and found a reduction in unnecessary laparotomies (69.9 % of patients with negative LWE and DPL were spared) [19].

## *Technique*

The goal of local wound exploration is to fully evaluate the depth of penetrating wounds to determine if the posterior peritoneal fascia has been violated. The use of local anesthetic containing epinephrine should be considered to help maintain a bloodless field for exploration. Each wound should be thoroughly examined at every layer of tissue, and if necessary the wound can be extended to improve exposure which can include the use of retractors or even extending the wound. Once it has been determined that no penetration of the posterior peritoneal fascia has occurred, the patient can be safely discharged home assuming they have no other conditions that require inpatient management. If posterior fascia has been violated, then the next management steps are variable (Fig. 6.12). In a stable patient, CT scan of the abdomen utilizing triple contrast to maximize sensitivity or serial exams is an option.

## *Outcomes*

In a hemodynamically stable patient with abdominal wound that can be evaluated with LWE and determine there has been no posterior fascial penetration, serial abdominal exams are likely the sufficient management. In patients in whom full exploration of the wound is impossible due to depth, tracking, or poor hemostasis, DPL or imaging with CT scanning should be pursued to rule out an intraperitoneal involvement.

Local wound exploration has no role in the hemodynamically unstable patient with penetrating abdominal wounds.

Fig. 6.12. Visualization of a violated peritoneal fascia.

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# 7. Ultrasound for Point-of-Care Imaging: Performing the Various Exams with Technical Tips

*Jacob J. Glaser, M.D. and Sarah B. Murthi, M.D.*

## Introduction

Ultrasound has uses in heavily resourced as well as remote, underdeveloped regions. It is being studied everywhere, even on the international space station [1]. A good working knowledge of ultrasound is essential when caring for trauma.

Focused assessment with sonography for trauma (FAST) is an important innovation in ultrasound, not because it is a technological advancement, but because it redefines who can use ultrasound and when [2, 3]. The FAST establishes the safety and feasibility of using US to diagnose and manage trauma in real time, thus creating the concept of point-of-care (POC) ultrasound. Currently POC ultrasound includes both diagnostic imaging, like the FAST, and ultrasound for procedural guidance, including central lines and percutaneous drains. More advanced Doppler capabilities make US useful as physiologic measurement tool as well. A variety of cardiac exams can be used to guide complex resuscitation from the trauma bay to the ICU [4–7]. Taken together, the US is a portable stethoscope, CT scanner, and pulmonary artery catheter in one.

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## History

Ultrasound has been used in medicine since the 1940s, but the technology was understood long before. In the 1700s an Italian physicist, Lazzaro Spallanzani, first recognized that bats used echolocation. With the improved understanding of ultrasound physics, and the discovery of the piezoelectric effect (the coupling of mechanical and electrical forces allowing the interpretation of ultrasound waves), the ability to use US for diagnostics was born. In 1942, Austrian Neurologist Karl Dussik used an "ultrasonic apparatus" to diagnose brain tumors. In 1948 George Ludwig, an American naval officer, first used US to diagnose gallstones. In 1958 Scottish physician Ian Donald pioneered the use of ultrasound for obstetrics. Through the 1950s US technology advanced, from large machines requiring submersion of the patient in fluid, to smaller devices, to modern handheld ultrasounds [8]. With the increasing access and availability, as well as the decreasing cost, US has spread across medical specialties. With tele-sonography and virtually guided sonograms, this market will only continue to grow [9].

### *Focused Assessment with Sonography for Trauma*

Physical exam after trauma is unreliable, as 20–40 % of patients with intra-abdominal bleeding will have a normal exam [10, 11]. Prior to the use of FAST, diagnostic peritoneal lavage (DPL) or surgical exploration was the primary assessment of intra-abdominal bleeding. In most institutions, the FAST exam has essentially replaced the DPL [12]. In the current, 9th edition of ATLS, DPL has become an optional skill station [13], while ultrasound is considered an adjunct to the primary survey. Early investigators realized that fluid is easy to see on ultrasound and that FAST could be used to rapidly, noninvasively detect blood in the pericardium and abdomen [14–16].

The FAST has four views: subxyphoid (SX), right upper quadrant (RUQ), left upper quadrant (LUQ), and pelvic (P). The EFAST adds anterior lung windows to evaluate for PNX [17]. Some centers have added functional evaluation of the heart and the inferior vena cava (IVC) to the FAST [18, 19]. The FAST is a reliable and repeatable exam, with a compressed learning curve. While experience yields improved accuracy, the ability to perform an adequate exam is obtained after only a few exams [20, 21].

In hypotensive patients with blunt abdominal trauma or precordial wounds, FAST is 100 % specific and sensitive for blunt abdominal trauma and 100 % specific and 99.3 % sensitive for precordial wounds [14, 22]. In a blunt trauma patient with hypotension, a FAST showing fluid is an indication for operative exploration. Absence of fluid makes it unlikely intra-abdominal, thoracic, or pericardial bleeding is the cause of hypotension. For penetrating abdominal trauma, FAST is only 25–56 % sensitive in detecting injury [23]. Furthermore, in stable patients with blunt trauma, FAST will miss up to 30 % of injuries, as it misses isolated visceral injury without significant hemorrhage [24–26]. These patients should get further evaluation—usually a CT scan or serial abdominal exams.

In 2004, Kirkpatrick coined the term EFAST and found that the EFAST was comparable in specificity to CXR but had superior sensitivity (48.8 % vs. 20.9 %) in diagnosing PNX. Other series confirm that US is superior to CXR to diagnose PNX but can fail to detect small pneumothoraces [27, 28].

At the Shock Trauma Center, we perform FAST on almost all patients as a positive FAST in a stable patient can result in more rapid work-up and better triage. We also feel it is necessary screen a high volume of patients to maintain ultrasound skills for trainees.

## *Tips for Learning Ultrasound*

Regardless of the exam being performed, the following tips are suggested:

1. *Getting to know your machine*: This is the most important factor in safely and reliably using ultrasound.
2. *Clean the transducer and keyboard*: Infection control and patient safety are key points that are often overlooked but are critical to patient safety.
3. *Turn the machine on*: All machines will have an on/off or power button. It is useful to keep the machine plugged in during and between uses. Machines left on may run low on battery power, and start-up can take longer.
4. *Enter the patient data*: Learn how to enter patient data and save the study.
5. *Select the transducer*: The appropriate transducer for the desired exam should be selected.
6. *Select the exam type (presets)*: Generally the machine will default to the last exam. Most machines can be set to start in a particular exam type. Again, it is important to know your machine!

7. *Find the gain and depth controls*: Manipulating depth and gain to optimize images.
8. *Get your patience on*: *BE PATIENT*! Even with the FAST exam, slow and steady scanning through more than one plane is very important.

## Pathology in the FAST and EFAST

*Diagnosis of Intra-abdominal Hemorrhage*: Fluid will appear black and collect in dependent portions of the abdomen. It is assumed that "fluid" is blood in a trauma patient; however, it could be ascites, free bladder rupture, or bowel contents (Fig. 7.1). In addition, clotted blood is echogenic and can mimic the appearance of solid organs.

*Diagnosis of Pneumothorax:* Diagnosis of a PNX has a steep but short learning curve. A normal lung on the contralateral side makes comparative diagnosis easier. US cannot penetrate air, so the finding is a *loss* of signal in the potential space between the parietal and visceral pleura of the chest. Normally, the parietal/pleural interface "slides," creating a sparkle or dancing effect, termed *sliding*. Comet tails (also called b-lines) can also be seen. These hyperdense lines originate at the pleural interface and will flash intermittently from the pleural line, almost like a

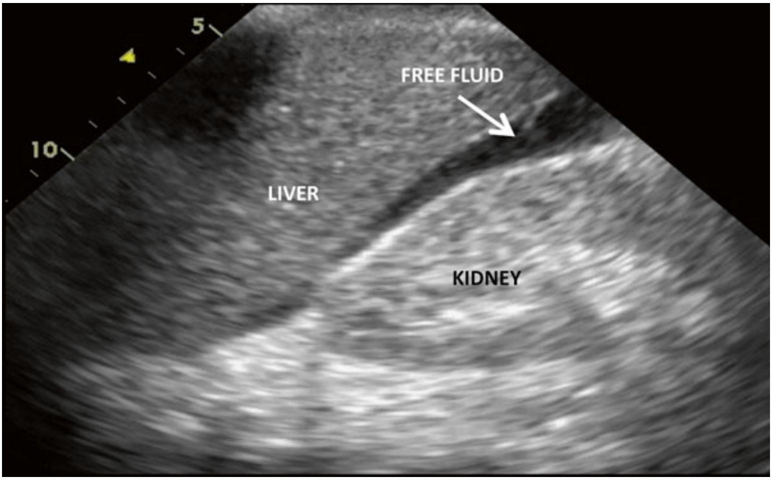


Fig. 7.1. FAST of RUQ with fluid in Morrison's pouch.

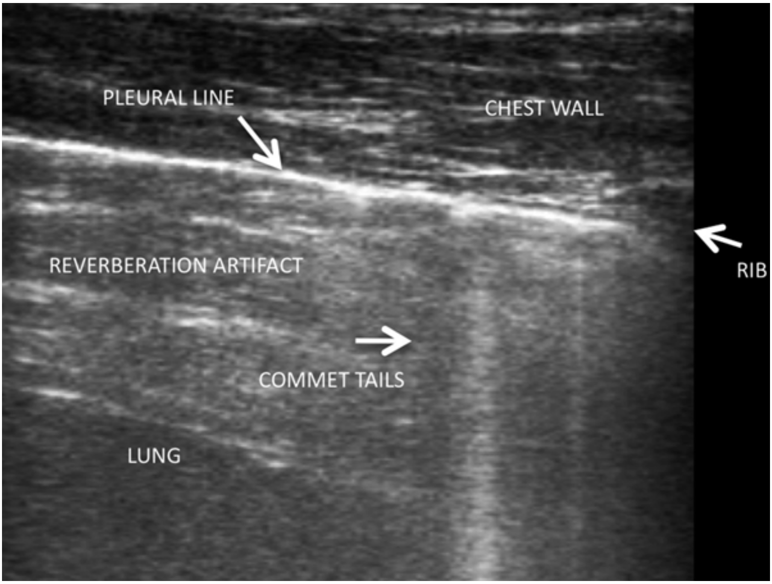


Fig. 7.2. Comet tails demonstrated across a fluid-filled lung.

small flashlight. *Comet tails* (Fig. 7.2) are a reverberation artifact, likely arising from congested pulmonary vasculature in contact with the pleural interface, and can be a sign of pulmonary edema. If pleural surfaces are intact, transmitted cardiac pulsations can be seen on the left side. When a PNX is present, sliding, comet tails, and pulsations are lost. A *lung point* occurs when the transition from sliding to no sliding can be clearly seen; it is 100 % specific for the diagnosis of PNX [29]. Lack of lung sliding alone can be caused by other processes including pneumonia, bullous disease, and other pleural pathologies.

M-mode can help confirm the PNX diagnosis and may be very helpful when initially learning to detect it, but the assessment can be entirely made from 2D imaging. On M-mode, a normal parietal/visceral interface will show the bright line of pleura with a smattering of signal returning to the probe from the lung parenchyma, called *seashore sign.* If air is present from a PNX, it will stop the signal, and instead of seashore sign, there will be a series of horizontal lines sometimes called *barcode* or *stratosphere sign* (Fig. 7.3).

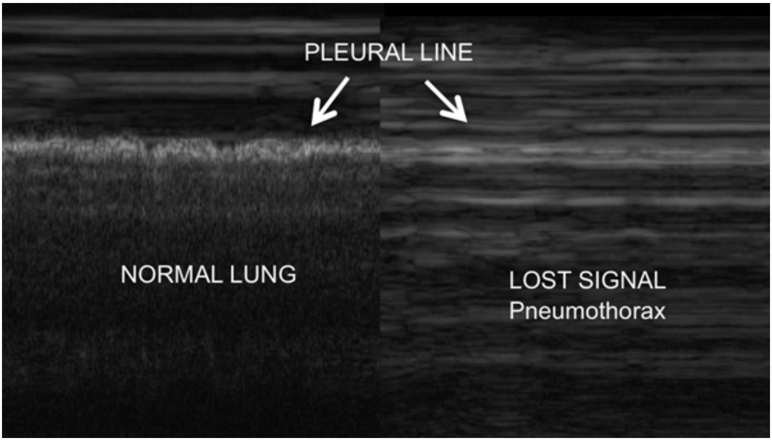


Fig. 7.3. Stratosphere sign (*right*) indicating loss of signal from pleural slide, pathognomonic for pneumothorax.

Summary of FAST (Fig. 7.4)

*Classic FAST Windows*

1. *SX*: The transducer is placed below the xyphoid, with the indicator to the right, and pointed to the left shoulder, attempting to look “under” the xyphoid to the heart.
   *Critical Image*: In the space between the right ventricle and the liver, blood will appear as a black stripe below the pericardial bright white strip (Fig. 7.5).
   PITFALL—in the case of penetrating cardiac trauma, blood can decompress into the chest rendering the pericardial window negative. In this case, thoracic ultrasound (or chest X-ray) will show a hemothorax. Suspicion of a cardiac injury must remain high.
2. *LUQ*: The transducer is moved to the posterior axillary line, below the costal margin on the left side. It may be necessary to press your knuckles into the gurney and orient the transducer anteriorly, as the view can be very posterior. Start at the costophrenic angle and then move caudally until the kidney comes into view. The probe should be fanned across the entire kidney. The space between the spleen and diaphragm should be viewed to avoid missing fluid above it. A simple cephalic sweep allows visualization of the lung fields, but at times the probe needs to be

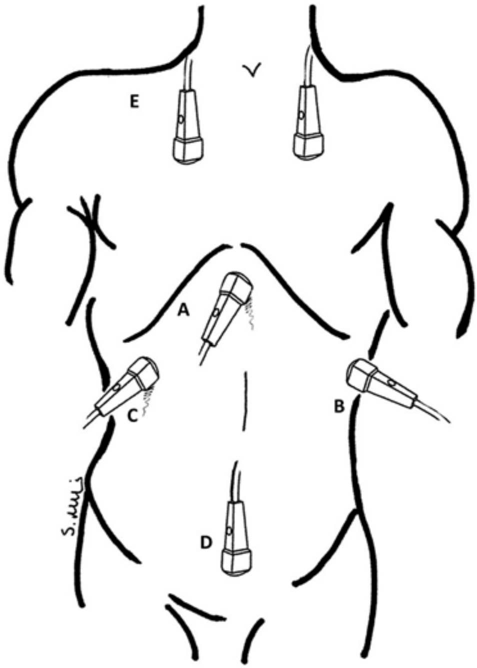


Fig. 7.4. Four transducer views on the FAST exam plus 2 views of the lungs added in the EFAST.

moved to adequately visualize above the liver. Over one or two respiratory cycles, one can easily evaluate for fluid in the thoracic cavity.

*Critical Image*: Fluid will appear as a black stripe above the kidney, separating it from the spleen (Fig. 7.6). The area above the diaphragm fluid will appear as a dark collection above the diaphragm or in the most dependent part of the chest.

3. *RUQ*: The probe is placed along the ribs at the mid-axillary line, oriented vertically as in the LUQ view. The right kidney is more anterior than the left. The liver appears as a homogenous gray, and the fascia of Glisson's capsule is a bright white line. Once the kidney is identified, fanning across the area can reveal any free fluid. Visualizing at the tip of the liver maximizes sensitivity. As with the LUQ, the probe is swept or moved above the liver and diaphragm to look for fluid in the thorax.

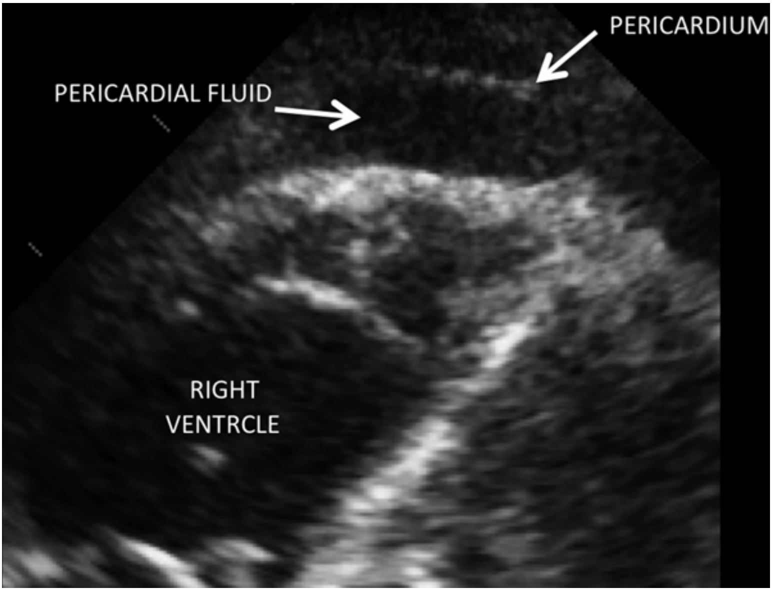


Fig. 7.5. A positive SX view on FAST. Note the fluid between the pericardium and ventricle.

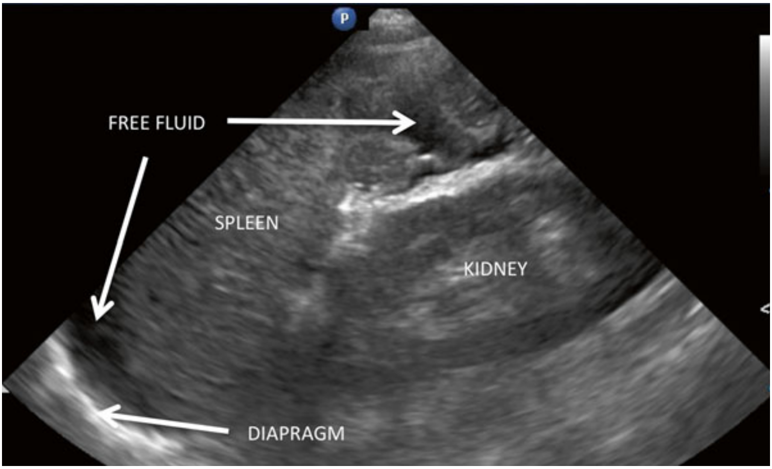


Fig. 7.6. A positive LUQ FAST. Fluid layers between the bright white diaphragm and the spleen.

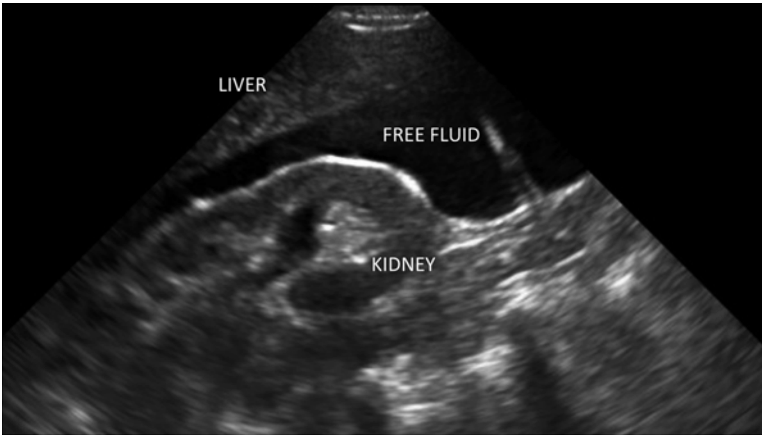


Fig. 7.7. A positive RUQ FAST, with fluid (presumably blood) between the liver and kidney.

*Critical Image*: The potential space between the liver and kidney, and the area above the diaphragm, is for thorax bleeding and blood collecting above the liver (Fig. 7.7).

*Note*: For large amounts of fluid, the RUQ is the best window and will show blood in 75 % of patients with a positive FAST. Perinephric fat, like epicardial fat, can be confused with fluid, but it will generally be gray rather than truly black.

4. *P*: The transducer is placed above the pubic symphysis along the midline abdomen, aiming toward the feet. The groove is oriented to the patient's right. The bladder is identified, and the probe swept across in transverse planes. Longitudinal planes can be added to improve sensitivity. The goal is to evaluate for fluid in the retrovesical space in men (between the pelvic floor and bladder) or pouch of Douglas in women.

   *Note*: The pelvic window is the best window for small amounts of fluid because the retrovesical pouch is the most dependent part of a supine patient; this is especially important in pediatric patients. Small amounts of fluid in women can be physiologic. This window is best obtained with a full bladder. An empty bladder can mimic free fluid.

   *Critical Image*: The potential space above and alongside the bladder. Fluid will appear as a dark collection in the dependent portions of the area (Fig. 7.8).

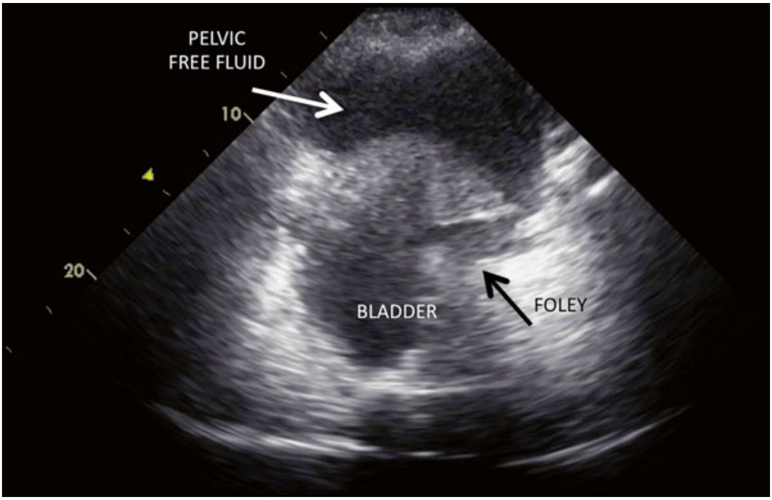


Fig. 7.8. A positive pelvic FAST. Fluid outlines the decompressed bladder. The Foley balloon is often visible in the decompressed bladder.

EFAST (Pneumothorax Evaluation)

5. *R&L Anterior Thorax*: The transducer is moved to the least dependent area of the left and right chest. In a supine patient, this is usually the midclavicular line of the second or third rib. An HF probe can be used, but it is not a requirement. The probe is oriented transversely across the rib. An acoustic shadow artifact makes the rib easy to see. Just below the rib, a shiny line representing the interface of the parietal and visceral pleura can be seen. M-mode can be applied to confirm 2D imaging if available. *Critical Image*: The pleural line of the most anterior aspect of both chests (Figs. 7.2 and 7.3).

## IVC and Cardiac Ultrasound in the FAST

The IVC can be easily visualized from the SX window, by simply fanning over the liver and finding the IVC/RA junction. The probe is then rotated so the IVC is in long axis. Both the diameter of the IVC (< 1 cm, 1–2 cm, and >2 cm or FLAT vs. FAT) and its respiratory variations are reflective of volume status. M-mode can be used to better

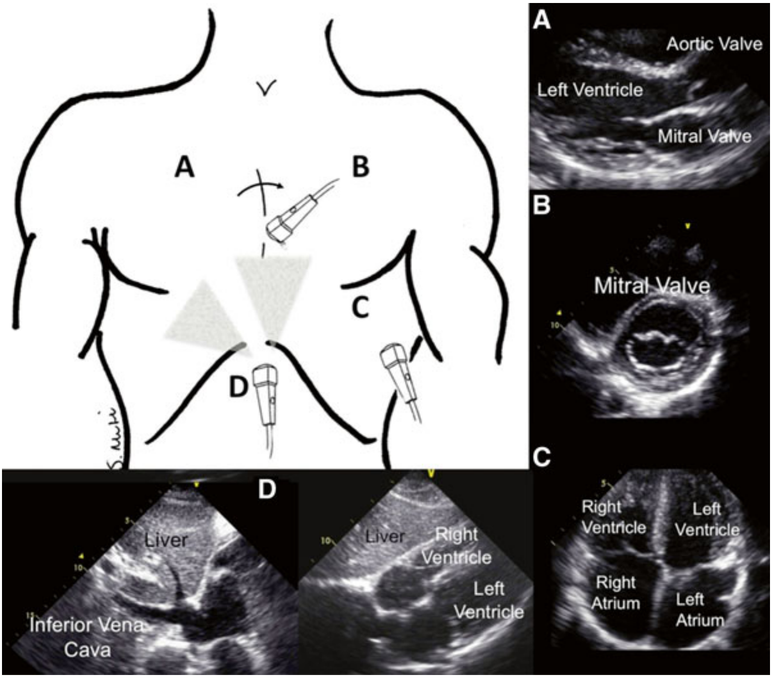


Fig. 7.9. Cardiac views obtained in POC cardiac imaging. (**a**) Parasternal long axis view. (**b**) Parasternal short axis view. (**c**) Apical four chamber view. (**d**) Subxyphoid and IVC views.

quantify both measures. The measurement is relatively easy and has utility in initial fluid management. If the patient is on positive pressure ventilation, it is unreliable.

In about 85 % of patients, the heart can also be well visualized from the SX window (Fig. 7.9d). The parasternal views (Fig. 7.9a, b) are sometimes used to obtain a better image or confirm significant findings. The majority of the time one can place left ventricular function into "depressed," "normal," or "hyperdynamic" categories. The right ventricle can occasionally be assessed as well as "full" or "empty" [6, 30].

## Pearls and Pitfalls of the FAST

- Should be able to be performed in 3–4 min.
- Low-frequency probe (3–5 MHz), curvilinear probe (C), or phased array (PA).

- High-frequency probe for EFAST (optional, can be done with low-frequency probe).
- Performed during the primary survey in an unstable patient and the secondary survey in a stable patient. It should never interfere with resuscitation. The patient is more important than the FAST.
- A negative for fluid FAST does not rule out injury and does not diagnose mesenteric, bowel, retroperitoneal, diaphragm, or solid organ injury.
- The FAST is far less accurate for fluid volumes less than 400 cc.
- The EFAST is more sensitive and specific than CXR in the diagnosis of PNX.
- Repeated FAST exams improve sensitivity and should be repeated with clinical changes.

# Cardiac Ultrasound

## *Background*

The assessment of volume status, responsiveness to fluids, and cardiac function is difficult, especially in the intubated patient. Focused cardiac ultrasound (FOCUS), like the FAST, is performed by the treating physician to answer specific questions. With a 1-day course and a limited number of proctored exams, practitioners can become competent in diagnosing severe LV and RV cardiac dysfunction [6, 31].

The focused rapid echocardiographic evaluation (FREE) is a hybrid between a formal echo and a bedside cardiac ultrasound. The FREE incorporates measurements of cardiac function and volume status, with clinical information, and characterizes hemodynamics [5].

There are four standard windows: the parasternal long axis (PLA), parasternal short axis (PSA), apical (AP), and SX. Echo-based presets will generally orient so that the groove on the right, which is the opposite of the abdominal presets. Familiarity with all windows is important, as each window provides different information. If performing the exam in abdominal or FAST presets, the probe would need to be turned 180°.

## Technique (Fig. 7.9)

1. *PLA*: The transducer is placed to the left of the parasternum from the second to the fourth interspace in spontaneously breathing and fourth to sixth interspace in mechanically ventilated patients. The groove is oriented to the right midclavicular line, and the transducer is gently rocked under the sternum. The LV can be seen in long axis (Fig. 7.9a).
2. *SLA*: The transducer is rotated 90° so that the groove bisects the left clavicle. The LV and RV are seen in cross section. The transducer is rocked up to visualize the aortic valve and then down to see the LV at the mitral, papillary muscles, and the apex. The RV can be seen above and to the right of the LV (Fig. 7.9b).
3. *APICAL*: The transducer is moved to the apex of the heart. This is usually located between the sixth and eighth interspace of the left chest. It is generally lateral (at anterior axillary line) in extubated patients and more medial and inferior in intubated patients. The groove is oriented to the left. Propping the right side of the patient up can improve the view. The LV and RV are visualized. If the transducer is rocked up, the aortic valve can be seen. This view is the best view for comparing the LV and RV (Fig. 7.9c).
4. *SX*: The transducer is moved 2–4 cm below the xyphoid, and the groove is oriented to the left. The transducer is rocked up and under the xyphoid. The RV and LV can be seen. The ventricles are often foreshortened and can appear globular. Pericardial fluid can be seen above the RV. The groove is then rotated up, and the face turned toward the liver to see the IVC in long axis. The IVC diameter and collapsibility can be determined (Fig. 7.9d).

## Future Directions

There may soon be a role for the US in the bedside evaluation of solid organ injury (especially with the use of IV contrast), in the initial work-up of traumatic brain injury (optic nerve sheath diameter may predict ICP), diagnosis of pelvic fracture, diagnosis and treatment of pneumothorax, confirmation of endotracheal tube placement, and assessment of long bone fractures. Ultrasound has been studied as a tool for mass casualty triage, as a triage tool in the prehospital environment, and for providing portable diagnostics in the battlefield or humanitarian environments. US is the only diagnostic modality available on the international space station. With cost pressures, convenience, and risk of ionizing radiation, it seems that US is poised to change the face of diagnostic imaging.

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# Part III
# Techniques in the Neck and Chest

# 8. Trachea, Bronchus, and Esophagus

*Brandon R. Bruns, M.D.*

## Introduction to the Problem

Injuries to the tracheobronchial tree and esophagus are relatively rare in even the busiest urban trauma centers. They most commonly occur in the neck, as the thoracic cage provides protection in the chest. Injuries in the neck tend to lend themselves to easier diagnosis, whereas those contained within the thorax may elude diagnosis for prolonged periods of time and lead to adverse outcome.

### *Tracheobronchial*

Because many patients with tracheobronchial injury expire before arrival to the hospital, the true incidence of the injury burden remains unknown [1]. Several autopsy studies estimate the incidence to be approximately 3 % [2, 3]. Prompt recognition and management of tracheobronchial injury remains paramount because of the physiologic impact that such injuries can cause. Compromise of the major airways can restrict oxygenation and ventilation and thus lead to physiologic collapse. Any sign of major airway injury should lead the trauma team to rapidly search for the anatomic lesion and initiate treatment.

Blunt injuries to the trachea and bronchus are believed to occur as direct impact to the neck, deceleration injuries suffered at fixed anatomic locations (carina and cricoid), or increased pressure within the tracheobronchial tree from blunt force applied to the thorax or abdomen. Blunt injury to the thoracic trachea most commonly occurs within 1 cm of the carina. Due to the high degree of energy necessary to injure tracheobronchial structures, these injuries are typically only a small part of a larger injury burden.

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Fig. 8.1. External injuries after stab wound to neck.

Penetrating injuries to the trachea in the neck are often the result of stab wounds (Fig. 8.1). Stab wounds are typically lower energy and are frequently associated with vascular and esophageal injuries. Attention to exsanguinating vascular injury takes priority in a patient with a stable or protected airway. Penetrating injury to the trachea and bronchus within the thorax is typically due to gunshot wounds and may be associated with cardiac, pulmonary, major vascular, or esophageal injury. Iatrogenic penetrating injury may also occur during invasive tests, tracheostomy, and orotracheal intubation.

## *Esophagus*

Penetrating injury is the predominant cause of esophageal trauma. In a recent series, 26 patients with esophageal trauma were identified over a 15-year time period. Twenty-two of those were penetrating and four blunt, with all blunt injuries occurring in the region of the cervical esophagus [4]. Blunt injuries to the esophagus remain are rare and are often associated with concomitant thoracic injury. Blunt injury occurs as a result of direct force to the cervical esophagus in conjunction with a hyperextended neck, or rarely as result of intraluminal distention secondary to blunt force trauma [5].

A 2013 review of the National Trauma Data Bank sought to better describe the current state of penetrating esophageal injury in the United States. Over a 2-year time period, 227 patients with penetrating injuries to the esophagus were treated at either level I or level II trauma centers. The overall mortality was 44 % and the overwhelming majority of deaths occurred within 24-h. Deaths occurring in the initial 24-h period were the result of concomitant injury, not the esophageal injury alone. In patients surviving greater than 24-h; 62 % had primary repair, 13 % underwent drainage, and 4 % underwent resection. The only predictor of death, in those surviving greater than 24-h, was injury severity score (ISS) [6].

Iatrogenic injury remains the leading cause of penetrating esophageal injury [7]. Nasogastric tube insertion, trans-esophageal echocardiography, flexible and rigid esophagoscopy and various procedures are all potential injurious agents. Therapeutic dilation of the esophagus for various strictures and achalasia remains the predominant cause of iatrogenic esophageal perforation [8].

## History of Care

Given the rare nature of tracheobronchial and esophageal injuries, the majority of discussion consists of case reports and single-institution series. Thus, the principles of treatment remain the same and have not changed in the past 50 years. Diagnostic adjuncts have continued to improve and assist in earlier identification of tracheobronchial and esophageal injury, which may allow more timely surgical intervention.

### *Tracheobronchial*

Kiser and colleagues performed a meta-analysis of the literature from 1873 to 1996, looking specifically at blunt intra-thoracic tracheobronchial injuries. They identified 256 injuries, of which 59 % were the result of motor-vehicle collisions and 27 % were the result of crush injury. The median time to diagnosis was 9-days with 47 % of cases involving the right bronchus and 32 % involving the left bronchus

(52 % of patients with right bronchial injuries and 14 % with left sided bronchial injuries were diagnosed within 24-h) [9].

Investigators at the Ratchaburi Hospital in Thailand reported on 11 tracheobronchial injuries in 10 years (7 penetrating and 4 blunt). Pneumothorax was present in two patients, subcutaneous emphysema was present in three patients, and dyspnea was in four. The authors concluded that a delay in diagnosis was the leading factor resulting in increased morbidity [10]. Similarly, Cassada et al., found that a delay in diagnosis was the single most important factor leading to poor outcome [11].

### *Esophagus*

As diagnostic modalities have advanced, the identification of injury to the esophagus has become easier to accomplish in an expeditious and noninvasive manner. A 1977 report from the Journal of Trauma describes the case of a young man status-post motorcycle collision with multiple injuries, which on the fourth day of his hospitalization manifested with mediastinitis and empyema. Surgical exploration revealed the presence of an esophageal perforation, which was successfully treated with drainage [12]. In the current era of enhanced imaging techniques and the wide availability of invasive procedures for diagnosis, clinicians are able to more quickly recognize and intervene with such lesions.

The management of esophageal injury has remained largely unchanged for the past five decades. Some have sought to define the role of endoscopic stenting in esophageal perforation, finding a greater risk of death with stenting than with surgery [13]. This led the authors to conclude that operative therapy is preferred. Thus, the primary goals of treatment remain: primary repair, wide drainage, and possible diversion if anatomic repair is impossible or physiology is exceedingly altered [14].

## Technique with Personal Tips

Attention to maintenance of the airway, breathing, and circulation is mandatory. Exsanguinating injuries must be rapidly identified and treated and neurologic insults must be addressed expeditiously. Tracheobronchial and esophageal injuries should be addressed next.

## *Tracheobronchial*

Clinical examination can lead the astute physician to suspect injury based on physical findings. Stridor, subcutaneous emphysema, pneumothorax with air leak, and bubbling from epidermal lacerations should increase suspicion of major airway injury.

An adequate airway is essential. A 1999 series from The University of Tennessee Medical Center at Knoxville showed 55 % of patients with tracheobronchial injury were stable on supplemental oxygen alone and did not require urgent intubation [11]. Great caution must be exercised as partial or complete transection of proximal airways can make the procedure difficult or impossible, leading to adverse outcomes. Liberal usage of laryngoscopy and fiberoptic bronchoscopy in this situation will ensure good visualization and assist with placement of a secure airway.

If transection of the trachea occurs in the neck, one may see two visible lumens. In this instance, intubation of the distal lumen with any available endotracheal tube or devise is wise (Fig. 8.2). A surgical airway remains an option in the unstable patient or in patient's unable to be successfully intubated. After ensuring temporary airway, definitive airway management can be established when the patient is stable.

Bronchoscopy and direct visualization of a mucosal defect remain the optimal study for diagnosis of tracheobronchial injury (Fig. 8.3). If bronchoscopy is performed under general endotracheal anesthesia, the clinician must withdraw the endotracheal tube over the bronchoscope to visualize the entirety of the proximal trachea. Bronchoscopy can be performed in either a trauma resuscitation area or an operating room; however, the operating room gives the surgeon the option of additional adjunctive measures as deemed necessary, including operative therapy. Distance from the incisors should be recorded, along with proximity to the carina.

In the patient with major airway injury that requires mechanical ventilation, decreased pressures will lessen the air leak and assist in oxygenation and ventilation. Airway pressure release ventilation (APRV) is a mode of ventilation frequently employed, which allows the patient to comfortably breathe and avoid dis-synchrony with the ventilator. Maintaining the lowest possible pressures to maintain oxygenation is wise.

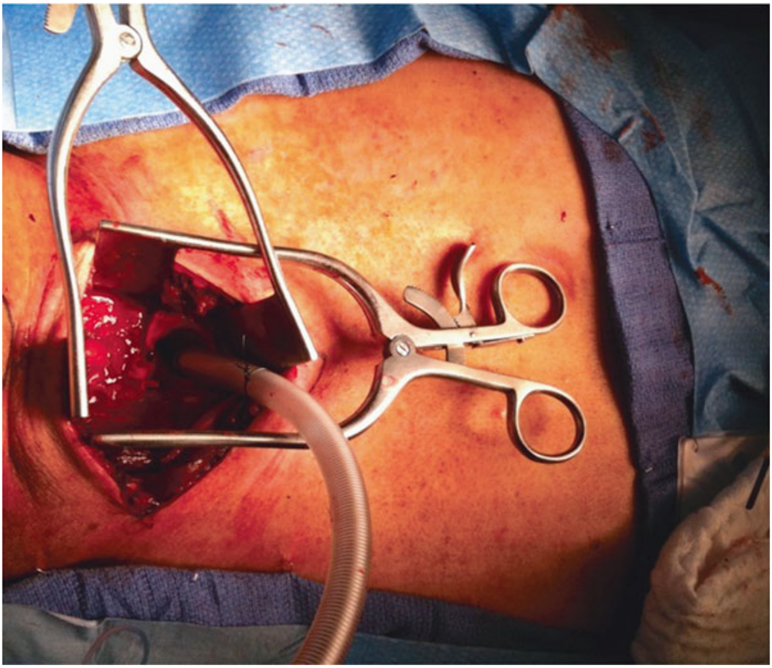

Fig. 8.2. Placement of tubing into distal trachea to facilitate ventilation and oxygenation.

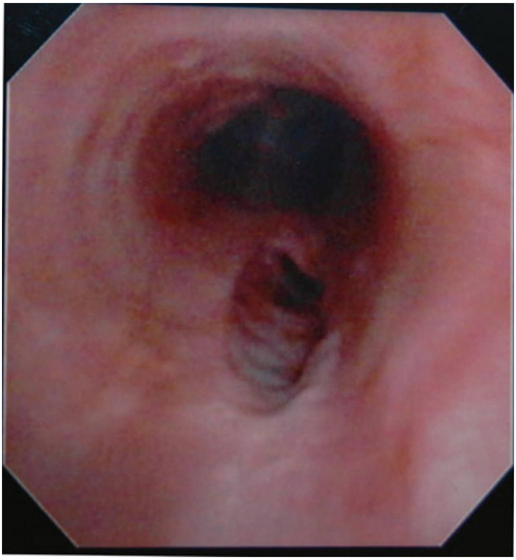

Fig. 8.3. Bronchoscopic view of mucosal injury to trachea.

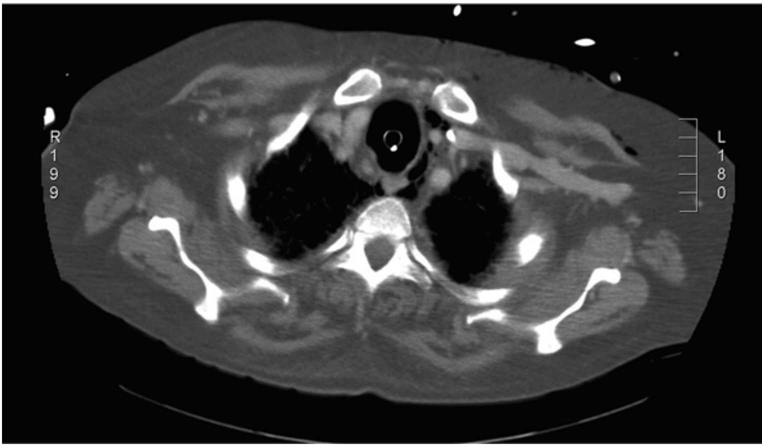


Fig. 8.4. CT showing extra-luminal air and tracheal mucosal abnormality suggesting tracheal injury.

CT imaging can be utilized as an adjunct to evaluate for tracheal injury [15] (Fig. 8.4). CT imaging of the neck offers the advantage of evaluating the vasculature and esophagus, in addition to the central airways. In a retrospective review, Chen et al. found CT to be 85 % sensitive in identification of tracheal injury, and the authors concluded that CT can aid in selecting patients that require bronchoscopy for definitive diagnosis [16]. In penetrating injury, the added advantage of assessing trajectory and determining structures at risk of injury makes axial imaging attractive [17]. In the rare case of suspected tracheal transection after blunt injury, axial imaging in a stable patient with CT may be an adjunct to direct visualization with bronchoscopy [18].

Nonoperative approaches to tracheobronchial injury have been described [19, 20], but operative therapy remains the preferred method of definitive treatment. Initial operative management of tracheobronchial injuries begins with appropriate setup of the operating room and operating equipment. A sternal saw, vascular instruments, and a variety of endotracheal and tracheostomy tubes should be available. Fiberoptic bronchoscopy and appropriately trained anesthesia providers are mandatory. The surgeon should be prepared to perform intra-operative bronchoscopy to assist in identification of the injury. A double-lumen endotracheal tube may be required if single-lung ventilation is desired for a thoracic approach to a bronchial injury.

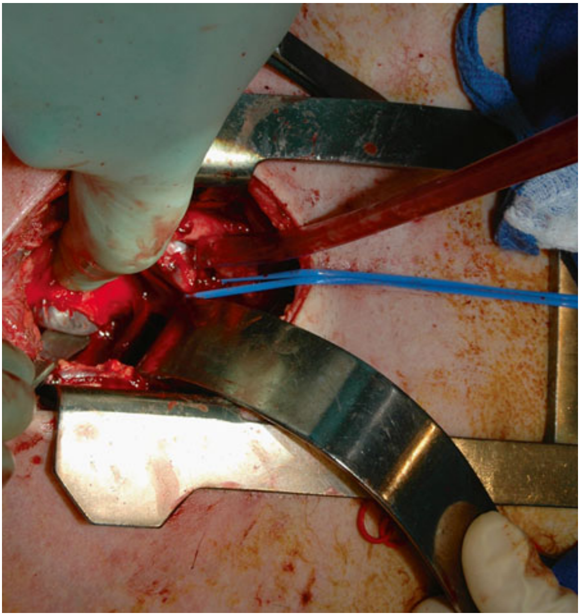

Fig. 8.5. Partial sternal split for evaluation of tracheal injury. The endotracheal tube balloon is visualized emanating from the injury.

Cervical injuries involving the trachea are most easily approached via a collar incision performed in approximately 2-fingerbreadths above the sternal notch. This incision is carried down through the platysma and sub-platysmal flaps are created. The strap muscles are divided in the midline. The thyroid isthmus can then be retracted cephalad to further increase exposure of the trachea as it enters the mediastinum. Alternatively, the thyroid isthmus can be divided. If the injury extends into the mediastinum, a partial sternal split can be performed without performing a full sternotomy (Fig. 8.5). In the face of a concomitant vascular or esophageal injury, the collar incision can be extended superiorly or inferiorly in the plane anterior to the sternocleidomastoid muscle.

The thoracic trachea, right mainstem bronchus, and proximal left mainstem bronchus are best approached via a right posterolateral thoracotomy performed through the fourth intercostal space (Fig. 8.6). Distal left mainstem bronchus injuries are best approached via a left posterolateral thoracotomy. Though lateral decubitus positioning provides optimal exposure of the intra-thoracic tracheobronchial structures,

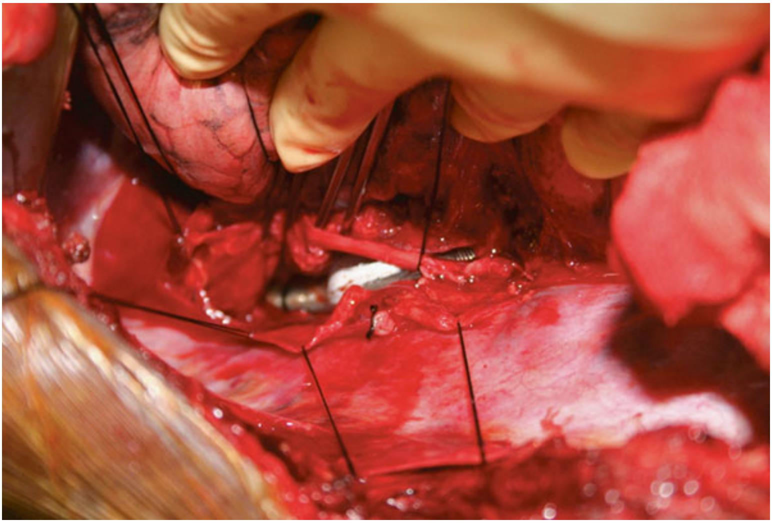

Fig. 8.6. Right posterolateral thoracotomy with mediastinal pleura opened and retracted with silk sutures. The endotracheal tube is seen within the lumen of the injured trachea. The lung is retracted upwards.

the surgeon must recognize that access to other body cavities is exceedingly limited.

Primary repair of tracheal injury is desirable if possible. A single layer of absorbable, monofilament suture is utilized to primarily repair the injury. Running or interrupted sutures can be utilized. Smaller diameter structures are best repaired in an interrupted fashion to avoid narrowing of the airway. Stellate areas should be sharply debrided back to healthy appearing tracheal tissues. Given the mobile nature of the trachea, resection of up to 2–4 cm of trachea with primary anastomosis is feasible (Fig. 8.7) with mobilization. Multiple techniques have been described for tracheal mobilization, including: division of the inferior pulmonary ligament, cervical flexion, and mobilization of the hilum of the lung. If tension is present on the anastomosis after mobilization, the chin can be sutured to the patient's chest. Mobilization of the trachea should proceed in the anterior and posterior planes as the blood supply comes in laterally. Suture lines are preferably buttressed with autologous and well-vascularized tissue present in the region of repair (intercostal muscle, pleura, pericardial, strap muscle (Fig. 8.8), or omental flaps). Occasionally, the tracheal injury is located only in the posterior

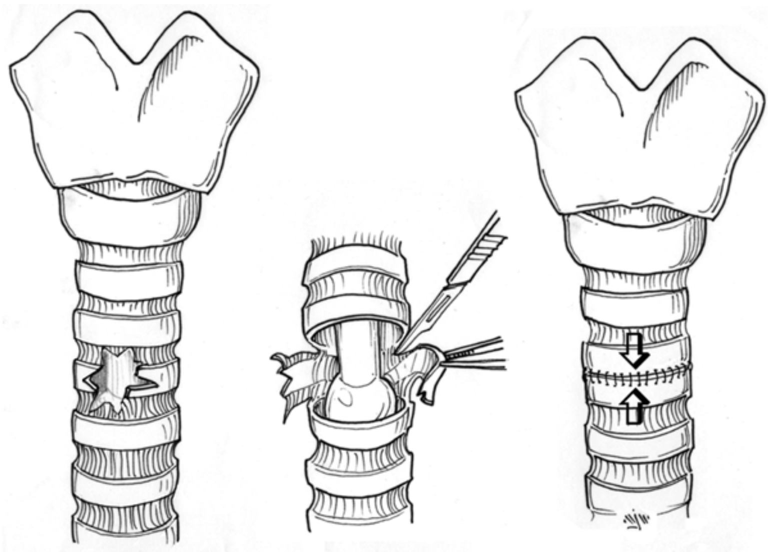


Fig. 8.7. The mobile nature of the trachea enables resection of 2–4 cm with primary anastomosis.

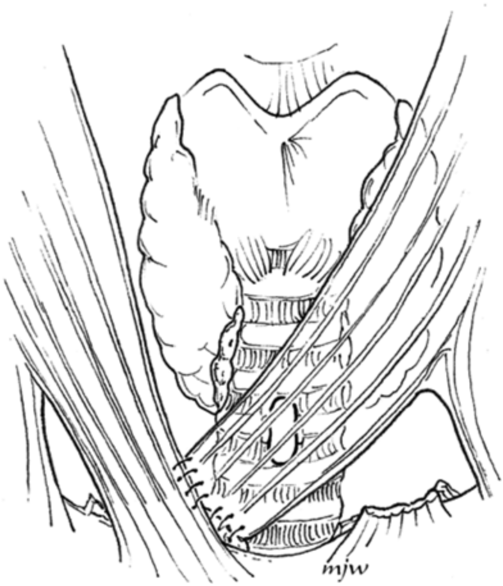


Fig. 8.8. Autologous flap of strap muscle to buttress tracheal injury/repair.

membranous portion. Some can be managed nonoperatively. If repair is necessary, they are best approached by opening the trachea anteriorly. The injured trachea is then repaired from the inside. It is necessary to precisely define the level of injury before opening the trachea. This is best done with intraoperative bronchoscopy. The light from the bronchoscope can be seen via the anterior trachea, making the repair as simple as possible. The endotracheal tube must be withdrawn to allow for adequate visualization of the injury. The maneuver may need to be repeated to be sure adequate oxygenation and ventilation is maintained. The anterior trachea is then closed as described above.

Damage control procedures have also been applied to devastating tracheal injuries with loss of significant length. Investigators at Parkland Hospital described a technique of silicone T-tube placement to bridge a tracheal gap of 6 cm caused by an oblique gunshot wound trajectory. Through the T-tube, an endotracheal tube was placed distally. Eight weeks after the injury, the tracheal injury had healed, without evidence of stenosis [21].

## *Esophagus*

Timely diagnosis of esophageal injury is imperative as missed esophageal injuries can lead to life-threatening sepsis. Given the relatively superficial course of the esophagus in the neck, diagnosis of penetrating esophageal injury is sometimes made on the basis of physical exam alone, as saliva or food particles emanating from the wound are highly suggestive. Diagnosis of thoracic esophageal injury requires a high degree of suspicion and various diagnostic modalities.

Plain film radiography is insufficient to diagnose esophageal injury (Fig. 8.9), but heighten the suspicion. The presence of pneumothorax, hemothorax, displacement of the naso-gastric tube, or mediastinal widening; all suggest a mechanism of sufficient force to injure the esophagus. The pervasive use of computed tomography (CT) in the trauma setting has led many to examine its utility in the diagnosis of esophageal injury. Investigators from the Aga Khan University Hospital showed a sensitivity of 53 % when using CT scan for diagnosis of esophageal injury [22]. In a study from 2006, authors conclude that certain CT findings are suggestive of esophageal injury and include: fluid and air in the mediastinum, subcutaneous tissues, and pleura; dissection of the esophagus; intramural hematoma formation; esophageal thickening; left lower lobe atelectasis [23] (Fig. 8.10).

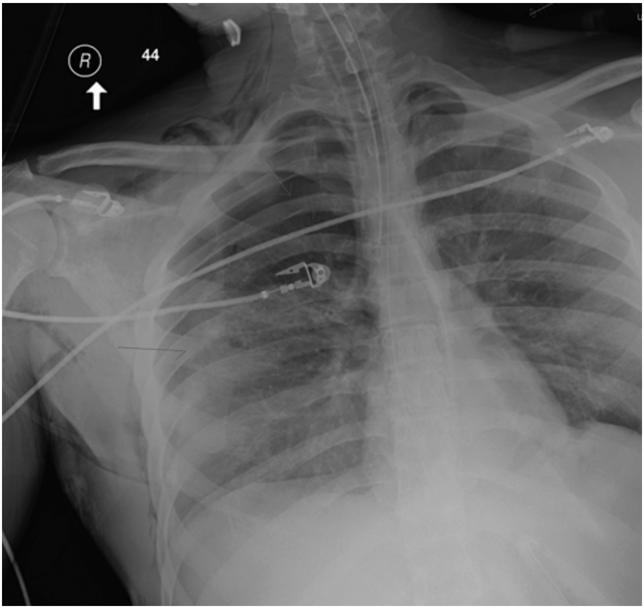


Fig. 8.9. Initial chest radiograph in a patient presenting with left sided chest gunshot wound and tracheal injury.

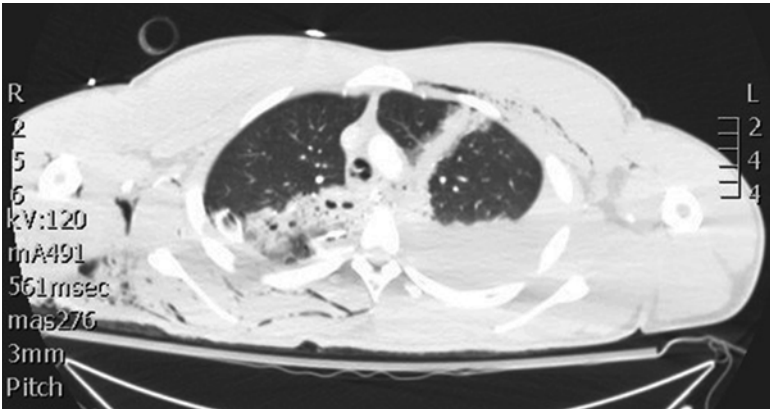


Fig. 8.10. Initial chest CT illustrating the trajectory of the missile, left hemothorax, and subcutaneous/mediastinal air; all suggestive of possible esophageal or tracheal injury.

The gold-standard for esophageal injury remains a combination of esophagoscopy and contrast-enhanced esophagography [24]. Because of its readily available nature and minimal resource utilization, flexible endoscopic evaluation of the esophagus is frequently employed as the initial screening test. However, series have demonstrated a sensitivity of only 38 % for flexible bronchoscopy versus 89 % for rigid [24]. If injury is suspected based on trajectory or mechanism, negative endoscopy should be followed by esophagography with gastrografin, to be followed by thickened barium if gastrografin does not show injury.

Selected nonoperative approaches may be entertained in a limited number of circumstances. A 2013 meta-analysis of studies evaluating management of esophageal perforation demonstrated a 7.3 % pooled mortality for patients managed with esophageal stent, versus 13.8 % for patients undergoing esophagectomy. However, the authors warn about potential selection bias and limited experience with the technology [25].

Operative repair of esophageal injury is the mainstay of treatment. Cervical esophageal injury is best approached via an incision anterior to the sternocleidomastoid muscle on the left. Preoperative placement of a nasogastric tube may assist in identification of the esophagus. The sternocleidomastoid muscle is retracted laterally and blunt dissection commences in a medial direction. Circumferential placement of a rubber drain (Penrose) around the esophagus can assist in retraction. Care must be taken to avoid injury to the recurrent laryngeal nerve along its course in the tracheoesophageal groove.

Thoracic esophageal injury is best approached via a right posterolateral thoracotomy in almost all situations. However, injury in close proximity to the gastroesophageal junction is most accessible via a left posterolateral thoracotomy performed through the sixth or seventh interspace, a thoracoabdominal incision, or a laparotomy. If multiple cavities are to be explored, anterolateral thoracotomy with a bump under the thoracic cage can be utilized. Single lung ventilation, with a dual-lumen endotracheal tube greatly facilitates visualization of the involved esophagus.

The right posterolateral thoracotomy allows good exposure of the majority of the thoracic esophagus. Ligation of the azygous vein and wide opening of the mediastinal pleura enables the surgeon to bluntly dissect the esophagus and facilitates complete visualization and ease of repair. A large diameter rubber (Penrose) drain can be utilized to encircle the esophagus and assist with retraction (Fig. 8.11). Lesions on the left, as the esophagus begins it course through the diaphragmatic hiatus, are approached utilizing similar techniques.

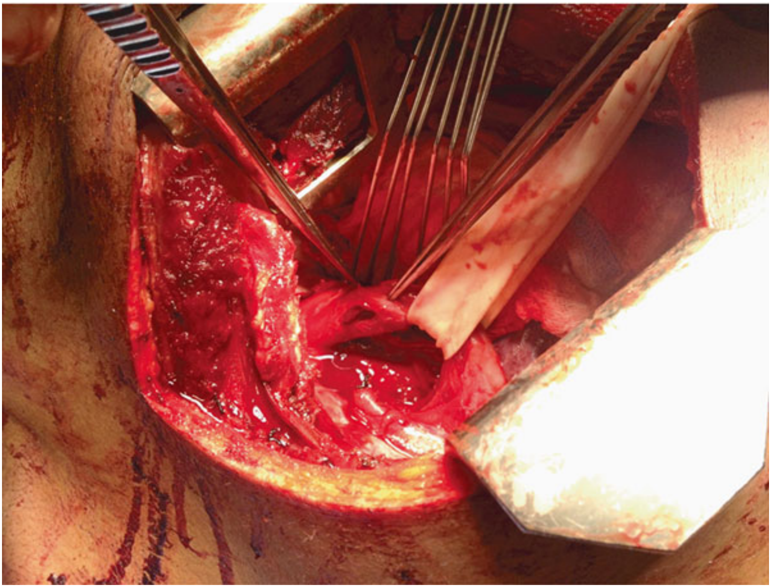

Fig. 8.11. Esophageal injury with esophagus retracted by rubber drain (Penrose) and nasogastric tube visible within the lumen of the esophagus. Exposure was obtained via a right posterolateral thoracotomy.

Primary repair of esophageal injury remains the mainstay of treatment. Sharp debridement of nonviable tissue should be performed. The surgeon must visualize the entirety of the mucosal injury, realizing that mucosal injury can extend beyond the visualized injury seen through the muscular defect. The muscular layer must be opened to ensure that the whole extent of the underlying injury is visualized and repaired. Esophageal repairs are performed in two layers, with an inner (mucosal) layer of absorbable suture followed by an outer (muscular) layer of absorbable, monofilament suture. The linear course of the outer muscular fibers mandates the surgeon place the sutures through this layer at a slight angle to avoid tearing through the fibers. A “mattress” type suture can be employed to ensure adequate repair. Placement of a nasogastric tube or bougie, under direct visualization, may help in preventing stenosis at the site of repair (Fig. 8.12).

In the case of extensive destruction of esophagus, resection of the nonviable tissue with primary anastomosis is sometimes feasible. In cases of severe hemodynamic compromise, copious contamination and

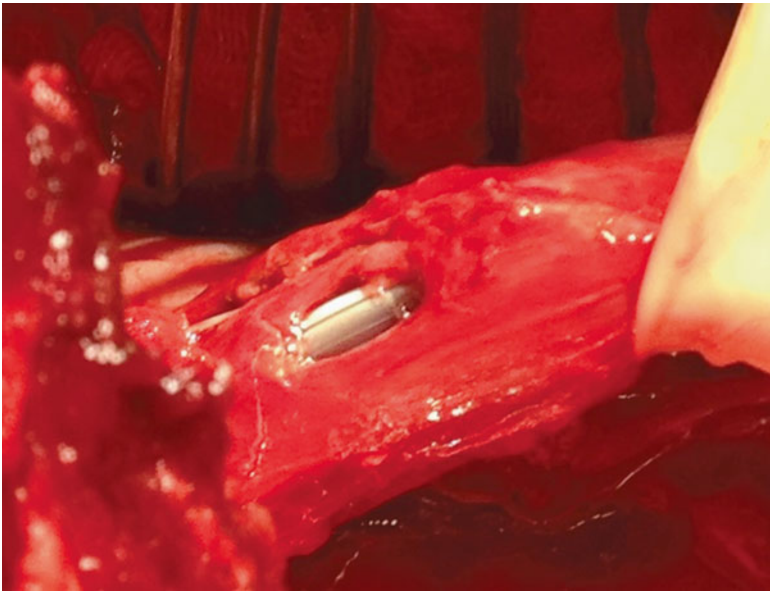

Fig. 8.12. Nasogastric tube within the injured esophagus to help prevent repair stenosis.

surrounding inflammation, or extensive destruction of the esophagus; damage control principles should be employed. Wide drainage of the area with thoracostomy tubes, in combination with closed-suction drains, should be utilized. Additionally, we have successfully managed these destructive lesions with retrograde drainage via trans-gastric tubes which then exit the patient's abdominal wall in combination with nasogastric tube drainage and exterior drainage via thoracostomy tubes and closed-suction drains (Fig. 8.13).

Primary repairs and esophageal resection with anastomosis should have the suture line protected with vascularized tissue to prevent anastomotic failure. Intercostal muscle, pleural, pericardial, and omental flaps can all be fashioned in a rather expeditious fashion. We employ wide drainage of the repair with thoracostomy tubes and closed suction drainage catheters. At least one drainage tube is left in place until the patient has undergone a contrast-enhanced imaging study that verifies no leak and begins to tolerate a PO diet without evidence of increasing output from the drainage tube.

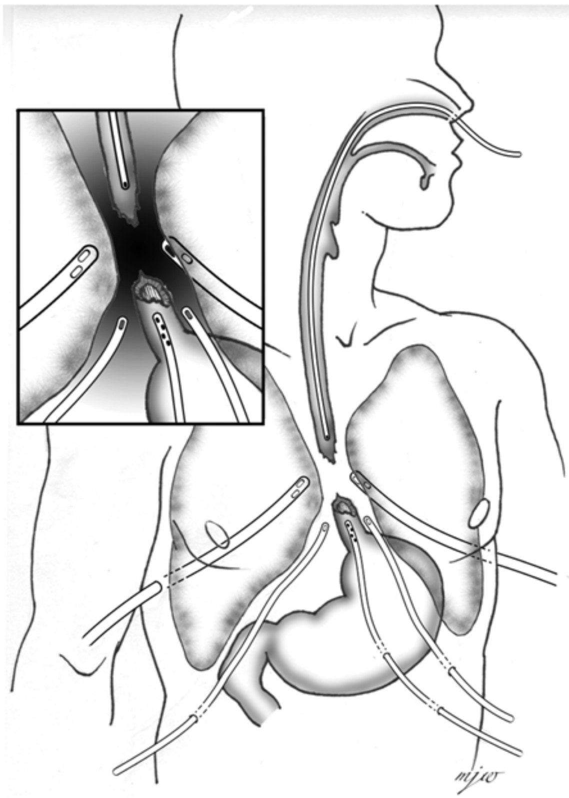


Fig. 8.13. Esophageal destructive injury drained via retrograde trans-gastric tubes, thoracostomy tubes, nasogastric tubes, and closed-suction drains.

Distal enteral access after esophageal repair, resection, or damage control is important, as the patient will remain NPO for a substantial amount of time. To avoid additional surgical access into the enteric tract, a naso-jejunal feeding tube placed under direct visualization at the time of initial operation may be preferred. Additionally, a gastrojejunal tube can be placed at the time of initial operation. This tube has the added benefit of gastric decompression, while allowing feeding distal to the ligament of Treitz. Another option remains a surgically placed jejunostomy tube.

Our practice is to image all repairs at 7–10 days postoperatively with a contrast-enhanced swallow study or via contrast given via a naso-esophageal tube. Initially, gastrografin is administered, which is followed by barium if no leak is evident on gastrografin-enhanced imaging. After the imaging study, the patient is allowed to take PO feeds and the drain output is monitored.

## Outcomes

The scarcity of tracheobronchial and esophageal injury limits the data available for true outcome analysis of such injuries. Multi-institutional studies performed over prolonged periods of time occupy the majority of the outcomes literature. This heterogeneity in patient population, and potentially management strategies, makes evaluation of long-term outcomes difficult. Studies have shown the risk of death to be significantly lower in the acutely injured patients cared for at a trauma center versus a nontrauma center [26].

### *Tracheobronchial*

Morality among patients with tracheobronchial injury has decreased greatly, with published mortality of 36 % before 1950 decreasing to 9 % in the era after 1970 [9]. In the absence of associated injuries, most patients undergoing major tracheobronchial injury repair or reconstruction will return to their baseline functional status, with minimal morbidity [27, 28].

### *Esophagus*

A 2013 analysis of trauma patients in Pennsylvania examined 231,964 patients and found 327 (0.14 %) with injury to the esophagus. Investigators found that patients with esophageal trauma were significantly more likely to die than those that did not incur esophageal injury. Higher morbidity and mortality were observed in thoracic esophageal injury versus injury occurring in the cervical portion [29].

### *Tracheobronchial*

Described complications of tracheobronchial trauma include postoperative suture granuloma, pneumonia, and surgical site infections [27].

Suture granulomas can be approached and treated using bronchoscopy and laser therapy [28]. Pneumonia is best managed with initiation of antibiotics after culture of bronchial secretions with rapid de-escalation of antibiotic therapy upon identification of the responsible microbe. Surgical site infections are managed with antibiotics and drainage.

Postoperative management of tracheobronchial injuries centers around rapid wean from the ventilator and minimizing intra-thoracic pressures. Anastomotic breakdown is the predominant concern in the postoperative period. If tracheal resection was performed or there is any concern of anastomotic tension, a stitch placed from the patient's chin to the soft tissue overlying the manubrium will allow healing and decrease strain on the repair. Repeat bronchoscopy at 7–10 days post-repair will enable visualization of the repair and verification of proper healing.

The identification of a significant postoperative air leak may herald the presence of a bronchopleural fistula. Management centers on decreasing intra-bronchial pressures and minimizing the plateau pressure. Nonoperative management is often followed by bronchoscopic techniques, or operative re-exploration.

## *Esophagus*

The most dreaded complication after esophageal injury and repair is anastomotic failure and leak. Leaks in the neck are readily identified by physical examination. The appearance of erythema, induration, pain, and occasionally the extrusion of esophageal contents or purulence onto the skin; signal that the anastomosis or repair may have failed. CT imaging may be useful to assist in diagnosis when not clinically evident. An unexplained leukocytosis, fever, or general malaise may indicate a dehiscence of the repair. Cervical leaks, though troubling, are easily accessible surgically and are amenable to wide drainage and irrigation. Rarely, cervical esophagostomy is required, but this remains low on the list of preferred interventions.

Thoracic esophageal leaks pose a much greater threat to the patient, as they are not easily accessible and jeopardize the pleural space and mediastinum. Leaks commonly manifest after an indolent course with fever, respiratory insufficiency or ventilator-dependent respiratory failure, leukocytosis, and a global failure to progress and clinically improve. Chest radiographs can give some suggestion as to the status of the repair, but contrast-enhanced swallow studies or chest CT remains the mainstay of diagnosis. Chest CT is able to evaluate pleural pathology and characterize the presence, or absence, of an empyema.

Treatment of esophageal leak is drainage (for this reason, we leave the drainage tubes until the patient tolerates a PO diet without difficulty), whether surgical or via interventional radiologic techniques. The patient is left NPO and continued on enteral feeds via the distal access obtained at the time of initial operation. Re-operation with primary repair or muscle buttress of the leak is sometimes necessary, but is technically difficult given the adhesions and inflammatory reaction that are invariably present. In the patient who is not deemed an operative candidate, attempts at endoluminal stenting can temporize the situation [30].

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# 9. The Lungs

*Joseph Rabin, M.D.*

## Introduction

A majority of patients with chest trauma, from either penetrating or blunt injury, can be managed nonoperatively with either observation or a chest tube [1–3]. When surgery is indicated, the purpose of pulmonary resection is to either control lung bleeding or excise injured tissue [4]. Patients who require thoracotomy following blunt trauma often have more severe injuries requiring a more complex operation and are associated with higher mortality [1–5].

Indication for urgent or emergent thoracic surgical exploration includes shock with a penetrating thoracic injury, chest tube output in excess of 1,000–1,500 cc after chest tube placement, continued chest tube output or ongoing bleeding greater than 200–300 cc/h, massive air leak, and cardiac tamponade [2, 6]. High chest tube output is indicative of continued bleeding that requires surgical control while large air leak is concerning for a major tracheobronchial injury. Bronchoscopy is often necessary to completely or thoroughly evaluate a major airway injury in order to help plan the appropriate operation and incision. Up to a third of patients who require thoracotomy for traumatic hemorrhage will also require a pulmonary resection [1]. Managing patients with severe chest trauma requires an understanding of thoracic surgical procedures, which can be effectively employed in unstable actively bleeding patients. The first issue is to determine what incision or approach should be utilized and the second consideration is to determine what procedure should be performed.

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## Incision

There are various options available for surgical exposure, and it is important to be familiar with the advantages and limitations associated with each approach. The thoracic incision that is ultimately utilized should be versatile enough to address potential injuries in adjacent locations including the neck and abdomen [7]. While covered elsewhere, a few comments may be helpful.

### *Anterolateral Thoracotomy*

This incision is rapid, avoids the time-consuming positioning associated with the traditional posterolateral thoracotomy, and does not require a sternal saw. It provides excellent exposure to the anterior hilum. This incision is the most common approach to the patient in extremis undergoing a salvage resuscitative procedure. It is also utilized in patients undergoing an exploratory laparotomy who decompensate and necessitate an emergent thoracic exploration. Finally, this incision permits an extension into the contralateral hemithorax providing wide exposure of both hemithoraces and the anterior mediastinum (clamshell thoracotomy). Limitations include limited exposure of the posterior mediastinum especially the esophagus, aorta, and posterior aspect of the lung.

The inframammary crease is the landmark for the incision. The pectoralis muscle is divided followed by the intercostal muscles within the desired interspace, often the fourth or fifth. The internal mammary artery and vein are in close proximity to the sternum, and they should be preserved if possible.

### *Bilateral Anterior Thoracotomies*

Also known as a clamshell thoracotomy, it is performed by starting with an anterolateral incision and extending it across the midline. It provides wide exposure of the anterior mediastinum, bilateral lungs, and pleural cavities. It does require either a Lebsche knife, sternal saw, or Gigli saw to divide the sternum horizontally. Retractors are placed to enhance exposure. This incision requires the identification and ligation of both internal mammary vessels.

## *Posterolateral Thoracotomy*

This is the classic incision utilized for thoracic surgery and provides the best exposure of the thorax, especially the entirety of the lung. It does require more extensive preparation. It should only be utilized if the patient is hemodynamically stable, and the injury is confined to a single hemithorax [8]. Correct positioning of the patient is essential and includes lateral positioning with the iliac crest at the level of the table break and rolls or an inflated bean bag to assist in stabilization. An axillary roll should be placed, while bending the lower leg to about a 90° angle, keeping the upper leg straight with a pillow in between. The upper arm is placed up toward the head, flexed at the elbow, and secured to an arm rest. Often one lung isolation is required and achieved with either a double lumen endotracheal tube or bronchial blocker placed by anesthesia. The bed is flexed to help expand the intercostal spaces.

The incision extends from the level of the mid-scapula in between its edge and the spinous processes, swinging down and anterior through a point about 2–3 cm below the tip of the scapula and then anteriorly to the anterior axillary line and into the inframammary fold as needed. The latissimus dorsi muscle is then divided. The serratus anterior muscle is identified, and the adjacent fascia divided in an attempt to preserve this muscle. A scapula retractor is utilized to elevate the scapula and help identify the desired interspace by counting the ribs. The thorax is entered in the desired interspace by dividing the intercostal muscles with the electrocautery in a posterior to anterior direction along the superior edge of the inferior rib. A Finochietto retractor is then inserted and carefully opened.

All incisions are closed after placing chest tubes, which are taken out through separate stab incisions and secured to the skin. The ribs are reapproximated with interrupted intercostal sutures. The muscles are sutured to the adjacent fascia, followed by a subdermal and skin layer.

## *Sternotomy*

This incision provides excellent exposure to the anterior mediastinum for quick access to the heart, great vessels, pericardium, and thymus. Thus, it is not a primary incision for pulmonary injuries. Injury to the lung may occur with an injury best repaired via a sternotomy. It does provide adequate exposure for many pulmonary procedures except for access to the left lower lobe.

The standard incision is from the jugular notch down to the xiphoid process. The ligamentous tissue just superior to the jugular notch should be divided with electrocautery, and the retrosternal space bluntly mobilized digitally. The midline of the sternum is identified, scored, and then divided with a sternal saw while respirations are temporarily held. After inspecting the sternal edges and controlling the sternal bleeding, a sternal retractor is placed. After placing chest tubes, the incision is often closed with sternal wires to reapproximate the sternum and Vicryl suture in layers for the soft tissue.

## Operative Technique with Personal Tips

Emergent thoracic trauma cases present challenges to achieving the isolated lung ventilation routinely employed in elective thoracic surgery. However, in patients who can be temporarily stabilized, placing a double lumen tube can be very helpful. Having an experienced anesthesia team helps keep time to a minimum. However, most operations in the trauma setting are performed with a single lumen endotracheal tube in patients with tenuous respiratory function. Temporary holding of ventilation and manual compression of lung parenchyma are some techniques that may facilitate the surgeon in overcoming this challenge of the lack of isolated lung ventilation [7].

Once the chest is entered, accumulated blood should be cleared and the injury assessed. The inferior pulmonary ligament should be divided to give maximal mobility to the lung (Fig. 9.1). Associated chest wall and/or vascular injuries should be identified before a definitive plan is made. One should assess the adequacy of exposure. If exposure is not adequate, the incision should be widened and/or a counter incision made to facilitate adequate exposure. If a sternotomy has been used, anterolateral thoracotomy should be considered. If an anterolateral thoracotomy has been used, converting to a clamshell should be considered. One should avoid struggling through an inadequate incision.

Formal pulmonary resections for trauma such as lobectomy and pneumonectomy are associated with high mortality rates. Other less morbid "lung-sparing" techniques have evolved and include pneumonorrhaphy, tractotomy, and non-anatomic pulmonary resections. These less extensive procedures often utilize staplers, have shorter operative times, decreased blood loss, and less parenchymal loss, all of which may

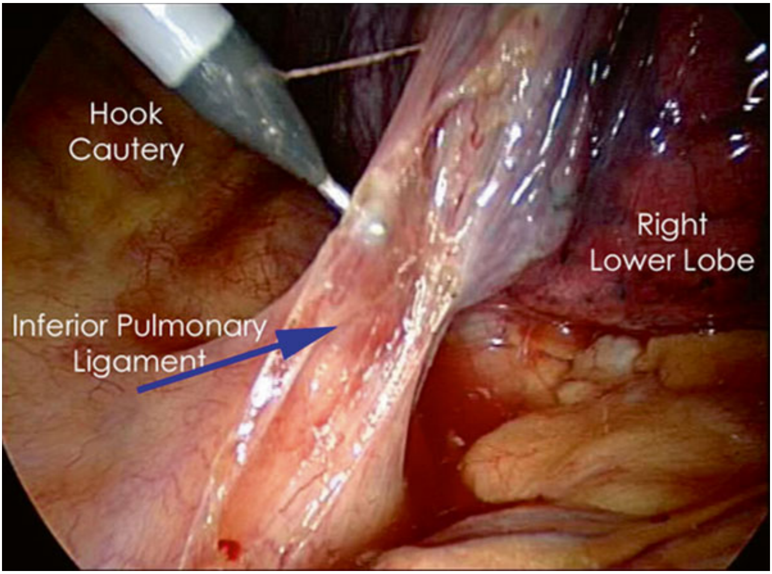


Fig. 9.1. Dividing the inferior pulmonary ligament. Copyright 2009, used with permission from CTSNet (www.ctsnet.org). All rights reserved.

contribute to improved outcomes [9, 10]. One should still be familiar with all the possible surgical options but be prepared to perform a more extensive resection if lung-sparing attempts fail [11]. When performing any type of lung procedure, adequate exposure is essential. This is accomplished by choosing the most appropriate incision as described earlier and by complete mobilization of the lung after entering the thoracic cavity. This includes lysing any pulmonary adhesions [7].

## *Pneumonorrhaphy*

This is a common technique in which hemostasis is achieved and air leak sealed by direct suturing of the actively bleeding pulmonary injury (Fig. 9.2). A running locked suture technique can be employed to help achieve hemostasis [12]. This should only be utilized on peripheral superficial pulmonary injuries. Entry and exit injuries from penetrating wounds should usually not be oversewn since hemostasis may not actually be achieved. The risk is that only visible bleeding may be controlled while active hemorrhage may remain hidden, with continued, uncontrolled bleeding into the underlying pulmonary parenchyma risking the

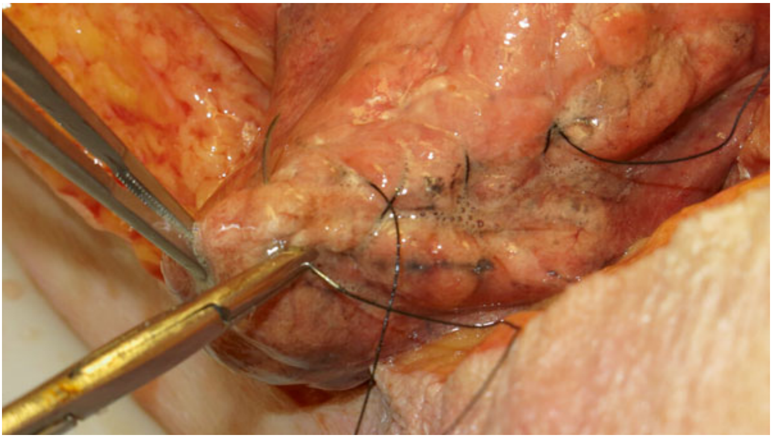

Fig. 9.2. Pneumonorrhaphy.

formation of an intrapulmonary shunt, bronchopulmonary fistula, aspiration, pneumonia or infection, and ARDS respiratory failure [2, 9, 13, 14].

## *Tractotomy*

This is a technique to rapidly control deep pulmonary parenchymal bleeding that does not involve the hilum or central bronchial vascular structures. It helps avoid a pulmonary resection, which was historically performed for such injuries, thus preserving lung tissue, while preventing retention of a parenchymal hematoma [1, 11, 14, 15]. The sites of the entry and exit wounds are identified, and lung clamps are placed along the injury tract (Fig. 9.3). A GIA or TA stapler is placed through these openings and fired, which opens the injury tract. Bleeding vessels and injured airways are identified and ligated with absorbable suture. After controlling bleeding and air leaks, the pulmonary tissue can be closed with a running locked suture, or if feasible, the edges can be stapled [8, 12, 14, 15].

Patients treated with tractotomy often have shorter operative times and lower blood loss relative to formal lung resection. These patients also have less severe hypothermia and coagulopathy. If while performing a tractotomy it becomes evident that bleeding cannot be adequately controlled, often due to a more central injury location, conversion to a more extensive resection should be considered early [13].

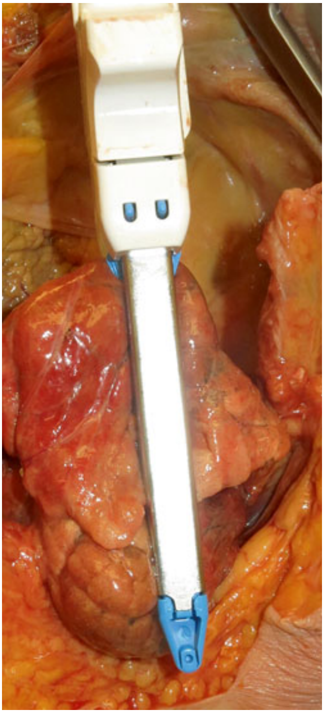

Fig. 9.3. Tractotomy: A GIA stapler placed through the entry and exit wound sites.

Postoperative complications include bleeding and respiratory failure. Bleeding may either be by surgical or secondary to coagulopathy and should be carefully assessed by the surgical team. These patients also need aggressive postoperative pulmonary toilet due to the common occurrence of atelectasis and lobar collapse, which may also require repeated bronchoscopy for secretion clearance to maintain adequate parenchymal aeration [15]. An increased risk of infection has also been reported for those treated with tractotomy [10]; however, this data is limited.

## *Wedge Resection*

These are small non-anatomic lung resections of peripheral injuries with surgical staplers [1] with the goal of minimizing the amount of resected normal lung parenchyma. These less extensive non-anatomic

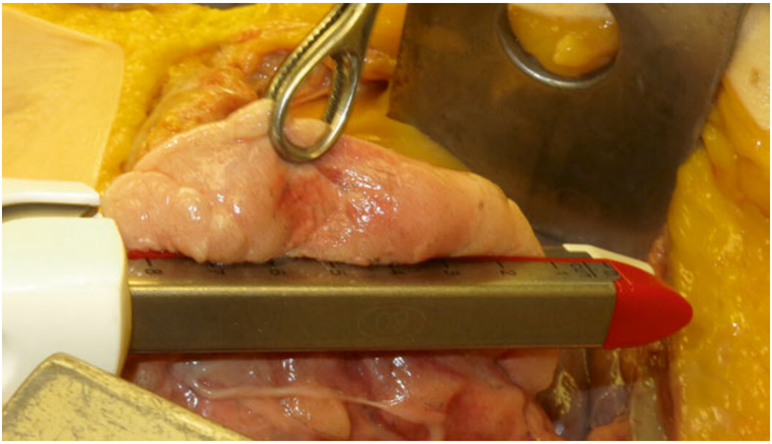

Fig. 9.4. Right lower lobe wedge resection with GIA stapler.

resections should be utilized when possible to help avoid the associated morbidities of a formal anatomic lobectomy in a trauma setting [9, 10].

The procedure is often straightforward and is performed by firing a linear cutting stapler across the lung tissue, just under the damaged parenchyma requiring resection which is stabilized with a lung clamp (Fig. 9.4). The staple lines should then be inspected to insure no air leak and with adequate hemostasis [16]. If necessary, the staple line can be reinforced with an additional firing or be oversewn.

## *Anatomic Resection: Lobectomy and Pneumonectomy*

This procedure is usually reserved for central injuries or extensive lobar involvement involving a complex injury that cannot be managed via limited resection [4, 13]. Most anatomic resections are for hemorrhage control, major bronchial injury, a hilar injury, or significantly damaged lung parenchyma in which lung salvage is not feasible. In a case of extensive parenchymal injury isolated to one lobe, it may be managed with a formal lobectomy. This may be performed in a standard anatomic approach or in a more expedited stapled fashion. Anatomic resections have been utilized more often for injuries in proximity to the main pulmonary artery or when stapling was not considered a viable safe option while stapled lobectomies were often performed in patients

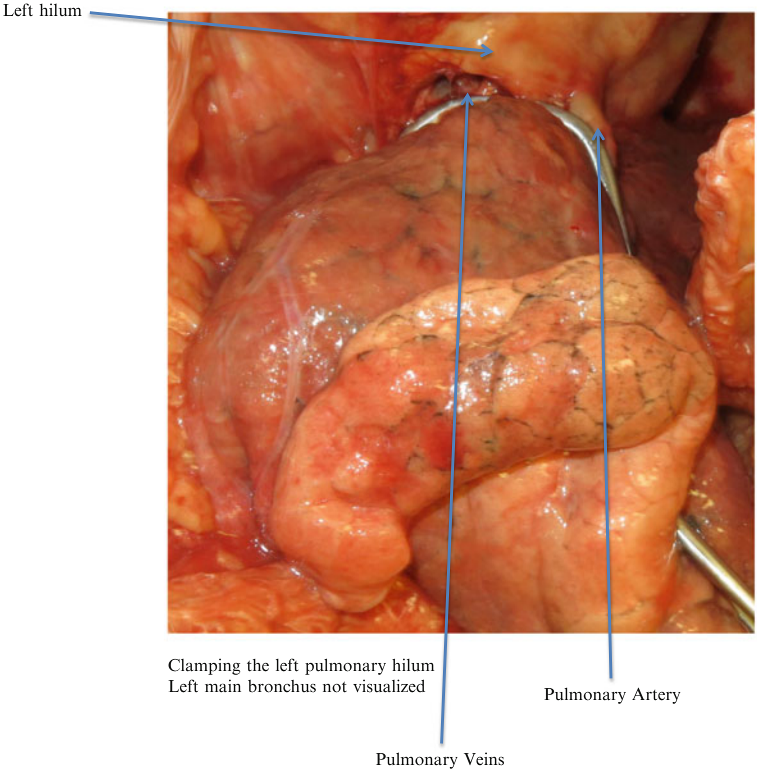


Fig. 9.5. Clamping the left pulmonary hilum. Left main bronchus not visualized.

who were more unstable and following blunt trauma [10]. A major hilar injury with resulting hemorrhagic shock may require a pneumonectomy. Control of hilar bleeding is challenging and some techniques that have been utilized include manual compression of the hilum, clamping the hilum en masse, and lung twisting (Figs. 9.5 and 9.6). Proximal hilar injuries may require opening the pericardium in an attempt to achieve vascular control [7] (Fig. 9.7).

Ideally, the pulmonary artery and vein branches are individually isolated and ligated, often with a vascular load of a stapler. Suture ligation with vascular sutures can also be used. The main stem bronchus is then also stapled, taking care to leave a short stump. If the patient is in extremis, the entire lobe may be resected en masse with a stapler (Fig. 9.8).

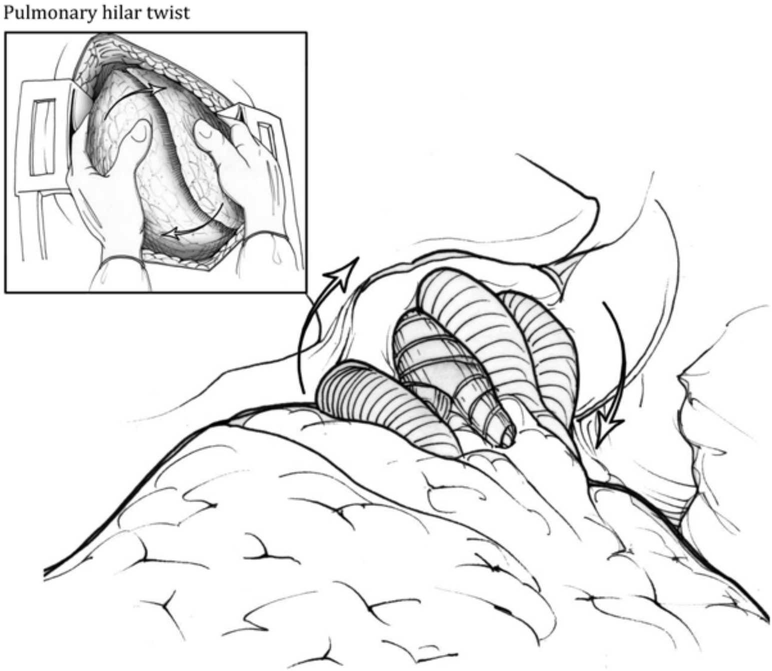


Fig. 9.6. Pulmonary hilar twist. The pulmonary hilar twist being performed by rotating the upper and lower lobes clockwise thereby occluding the proximal pulmonary vasculature.

If possible, we prefer to cover the bronchial stump closure. This is desirable in the event of lobectomy but we feel more strongly if a pneumonectomy has been performed. Many options exist. Mobilizing an intercostal muscle is the easiest and is usually bulky enough to provide coverage (Fig. 9.9). A tongue of pericardium or diaphragm also can be used (Fig. 9.10). It can be made as large as needed. Finally, either a latissimus dorsi or pectoris flap can be used. These are bulky and provide the best coverage.

Trauma pneumonectomy is associated with significant postoperative morbidity and mortality often associated with right heart failure due to an acute increase in pulmonary vascular resistance. The most important decision is to decide to do the pneumonectomy early. Acute right heart failure, while common, can be minimized if the procedure is performed early, before the patient is in refractory shock. We often begin supportive

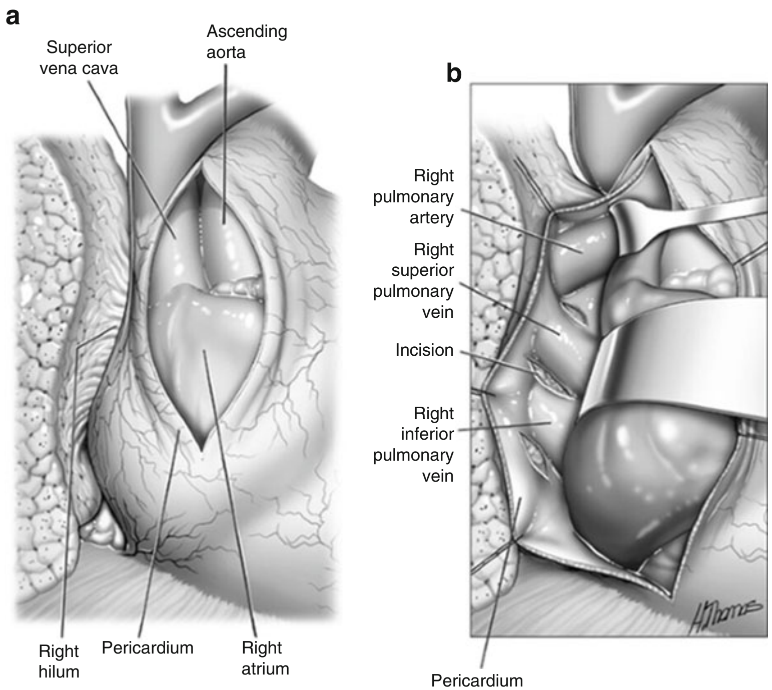


Fig. 9.7. Intrapericardial exposure of the right hilum. (**a**). Pericardial incision. (**b**). Exposure of the pulmonary vessels lateral to superior vena cava. Reprinted with permission from : Shields, LoCicero, Ponn, and Rusch. General Thoracic Surgery 6th edition. Lippincott Williams and Wilkins. 2005.

therapy such as pulmonary artery vasodilators and vasodilating inotropic support in the OR. A transesophageal echocardiogram can provide useful information. Finally, we typically leave the pericardium open to allow room for the right side of the heart to swell to avoid tamponade. There are also some limited experiences that suggest early initiation of ECMO support that may also improve outcomes [17]. In contrast to elective pneumonectomy which often does not have continuous post-op drainage of the pleural cavity, trauma pneumonectomy patients will often require at least passive drainage due to concern for postoperative bleeding and coagulopathy. The chest tube should be connected to water seal but not suction.

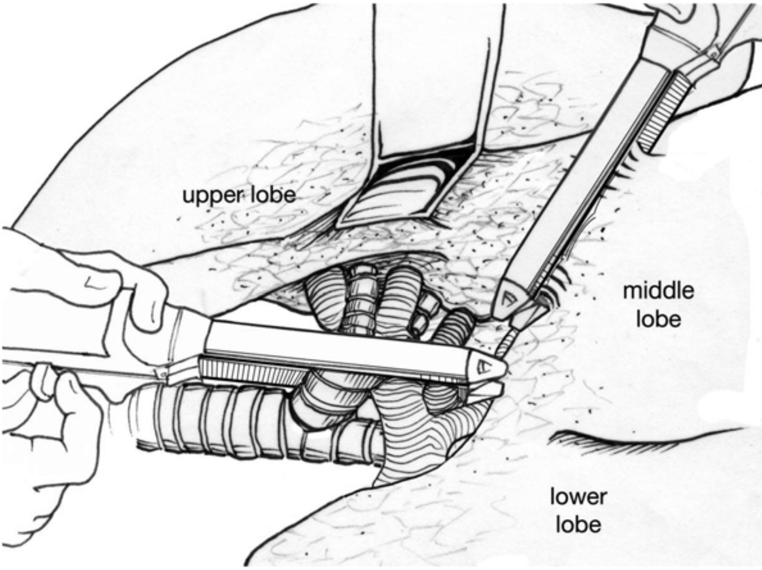


Fig. 9.8. Stapled lobectomy. An expedited stapled lobectomy performed with a GIA stapler dividing the bronchus and vessels en masse, and a GIA stapler dividing the fissure.

## *Damage Control*

The principle of damage control involves an abbreviated operative procedure in which life-threatening hemorrhage is controlled, the chest temporarily closed, and the patient is taken to the intensive care unit. Once stabilized physiologically, the patient is returned to the operating room for definitive management and chest closure [18]. Patients with severe chest trauma and associated physiologic derangements with associated shock that requires emergent thoracic operations should be considered for a damage control approach. The temporary chest closure helps prevent thoracic compartment syndrome while the patient is resuscitated in the intensive care unit [19]. Specific types of pulmonary wounds include those with penetrating thoracic injuries and a systolic blood pressure <90 mmHg and those patients who underwent an emergency department thoracotomy [20].

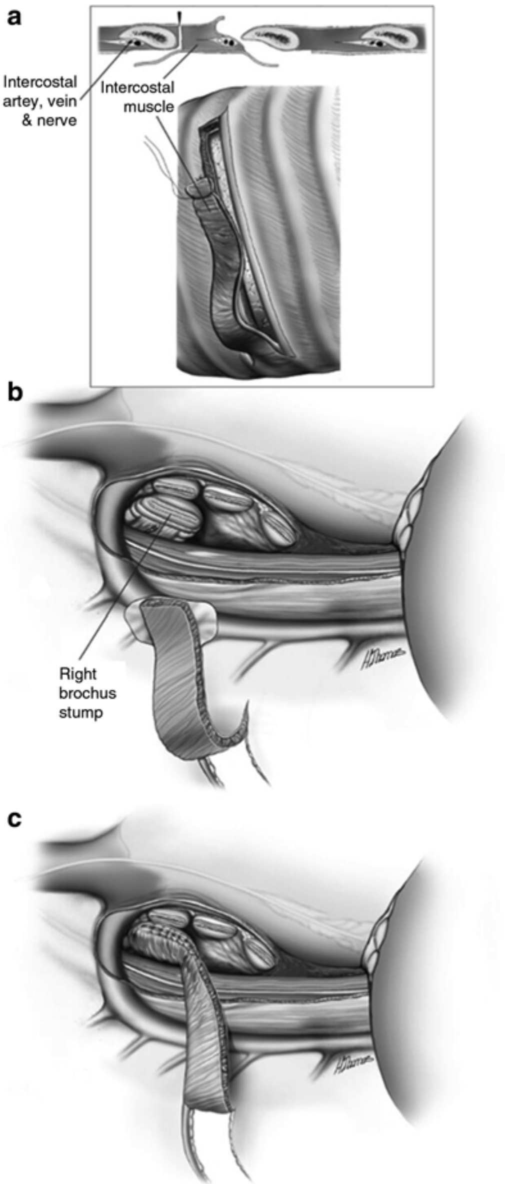


Fig. 9.9. Intercostal muscle flap. (**a**) Construction of intercostal pedicle flap. (**b**) Right hilum before application of intercostal pedicle flap of bronchus. (**c**) Flap applied to bronchus and suture applied to peribronchial tissues. Reprinted with permission from: Shields, LoCicero, Ponn, and Rusch. General Thoracic Surgery 6th edition. Lippincott Williams and Wilkins. 2005.

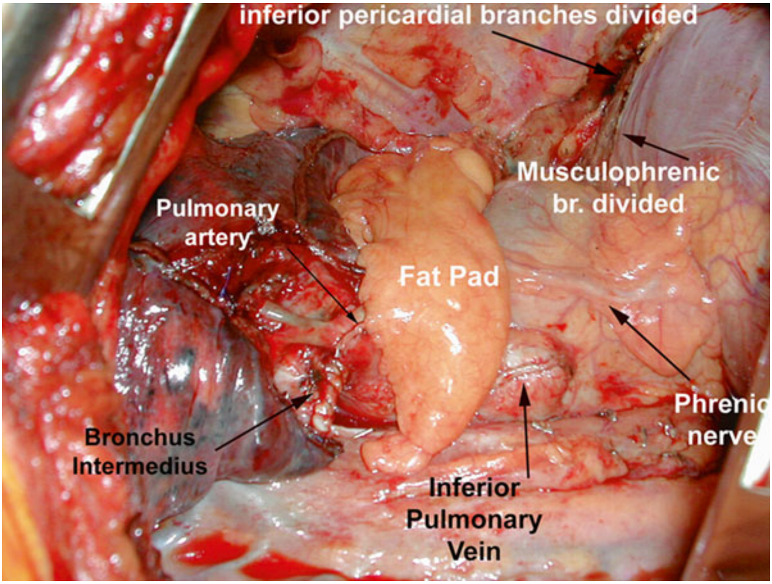


Fig. 9.10. The pericardial fat pad is mobilized to cover the bronchus intermedius stump while preserving the phrenic nerve. Copyright 2008, used with permission from CTSNet (www.ctsnet.org). All rights reserved.

Maneuvers for thoracic damage control for severe pulmonary injury include cross clamping the pulmonary hilum, stapling across the hilum, and the hilar twist. The hilar twist involves taking down the inferior pulmonary ligament and rotating the lower lobe up, thus twisting the major pulmonary vasculature and controlling the hemorrhage. Formal lung resections and classic control of the hilar vasculature is deferred for these faster techniques [21–23]. Other thoracic damage control strategies include utilizing large staplers for non-anatomic wedge resections and tractotomy. Suture closure of deep entry and exit wounds to the lung with significant bleeding and air leak should be avoided in order to prevent air embolism and continued intraparenchymal bleeding with subsequent infection [22, 23].

## *Post-op Complications*

Postoperative complications are common following thoracic trauma procedures with atelectasis and persistent air leaks as two of the most frequent ones. Treatment of atelectasis involves early mobilization, incentive spirometry, nasotracheal suctioning, and aggressive secretion management that may also necessitate bronchoscopy. Air leaks often resolve but additional procedures such as bronchoscopy and even reoperation may be necessary for leaks lasting longer than a few weeks. Development of a delayed leak is often associated with infection and requires immediate drainage and antibiotics and if no improvement surgical repair of the bronchial stump with a buttressed closure. In general, mortality and morbidity increase with extensiveness of pulmonary resection. In particular, traumatic pneumonectomy patients have greater than 50 % mortality and overall very poor outcomes. Other morbidities include infection, pneumonia, respiratory failure, coagulopathy, and empyema [4, 24].

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# 10. Cardiac Injury

*Ron Tesoriero, M.D., F.A.C.S.*

> The heart is the chief mansion of the Soul, the organ of vital faculty, the beginning of life, the fountain of the vital spirits … the first to live and the last to die …
>
> Ambrose Paré (1510–1590)
> French Barber-Surgeon

## Scope of the Problem

Cardiac wounds are uncommon and seen mainly at urban trauma centers [1]. Despite advancements in surgical care, prehospital treatment, and resuscitation, cardiac injury remains highly lethal. In fact, over several decades survival has not improved, underscoring their lethality [1–6]. One factor that may influence the poor outcome is a mortality bias due to the rapid transit of patients with devastating, non-survivable injuries to the hospital [4, 7].

When considering only the patients who survive to treatment at trauma centers, the incidence of cardiac injury is quite low. Asensio [8] defined the national incidence of penetrating cardiac injuries to be 0.16 % in a study utilizing the National Trauma Data Bank (NTDB), and Rhee [4] defined the penetrating rate as 1 in 210 admissions in a single-center retrospective analysis over 7 years. The number of patients with blunt cardiac rupture who survive to treatment is even less common, with an overall incidence of 0.041 % [9]. It is estimated that 8–86 % of immediate deaths after significant blunt chest trauma are a result of blunt cardiac rupture [9].

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Gunshot wounds (GSWs) account for the majority of penetrating cardiac injuries (58–76 %) [1, 4, 8], while stab wounds account for most of the remainder. Unfortunately the mortality associated with GSWs is significantly higher (32.6–84 %) than that of stab wounds (9.7–35 %) [1, 4, 10]. Blunt cardiac rupture is the most lethal of cardiac wounds with rates of mortality approaching 90 % [9].

## History of Care

Claude Beck discussed the history of cardiac injuries in a 1926 review article and described three distinct periods: mysticism (ancient times to the sixteenth century), experimentation and observation (sixteenth to the late nineteenth century), and cardiac repair (early twentieth century to present) [11].

Homer's *Iliad* [12] includes the earliest known description of cardiac injuries, and authors in antiquity including Hippocrates [13, 14], Aristotle [15], and Galen [16] considered these wounds to be universally fatal [14]. In the sixteenth and seventeenth century, Hollerius [14, 17] promoted the idea that not all wounds to the heart were necessarily mortal, and Wolf [18] and Cabriolanus [14] described healed cardiac wounds.

Morgagni reported the first case of traumatic pericardial tamponade. Larrey described successful treatment of traumatic pericardial tamponade by inserting a catheter through a stab wound to the chest [14]. There was strong resistance to surgeons attempting cardiac repairs, which was typified by Billroth's assertion that such an attempt "approaches very closely to that kind of intervention which some surgeons would term a prostitution of the surgical act and other madness" [11, 14].

Despite this resistance, Roberts suggested cardiac injuries could be sutured, and Block demonstrated that successful repair of cardiac wounds with survival in a rabbit model was possible [11, 14]. This was ultimately demonstrated in humans in the late 1890s when Axel Cappelen successfully repaired a left ventricular laceration, though the patient subsequently succumbed to sepsis [11, 14].

The new era of cardiac repair began when Ludwig Rehn, at the 26th Congress of the German Surgical Society in 1897, described the successful repair of a right ventricular wound with survival. He stated, "The feasibility of cardiorrhaphy no longer remains in doubt … I trust that this case will not remain a curiosity, but rather, that the field of cardiac surgery will be further investigated. Let me speak once more my conviction that by the means of cardiorrhaphy, many lives can be saved that were previously counted as lost" [19].

The ensuing century saw an explosion of innovation and advancement in cardiac surgery, which included the advent of positive pressure ventilation and cardiopulmonary bypass. In parallel were improvements in care of the trauma patient including prehospital care, patient transport, and concepts of volume resuscitation, as well as the development of anesthesia and critical care specialties. These all led to the improved outcome of those sustaining cardiac injuries [20, 21].

## Techniques

### *Diagnosis*

#### Initial Evaluation

Cardiac injury occurs in 6.4 % of cases of penetrating thoracic trauma [22]. Those involving the "cardiac box" (an imaginary area inferior to the clavicles, superior to the costal margins, and medial to the midclavicular lines) (Fig. 10.1) are the most worrisome [23]. However, wounds that occur outside "the box" can also result in cardiac injury [24, 25], and the increased mortality with such injuries is at least in part related to the clinician having a lower suspicion leading to delays in diagnosis [24].

Patients who arrive at the trauma center after cardiac injury may present anywhere along the range from hemodynamically stable to cardiac arrest. Patients who manifest hemodynamic compromise may have exsanguinating hemorrhage, cardiac tamponade, or both. The classic findings of Beck's triad (muffled heart sounds, hypotension, and jugular venous distension), caused by the rapid accumulation of a small amount of blood (30–50 ml) in the non-expansible fibrous pericardium, are rarely recognized in the resuscitation suite. Delayed recognition of hemopericardium will result in the development of tamponade physiology, decreased cardiac filling due to high intra-pericardial pressures, impaired cardiac output, hypotension, and death.

On presentation an evaluation that includes a brief history, identification of the location and possible trajectory of wounds, and an evaluation of the cardiopulmonary status of the patient must be completed rapidly. Resuscitative thoracotomy may be lifesaving for patients who present in extremis [1, 10, 20, 23, 26, 27]. As recommended by the Western

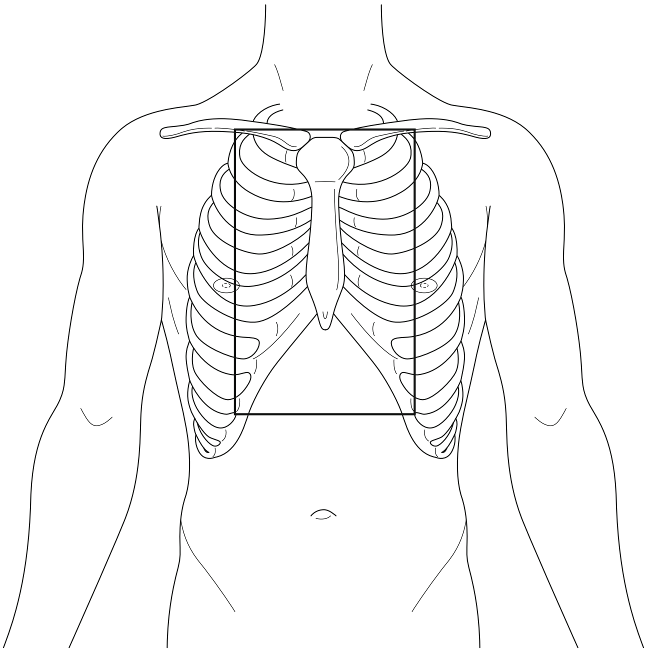

Fig. 10.1. The cardiac box. Penetrating injuries within the borders inferior to the clavicles, superior to the costal margin, and between the midclavicular lines should increase the concern for cardiac injury. However, wounds that occur outside these borders do not exclude cardiac injury.

Table 10.1. Limits of resuscitative thoracotomy.

| Limits of resuscitative thoracotomy |
| --- |
| Prehospital CPR >10 min after blunt trauma without response[a] |
| Prehospital CPR >15 min after penetrating trauma without response[a] |
| Asystole is presenting rhythm, and there is no pericardial tamponade |

Adapted from a *Western Trauma Association* study [27]

[a]Cardiac electrical activity present or cardiac activity detected by focused assessment with sonography for trauma (FAST)

Trauma Association, its use has expanded to include patients without signs of life with short prehospital times and a blunt mechanism and asystole if signs of tamponade are present or cannot be excluded (Table 10.1) [27, 28].

## FAST

The focused assessment with sonography for trauma (FAST) examination is extremely sensitive for detecting hemopericardium in precordial and penetrating transthoracic wounds, with sensitivity and specificity that approach 100 % [29–31]. It is especially useful in patients who present with maintained hemodynamics to assess the safety of subsequent diagnostic testing [30] and to determine the appropriate management in hemodynamically compromised patients with multiple wounds and potential for multicavitary hemorrhage. Penetrating precordial stab wounds with concurrent hemothorax require special consideration as the FAST examination has been shown to produce false-negative results due to cardiac injury decompressing into the left hemithorax [32]. In these cases, the liberal use of subxiphoid pericardial window is wise, as repeat ultrasonography and echocardiography may fail to diagnose underlying cardiac injury [32]. Occasionally, adequate windows will not be obtainable due to concomitant hemopneumothorax or subcutaneous emphysema.

Extended FAST (EFAST) is extremely useful for the diagnosis of pneumothorax with a high specificity (99 %) and sensitivity (>95 %) when compared to chest X-ray (CXR) [33, 34]. It may also be utilized to diagnose hemothorax.

## CXR

A CXR is important to assist in missile trajectory, presence of concomitant thoracic injury, and operative planning. It can be obtained in most patients even when hemodynamically marginal. For those who need emergent operative intervention, a plate can be placed on the operating room table and a CXR obtained prior to incision [25].

## Subxiphoid Pericardial Window

Subxiphoid pericardial window has been validated to be extremely accurate for overt and occult cardiac injuries [6]. It can be utilized to diagnose hemopericardium in patients with equivocal ultrasound results, when ultrasound windows are unobtainable, when ultrasound is unavailable, or when a precordial stab wound is associated with a left hemothorax [32]. It should be performed under general anesthesia in the operating room (OR) with the patient prepared and draped in an adequate fashion to proceed with sternotomy if necessary. When possible it is wise to have the patient adequately prepared and draped prior to the induction of anesthesia as patients with compensated tamponade may quickly deteriorate to cardiac arrest when preload is decreased from vasodilation and positive pressure ventilation [6]. An incision is made in the midline overlying the xiphoid, which should be excised to facilitate dissection and exposure [6]. The distal sternum is then elevated with a retractor. The diaphragm is identified and kept inferior, while blunt dissection is utilized to identify the pericardium. Meticulous hemostasis is necessary to prevent difficult-to-interpret results of the pericardial window. Once identified, the pericardium is grasped with Allis clamps and incised. If clot or blood is returned, immediate conversion to a sternotomy should occur.

## *Incisions*

### Median Sternotomy

Median sternotomy is most useful for stable patients who have proven cardiac injury or those that are at least marginally stable [20]. It provides excellent exposure to the mediastinum and can be extended for a laparotomy if indicated. It is our practice to explore most of these wounds via sternotomy even with a concomitant lung injury, as both pleural spaces are accessible. Surgeons with less experience may find the incision limiting and should utilize anterolateral thoracotomy with extension as necessary.

### Anterolateral Thoracotomy

Anterolateral thoracotomy is the incision of choice for patients arriving in extremis with severe hemodynamic compromise (Fig. 10.2) and may be extended to a right anterior “clamshell” thoracotomy (Fig. 10.3) when necessary. It is the most useful for ED thoracotomy [1, 4, 10, 20, 23, 26]. It is also useful in patients who deteriorate during laparotomy from a suspected cardiac injury and for those who are hemodynamically unstable from injuries that have traversed the mediastinum [20, 23]. Care must be taken to not perform the incision too inferiorly or optimum exposure may be limited and subsequent thoracic and sternal closure may be compromised [6]. Elevating the left hemithorax 20° by placing a roll under the left chest improves exposure [6] and should be considered in hemodynamically maintained patients and those with penetrating thoracic wounds who are undergoing laparotomy in case rapid entry into the chest is necessary.

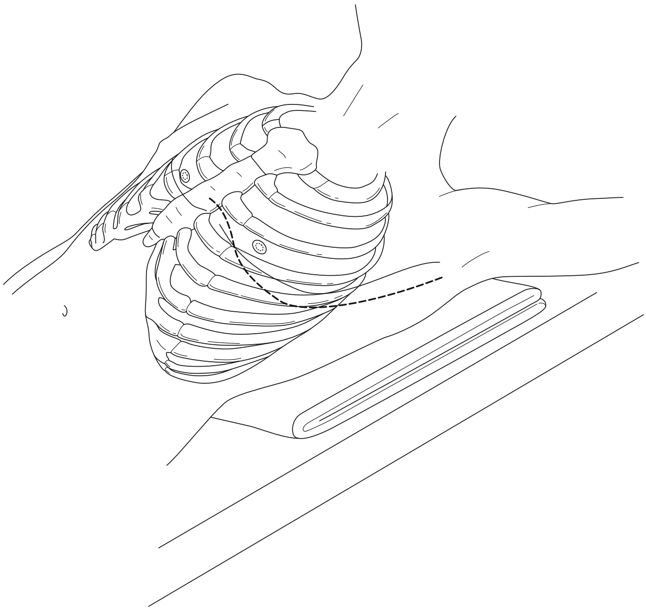

Fig. 10.2. Left anterolateral thoracotomy. The incision is made at the inframammary fold, carried into the fourth intercostal space, and curved toward the ipsilateral axilla. Positioning a rolled towel under the left hemithorax allows for additional extension of the incision and improved visualization of the posterior thoracic structures.

When the clamshell thoracotomy is utilized, it is important to ligate the transected internal mammary arteries, after repairing the cardiac injuries [20]. In this situation, the arteries will often be in vasospasm and thus easy to overlook. The surgeon who omits this step will have the opportunity to return to the operating room to correct their mistake should the patient survive the subsequent hemorrhage.

## *Exposure and Immediate Control*

Pericardiotomy is the first step in evaluation of the injured heart. In the presence of tamponade, the pericardium can be tense and difficult to grasp. Uncontrolled opening can result in injury to the underlying cardiac structures. The use of Allis clamps to grasp the pericardium helps. Initially, it is wise to make a 1–2 cm incision. The pericardium is further incised with Metzenbaum scissors [20, 23]. When approached from an

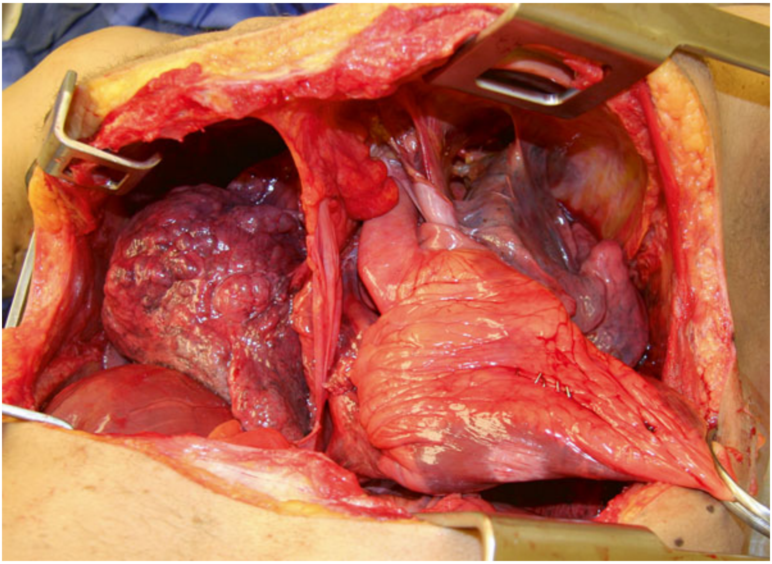

Fig. 10.3. Bilateral anterolateral "clamshell" thoracotomy. A left anterolateral thoracotomy can be extended across the sternum and into the fourth intercostals space on the right. This affords excellent exposure to the mediastinum and bilateral pleural spaces. Attention must be paid to proper incision placement, as incisions that are made too low may limit access to the upper mediastinum and great thoracic vessels (Facilities: Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB. Cadavers and specimens: Anatomical Donor, Maryland State Anatomy Board).

anterolateral thoracotomy, the phrenic nerve is identified and the pericardium is widely opened anterior and longitudinal to it. The incision can be extended medially at the pericardial base if further exposure is needed. The pericardium is opened in the midline when a sternotomy incision is utilized and may be teed off at its inferior aspect for better exposure, again avoiding the phrenic nerve. In the stable patient, taking the time to suture the pericardium to the skin to create a cardiac sling facilitates visualization and repair [6].

Once the pericardium is opened, the surgeon should rapidly assess for location and degree of cardiac injury, paying special attention to wounding patterns that suggest multiple, posterior, septal, or valvular injuries. Involvement of the thoracic great vessels is also important to identify. The American Association for the Surgery of Trauma (AAST) Organ Injury Scale (OIS) [35] (Table 10.2) can be utilized to classify

Table 10.2. American association for the surgery of trauma organ injury scale: heart injury.

| AAST-OIS: heart injury scale | |
|---|---|
| Grade | Description of injury |
| I | Blunt cardiac injury with minor ECG abnormality (nonspecific ST or T wave changes, premature atrial or ventricular contraction, or persistent sinus tachycardia) |
| | Blunt or penetrating pericardial wound without cardiac injury, cardiac tamponade, or cardiac herniation |
| II | Blunt cardiac injury with heart block (right or left bundle branch, left anterior fascicular, or atrioventricular) or ischemic changes (ST depression or T wave inversion) without cardiac failure |
| | Penetrating tangential myocardial wound up to, but not extending through, the endocardium, without tamponade |
| III | Blunt cardiac injury with sustained (≥6 beats/min) or multifocal ventricular contractions |
| | Blunt or penetrating cardiac injury with septal rupture, pulmonary or tricuspid valvular incompetence, papillary muscle dysfunction, or distal coronary arterial occlusion without cardiac failure |
| | Blunt pericardial laceration with cardiac herniation |
| | Blunt cardiac injury with cardiac failure |
| IV | Penetrating tangential myocardial wound up to, but not extending through, the endocardium, with tamponade |
| | Blunt or penetrating cardiac injury with septal rupture, pulmonary or tricuspid valvular incompetence, papillary muscle dysfunction, or distal coronary arterial occlusion producing cardiac failure |
| | Blunt or penetrating cardiac injury with aortic or mitral valve incompetence |
| | Blunt or penetrating cardiac injury of the right ventricle, right atrium, or left atrium |
| | Blunt or penetrating cardiac injury with proximal coronary arterial occlusion |
| | Blunt or penetrating left ventricular perforation |
| | Stellate wound with <50 % tissue loss of the right ventricle, right atrium, or left atrium |
| V | Blunt avulsion of the heart; penetrating wound producing >50 % tissue loss of a chamber |
| VI | |
| Advance one grade for multiple wounds to a single-chamber or multiple-chamber involvement | |

Modified with permission from Moore EE, Malangoni MA, Cogbill TH, Shackford SR, Champion HR, Jurkovich GJ, et al. Organ injury scaling IV: thoracic vascular, lung, cardiac and diaphragm. J Trauma. 1994 Mar;36(3):299–300

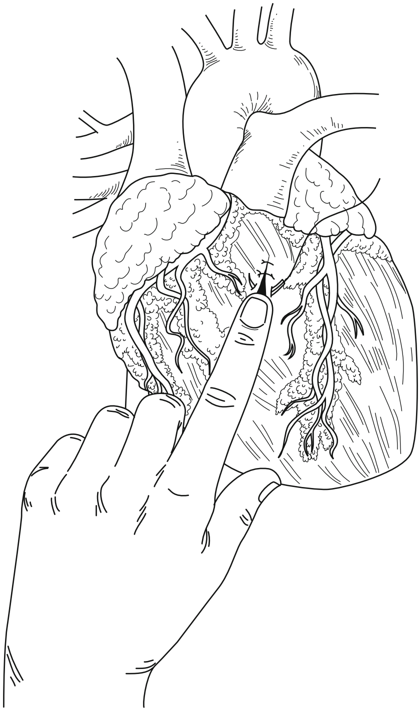

Fig. 10.4. Direct digital control of cardiac wound. Wounds of amenable size are best controlled with direct digital pressure as there is minimal chance for wound extension. The physician's other hand is freed to achieve repair by placing sutures directly under the finger controlling the wound.

injury and has been validated to predict mortality [1, 10, 20] but offers little benefit for intraoperative decision-making.

Techniques that can be employed to gain temporary control include direct digital pressure, placement of a Foley catheter, application of a partial occluding clamp, and the use of skin staples. Direct digital control (Fig. 10.4) proves the most useful for amenable wounds. It allows for tactile feedback, minimizes chances of wound extension, and frees the surgeon's other hand to achieve repair. Foley catheter placement (Fig. 10.5) can be utilized to partially occlude larger wounds, but one must remember to clamp the catheter to prevent continued hemorrhage through it, and to inflate the balloon with saline to prevent air embolism should rupture occur due to inadvertent needle injury. Undue traction on the Foley may easily cause extension and enlargement of the cardiac

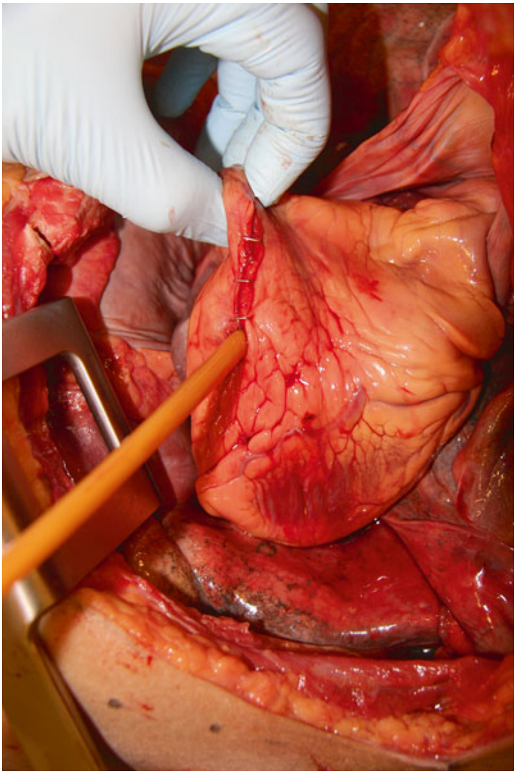

Fig. 10.5. Foley catheter placement to control cardiac wound. For larger wounds, a Foley catheter may be employed to partially control ongoing hemorrhage while a temporary or permanent repair is achieved. Care must be taken to avoid undue traction on the catheter as wound extension and enlargement may easily occur (Facilities: Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB. Cadavers and specimens: Anatomical Donor, Maryland State Anatomy Board).

injury [6]. A partial occluding clamp is an attractive option when the injury is to the atria. Skin staples, though rapid, can be difficult to place to achieve hemostasis, can result in wound extension, should always be followed with definitive repair, and are difficult to remove [1, 10, 20, 23].

Near-total inflow occlusion with Sauerbruch's maneuver can be achieved by placing the third and fourth finger behind the right atrium and compressing it between the second and third finger; vascular clamps may be added to the inferior vena cava and superior vena cava if needed due to injury pattern (Fig. 10.6). It may be necessary for large posterior

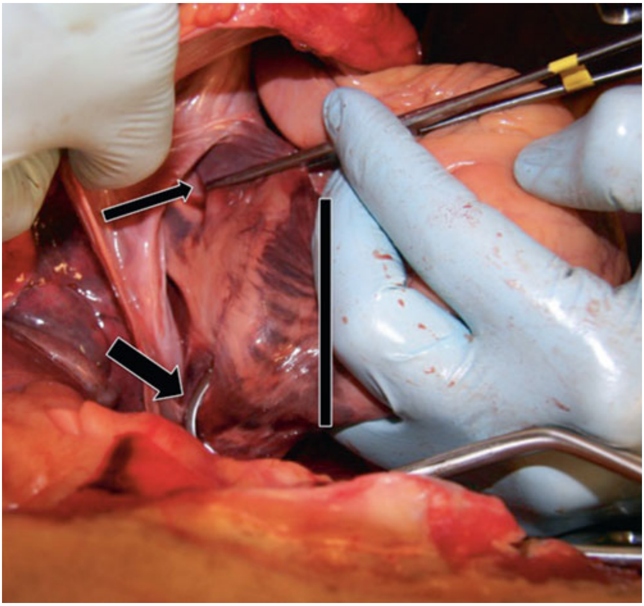

Fig. 10.6. Sauerbruch's maneuver. To achieve total inflow occlusion of the heart, the junction of the vena cava and right atrium may be compressed between the third and fourth fingers (*solid vertical line*). For injuries to the medial aspect of the atrium or the atrio-caval junction, the brief application of vascular clamps to the superior vena cava (*narrow arrow*) and inferior vena cava (*wide arrow*) may be necessary to achieve temporary control with a vascular or intestinal Allis clamps (Facilities: Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB. Cadavers and specimens: Anatomical Donor, Maryland State Anatomy Board).

injuries, left atrial injuries, and injuries that occur in the very lateral aspect of the right atrium and to the superior and inferior atrio-caval junction. Unfortunately, it is poorly tolerated in the acidotic, hypotensive patient and often results in rapid deterioration to cardiac arrest from which the patient may not be resuscitatable [20, 23].

Patients with central pulmonary injuries may require pulmonary hilar control with cross clamping or a lung twist to arrest hemorrhage and prevent air embolism. These techniques should be used cautiously as they are poorly tolerated, significantly increase the afterload of the right ventricle, and can result in acute right failure or fibrillation in the acidotic and ischemic heart [20, 23]. When employed, rapid control of the injury with stepwise release of the clamp should follow to minimize this risk.

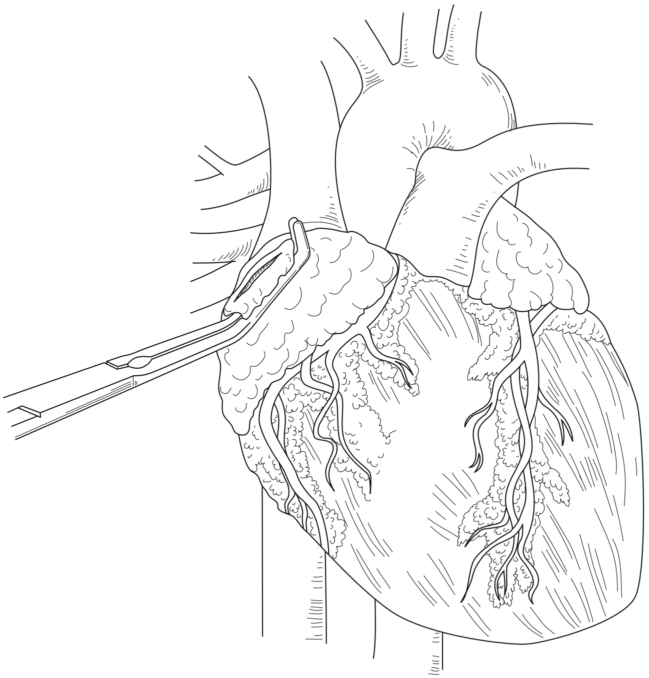

Fig. 10.7. Atrial control with a Satinsky clamp. The low-pressure nature and anterior location of the right atrium lend itself well to control with an angled vascular clamp. Repair may then proceed with a 4-0 polypropylene suture in a horizontal mattress fashion. Although this also may be employed for left atrial wounds, the posterior location and inability of the heart to tolerate anterior displacement make placement of a clamp impractical.

## *Definitive Repair*

### Atrial Injuries

Due to their low pressure, atrial injuries are generally easier to repair than ventricular injuries. Control can be achieved with a partial occluding clamp (Fig. 10.7). Once controlled they should be repaired utilizing 3-0 or 4-0 polypropylene suture in either a running or interrupted horizontal mattress fashion. To prevent tearing of their thin walls, we prefer the horizontal technique. Pledgeted repairs are generally unnecessary.

Injuries to the lateral aspect of the right atrium and to the atrio-caval junctions may require total inflow occlusion for visualization as discussed earlier. This may be followed by the rapid sequential placement of intestinal Allis clamps [36] allowing for release of inflow occlusion and controlled repair of the injury without continued compromise of venous return to the heart.

## Ventricular Injuries

The ventricles are the most commonly injured structure in the heart from penetrating trauma [1, 4, 8, 10, 20, 23]. Wounds that are amenable should be controlled with digital pressure as mentioned. Precise needle placement is necessary, and utilizing a needle with appropriate length and curvature, while following the curve of the needle, facilitates adequate tissue bites, thus avoiding myocardial tearing with extension of the injury [6]. We usually use a 3-0 polypropylene suture on an MH needle, but if unavailable an SH needle will suffice. Timing the suture placement to myocardial contraction will also help to limit the chance of iatrogenic injury [6]. Stab wounds may be closed in a running or horizontal mattress fashion. GSWs tend to create larger injuries with additional contused myocardium due to blast effect. These are best repaired in a horizontal mattress fashion. Though most can be repaired without the use of pledgets, they are useful when the myocardium is thin or especially friable.

## Posterior Injuries

Posterior injuries can be exceedingly challenging to repair as their location requires lifting of the heart, causing both inflow and outflow occlusion, with resultant hypotension, bradycardia, and rapid deterioration into cardiac arrest [6]. In patients with a perfusing cardiac rhythm these repairs are best accomplished in a sequential fashion. The heart should be briefly lifted, the injury assessed, and then the heart placed back in its normal position. After recovery, the heart is again lifted, a suture is placed, the heart is returned to its normal position, and the suture is tagged. This sequence may be repeated multiple times until all sutures are placed and tied. The technique requires surgical patience and close communication with the anesthesia team but offers the best chance for successful completion of repair without patient deterioration [6].

Fig. 10.8. Repair of cardiac injury in close proximity to coronary artery with mattress suture. A non-pledgeted horizontal mattress suture of 3-0 polypropylene is utilized to repair cardiac wounds that are in close proximity to the coronary arteries to avoid their narrowing or occlusion. Precise suture placement may be facilitated by small doses of adenosine to slow or cause brief episodes of asystole in the heart.

## Injuries Adjacent to/and Coronary Artery Injury

Injuries in close proximity to the coronary arteries are especially difficult to repair and require meticulous suture placement to avoid narrowing the artery, or one of its side branches, with resultant distal ischemia [6, 20, 23]. These are best repaired using vertical mattress sutures placed below the bed of the coronary artery (Fig. 10.8). Teflon pledgets should generally be avoided as they make suture placement imprecise and increase the risk of compromising the artery [6]. Administration of 3 mg of adenosine causes brief asystole, has been shown to safely facilitate cardiac repair in penetrating trauma [37], and may be of particular use in these cases.

Direct coronary artery injury greatly increases the complexity of cardiac trauma. If a small side branch or the distal third of the artery is involved, it may be ligated without the resultant ischemia being of severe clinical significance. If the proximal coronary artery is injured, early involvement of a cardiac surgeon to provide coronary bypass, which may need to be done under cardiopulmonary bypass and cardioplegic arrest, is necessary [6, 8, 20, 23].

## Intracardiac Injuries

Injury to the internal cardiac structures, including the valves and septum, is often overlooked at the time of initial repair and results in much of the reported postoperative complications in patients sustaining cardiac injuries [7, 38–40]. Rarely a left-to-right shunt, from a septal injury or aortopulmonary fistula, may be diagnosed intraoperatively due to the clinician noting a dilated right ventricle or pulmonary artery and detecting a palpable thrill [6, 38]. Most post-traumatic valvular lesions present with insufficiency but are generally not recognized at the time of initial cardiac repair. The liberal use of intraoperative transesophageal echocardiography (TEE) can assist in making the diagnosis of intracardiac and proximal great vessel injury [6, 41] and may allow repair by a cardiac surgeon at the index operation. If initially unavailable, postoperative echocardiography is invaluable in making the diagnosis [7, 38, 39] and should be obtained in all patients who sustain cardiac injury requiring operative repair.

## Blunt Cardiac Injury and Rupture

Blunt cardiac rupture is a devastating injury with few survivors. Most patients die at the scene [9, 42], and there is a near 90 % mortality for those who survive to be evaluated at a trauma center [9]. Dual-chamber injuries, left ventricular injuries, and injuries with concomitant pericardial laceration have been associated with dismal outcomes [9]. Patients who survive to operative intervention most commonly have tamponade.

The most common injuries in these patients are disruptions of the superior vena cava or right atrial junction (36.4 %) and right ventricular rupture (36.4 %) [42]. Repairs should be pursued as discussed previously but are often more difficult due to the size of the wounds.

Blunt valvular disruption and septal defects, though rare, have been described and are thought to be due to direct trauma to the chest during the isovolumetric phase of the cardiac cycle [8, 40]. This period occurs in late diastole/early systole when the aortic and atrioventricular valves are closed, and the heart has maximum volume. Due to the inability of the blood to eject across the valves, sudden increases in intracardiac pressure may lead to valvular and septal injury. Aortic valves are most commonly injured followed by mitral valves.

Symptoms of valvular insufficiency after blunt trauma are often missed in these multiply injured patients. Unexplained hemodynamic compromise, failure to clear lactate, and abnormal conduction patterns or ventricular dysrhythmias on electrocardiogram (ECG) should be aggressively investigated with echocardiography to search for these lesions [40]. When present and symptomatic they will frequently require repair by a cardiac surgeon under cardiopulmonary bypass and cardioplegic arrest.

## Air Embolism

Air embolism may occur much more commonly than recognized in both blunt and penetrating cardiac and thoracic traumas [43]. Mechanism of introduction may be direct entry from atrial or ventricular injury or from traumatic alveolo-venous connections due to pulmonary injury. In the latter cases, rapid control of the pulmonary hilum with a vascular clamp or pulmonary twist should be accomplished to prevent continued embolism. Ensuing hemodynamic compromise and cardiac arrest may be due to reduction in cardiac output due to air trapping within the outflow tracts of the heart and/or coronary artery occlusion with resultant cardiac ischemia. The patient with air embolism should be placed in Trendelenburg position to help maintain the air within the apex of the ventricles. Internal cardiac massage may help to dissipate air that is trapped in the coronary circulation and outflow tracts. Needle aspiration of the ventricles, aortic root, and the coronary arteries can be attempted and may be lifesaving. Open cardiac ultrasound may assist in deciding the locations and times when needle aspiration would be appropriate.

## Outcomes

The overall survival rate for patients sustaining penetrating cardiac wounds is 19.3 % [4], and many die at the scene of injury. The survival rate for patients who are transported and evaluated at a trauma center is 33–43 % [4, 10, 23]. Unfortunately, the more common cause of injury, GSW, is associated with a much lower survival (16 %) than are victims of stab wounds (65 %) [10, 20]. Those that require emergency resuscitative thoracotomy have a less than 20 % [10, 26] chance of survival.

Several studies have attempted to delineate the variables that are predictive of survival. In a large retrospective analysis, Tyburski noted that hemodynamic stability on arrival, stab wounds, and presence of tamponade conferred a survival benefit [2]. Asensio [1] identified mechanism of injury (GSW versus stab), Glasgow coma scale (GCS) $\leq 8$, revised trauma score (RTS) $\leq 1$, cardiovascular-respiratory score (CVRS) $\leq 3$, presence of coronary artery injury, need for resuscitative thoracotomy, and absence of sinus rhythm when the pericardium is opened as predictors of mortality. Though the anatomic site of injury did not predict outcomes, the AAST-OIS did predict chance of survival. Mortality worsened as grade increased with grades IV, V, and VI having respective mortality rates of 56, 76, and 91 %. In contrast to previous studies, presence of tamponade did not affect an outcome benefit.

Survival after blunt cardiac rupture is even more dismal. In a 5-year analysis of the NTDB, Teixeira and coauthors [9] defined the survival rate of patients who presented to a trauma center alive after blunt cardiac rupture as 10.8 %. For those who survived to the operating room, this was increased to 32.4 %. Patients with isolated right atrial injuries may have a reasonable chance at a good outcome, while bi-chamber injuries and blunt cardiac rupture with exsanguinating hemorrhage due to pericardial laceration and loss of containment are nearly uniformly fatal [44].

## Complications

Complications common in all injured patients who present in shock—including hospital/ventilator acquired pneumonia, prolonged ventilator requirements, and multisystem organ dysfunction—also affect the patient with cardiac injury. Patients presenting in extremis with cardiac arrest have the added risk of sustaining neurologic and cognitive deficit, which may be profound. The risk approaches 20 % in those surviving a resuscitative thoracotomy [27]. Additionally, the risks of surgical site infection—including infections of the mediastinum, pericardium, pleural spaces, and chest wall—are ever present in patients whose thoracic incisions are often made in times of duress and compromised sterile surgical technique. Unfortunately rates have not been reported in the literature [45].

Cardiac-specific are comprised mostly of missed injuries to the septum, valves, and conduction system [7, 38]. Patients are also at risk for ventricular aneurysm, cardiac pseudoaneurysm, pericarditis, retained intracardiac missiles, and missile embolus. Tang and coauthors [7] reported a 17.4 % incidence of cardiac complications when echocardiography was routinely used in postoperative evaluation of patients who underwent repair of cardiac injury. Of those complications, pericardial effusion (47 %) was most frequent, followed by abnormal wall motion (42 %), ejection fraction less than 45 % (42 %), intramural thrombus (21 %), valvular injury (21 %), conduction abnormality (10 %), ventricular pseudoaneurysm (5 %), and ventricular aneurysm (1 %). No patients required operative management. In contrast, Cha and colleagues [38] reported the rate of post-procedural cardiac complication to be 23 %, with nearly all patients requiring further operative intervention. The most common complication was ventricular septal defect (45 %) followed by aortic valve injury (18 %) and conduction abnormalities (18 %). Most patients had new-onset murmurs, and many developed dyspnea on exertion, cardiomegaly, and congestive heart failure prior to diagnosis.

As many of these complications are clinically silent or masked by concomitant injury, liberal use of intraoperative TEE is warranted to prevent delays in diagnosis and increased morbidity [6, 41]. When unavailable, the use of postoperative echocardiography in all patients who sustain cardiac injury requiring repair is wise [7, 38, 39].

## Conclusion

Cardiac injury remains a devastating event, and most patients succumb before ever reaching the trauma center. For initial survivors the mortality is exceedingly high, despite shortened transport times and advances in prehospital efforts, surgical care, and resuscitation strategies. Many survivors are plagued by persistent neurologic and cognitive deficits, although there is hope that post-resuscitation therapeutic hypothermia may improve this outcome [6]. Successful outcomes require a high index of suspicion, swift diagnosis, and an aggressive, precise, and coordinated effort on the part of the surgeon, trauma service, and anesthesia team.

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# Part IV
# Techniques in the Abdomen

# 11. Liver Injuries

*Deborah M. Stein, M.D., M.P.H.*

## Introduction of the Problem

The liver is the largest organ in the abdomen and is frequently injured. Although minor or moderate injuries can be managed with simple observation, the extensive vascular supply of the liver makes severe liver injuries extremely challenging. Frequently, patients who require liver-specific operations have exsanguinating hemorrhage. Despite improvements in resuscitation, mortality of operative liver injuries remains approximately 50 % [1, 2], with mortality of up to 80 % for patients with juxtahepatic venous injuries [3–6]. Morbidity rates following operation for high-grade liver injuries are as high as 30–80 % depending on the grade of injury and types of complications [7–10].

## History of Care

The treatment of injuries to the liver has undergone a revolution, from the first description of injuries to the liver in Greek and Roman mythology to Hogarth Pringle's description of the "Pringle maneuver" in 1908 [11]. Since that time, the management of hepatic injuries has transformed from early laparotomy with definitive repair and resection to damage control techniques in unstable patients and nonoperative management (NOM) in hemodynamically stable patients [12–14]. Successful operative management of liver injury was first reported in the early seventeenth century [15]. Reports from both military and civilian traumas documented successful operative management of hepatic injury,

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but morbidity and mortality rates remained extremely high, as was true for all major hemorrhage prior to the era of modern medicine [16–20]. In 1965, Root first described the diagnostic peritoneal lavage (DPL) [21]. As operative management of patients sustaining abdominal trauma who had hemoperitoneum on DPL was considered standard of care, the incidence of liver injury dramatically increased as did the experience with operative management. In the early 1980s, introduction of computed tomography (CT) allowed selective management of liver injuries to emerge [22]. In 1989, Moore et al. introduced the American Association for the Surgery of Trauma Organ Injury Scale (AAST-OIS) for liver injury, which was updated in 1995 and allows for a stratified qualification of liver injuries that is used to both guide intervention and allow for scientific comparisons of hepatic trauma [23, 24]. Grades from I to VI are described. Grade I and II are minor, grade III are moderate, and grade IV and V injuries are major. Grade VI injuries are uniformly fatal hepatic avulsion. See Table 11.1.

Table 11.1. AAST-OIS liver injury scale.

| Grade of injury | Type of injury | Description of injury |
|---|---|---|
| I | Hematoma | Subcapsular, <10 % surface area |
| | Laceration | Capsular tear, <1 cm depth |
| II | Hematoma | Subcapsular, 10–50 % surface area; intraparenchymal, <10 cm diameter |
| | Laceration | 1–3 cm depth, <10 cm length |
| III | Hematoma | Subcapsular, >50 % surface area or expanding; ruptured subcapsular or parenchymal hematoma; intraparenchymal hematoma >10 cm or expanding |
| | Laceration | >3 cm depth |
| IV | Laceration | Parenchymal disruption involving >25–75 % of lobe or 1–3 Couinaud's segments within a lobe |
| V | Laceration | Parenchymal disruption involving >75 % of lobe or >3 Couinaud's segments within a lobe |
| | Vascular | Juxtahepatic venous injury |
| VI | Vascular | Hepatic avulsion |

Reprinted with permission from Moore EE, Cogbill TH, Jurkovich GJ, Shackford SR, Malangoni MA, Champion HR. Organ injury scaling: spleen and liver. J Trauma. 1995;38(3):323–4

Successful NOM of liver injuries in pediatric patients was then adopted in adults, with many large series published in more recent years [25–29]. It was in 1908 that Pringle published the landmark study that not only first described the "Pringle maneuver," but was also likely the first surgeon to advocate for NOM of low-grade injuries and stratify treatment options by severity of injury:

> It is very probable that slight ruptures will occasionally heal without surgical interference in consequence of this increased tension of the abdominal wall leading to the arrest of hemorrhage, but in the cases of severe injury to the liver this will not happen. [11]

Although for low-grade injuries, NOM has been advocated for decades, there was considerable controversy about the management of high-grade injuries. Studies by Croce and Pachter in the mid-1990s convincingly demonstrated that high-grade injuries could be managed safely [25, 26]. Both found that NOM is safe for hemodynamically stable patients regardless of injury severity and/or amount of hemoperitoneum. The current paradigm is that hemodynamics alone should dictate which patients require immediate operative intervention for hepatic trauma [30].

## Technique with Personal Tips

Knowledge of vascular anatomy—the hepatic arteries, the portal venous system, and the hepatic veins—is essential to manage hemorrhage while preserving hepatic function in complex hepatic injury. Familiarity with the anatomic relationships and preservation of main conduits of the biliary tree is also essential (Fig. 11.1). The classic description of the liver anatomy is based on external appearance in which the falciform ligament extends from the diaphragmatic surface to the abdominal wall and divides the liver into the right and left anatomic lobes. The liver is most commonly described by the eight Couinaud's segments, which are dictated by the vascular anatomy rather than external landmarks [31] (Figs. 11.2 and 11.3). This classification is more useful for operative liver management, since it divides the liver into units based on the key structures essential for safe operative technique. The center of each Couinaud's segments contains the supplying branch of the portal vein and hepatic artery running with the bile duct while hepatic veins lie in the periphery of each segment. A functional left and right liver is divided by a main portal fissure known as Cantlie's line,

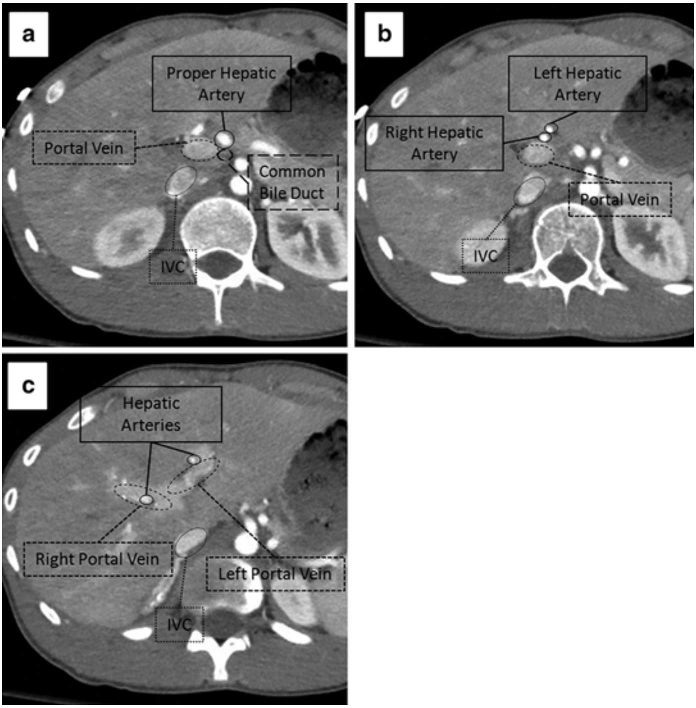


Fig. 11.1. Hepatic anatomy. (**a**) The relationship of the portal vein (*dashed line*), proper hepatic artery (*solid line*), and common bile duct (*large dashed line*) in the porta hepatis. (**b**) The relationship of the portal vein (*dashed line*) and right and left hepatic arteries (*solid lines*). (**c**) Bifurcation of the portal vein (*dashed line*) separating segments 8 (superiorly) and 5 (inferiorly) on the right from segment 4 on the left. The main branches of the hepatic arteries (*solid line*) can be seen running with the portal vein.

which runs from the middle of the gallbladder fossa to the inferior vena cava (IVC) and contains the middle hepatic vein. The portal vein divides the liver into upper and lower segments by the left and right portal veins, which then branch superiorly and inferiorly. The hepatic arteries run with the portal veins as do the main biliary ducts. The hepatic venous drainage includes the right hepatic vein, which divides the right lobe into anterior and posterior segments; the middle hepatic vein, which divides the liver into right and left lobes in a plane along Cantlie’s line; and the left hepatic vein, which divides the left lobe into a medial and lateral part. The caudate lobe, segment I, is drained by one

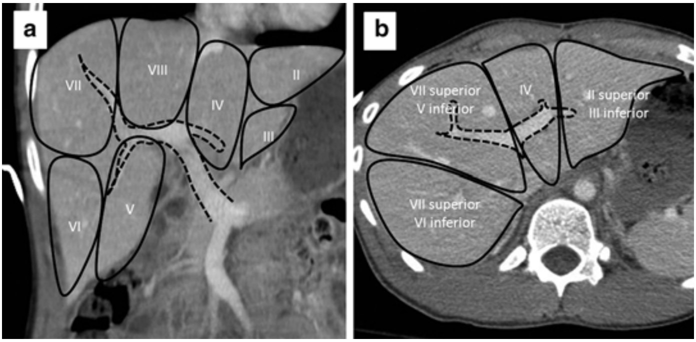


Fig. 11.2. Portal venous anatomy (*dashed line*) dividing the liver into Couinaud's segments. Segment I (not shown) is the caudate lobe. (**a**) Coronal view. (**b**) Axial view.

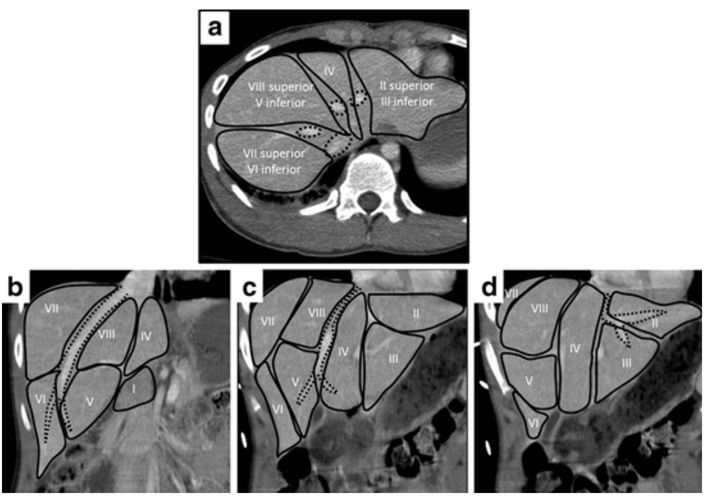


Fig. 11.3. Hepatic venous anatomy (*dotted line*) dividing the liver into Couinaud's segments. Segment I is the caudate lobe. (**a**) Axial view. *Dotted circles* indicate IVC, right, middle, and left hepatic veins (clockwise from bottom). Coronal views showing the right hepatic vein (**b**), middle hepatic vein (**c**), and left hepatic vein (**d**) and relationships to the functional hepatic segments.

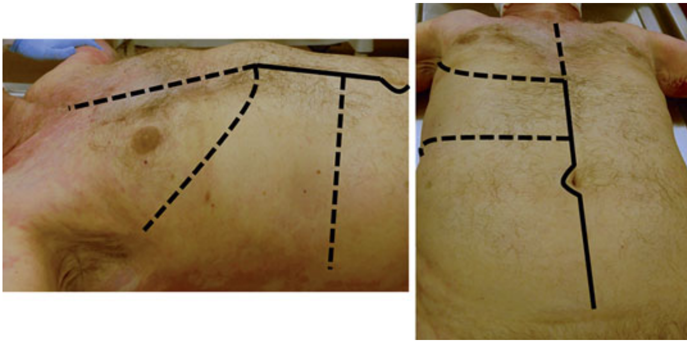

Fig. 11.4. Exposure for operative management of liver injuries. Standard midline laparotomy (*solid line*). Additional incisions for exposure when needed (*dashed line*). Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

or more short hepatic veins that drain directly into the IVC. Another key consideration is the external hepatic artery anatomy, which can be aberrant in 25 % of patients [32]. The most common of these is the "replaced right hepatic artery" in which the right hepatic artery originates from the superior mesenteric artery rather than the proper hepatic artery, which is an important consideration when dissecting out the porta hepatis and/or applying a "Pringle maneuver."

Operative management of liver injuries typically occurs in one of two settings:

1. The patient is being explored for both diagnosis and therapy—most typically in the situation of hemodynamic instability, peritonitis, or a transperitoneal penetrating trajectory.
2. The patient is being explored for another indication such as bowel or bladder injury, and a liver injury is encountered.

In the first situation, a standard midline trauma exploratory laparotomy should always be performed with initial packing (Fig. 11.4). Exsanguinating hemorrhage should be anticipated, and activation of a massive transfusion protocol, availability of rapid transfusion systems, and careful coordination with the anesthesia providers are essential. The anterior portion of the falciform ligament is taken down between

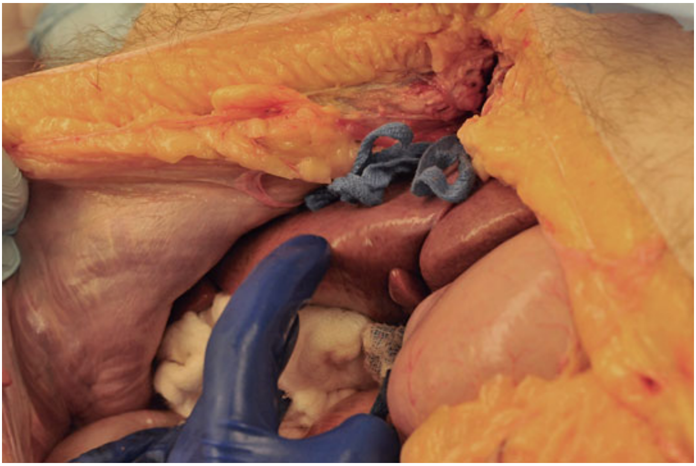

Fig. 11.5. Simple "lap pad" packing of the liver. Typically three lap pads are packed above and three lap pads below the liver for temporary hemostasis. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

hemostats and tied to minimize risk of bleeding from a patent remnant umbilical vein. At this point in the operation, the falciform ligament should not be taken down any farther posteriorly than required to gain adequate access to the peritoneal cavity to minimize the risk of release of retrohepatic tamponade. Packing around the liver typically includes three laparotomy pads ("lap pads") above and below the liver to compress the liver up against the diaphragm (Fig. 11.5). Even at this early stage in the operation, significant liver injuries should be readily apparent. There are two crucial questions that need to be answered:

1. Is the patient bleeding through packs?
2. Does the patient's physiology dictate that a damage control (DC) approach should be used?

If the answer to question #1 is "no," then time is given to allow the anesthesia providers to administer blood products and stabilize the patient's hemodynamics. Definitive repair and hemostasis is then dictated by the answer to question #2. If the patient is physiologically normal, then definitive hemostasis and repair can be performed as discussed below.

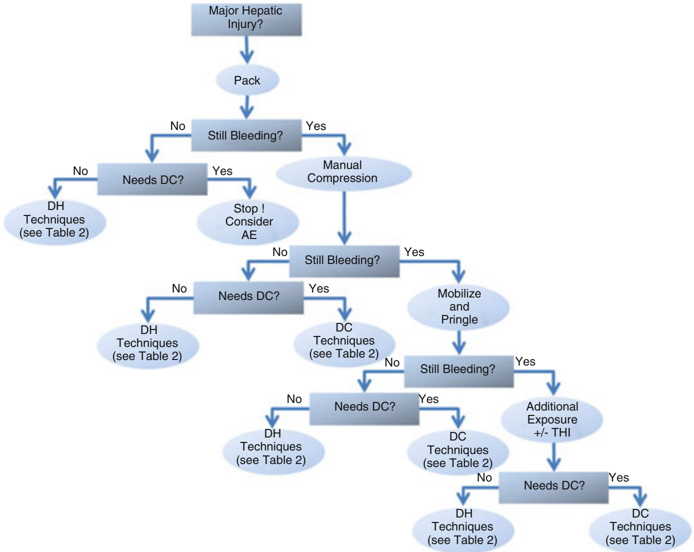


Fig. 11.6. Algorithm for initial operative management of major hepatic injury. DC = damage control, DH = definitive hemostasis, THI = total hepatic isolation.

If a DC approach is advisable and the patient is not actively bleeding with the lap pads in place, no further liver-specific intervention is indicated at that time and other active issues can be addressed such as control of enteric contamination.

If the answer to question #1 is "yes," then a series of maneuvers should be performed in an orderly and sequential fashion (Fig. 11.6). The right upper quadrant should be unpacked and inspected. *Manual compression* is the first-line therapy for all hemorrhage from the liver and is surprisingly effective. While the assistant is compressing the liver parenchyma, the liver must be fully mobilized. The exception to this is in patients with retrohepatic hematoma that appears to be stable. In this situation, full mobilization of the liver may result in release of tamponade from bleeding from a major hepatic venous injury or retrohepatic caval injury. All other injuries are best approached with *full mobilization of the liver* (Fig. 11.7). The liver is mobilized by taking down the falciform ligament all the way to the suprahepatic IVC using either electrocautery or Metzenbaum scissors. The hepatic veins are not encountered until the leaflets of the falciform ligament diverge so the ligament can be dissected all the way back to the IVC with impunity. The right and left triangular ligaments are similarly transected until the

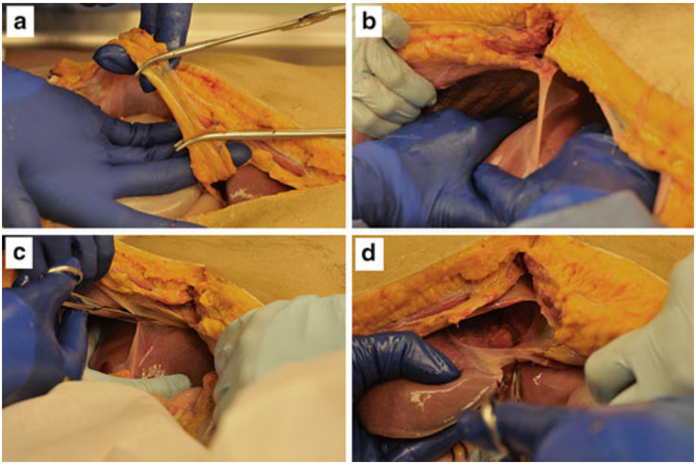


Fig. 11.7. Mobilization of the liver. (**a**) The anterior portion of the falciform ligament is clamped and tied. (**b**, **c**) The liver is retracted downward and the falciform ligament is sharply transected back to the IVC. (**d**) The right (not shown) and left triangular ligaments are similarly transected. Photo credit: Facilities, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens: Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

liver can be mobilized out of the right upper quadrant and inspected. This should be done extremely rapidly and take only a minute or two to completely mobilize the liver. At this point the liver can be fully inspected, and the major source of hemorrhage can be identified.

If active hemorrhage is still encountered that cannot be controlled with simple manual pressure, a "Pringle maneuver" is next applied (Fig. 11.8). The gastrohepatic ligament is opened, taking care to avoid injury to the left gastric artery, and the porta hepatis is encircled through the foramen of Winslow. A vascular clamp or Penrose drain can then be used to compress the portal vein and proper hepatic artery at the porta hepatis. This maneuver controls all but hepatic venous flow, so if the hemorrhage from the liver is stemmed, a major hepatic venous injury is unlikely. Decisions about definitive hemostasis for a hepatic arterial or portal venous injury can then be made. If massive exsanguination continues, then the diagnosis of hepatic venous injury is likely and the techniques described next will need to be rapidly employed. If the majority of the bleeding appears to be from the posterior aspect of the liver, a major hepatic vein or retrohepatic caval injury is likely.

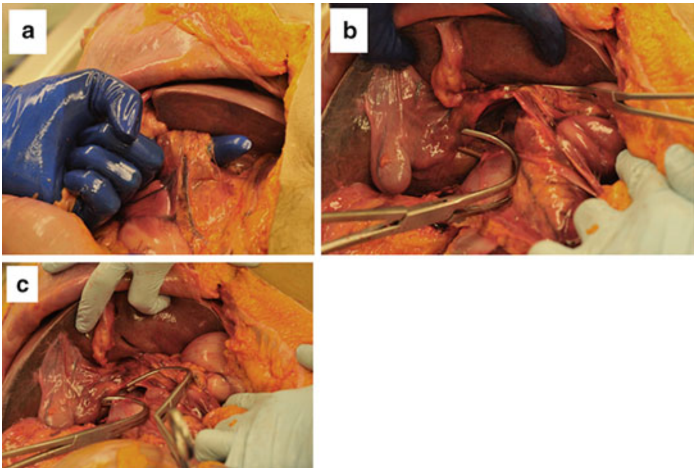

Fig. 11.8. (**a**) Dissecting out the porta hepatis for a “Pringle maneuver.” (**b**) Exposure to the infrahepatic IVC. (**c**) Infrahepatic IVC occlusion with the portal triad occluded. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

If a major hepatic vein or retrohepatic caval injury is suspected, *additional exposure* is advisable. There are several strategies for this. Access to the hepatic veins and IVC requires a more extensive mobilization and, in our opinion, is best accomplished by opening the thorax. The best exposure will be obtained by extending the midline laparotomy incision across the right chest at about the eighth intercostal space and transecting the costal cartilages (Fig. 11.4). The diaphragm is then taken down from the anterior midline radially all the way back to the IVC, remembering to leave enough diaphragm on the chest wall side of the incision for later repair (Fig. 11.9). At this point a chest retractor can be placed and exposure to the entire retrohepatic area is achieved (Fig. 11.10). The other strategy that can be used to gain additional exposure to the liver, particularly the posterior right lobe and retrohepatic area, is to “t-off” the laparotomy incision through a right lateral transverse incision in which the rectus muscles are transected (Fig. 11.4). This allows for improved access to these structures and facilitates mobilization and the ability to apply direct circumferential pressure to the liver parenchyma.

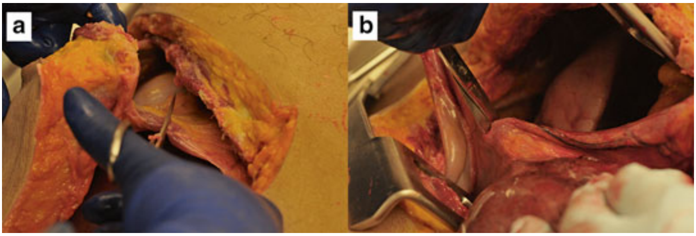

Fig. 11.9. Extension of the midline laparotomy to the right chest at the eighth intercostal space and transecting the costal cartilages. The diaphragm is then taken down from the anterior midline (**a**) radially all the way back to the IVC (**b**), remembering to leave enough diaphragm on the chest wall side of the incision for later repair. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

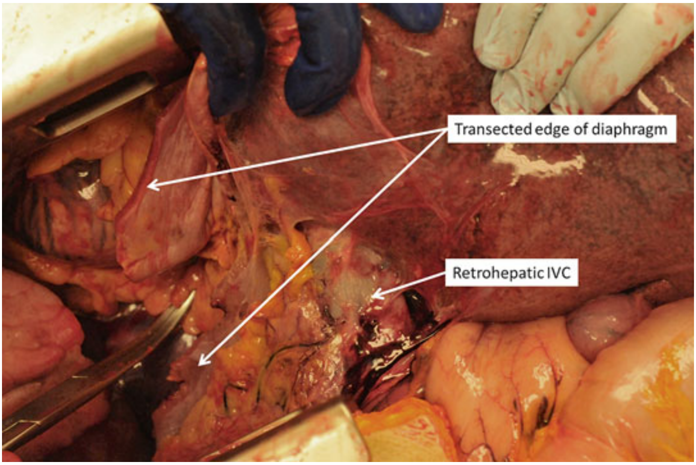


Fig. 11.10. Retrohepatic IVC exposure after extension of the midline laparotomy into the right thorax. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

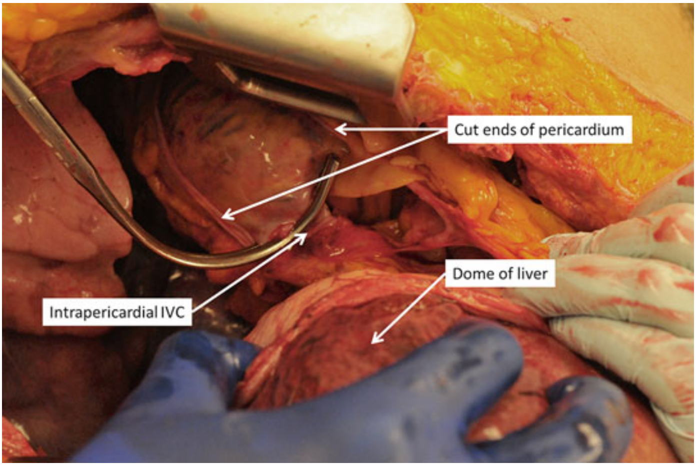


Fig. 11.11. Suprahepatic IVC clamped after exposure through the right thorax with incision in the pericardium. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

Although classically taught, the technique of *total hepatic isolation* is, in our opinion, not as effective or as straightforward as typically described. Additionally, the profound reduction in preload that occurs with clamping of the suprahepatic IVC in a patient who already is in shock often leads to cardiac arrest. If total hepatic isolation is desired, however, once the chest is open, the suprahepatic IVC can be easily clamped by simple incision of the right lateral pericardium, taking care to avoid injury to the phrenic nerve (Fig. 11.11). Alternative access to the suprahepatic IVC without thoracic exposure can be obtained via gentle traction down on the dome of the liver with upward traction on the diaphragm and intraperitoneal dissection and exposure. An incision through the peritoneal side of the diaphragm into the pericardium and clamping of the suprahepatic IVC in the pericardium is another approach to suprahepatic IVC control (Fig. 11.12). A median sternotomy also provides immediate access to the suprahepatic IVC. The infrahepatic IVC is accessed either through the gastrohepatic ligament or, more commonly, via a complete right medial visceral rotation with a Kocher maneuver. The IVC is carefully encircled above the renal veins and clamped with a vascular clamp (Fig. 11.8). With the porta hepatis, the

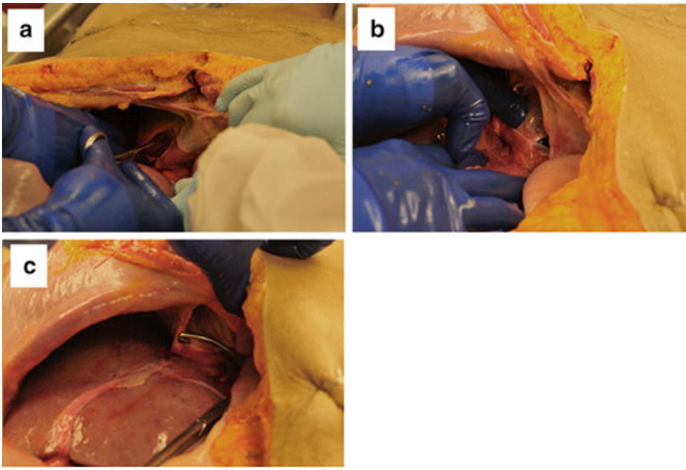


Fig. 11.12. Accessing the suprahepatic IVC. The pericardium is incised through the diaphragm (**a**), and the suprahepatic IVC is encircled (**b**) and clamped (**c**). Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

suprahepatic IVC, and the intrahepatic IVC now occluded, total hepatic vascular isolation is achieved. As stated previously, however, this is typically poorly tolerated by patients in extremis.

The use of *veno-venous bypass* can allow for preservation of preload and venous return to the heart with total hepatic isolation [33, 34]. Venous cannulae can be placed percutaneously in the right internal jugular and right femoral veins allowing for preservation of flow to the heart. Additionally, this technique can be employed without the use of total hepatic isolation as a way to markedly decrease bleeding from the hepatic veins and the IVC to allow for better visualization and a reduction in blood loss during repair or ligation of these structures. Veno-venous bypass is exceptionally helpful when major resection is needed at planned "second-look" laparotomy or for management of major complications.

The atriocaval shunt was first described in 1968 by Schrock et al. as a strategy of controlling hemorrhage from retrohepatic IVC and hepatic venous injury [35]. The technique includes placement of a large-bore chest tube into the right atrium after a purse-string suture is placed in the atrial appendage. The side hole of the chest tube must be within the atrium to allow for maintenance of venous inflow. The tip of the tube is clamped, and the tube is then passed down into the IVC and secured at the intrapericardial and infrahepatic IVC with simple ties, Rummel tourniquets, or umbilical tape. When used with a Pringle maneuver, it should provide almost total hepatic vascular occlusion. Case series have reported survival in these highly lethal injuries [36, 37]. In 1986, Pachter reported six consecutive patients with juxtahepatic venous injuries managed without a shunt with a remarkable survival of 83 % [38]. While we are not big proponents of its use, the key to its successful employment is clearly the decision to utilize the technique early in the operation before the patient is moribund [36].

Specific techniques for hemostasis are dictated by three main factors: the location of the injury, the anatomy of the injury, and the need for a DC approach (Table 11.2). Each of the techniques that will be described in this chapter is divided into "definitive hemostasis" and "damage control" or "temporary hemostasis." Any of the definitive hemostasis techniques can also be used for DC if it will be the most rapid way of controlling hemorrhage, and any of these techniques are appropriate for use at both the index operation or during the take-back second-look laparotomy after DC and in the event of re-exploration for recurrent hemorrhage.

Capsular tears of the liver are typically minor and easily controlled. In the hemodynamically stable and physiologically normal patient, definitive treatment of these injuries ranges from no intervention to simple hepatorrhaphy with electrocautery, argon beam coagulation, or topical hemostatic agents, such as EVICEL® Fibrin Sealant (Ethicon, Inc.) or Crosseal™ Fibrin Sealant (OMRIX Biopharmaceuticals, Ltd). A very helpful technique useful for minor bleeding is placement of a piece of SURGICEL® (Ethicon, Medline Industries, Inc.) or other absorbable hemostatic agent, which can then be cauterized on the surface of the liver by "arcing" the electrocautery or using the argon beam. Large capsular tears can be additionally treated with a technique of the use of an absorbable material such as Vicryl™ Knitted Mesh or SURGICEL® NU-KNIT® Absorbable Hemostat (Ethicon, Medline Industries, Inc.) sprayed with a topical hemostatic agent. These are also applicable to treat "ooze" from the raw liver surface that is left after hepatotomy or hepatectomy. In the physiologically deranged patient, DC approach includes simple laparotomy pad placement or the use of a temporary topical hemostatic gauze pack or pad such as QuikClot® Trauma Pad™ (Z-Medica). This product is kaolin impregnated, which activates factors

Table 11.2. Preferred techniques for hemostasis.

| Type of injury | Definitive hemostasis | Damage control |
|---|---|---|
| Capsular tear/ subcapsular hematoma or any "raw surface" | • Electrocautery<br>• Argon beam coagulation<br>• Topical hemostatic agents<br>• Absorbable mesh with hemostatic agent (EVICEL®, Crosseal™, etc.) | • Lap pad packing<br>• QuikClot® or other nonabsorbable hemostatic agent |
| Minor parenchymal injury | • Electrocautery<br>• Argon beam coagulation<br>• Topical hemostatic agents<br>• Absorbable mesh with hemostatic agent (EVICEL®, Crosseal™, etc.)<br>• Direct vessel ligation<br>• Suture hepatorrhaphy (horizontal mattress 0 chromic liver suture with omental patch) | • Lap pad packing<br>• QuikClot® or other nonabsorbable hemostatic agent |
| Major parenchymal injury | | |
| Peripheral | • Direct vessel ligation<br>• Suture hepatorrhaphy (horizontal mattress 0 chromic liver suture with omental patch)<br>• Hepatotomy with direct vessel ligation<br>• Resectional debridement/ nonanatomic resection<br>• Anatomic resection<br>• AE | • Lap pad packing<br>• QuikClot® or other nonabsorbable hemostatic agent |
| Central | • Direct vessel ligation<br>• Hepatotomy with direct vessel ligation<br>• Resectional debridement/ nonanatomic resection<br>• Anatomic resection<br>• Selective hepatic artery ligation<br>• AE | • Lap pad packing<br>• QuikClot® or other nonabsorbable hemostatic agent<br>• Foley balloon tamponade<br>• Veno-venous bypass<br>• Total hepatectomy |

(continued)

Table 11.2. (continued)

| Type of injury | Definitive hemostasis | Damage control |
|---|---|---|
| Transhepatic GSW | • Direct vessel ligation<br>• Hepatotomy/"tractotomy" with direct vessel ligation<br>• Resectional debridement/ nonanatomic resection<br>• Selective hepatic artery ligation<br>• AE | • Lap pad packing<br>• QuikClot® or other nonabsorbable hemostatic agent<br>• Foley balloon tamponade<br>• Saline-filled Penrose drain tamponade<br>• Veno-venous bypass<br>• Total hepatectomy |
| Major hepatic vein injury | • Direct vessel ligation or repair | • Lap pad packing |
| Retrohepatic IVC injury | • Vessel repair<br>• Interposition graft | • Lap pad packing<br>• Total hepatic vascular isolation<br>• Atriocaval shunt with veno-venous bypass<br>• Total hepatectomy if not repairable |

Any of the techniques for definitive hemostasis can also be used for DC if it will be the most rapid way of controlling hemorrhage and are appropriate for use at both the index operation or during the take-back second-look laparotomy after DC
DH = definitive hemostasis, DC = damage control, GSW = gunshot wound, IVC = inferior vena cava, AE = angiographic embolization

in the blood, thus triggering the coagulation cascade. This product is only US Food and Drug Administration (FDA) approved for external use, but is X-ray detectable. The majority of subcapsular hematomas require no specific treatment in the stable patient, but in a DC control setting, they can expand significantly due to underlying coagulopathy and may require any of the above approaches.

Minor parenchymal injuries can typically be managed as described previously for capsular tears, particularly in the setting of definitive hemostasis. An additional technique that is used for either definitive

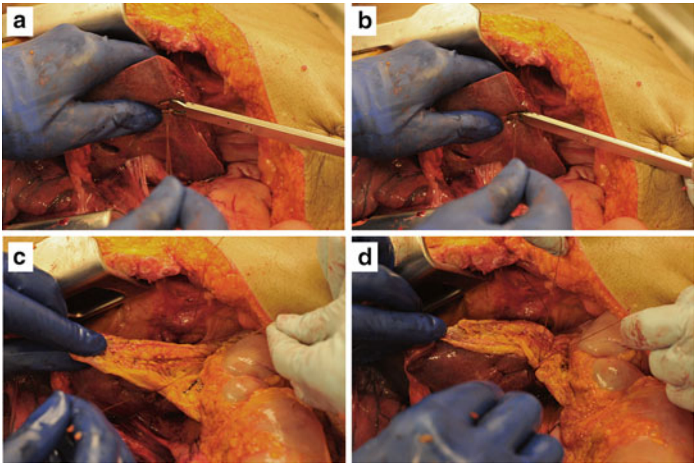


Fig. 11.13. Suture hepatorrhaphy. Placement of “liver sutures” whereby a 0 chromic with a blunt-tipped needle is placed on either side of the defect in the parenchyma in a horizontal mattress fashion creating a tamponade effect on the injured liver. (**a**, **b**) To help prevent tearing of the capsule, a hemoclip can be used to “set the tension” and then tie down the suture. (**c**, **d**) If the sutures are placed opposite each other and left long, the omentum can be placed on the defect and the sutures tied over it to minimize the need to place additional sutures. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

hemostasis or DC includes suture hepatorrhaphy. If bleeding vessels are visualized, they can be directly ligated, typically with a 2-0 Vicryl suture. Another technique useful for more significant parenchymal injury is placement of “liver sutures” whereby a 0 chromic with a blunt-tipped needle is placed on either side of the defect in the parenchyma in a horizontal mattress fashion, creating a tamponade effect on the injured liver (Fig. 11.13). A few tricks can be very helpful. The defect can be packed with hemostatic material such as SURGICEL® (Ethicon, Medline Industries, Inc.) or omentum prior to tying down the sutures. If the sutures are placed opposite each other and left long, the omentum or other hemostatic agent can be placed on the defect, and the sutures tied over it to eliminate the need for additional sutures. Additionally, one technique that helps prevent tearing of the capsule is to “set the tension” on the suture using a hemoclip and then tie down the suture. We typically do not use pledgets, but if we do, we avoid the use of Teflon® (Deknatel®, Teleflex Incorporated) or other nonabsorbable material as these can become a nidus for infection. Instead, a piece of rolled or folded SURGICEL®, Vicryl™ Knitted Mesh, or NU-KNIT® can be used.

Major parenchymal disruptions require the use of more advanced surgical techniques whether as a damage control procedure or in the setting of definitive repair. Techniques include suture and other hepatorrhaphy techniques as described previously, hepatotomy with direct vessel ligation, resectional debridement/nonanatomic resection, or anatomic resection. Often a combination is required. Peripheral and central injuries often require different approaches.

Major peripheral injuries are best served by resectional debridement or nonanatomic resection. This is the most rapid way of controlling hemorrhage and is typically well tolerated. The liver tends to bleed from both "halves" of the injured liver, and once the lateral parenchyma is resected, the bleeding is stemmed by "half" and is easily controlled with manual compression and direct vessel ligation. Techniques for transecting liver parenchyma are identical for resectional debridement, hepatotomy, nonanatomic resection, and anatomic resection and include a number of techniques such as finger fracture or crush clamping and devices such as the ultrasonic desiccator (Cavitron Ultrasonic Surgical Aspirator—CUSA, Soma Technology, Inc), water-jet dissectors (HELIX HYDRO-JET®, Stormoff), harmonic scalpel (© Ethicon Endo-Surgery, Inc.), or dissecting/radio-frequency sealers (TissueLink, Medtronic, Inc). These specialized devices are too slow for use in acute trauma due to the need for prolonged tissue contact time for efficacy. These devices can be very helpful, however, upon reoperation for definitive hemostasis after DC or for management of liver-related complications. We typically favor a simple finger fracture technique or the use of gastrointestinal anastomosis (GIA) staplers. The finger fracture technique uses gentle fracturing of the liver parenchyma between the thumb and index finger or uses the blunt tip of an instrument in a back-and-forth motion after the liver capsule is "scored." The liver parenchyma is dissected, leaving the blood vessels and biliary ducts exposed in the tract for ligation with sutures or clips. The use of GIA staplers using a "vascular" load, typically 2.5 mm staples, accomplishes the same thing in less time. Care must be taken in inserting the blade of the stapler into the parenchyma blindly, and creation of a gentle tract with a hemostat is advised (Fig. 11.14). We always have our operating room (OR) personnel have two open devices on the operative field so that a loaded device is always

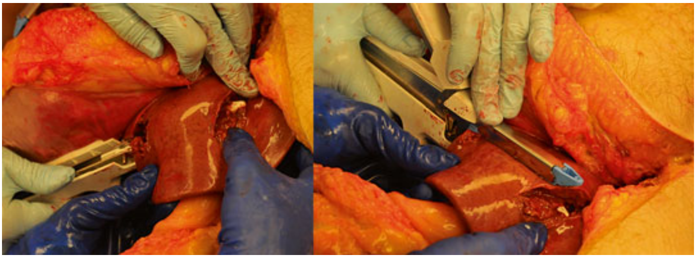

Fig. 11.14. Hepatotomy/tractotomy of liver parenchyma using GIA stapler. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

available to allow rapid parenchymal division. The raw edge of the liver that is left can then be treated with any of the techniques described previously for hepatorrhaphy. For all major parenchymal injuries or if a significant "raw" edge of the liver is left, we place closed suction drains in anticipation of biliary leaks that occur frequently [11].

Major central peripheral injuries to the liver can be exceptionally difficult to manage (Fig. 11.15). These patients are almost universally unstable and therefore DC is wise. If the injury can be largely controlled with simple packing, we use temporary abdominal closure and emergent diagnostic angiography and angiographic embolization (AE). If bleeding cannot be controlled, then more advanced techniques are indicated. Suture hepatorrhaphy with large liver sutures to "close down the parenchymal defect" should not be used for these injuries. Although approximation of tissue may create a local tamponade effect, it risks rebleeding, intrahepatic hematoma, abscess, and biloma formation [39]. Additionally, the blind placement of large central liver sutures causes a risk of injury to underlying major vascular and biliary structures. These injuries are best treated with hepatotomy with direct vessel ligation, often with portal occlusion in place. These injuries particularly require a keen appreciation of hepatic anatomy to avoid injury or transection of noninjured essential vascular and biliary structures. If anatomically amenable, without causing disruption of the vascular supply to the uninjured liver, nonanatomic resection or resectional debridement can be performed (Fig. 11.16). Anatomic resection with direct vascular ligation of major vascular and biliary structures can be performed. However, it is rare that the patient is stable enough to allow for anatomic resection

Fig. 11.15. Example of major central parenchymal injury.

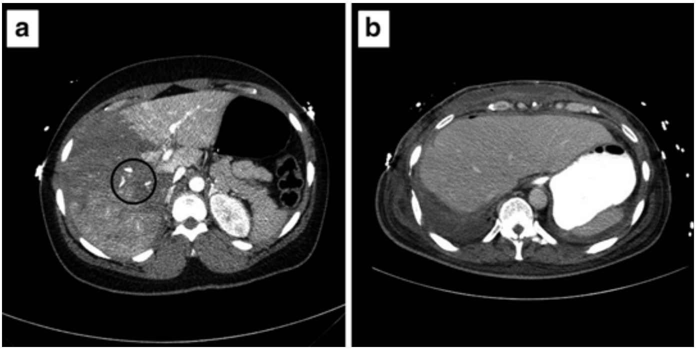


Fig. 11.16. (**a**) CT scan of a 48-year-old female after a motor vehicle crash with a grade V liver injury with active areas of extravasation (*circle*). The patient was initially hemodynamically stable but then decompensated and was taken to the OR where she had percutaneous cannulation for veno-venous bypass and a non-anatomic resection of the right lobe of her liver. Forty-eight hours later she was taken back for completion anatomic resection and decannulation. (**b**) CT scan done 4 weeks postoperatively.

at the index operation, and this technique is usually reserved for the "take-back" operation or for management of complications such as major hepatic necrosis [40]. Another option for major central hepatic parenchymal injuries is selective hepatic artery ligation. This technique

Fig. 11.17. Placement of a Foley balloon for tamponade in a central hepatic injury. Photo credit: Facilities, Surgical Laboratory, Anatomical Services Division, School of Medicine, UMB; Cadavers and Specimens, Anatomical Donors, Maryland State Anatomy Board; Ronn Wade, State Anatomy Board, Department of Health and Mental Hygiene.

should be reserved for use in patients with exsanguinating hemorrhage in which there is not time for more selective AE to be done. There are a few additional DC techniques that can be applied to the patient with central parenchymal injuries, particularly transhepatic gunshot wounds. Tamponade with a Foley balloon can be used to provide intraparenchymal pressure on vascular structures for temporary hemostasis, and the technique of a saline-filled Penrose drain passed through a central injury tract for temporary hemostasis can be lifesaving [41–43] (Fig. 11.17).

The use of angiographic embolization (AE) is an essential adjunct to any major hepatic parenchymal injury, whether peripheral or central. AE is typically used as a part of NOM, for management of subsequent complications, and as an adjunctive measure for operative management, typically in the setting of DC. Numerous studies have advocated the use of adjunctive AE either pre- or postoperatively [2, 4, 9, 10, 44–50]. The key to successful use of AE is anticipating its need. In most institutions, mobilizing the interventional radiology (IR) team takes some time, especially off-hour on nights and weekends. We typically notify our IR team as soon as we identify that a patient has severe hepatic trauma. This allows for the team to be ready so the patient can be transported directly to the IR suite from the OR. Ongoing resuscitation can be carried out in the IR suite, and the patient brought directly back to the OR as needed. If ongoing substantial bleeding has occurred since the index operation and successful AE, we are advocates of returning the patient directly to the OR for a quick “unpack and repack” as the lap pads are typically soaked with blood and are no longer providing effective tamponade. A temporary abdominal closure is then performed, and the patient is brought to the ICU for ongoing resuscitation. Alternatively, as hybrid operating suites are becoming more widely available, the patient can ideally undergo an AE procedure while in the OR, allowing for ongoing resuscitation without extensive movement through various parts of the hospital.

Retrohepatic caval and hepatic venous injuries are both lethal and extremely challenging. Access to visualize and ligate or repair these structures is the key to successful management. Direct pressure should be applied during hepatic mobilization and attainment of additional exposure. Typically these injuries are associated with massive hemorrhage, and even when exposure is optimal, it is exceptionally difficult to maintain a dry enough field to identify bleeding sites. Once the injury is visualized, the hepatic veins can typically be ligated without consequence. The retrohepatic IVC, however, should be repaired whenever possible. One effective technique that can be applied to all major venous injuries is the use of “intestinal Allis” clamps, which can be used to approximate the edges of the vein and provide temporary hemostasis [51]. The clamps are “stacked” along the injury, and a suture can then be run under the clamps for repair of the vessel wall.

In the patient with a massively destructive liver injury, total hepatectomy is a viable, albeit last resort, option [7, 39, 52, 53]. Outcomes following total hepatectomy and transplantation are acceptable enough to make this an option in patients with liver injury not amenable to other hemostatic techniques. If total hepatectomy is to be done, there are a few key steps that should be undertaken. First, the IVC should be left as intact as possible or reconstructed with a prosthetic graft to maintain venous drainage and preload to the heart. Second, portal decompression is essential. This can be accomplished with either extracorporeal support using veno-venous bypass or with the creation of a portal-systemic shunt/bypass. Failure to provide portal decompression will almost invariably result in mesenteric ischemia and death from sepsis.

Use of veno-venous bypass in these patients with or without a portal decompression cannula is also extremely helpful in stabilizing the patient enough to allow them to survive to transplantation. Third, involvement of a transplant service or referral to a transplant center should be done immediately so that the patient can be listed as a "Status 1" candidate for emergent hepatic transplantation.

## Outcomes

Outcomes following liver injury are highly variable depending on the type and severity of injury. For patients who are candidates for NOM, liver-related mortality is well below 1 % [26]. For patients that require operative intervention, mortality rates have been reported to be as low as 2 % for highly selected patients [8] but >80 % for patients with retrohepatic IVC or major hepatic venous injuries [36, 37]. In most large studies of patients with operative hepatic trauma, mortality rates are typically approximately 50 % [1, 2, 54]. In more selected patient populations in which early deaths from acute hemorrhage were excluded, liver-specific mortality rates are 11–30 % [9, 11]. Morbidity rates for patients who require operative intervention are as high as 80 %, with the most frequent complications being recurrent hemorrhage, sepsis and organ system dysfunction, abdominal compartment syndrome (ACS), bile leak, hepatic necrosis, and liver abscess [7, 9–11, 44]. After adjunctive AE, complication rates as high as almost 90 % have been reported due to the severity of the primary injury combined with the hepatic ischemia from embolization [10].

## Complications with Treatment

Patients with severe liver injury can develop devastating sepsis and/or organ dysfunction that can require intensive supportive therapy. The complications discussed here are the ones that specifically require additional operative therapy or intervention.

Rebleeding or recurrent hemorrhage occurs both after NOM and operative management. Strategies for management are dependent on the original approach used, degree of hemodynamic stability, presence of coagulopathy, and availability of resources. If major vascular bleeding is suspected, the patient can be managed with either AE or laparotomy.

Angiography is the procedure of choice if immediately available in a patient who underwent a diagnostic angiogram initially without AE performed or in a patient who has already had DC laparotomy without postoperative angiography. If IR is not immediately available and the patient is hemodynamically unstable, then additional operative intervention is warranted. Diffuse "ooze" and coagulopathy is best managed with emergent factor and platelet administration. Returning these patients to the operating room to repack may be beneficial, but the risks of additional operative insult and physiological derangements must be weighed against the potential benefits.

Hepatic abscesses occur following major liver injury, particularly in the setting of concomitant bowel injury. Most can be managed with IR drainage and antibiotics. Operative intervention is typically reserved for patients in whom this approach fails to resolve the abscess or with signs and symptoms of persistent sepsis.

Biliary complications are some of the most frequently encountered after major hepatic injury [44, 55]. Bile leaks, biloma formation, and hemobilia can all occur. Bile leaks are typically diagnosed when persistent bilious drainage is noted from operatively placed drains or with the development of bile peritonitis. Hepatobiliary iminodiacetic acid (HIDA) scan is diagnostic [55]. Small contained leaks can be effectively managed with drainage alone. Persistent or high-volume leaks are best treated with drainage and endoscopic retrograde cholangiopancreatography (ERCP) and stent placement which is highly effective [56]. Diffuse leaks with bile peritonitis are best managed with operative "washout" [55]. Bilomas are typically intraparenchymal contained bile leaks. Small bilomas often will resolve, but larger ones should be treated with percutaneous drainage +/− ERCP and stenting if persistent. Hemobilia, typically a late complication of severe liver injury, is caused by an arterial fistula to some part of the biliary tree. These patients present most typically with upper gastrointestinal bleeding. Treatment is AE of the involved artery and fistulous connection. Gallbladder necrosis is also seen following AE for high-grade liver injuries and requires cholecystectomy [9].

Major hepatic necrosis is now a well-recognized complication following severe liver injury, particularly when AE is used to control hemorrhage [9, 10] (Fig. 11.18). It typically presents with fever, leukocytosis, hyperlactemia, and persistent elevation of transaminases [9]. Contrast-enhanced CT is diagnostic. These patients are often critically ill, and areas of necrosis must be distinguished from simple abscess. We, and others, have favored an aggressive surgical approach to these

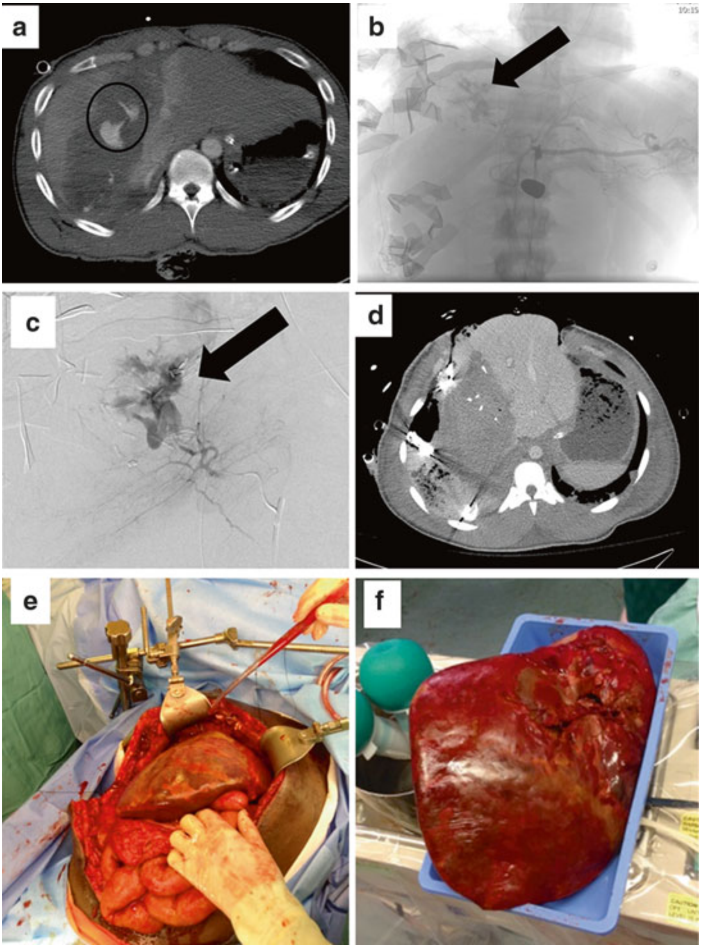


Fig. 11.18. (**a**) CT scan of a 17-year-old male after a gunshot wound with a grade V liver injury with large area of extravasation (*circle*). The patient became hemodynamically unstable and was taken to the OR where hepatotomy and direct vessel ligation was performed with packing. (**b**, **c**) The patient was brought emergently to IR, which demonstrated active bleeding from the right hepatic artery (*arrows*). Coil embolization was performed. Three days later, patient developed fever, leukocytosis, and increasing transaminases. (**d**) CT scan demonstrated hepatic necrosis of the entire right lobe of the liver. (**e**) Intraoperative photograph of the right hepatic lobe with extensive necrosis. A formal right hepatic lobectomy was performed with veno-venous bypass. (**f**) Resected right lobe of the liver demonstrating the previous hepatotomy site and parenchymal necrosis.

complications with anatomic or nonanatomic resection of the necrotic liver [10, 40]. For large areas of necrosis, we favor placing the patient on veno-venous bypass for these procedures as it markedly reduces intraoperative blood loss and facilitates resection. Alternatives to resection include a combination of operative debridement and IR drainage. Often multiple procedures are required, and the complication rate is higher with this approach [40].

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# 12. The Spleen

*Matthew E. Lissauer, M.D.*

## Introduction

The spleen is one of the most commonly injured organs following blunt trauma. The injured spleen is a major source of morbidity and mortality and can be rapidly fatal if hemostasis is not achieved early. Up to one-third of patients with injured spleens proceed directly to the operating room for surgical exploration [1]. Patients who have had splenectomy are at risk for the usual morbidities of laparotomy such as incisional hernia and small bowel obstruction. Additionally, they are at increased risk for overwhelming sepsis syndromes due to asplenia. Nonoperative management also has risks including failure of nonoperative management, delayed hemorrhage, splenic infarction and abscess, and complications of angiography, if used. Given the common nature of the injury and the risks with all forms of management, the trauma surgeon must be well versed in the techniques required to care for this disease.

## History of Care

Until recently, the spleen seemed a mystery, and it was considered nonessential for survival. The Talmud describes the spleen as a laughter-generating organ. Babylonian, Greek, and Roman texts incriminate the spleen as a cause of poor athletic performance [2]. Galen, Vesalius, and Malpighi all debated whether or not the spleen was necessary for survival [3]. There were accounts of asplenic patients, however, with no documented obvious adverse sequela suggesting lack of function of the organ.

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During the early history of surgery for the injured spleen, splenectomy, though usually fatal, was considered as the only treatment for injury since its true function was unknown and death seemed more certain without operation. The spleen was considered frail and unable to heal. Early attempts at splenectomy for trauma described in the 1800s were quite often failures. Still, no consideration at that time was given to splenic salvage. It was incorrectly thought that the bone marrow and thyroid could substitute for the spleen's perceived "blood producing quality."

By the early twentieth century, however, splenectomy became more safe and hundreds of total splenectomies for trauma had been reported [4], many of them successful. Over the course of the twentieth century, the immunologic function of the spleen became better known and characterized. As early as 1952, data emerged that asplenic patients were at higher risk for overwhelming sepsis [5]. As this risk became better delineated, splenic salvage and conservative management of the spleen emerged as a management option [6].

Prior to the era of computed tomography (CT) scan, conservative management of splenic injury was splenorrhaphy or repair since diagnosis was usually made at laparotomy. With the advent and widespread use of CT scans, preoperative diagnosis became common. Concurrently, advances in catheter-based technologies allowed development of embolization. These technologies permitted true nonoperative, conservative management of the injured spleen. Splenectomy for trauma became significantly more uncommon.

The incidence of overwhelming postsplenectomy sepsis now appears lower than once perceived, perhaps due to advances in vaccine and prophylactic therapy. Further, compared to nonoperative management, the morbidity of laparotomy is high. One must weigh the benefits of definitive bleeding control and the risks of laparotomy to the potential benefit and risks of nonoperative management, including a defined failure rate. While in general, splenectomy for trauma might sometimes be a simple technical procedure; it is not one to be undertaken lightly due to the rare, but highly lethal, complication of overwhelming postsplenectomy sepsis. The remainder of the chapter is devoted to the issues that directly confront the trauma surgeon: how to diagnose and treat injuries of the spleen and care for complications of this treatment.

# Techniques with Personal Tips

## *Techniques for Diagnosis*

Approximately 30 % of patients with splenic injury are treated with primary operative exploration. Typically these patients present with hemodynamic instability and hemoperitoneum. While hemoperitoneum may be readily diagnosed in the trauma bay by focused assessment with sonography for trauma (FAST), the splenic injury as the source of the hemoperitoneum is typically diagnosed in the operating room (OR). Standard techniques of trauma laparotomy described earlier in this book should be followed, with packing of all four quadrants to obtain immediate hemostasis followed by controlled removal with inspection for injury and plans for prompt hemorrhage control as injuries are identified.

Many patients with splenic injury, however, are hemodynamically stable enough for diagnostic work-up to be performed after FAST in the trauma bay. In one review, ultrasound was 62–99 % sensitive for the detection of free intraperitoneal fluid. A large percentage of these patients will have splenic injury. However, up to 25 % of patients with splenic injury may not manifest hemoperitoneum [7]. A negative FAST in a hemodynamically stable patient who has significant mechanism concerning for solid organ injury should undergo further evaluation.

In most trauma centers, that diagnostic modality is multidetector CT imaging. CT provides very high sensitivity and specificity for diagnosing injury to the spleen. At the R Adams Cowley Shock Trauma Center, dual-phase imaging with both arterial phase and portal venous phase demonstrates the best diagnostic performance and can help guide management [8]. However, some patients may have discrete contraindications to intravenous (IV) contrast. While image quality may not be as good and detection of vascular lesions is limited, determination of significant injuries that require close follow-up or intervention can be made with a non-contrast-enhanced CT scan [9]. Once splenic injury is diagnosed, several important radiologic features should be evaluated as they impact treatment and outcomes: grade of injury, which should be based on the American Association for the Surgery of Trauma (AAST) grading system (Table 12.1) [10]; the presence or absence of active extravasation of IV contrast; the presence or absence of pseudoaneurysms; and the degree of hemoperitoneum. While CT does not detect all lesions, it

Table 12.1. AAST injury scale for the spleen.

| Grade | Type | Description |
|---|---|---|
| I | Hematoma | Subcapsular, <10 % surface area |
| | Laceration | Capsular tear, <1 cm parenchymal depth |
| II | Hematoma | Subcapsular, 10–50 % surface area; intraparenchymal, <5 cm in diameter |
| | Laceration | Capsular tear, 1–3 cm parenchymal depth that does not involve a trabecular vessel |
| III | Hematoma | Subcapsular, >50 % surface area or expanding; ruptured subcapsular or parenchymal hematoma; intraparenchymal hematoma ≥5 cm or expanding |
| | Laceration | >3 cm parenchymal depth or involving trabecular vessels |
| IV | Laceration | Laceration involving segmental or hilar vessels producing major devascularization (>25 % of spleen) |
| V | Hematoma | Completely shattered spleen |
| | Laceration | Hilar vascular injury devascularizes spleen |

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detects lesions requiring treatment rather reliably, especially in high-grade injuries, and is useful for directing the initial care of the injured patient [11].

## *Techniques for Operative Treatment of Splenic Trauma*

For the patient who is taken immediately to the operating room with hemodynamic instability, hemorrhage control must be quick. If at laparotomy, the spleen is found to be the cause of hemorrhage, splenectomy is the wisest choice in this patient. Our technique for emergent splenectomy is described:

While standing on the right side of the patient, the surgeon uses his/her right hand to rapidly mobilize the spleen by bluntly dividing the splenorenal and splenophrenic ligaments (Fig. 12.1a, b). The spleen is mobilized medially into the abdominal incision. It is an error to operate on the spleen in the left upper quadrant, as exposure is inadequate. The spleen can be elevated on some lap pads (Fig. 12.1c). If needed, a left medial visceral

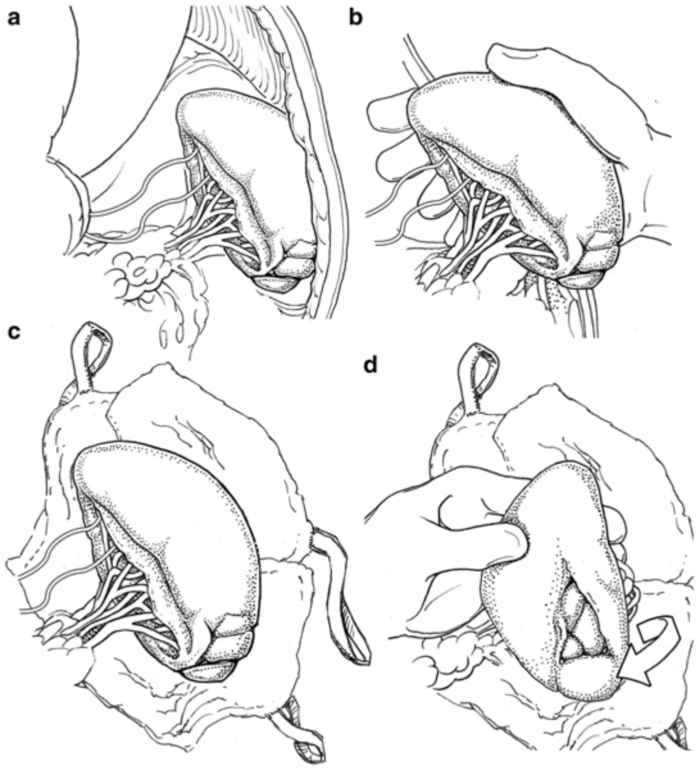


Fig. 12.1. (**a**) The spleen in situ. (**b**) Manual mobilization of the spleen from its attachments. (**c**) The spleen mobilized into the operative field resting on laparotomy pads. (**d**) Medial rotation of the spleen to control the hilum from its posterior aspect.

rotation or "Mattox maneuver" can be rapidly completed almost entirely with blunt dissection if other organs are injured in proximity to the spleen or retroperitoneal hemorrhage is identified in addition to splenic hemorrhage. We generally prefer to approach the spleen from its posterior aspect as it allows the best visualization of the pancreatic tail (Fig. 12.1d). The splenic vascular anatomy is variable. Sometimes, the splenic artery and vein extend onto the hilum. If so, they can be ligated flush with the spleen. Other times, they branch proximal to the hilum. If so, each branch should be ligated separately. The short gastric vessels are then ligated and the spleen is removed. The stomach should be carefully inspected to be sure every short gastric has been ligated.

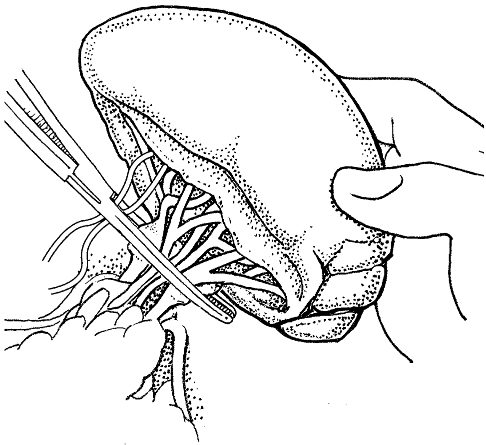

Fig. 12.2. Single clamp splenectomy with the clamp obtaining total vascular control of the hilum and short gastric vessels.

If the patient is in extremis, a one clamp splenectomy can be performed. An aortic vascular clamp is placed across the hilum and short gastric vessels. Care should be taken with this technique to avoid clamping the stomach. The clamp should be placed distal enough to avoid the tail of the pancreas as well (Fig. 12.2). Scissors are then used to remove the organ. The hilum and short gastric vessels can be controlled separately at this point by either ties or suture ligation. We use a combination of ties on all major vessels followed by additional suture ligature to reinforce the splenic artery and vein. Even if there is minimal concern for pancreatic injury from the rapid splenectomy, a closed suction drain can be left as energy transmitted to the injured spleen could also cause occult injury to the tail of the pancreas.

In a hemodynamically stable patient taken to the OR for laparotomy, if splenic injury is found, splenorrhaphy can be an option. In general, a stable patient with minimal blood loss and low-grade injury (grade 1 or 2) is a candidate for splenorrhaphy. However, if a patient has a severe traumatic brain injury such that recurrent hemorrhage may cause secondary brain injury or if the patient is coagulopathic or has comorbidities that may predispose to bleeding (such as chronic liver disease), splenectomy may be a better choice. We usually prefer splenectomy for higher-grade injuries as repeat laparotomy may be difficult if delayed bleeding occurs.

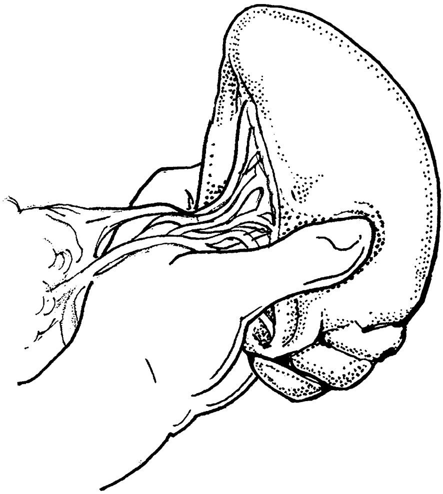

Fig. 12.3. Direct manual control of splenic bleeding in preparation for splenorrhaphy.

If splenorrhaphy is chosen, there are many options for surgical technique. Partial splenectomy can be done if the injury is limited to one pole. After mobilizing the spleen, temporary hemostasis may be obtained with finger pressure (Fig. 12.3). The corresponding vascular supply to that pole is ligated and divided. The splenic parenchyma is then cut with a scalpel (Fig. 12.4). The raw edge of the parenchyma is compressed with pledgeted horizontal mattress sutures. O-Vicryl or 2-0 Vicryl suture works well and some of the new bioabsorbable pledgets may reduce infectious risk (Fig. 12.5). Argon beam coagulation or placement of fibrin hemostatic sealant can be added to augment hemostasis. For smaller injuries, direct pledgeted suturing can be used to control bleeding from the spleen (Fig. 12.6). If the capsule of the spleen is torn and peeling off the spleen, but parenchymal damage is limited, either an omental patch or mesh wrap can be used (Fig. 12.7). For mesh, we prefer knitted Vicryl mesh soaked in a fibrin gel sealant. The mesh is wrapped around the area of injury (Fig. 12.8a). The sealant allows the mesh to adhere to the parenchyma and provides some additional hemostatic effect. Vicryl sutures can be used to tighten the mesh to compress the spleen and provide further hemostasis (Fig. 12.8b). The argon bean can be useful to weld the mesh to the spleen in some cases (Fig. 12.9). For very minor injuries, direct suture repair may work (Fig. 12.10).

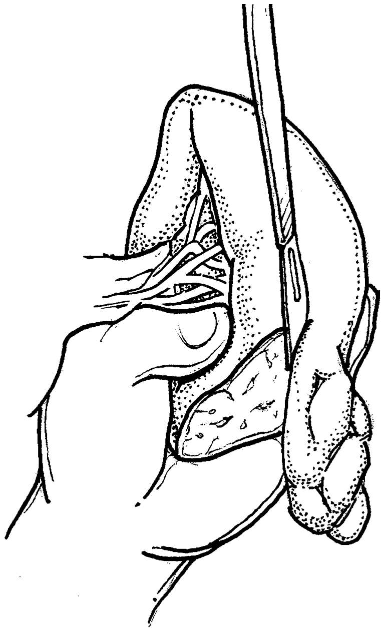

Fig. 12.4. Partial splenectomy for splenic salvage. Manual pressure is used to maintain control until the cut end is hemostatic.

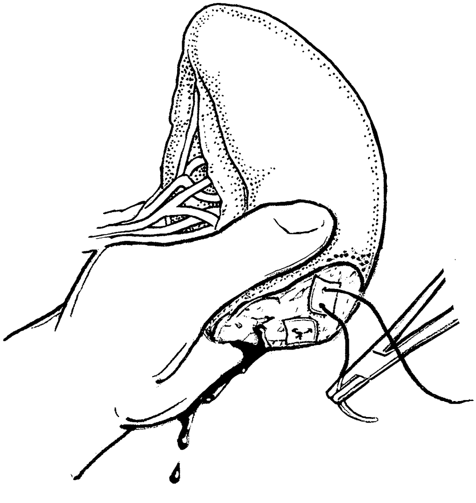

Fig. 12.5. Mattress repair of the cut end of the spleen.

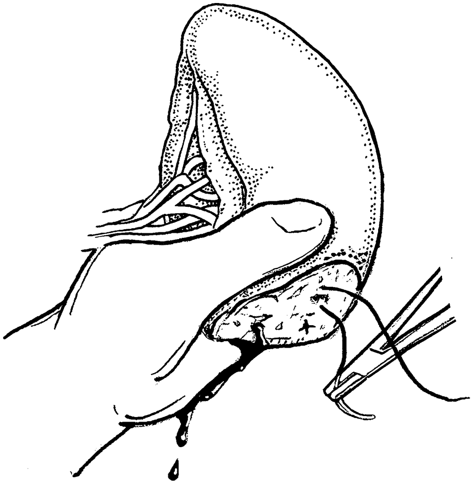

Fig. 12.6. Direct repair of vessels of cut end of spleen.

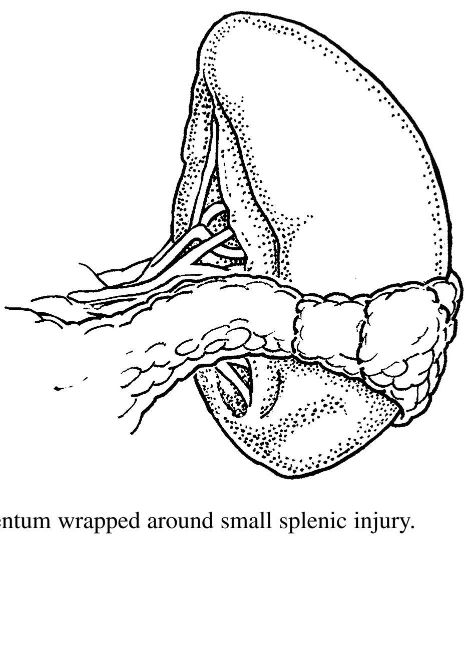

Fig. 12.7. Omentum wrapped around small splenic injury.

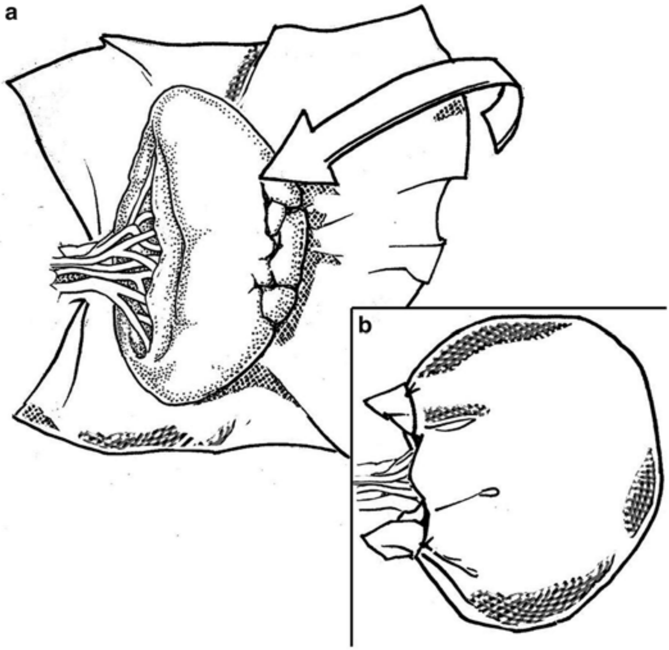


Fig. 12.8. Vicryl mesh wrap of the injured spleen.

## *Techniques for Nonoperative Management*

In the hemodynamically stable patient, splenic injury is usually diagnosed by CT scan. As noted, conservative management is appropriate for many splenic injuries in the stable patient. However, there may be other issues such as brain injury, comorbidities, or other concurrent injuries that change this decision making. Injuries that preclude reliable physical exams or would be exacerbated by even mild hypotension prior to OR for salvage therapy should be considered when deciding on nonoperative management. Conservative management includes admission to the hospital, serial abdominal exams, serial hemoglobin measurements, and close observation. Splenic angioembolization is an important adjunct to conservative management.

Conservative management is best guided by protocols. For instance, a predetermined transfusion requirement should be agreed upon at admission, and if the patient requires more blood than specified, nonoperative

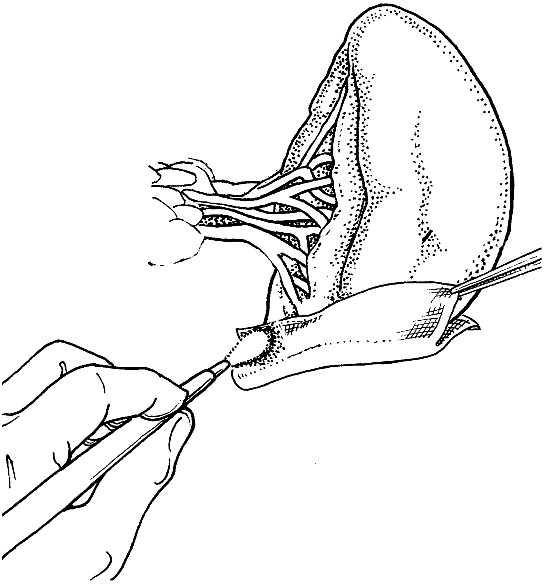

Fig. 12.9. Argon beam coagulation of the spleen.

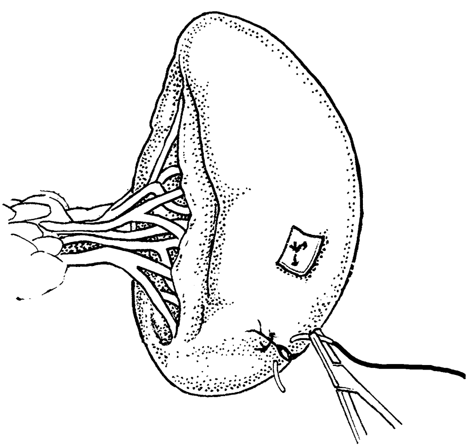

Fig. 12.10. Suture repair with pledget of grade 1 splenic injuries.

management should be considered a failure and the patient should proceed to the operating room. In adult patients with isolated splenic injury, the need for any blood transfusion should prompt real consideration for operative exploration. Similarly, changes in hemodynamics or clinical exam should be indications for laparotomy. Institutional protocols have proven useful to optimize outcomes and guide management [12]. National evidenced-based guidelines may assist in the creation of institutional protocols [13], and consensus strategies have been evaluated that may also assist with creation of local institutional protocols [14].

Numerous risk factors have been identified that may predispose patients to failure of conservative treatment. High AAST injury grade, quantity of hemoperitoneum, evidence of active hemorrhage, and vascular lesions such as pseudoaneurysms may predict failure of conservative therapy [1, 11]. Age is a controversial risk factor for failure. While advancing age may be a risk [15–17], some analysis suggests age should not be considered when deciding to pursue nonoperative therapy [18]. One recent review identified clinical features including age over 40 years, splenic injury grade of 3 or higher, Injury Severity Score (ISS) of 25 or higher, abdominal Abbreviated Injury Score of 3 or greater, TRISS of less than 0.80, the presence of an intraparenchymal contrast blush, and an increased transfusion need as predictors for failure of nonoperative management [19]. All of these factors should be considered when deciding upon the appropriate therapeutic algorithm.

Angioembolization has a major role in conservative therapy for high-grade lesions. At the R Adams Cowley Shock Trauma Center, stable patients with grade 3 splenic injuries undergo angiography, with angioembolization if any extravasation or vascular injury is identified, within 24 h of admission. In stable patients, angiography need not be performed emergently but as soon as resources are readily available. If any vascular injury is identified, angiography becomes more urgent similar to management of higher-grade injuries. For hemodynamically stable patients with grade 4 and 5 injuries, embolization should be performed early and is considered emergent treatment as an adjunct to nonoperative therapy. Proximal coil embolization is the technique of choice as it minimizes the risk of ischemia of the spleen, which maintains adequate blood supply through the short gastric vessels. Distal coil embolization, although effective, is associated with higher rates of splenic infarction. Proximal coil embolization involves first performing a diagnostic angiogram. The catheter is advanced into the proximal splenic artery and the size of the artery is determined. A coil, slightly larger than the artery, is then introduced into the artery. Repeat angiography should demonstrate both occlusion of the splenic artery and distal filling of the splenic artery and spleen via collaterals such as the short gastric vessels, the gastroepiploic vessels, and the pancreatic branches.

Early analysis of angioembolization demonstrated splenic salvage rates as high as 92 %, even on patients with vascular lesions [22, 23]. A splenic salvage rate of 80–95 % can be achieved for grade 4 and 5 injuries, and embolization significantly improves salvage rates in patients with high-grade injuries and contrast blush on CT scan [23–26]. Even if no extravasation or pseudoaneurysm is noted on CT scan, a patient with a grade 4 or 5 splenic injury should undergo embolization to maximize the chance for success of nonoperative therapy [27]. Patients managed nonoperatively with grade 3 or higher injury should be observed in a monitored setting. Abdominal exams and serial hemoglobin measurements should be performed every 6 h for 24 h then every 12 h for another day. After this time point, care can be de-escalated. Repeat CT should be obtained 48–72 h after injury to evaluate for delayed pseudoaneurysm formation. If delayed or persistent pseudoaneurysms are found, repeat embolization is indicated and salvage rates remain greater than 90 % [28].

If a patient fails conservative therapy, splenectomy is generally indicated. There are reports, however, of angioembolization for salvage therapy. In one series, over 80 % of patients with delayed splenic rupture were successfully treated nonoperatively either with observation or angioembolization [29].

Figure 12.11 represents the R Adams Cowley Shock Trauma management algorithm for splenic trauma as of 2013. Grade 1 and 2 injuries can be managed nonoperatively and without angiography unless a contrast blush or other vascular injury is identified, in which case angiography should be performed urgently. Serial abdominal exams and hemoglobin levels should be performed every 6–8 h for 24 h. After 24 h of stability, care can be de-escalated and exams/lab draws can be performed less frequently. Follow-up CT scan is not necessary for grade 1 injury. In one study, less than 2 % of patients required delayed intervention, and those who did were noted to have decreasing hemoglobin levels early in their hospital course [20]. Controversy exists about whether grade 2 injuries require repeat CT, but CT 24–48 h after injury may help identify delayed vascular injury such as pseudoaneurysm. When managing patients nonoperatively, thromboembolism prophylaxis with low-molecular-weight heparin should be provided as it does not increase the rate transfusion or rate of failure of therapy [21].

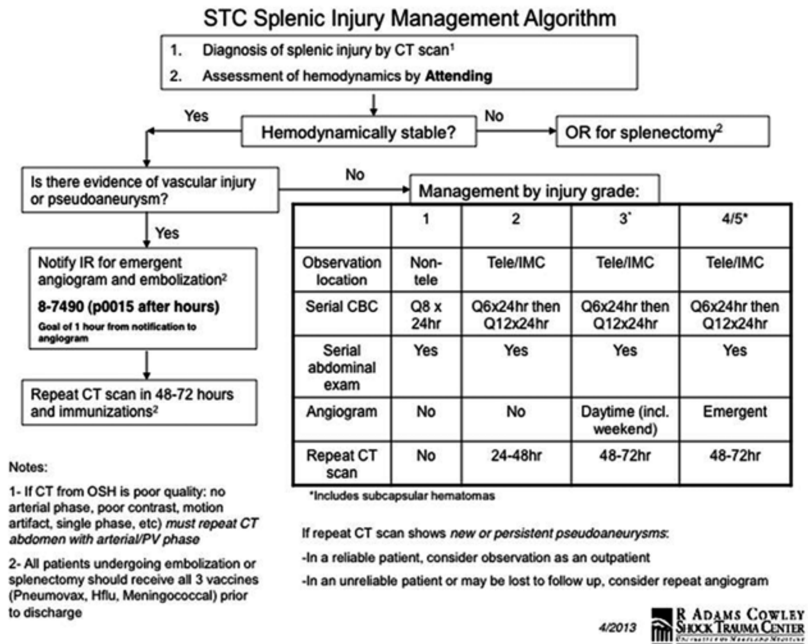


Fig. 12.11. R Adams Cowley Shock Trauma Center blunt splenic injury protocol.

At the R Adams Cowley Shock Trauma Center, all patients who either undergo splenectomy or receive coil embolization of the spleen receive vaccines to reduce the incidence of postsplenectomy sepsis prior to discharge. In our opinion, the risk of losing patients to follow-up after discharge is not worth the benefit that may be obtained by delayed vaccination. There is some evidence as well that embolization alone may allow preserved splenic immune function [30–32]. With further study, it may prove unnecessary to vaccinate patients who undergo angiographic embolization of the spleen, but currently the data is simply not available to preclude vaccinations.

## Outcomes

Attributable mortality to splenic injury is not well reported, but with current management protocols, death from splenic injury should be exceedingly rare. Most patients who die suffer from polytrauma and succumb to multiple injuries. Overall, the success rate of nonoperative management is greater than 96 % when all grade injuries are included. The salvage rate is significantly higher in trauma centers that perform a high volume of angioembolization as well, with 99 % salvage rates reported [16]. This difference is more marked in higher-grade injury (greater than AAST grade 3) with high-volume angiography centers reporting salvage rates of 90 % compared to salvage rates of 79 % at low-volume angiography centers. In general, bleeding from the spleen should rarely be fatal unless the patient arrives in extremis from the field. Nonoperative management can be utilized for splenic salvage even in high-grade injuries. With appropriate monitoring and follow-up, even the patient who fails conservative management and requires a trip to the operating room is provided safe and effective care.

## Complications

Complications of splenectomy include the usual complications of laparotomy such as incisional hernia and small bowel obstruction. Specific to splenectomy, one major risk is postsplenectomy sepsis. A recent analysis demonstrated that splenectomy as compared to splenic salvage was the most significant factor predicting infectious complications in the hospital, even when controlling for injury severity and other confounders [33]. After discharge, patients must remain vigilant for signs of postsplenectomy overwhelming sepsis, as rates up to 3.2 % have been described in patients after splenectomy. The mortality of sepsis is higher after splenectomy than the general population as well [34].

Though conservative management with angioembolization is associated with improved outcomes and fewer infectious complications, there are still many significant associated complications of which it is important to be cognizant. Patients can have procedural-associated bleeding, failure of therapy, pseudoaneurysms or hematomas of the access vessel, contrast-induced nephropathy, and complications of anesthesia. Up to 20 % of patients may suffer major complications. One common complication is infection due to splenic infarction that may occur in up to 4 % of patients who receive angioembolization [35–37]. Splenic infarct may be managed conservatively unless the patient has severe pain or systemic signs of sepsis in which case splenectomy should be considered. Interventional radiology placed drains may also be appropriate for localized infarction or abscess. The elderly, who may benefit the most from avoidance of laparotomy, may suffer from an even higher complication rate [38]. There may be differences in complications depending on the method of angioembolization used. Proximal coil embolization of the main splenic artery is associated with similar initial failure rate to selective distal embolization but may lead to fewer splenic infarcts [39] and fewer major complications [37].

In summary, in the appropriately selected patient, the benefits of nonoperative therapy usually outweigh the risks as complications of splenic salvage techniques tend to be less morbid than those of laparotomy. Care must be taken to ensure that attempts at splenic salvage are not carried so far as to endanger the patient via excessive blood loss when conservative management is failing.

While simple in anatomy, the spleen is difficult in concept. Conservative management is the best option in stable patients, but care has to be taken to ensure that the care provider acknowledges when nonoperative management has failed to avoid serious morbidity or mortality from hemorrhage. Early splenectomy and hemorrhage control in the unstable patient is equally important for maximizing outcomes.

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# 13. Pancreas and Duodenum

*Raymond Fang, M.D., F.A.C.S.*

## Introduction

> Eat when you can, sleep when you can, and don't mess with the pancreas.
>
> Surgical Dictum

The pancreas and the duodenum are retroperitoneal organs intimately associated with one another and deeply positioned in the mid-abdomen. Isolated injuries are infrequent from either blunt or penetrating mechanisms as these organs are surrounded by numerous other vital structures (Tables 13.1 and 13.2) [1]. Early mortality is high due to associated injuries to the vascular or central nervous systems, but delays in diagnosis and complications in the treatment of pancreatic and duodenal injuries contribute to later deaths from sepsis and multiple organ dysfunction. Even in tertiary trauma centers, these injuries are rare. Consequently, surgeons generally possess limited, first-hand experience in operative care and overall management. A query of the Shock Trauma Center Registry for the inclusive period between January 2000 and September 2013 identified only 466 pancreatic and/or duodenal injuries (34/year) from a total of 68,053 trauma admissions.

## History of Care

> Wounds of the pancreas are to be concluded mortal if its duct or blood vessels are injured, whence the succus pancreaticus or blood may be discharged into the cavity of the abdomen, and there putrefying, cause inevitable death. Benjamin Gooch (*Collected Works*, 1792) [2]

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Table 13.1. Associated injuries in 1,086 cases of pancreatic trauma.

| Associated organ injury | Patients (%) (total 1,086) |
|---|---|
| Liver | 500 (46) |
| Stomach | 449 (41) |
| Major vascular | 300 (28) |
| Spleen | 277 (26) |
| Kidney | 240 (22) |
| Colon | 189 (17) |
| Duodenum | 173 (16) |
| Small bowel | 165 (15) |
| Gallbladder/biliary tree | 46 (4) |

Adapted from [1]

Table 13.2. Associated injuries in 1,234 cases of duodenal trauma.

| Associated organ injury | Patients (%) (total 1,234) |
|---|---|
| Major vascular | 596 (48) |
| Liver | 543 (44) |
| Colon | 378 (31) |
| Pancreas | 368 (30) |
| Small bowel | 363 (29) |
| Stomach | 279 (23) |
| Kidney | 237 (19) |
| Gallbladder/biliary tree | 176 (14) |
| Spleen | 41 (3) |

Adapted from [1]

Routinely cited as the earliest report of pancreatic trauma, Travers in 1827 described in *The Lancet* the case of an intoxicated woman struck by a stage coach who survived for several hours after the incident [3]. "The pancreas, on [postmortem] examination of the body, was found to be completely torn through transversely" [3].

Prior to the 1900s, injuries to the pancreas and duodenum were fatal. In 1903, Mickulicz-Radicki summarized the collective medical experience on pancreatic trauma after identifying 45 published cases: 21 penetrating and 24 blunt injuries [4]. All 20 patients managed nonoperatively died, but only 7 of 25 patients (28 %) treated operatively died. From more than 100 years ago, Mickulicz's recommendations for the management of suspected pancreatic injuries endure as surgical principles today: (1) thorough abdominal exploration through a midline abdominal incision, (2) suture control of bleeding, and (3) drain placement.

The first successful surgical repair of a blunt duodenal injury is attributed to Herczel in 1896 and of a penetrating duodenal injury to Moynihan in 1901. In 1946, Cave reported on 118 duodenal injuries sustained by the US Army during combat operations during 1944 and 1945 [5]. Ten-day mortality in this cohort was 55.9 % in an era that predates antibiotic therapy. In 1977, Vaughan et al. reported on their institution's 7-year experience utilizing pyloric exclusion and gastrojejunostomy for duodenal trauma, and this procedure currently remains a frequent adjunct in the management of severe injuries [6].

## Operative Technique

### *Surgical Anatomy*

The pancreas measures approximately 20 cm long, 3 cm wide, and 1.5 cm thick and lies transversely across the upper abdomen in the retroperitoneum (Fig. 13.1). It is divided into four anatomic sections: the head lies to the right of the midline and is nestled within the C-loop of the duodenum, the neck overlies the superior mesenteric artery and vein in the midline, the body continues laterally to the left, and the tail ends

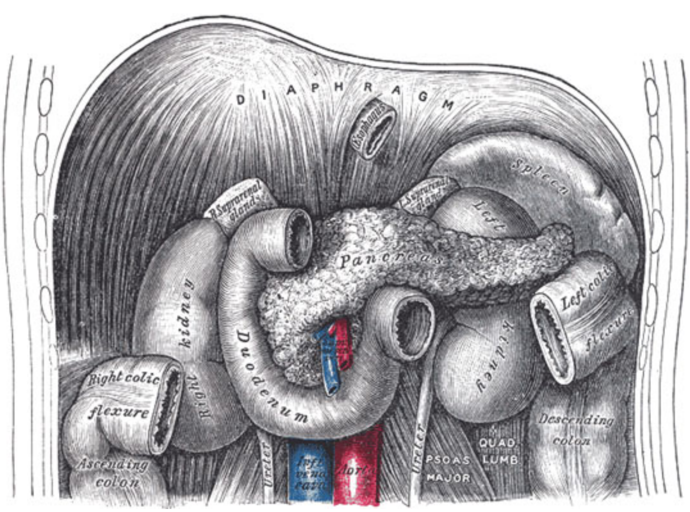


Fig. 13.1. Anatomy of the upper abdomen. Gray's Anatomy, Fig. 1056. 1918.

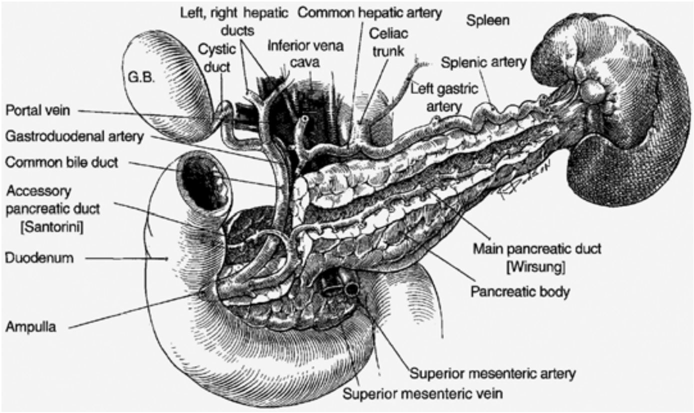


Fig. 13.2. Anatomy of the pancreas. Reprinted with permission from Bulger EM, Jurkovich GJ. Operative management of pancreatic trauma. Oper Tech Gen Surg 2000;2(3):221–33.

in proximity of the spleen anterior to the left kidney (Fig. 13.2). The uncinate process is a small extension of the head that is nestled behind the superior mesenteric vessels. The splenic artery courses along the upper posterior border of the pancreas. Behind the pancreas, the splenic vein travels close to its lower border and is joined by both the inferior and superior mesenteric veins to form the portal vein. Also posterior to the pancreas lie the aorta, the inferior vena cava, the left kidney, both renal arteries, and the left renal vein. The stomach and root of the transverse mesocolon overlie the pancreas.

The duodenum extends from the gastric pylorus to the ligament of Treitz and measures approximately 30 cm in length. The duodenum is similarly divided into four anatomic sections: superior (D1), descending (D2), transverse (D3), and ascending (D4) (Fig. 13.2). The transition from D1 to D2 occurs as the duodenum crosses the common bile duct and the gastroduodenal artery, from D2 to D3 occurs at the ampulla of Vater, and from D3 to D4 occurs as the superior mesenteric vessels cross anteriorly over the duodenum. The aorta, inferior vena cava, right kidney, spinal vertebrae, and psoas muscles lie posterior to the duodenum. The liver, gallbladder, right colon, transverse colon, and stomach overlie the duodenum.

The blood supply of the pancreas and duodenum arises from arcades originating from the gastroduodenal, superior mesenteric, and splenic arteries. Variations in the arterial and the pancreatic/biliary ductal anatomy exist.

## *Damage-Control Management of Pancreatic and Duodenal Injuries*

If hemodynamic instability necessitates urgent abdominal exploration, the highest priority is rapid control of bleeding. An abundance of vascular structures surrounds the pancreas and duodenum so that exsanguinating hemorrhage is a common cause of early mortality. A generous midline laparotomy incision is used. Continued bleeding from the midline structures may necessitate total occlusion of aortic inflow by clamping the supraceliac aorta. More recently, empiric placement of a REBOA (*r*esuscitative *e*ndovascular *b*alloon *o*cclusion of the *a*orta) catheter via a femoral artery cutdown may be considered in select patients [7]. Preoperative placement allows for rapid aortic occlusion by balloon inflation only should aortic occlusion prove to be necessary [8]. Rapid division of the pancreatic neck with a surgical stapler may be required to expose bleeding vessels such as the superior mesenteric vein located behind the pancreas for direct surgical control.

After control of hemorrhage, minimizing bacterial contamination is the next priority. Injuries are rapidly managed by either gross suture closure or stapling with or without resection. This is not the time for pancreatic or duodenal reconstructions, and wide drainage is the acceptable bailout maneuver. Once hemorrhage and contamination are controlled, a temporary abdominal dressing is placed and continued aggressive resuscitation undertaken to correct acidosis, coagulopathy, and hypothermia. Due to the nature of their digestive secretions, delays in management of pancreaticoduodenal injuries with suboptimal initial drainage will contribute to increased morbidity and mortality. A second-look operation should be performed as promptly as the patient's physiology allows.

## *Exploration of the Pancreas and Duodenum*

Thorough evaluation of the pancreas and duodenum is mandatory if there is any suspicion of injury from the mechanism of injury, computed tomography (CT) imaging results, trajectory of penetrating wounds, or intraoperative findings. Suggestive operative findings at initial or second-look abdominal exploration include central retroperitoneal hematoma, retroperitoneal bile staining, peritoneal fat saponification or necrosis, and pancreatic and lesser sac edema (Fig. 13.3).

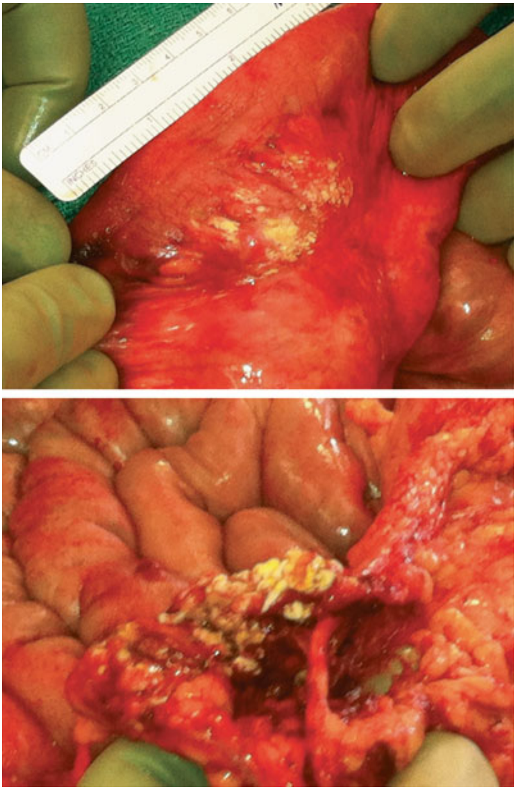

Fig. 13.3. Fat saponification discovered on abdominal exploration suggests possible pancreatic injury.

Good exposure is the key to good surgery.

Surgical Dictum

Adequate exposure is crucial to investigate for pancreaticoduodenal injury (Fig. 13.4). The anterior surface of the pancreas is visualized by widely opening the lesser sac between the stomach and the transverse colon through the gastrocolic ligament. A curved, handheld Sweetheart (also known as Harrington) retractor that retracts the stomach cephalad facilitates exposure. Mobilization of the inferior border of the pancreas and cephalad rotation then exposes the posterior surfaces of the body and tail. (The splenic artery courses along the superior border and distributes branches to the pancreas making mobilization of this border perilous.) The pancreatic tail can be mobilized with the

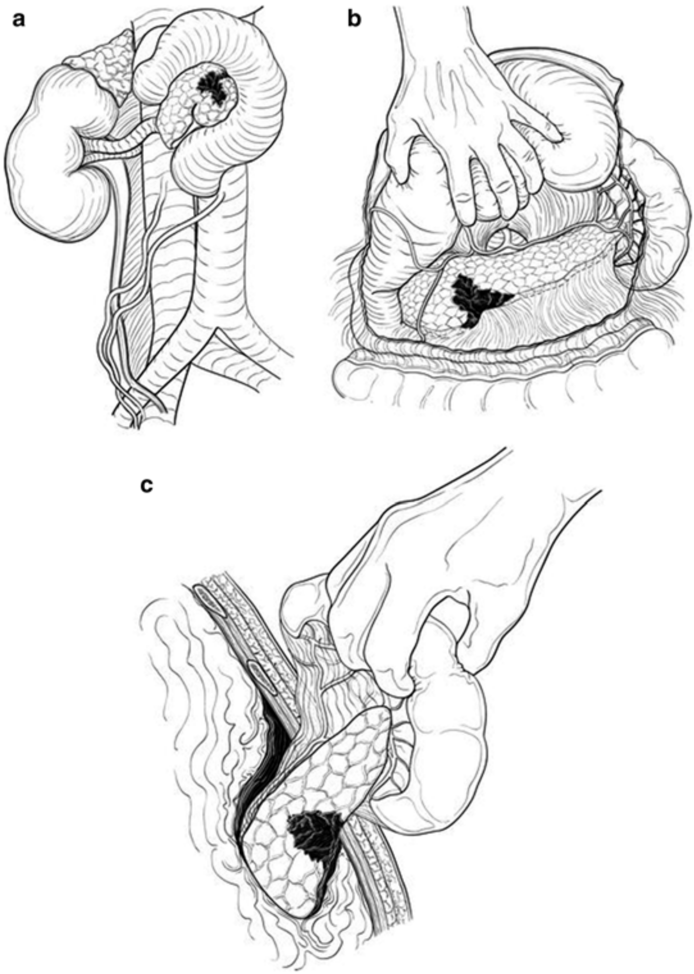

Fig. 13.4. Surgical exposure of the pancreas and duodenum. (**a**) Exposure of the head of the pancreas and duodenum is obtained via a generous Kocher maneuver. (**b**) Exposure of the body and tail of the pancreas by entry into the lesser sac. (**c**) Complete exposure of the tail of the pancreas requires lateral to medial splenic mobilization. Reprinted from Brown T. Chapter 9, Pancreatic and duodenal injuries (Sleep when you can…). In: Martin MJ, Beekley AC (eds). *Front Line Surgery*. New York: Springer 2011, p. 115–28.

spleen from the left upper quadrant to the midline by blunt dissection of an avascular posterior plane between the pancreas and the left kidney. Following mobilization of the hepatic flexure and proximal transverse colon, the Kocher maneuver mobilizes the duodenum and pancreatic head to the midline. This allows inspection of the anterior and posterior surfaces of the duodenum as well as the pancreatic head and neck.

## *Management of Pancreatic Injuries*

Integrity of the main pancreatic duct is the most important determinant of outcome specific to the pancreatic injury itself. Intraoperative inspection of the pancreas is adequate in most cases to assess whether the duct remains intact. Secretin, 1 unit/kg, can be administered intravenously to facilitate visual identification of a pancreatic duct leak [9]. Ductal integrity may be confirmed by postoperative endoscopic retrograde cholangiopancreatography (ERCP) or postoperative magnetic resonance cholangiopancreatography (MRCP). Intraoperative needle cholecystocholangiopancreatography may be attempted although is often not successful [10].

Intraoperative cholecystocholangiopancreatography:

1. Place a 3-0 silk purse-string suture onto the gallbladder fundus.
2. Cannulate the gallbladder fundus with a 16- or an 18-gauge angiocatheter (Fig. 13.5).

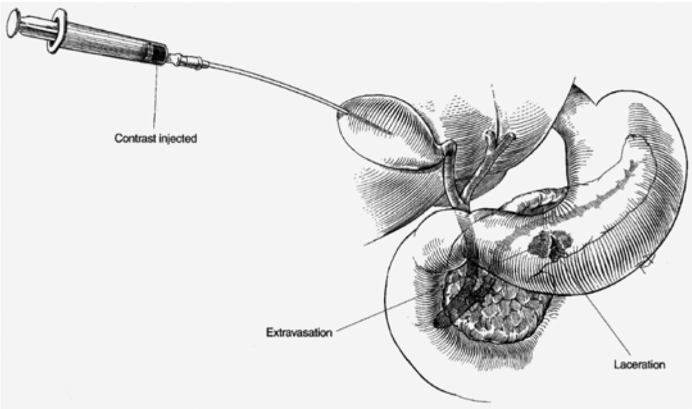


Fig. 13.5. Intraoperative cholecystocholangiopancreatography. Reprinted with permission from Bulger EM, Jurkovich GJ. Operative management of pancreatic trauma. Oper Tech Gen Surg 2000;2:221–33.

Table 13.3. American Association for the Surgery of Trauma Organ Injury Scale—pancreas.

| Pancreatic injury grading scale | | |
|---|---|---|
| Grade | Injury | Description of injury |
| I | Hematoma | Minor contusion without duct injury |
| | Laceration | Superficial laceration without duct injury |
| II | Hematoma | Major contusion without duct injury or tissue loss |
| | Laceration | Major laceration without duct injury or tissue loss |
| III | Laceration | Distal transection or parenchymal injury with duct injury |
| IV | Laceration | Proximal transection or parenchymal injury involving ampulla |
| V | Laceration | Massive disruption of pancreatic head |

Modified with permission from Moore EE, Cogbill TH, Malangoni MA, Jurkovich GJ, Champion HR, Gennarelli TA, et al. Organ injury scaling, II: Pancreas, duodenum, small bowel, colon, and rectum. J Trauma. 1990 Nov; 30(11):1427–9

Advance one grade for multiple injuries up to grade III

3. Clamp the common hepatic duct with an atraumatic clamp.
4. Inject 30–75 mL of water-soluble contrast under fluoroscopic imaging.

Management closely follows the injury severity as classified by the American Association for the Surgery of Trauma (AAST) Organ Injury Scale (OIS) (Table 13.3) [11, 12]. A Western Trauma Association management algorithm for the management of pancreatic injuries was published in 2013 [13] (Fig. 13.6). In all pancreatic injuries, placement of an enteral feeding tube distal to the ampulla should be strongly considered prior to abdominal closure. This may be via a nasoenteral feeding tube for lower-grade injuries or by a feeding jejunostomy or gastrojejunostomy tube in higher-grade injuries.

## Grade I and II Injuries

Low-grade injuries comprise 75 % of pancreatic injuries and are usually managed nonoperatively when diagnosed by CT imaging. If discovered intraoperatively, only hemostasis and liberal closed-system suction drainage anterior and posterior to the gland are required. Pancreatic lacerations should NOT be closed as this may convert a simple, self-limited leak into a subsequent pseudocyst. Drains are removed when the

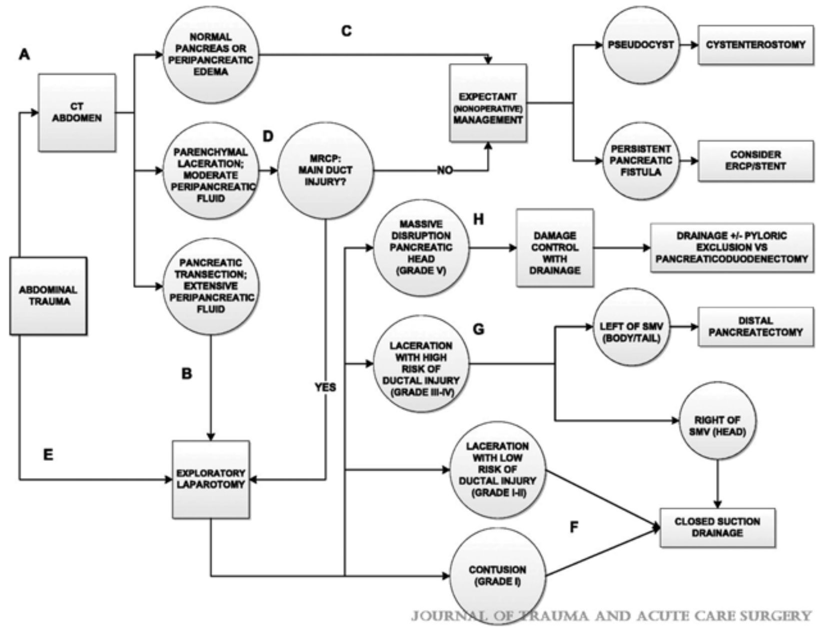


Fig. 13.6. Western Trauma Association management algorithm for pancreatic injuries. Reprinted with permission from Biffl WL, Moore EE, Croce M, et al. Western Trauma Association Critical Decisions in Trauma: Management of pancreatic injuries. J Trauma 2013;75(6):941–6.

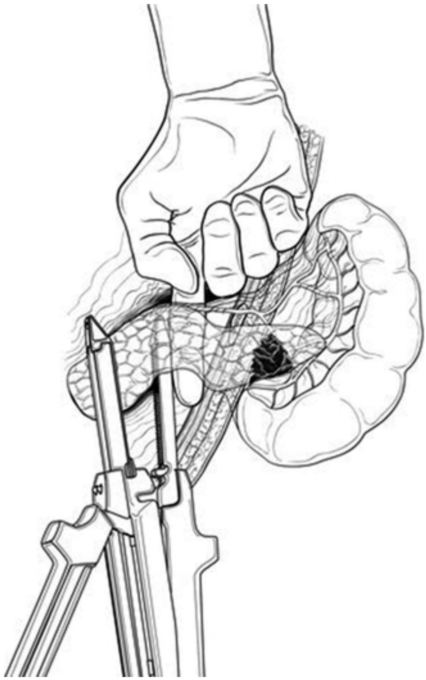

Fig. 13.7. Technique for a stapled distal pancreatectomy. Use a finger or blunt instrument to encircle the pancreas and guide a linear stapler through the retro-pancreatic tunnel. Reprinted from Brown T. Chapter 9, Pancreatic and duodenal injuries (Sleep when you can…). In: Martin MJ, Beekley AC (eds). *Front Line Surgery*. New York: Springer 2011, p. 115–28.

patient is tolerating enteral nutrition and there is no evidence of continued leakage by both minimal daily drainage volume and effluent amylase concentration analogous to serum.

## Grade III Injuries

Traumatic pancreatic transection (often from compression of the pancreas against the vertebral column) or parenchymal injuries to the body or tail with disruption of the main pancreatic duct require surgical management. These injuries often occur at the pancreatic neck and are definitively managed by distal pancreatectomy (Fig. 13.7). Resection at the pancreatic neck leaves more than 50 % of residual gland and preserves adequate pancreatic exocrine and endocrine function. The splenic artery and vein are ligated along the superior and inferior borders of the gland 1–2 cm proximal to the site of planned resection, either at the site of traumatic transection or just proximal to the ductal injury. Atraumatic bowel clamps are applied to the pancreas, the gland is transected, and the distal gland is removed en bloc with the attached spleen. The superior and inferior pancreaticoduodenal arteries are controlled by suture ligation, and the pancreatic stump may be closed with interrupted, horizontal mattress sutures. Alternately, the pancreas can be clamped and closed with a linear stapler firing two, double-staggered rows of 4.8-mm staples simultaneous to gland transection. Overly tight closure of the stump can lead to parenchymal necrosis and fistula or pseudocyst formation. Ideally, the pancreatic duct is identified and individually ligated, but this is rarely possible. A titanium clip marking the distal transected duct can be a useful landmark for later ERCP or MRCP. A closed-system suction drain is placed in proximity to the closure as transient leaks are common regardless of the closure technique performed.

Postsplenectomy sepsis in adult trauma patients is rare [14]. In adults, splenic preservation should only be considered for the patient who presents with an isolated pancreatic injury and complete physiologic normality [15]. Attempted splenic preservation during distal pancreatectomy adds an average of 50-min operative time in experienced hands and increased operative blood loss to identify and ligate an average of seven splenic artery and 22 splenic vein branches associated with the pancreas for only questionable benefit [16].

If the spleen is to be preserved, the spleen and distal pancreas are completely mobilized. The small branches of the splenic artery and vein that support the distal pancreas must be individually identified and ligated with fine ties. The pancreas is then divided taking care not to injure the splenic artery and vein.

## Grade IV and V Injuries

The management of grade IV and V injuries remains controversial with poor data in the literature. Definitive management of injuries to the pancreatic head should not always be undertaken in the acute setting, as delineation of the ductal anatomy is particularly crucial for these injuries. Even if intraoperative pancreatography or ERCP is possible, wide external drainage and postoperative ERCP/MRCP might be a suitable alternative. The rationale for damage control in this circumstance is not only patient instability but may also be to seek additional expertise to optimize the definitive management plan for this extremely challenging injury.

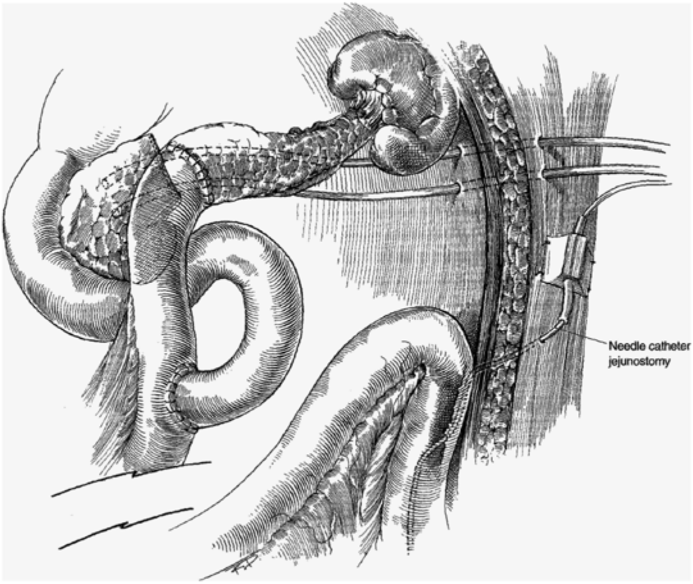


Fig. 13.8. Roux-en-Y pancreaticojejunostomy. Reprinted with permission from Bulger EM, Jurkovich GJ. Operative management of pancreatic trauma. Oper Tech Gen Surg 2000;2:221–33.

Injuries that spare the pancreatic duct and ampulla are potentially managed by drainage alone. Proximal ductal injuries that spare the ampulla and duodenum may be treated by extensive (subtotal) pancreatectomy. This creates the potential for pancreatic insufficiency, but only 10–20 % of gland tissue is required for normal function. Pancreatic duct stenting for trauma has been reported, but it is dependent on local ERCP expertise, and published results are limited to small case series [17]. While rarely performed, the surgeon may choose in very select cases to blind the distal portion of the head and then perform a Roux-en-Y pancreaticojejunostomy (Fig. 13.8) to drain the uninjured distal gland. This preserves residual pancreatic function but has been largely abandoned due to high incidence of complications. Injuries to the pancreatic head that involve the ampulla or that also devitalize the duodenum may require a pancreaticoduodenectomy for definitive management. A "trauma Whipple procedure" may be done two ways. In some stable patients, such as an isolated, low-energy penetrating wound to the ampulla, the Whipple can be done in a single stage with the advantage of good tissues to anastomose. In a damage-control scenario, a two-stage procedure with rapid resection of the duodenum and pancreatic head to control hemorrhage and contamination followed by reconstruction after physiologic resuscitation is wise. As opposed to the single-stage operation, returning to the operating room for delayed reconstruction may also produce a firmer pancreas, reduced bowel edema, and a dilated bile duct facilitating reconstruction [18]. Additional surgical expertise and ancillary support may also be recruited to assist with this challenging procedure. Even when limiting crystalloid administration in these patients to avoid over-resuscitation, tissues at the time of the second look in some patients are simply too edematous to allow reconstruction. In these patients, (1) external drainage of the common bile duct with a small catheter, (2) placement of a gastrostomy and feeding jejunostomy, and (3) wide drainage of the pancreas may remain the best option. Definitive reconstruction can occur later, usually after 6 months. A cholecystectomy is not a component of the Whipple procedure for trauma because the gallbladder may be utilized for future biliary-enteric reconstruction.

## *Management of Duodenal Injuries*

Most duodenal injuries result from penetrating trauma, are low grade, and are amenable to primary repair [19]. Blunt injuries may present insidiously, leading to delayed diagnosis and more challenging care. Management of duodenal injuries follows the injury severity as classified by the AAST-OIS (Table 13.4) [11]. In all duodenal injuries, placement of a distal enteral feeding tube should be strongly considered prior to abdominal closure. This may be via a nasoenteral feeding tube for lower-grade injuries or a feeding jejunostomy or a gastrojejunostomy tube in higher-grade injuries.

### Grade I and II Injuries

#### Intramural Hematoma

If identified by CT imaging, intramural duodenal hematomas causing proximal obstruction are initially managed nonoperatively with supportive care measures such as nasogastric decompression, intravenous hydration, and parenteral nutrition. Most cases will resolve spontaneously within 3 weeks. For unrelenting cases demonstrating no clinical improvement after 7–10 days, repeat CT scanning may precede opera-

Table 13.4. American Association for the Surgery of Trauma Organ Injury Scale—duodenum.

| Duodenal injury grading scale | | |
|---|---|---|
| Grade | Injury | Description of injury |
| I | Hematoma | Involves single portion of duodenum |
| | Laceration | Partial thickness, no perforation |
| II | Hematoma | Involving more than one portion |
| | Laceration | Disruption <50 % of circumference |
| III | Laceration | Disruption 50–75 % of circumference of D2 |
| | | Disruption 50–100 % of circumference of D1, D3, D4 |
| IV | Laceration | Disruption >75 % of circumference of D2 |
| | | Involving ampulla or distal common bile duct |
| V | Laceration | Massive disruption of duodenopancreatic complex |
| | Vascular | Devascularization of duodenum |

Modified with permission from Moore EE, Cogbill TH, Malangoni MA, Jurkovich GJ, Champion HR, Gennarelli TA, et al. Organ injury scaling, II: pancreas, duodenum, small bowel, colon, and rectum. J Trauma. 1990 Nov;30(11):1427–9

Advance one grade for multiple injuries up to grade III. *D1* first portion of the duodenum, *D2* second portion of the duodenum, *D3* third portion of the duodenum, and *D4* fourth portion of the duodenum

tive decompression of the hematoma by either an open or laparoscopic approach. Successful percutaneous drainage of these lesions has also been reported [20].

Intraoperative evaluation of the duodenum begins with mobilization to allow meticulous inspection of both its anterior and posterior surfaces. If identified at laparotomy, smaller hematomas with <50 % luminal compromise may be managed as previously described. Larger hematomas with >50 % luminal compromise should be evacuated. The serosa overlying the hematoma is incised, the hematoma evacuated, and the duodenal wall carefully inspected to exclude a full-thickness injury. After ensuring hemostasis, the serosal defect is closed with Lembert sutures and buttressed with omentum if readily available.

## Lacerations

Partial thickness lacerations may be reinforced with interrupted Lembert sutures. Full-thickness lacerations involving <50 % of the circumference are generally amenable to primary repair. Devitalized edges must be debrided to ensure that closure approximates healthy tissues in a tension-free manner. Closure is commonly performed transversely in

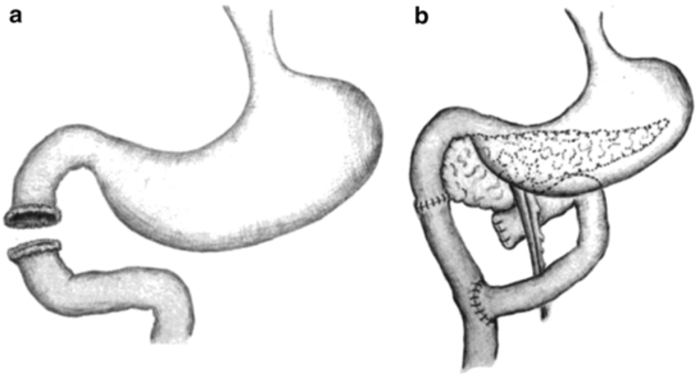


Fig. 13.9. Management of grade III duodenal injuries by (**a**) tension-free primary repair after debridement or (**b**) Roux-en-Y duodenojejunostomy with distal duodenal stump closure. Reprinted with permission from Britt LD. Duodenal primary repair, diversion and exclusion. Oper Tech Gen Surg 2000;2(3):234–9.

two layers: a running mucosal closure using absorbable suture followed by interrupted Lembert nonabsorbable sutures buttressed with omentum if readily available.

## Grade III Injuries

Some lacerations involving >50 % of the duodenal wall circumference may be amenable to primary repair. While resection, mobilization, and tension-free end-to-end duodenoduodenostomy (Fig. 13.9) may be possible for short-segment injuries in D1, D3, and D4, it is less feasible in D2 because its shared blood supply with the pancreas limits mobilization. Full-thickness lacerations to the duodenum abutting the pancreas may require repair from within the duodenal lumen exposed through an iatrogenic duodenotomy created on the opposite wall.

Pyloric exclusion is advocated as an adjunct to protect "high-risk" duodenal suture lines by diversion of gastric contents away from the repair.

Pyloric exclusion [21]:

1. Locate the pylorus by palpation.
2. Create 5-cm gastrotomy at the most dependent portion of the greater curvature of the stomach.
3. Evert the pyloric ring into the stomach and close with interrupted sutures (use of absorbable versus nonabsorbable suture will impact

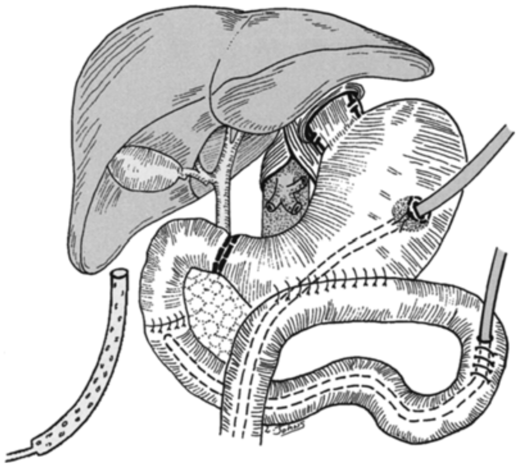

Fig. 13.10. Stapled pyloric exclusion. Reprinted with permission from Vargish T. Pyloric exclusion. Oper Tech Gen Surg 2000;2(4):278–82.

the duration of closure). Alternately, a non-cutting linear stapler can be used to close the pylorus. Care must be exercised to avoid isolating the gastric mucosa distal to the suture line as this would be ulcerogenic.

4. Fashion a two-layer gastrojejunostomy to initial gastrotomy.
5. Place a G-J tube into the gastric fundus with jejunal extension crossing anastomosis into the jejunum to provide gastric decompression (G-port) and enteral feeds (J-port).
6. Alternately, place a nasogastric tube for gastric decompression and a nasojejunal tube for enteral feeds.
7. Place a retrograde jejunal tube to decompress the lumen in proximity to duodenal repair.
8. Place a closed-system suction drain in the peritoneal cavity in proximity of duodenal repair (Fig. 13.10).

Damage-control maneuvers for higher-grade duodenal injuries require thorough operative planning for reconstruction to include external drainage in proximity to the injury site as well as intraluminal suction to minimize effluent flow. Injuries proximal to the ampulla may be managed by "duodenal diverticulization" with antrectomy, duodenal stump closure, and gastrojejunostomy (Fig. 13.11); distal injuries may be managed by Roux-en-Y duodenojejunostomy with closure of the distal duodenal stump (Fig. 13.9).

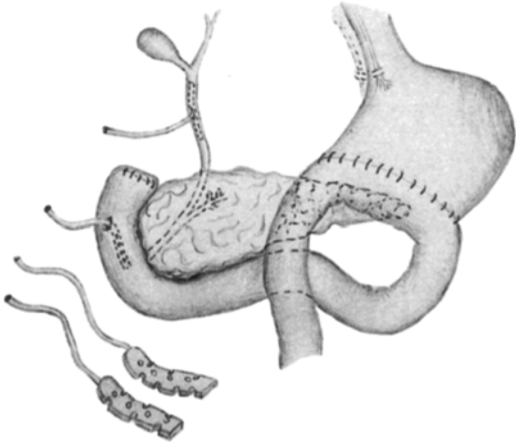

Fig. 13.11. Duodenal diverticulization with antrectomy, duodenal stump closure, and gastrojejunostomy. Reprinted with permission from Britt LD. Duodenal primary repair, diversion and exclusion. Oper Tech Gen Surg 2000;2(3):234–9.

### Grade IV and V Injuries

Extensive D2 lacerations, injuries to the ampulla and distal common bile duct, and destructive pancreaticoduodenal injuries require careful operative planning prior to reconstruction. A “damage-control Whipple procedure” may rarely be required for urgent control of hemorrhage and reconstruction. Otherwise, liberal external drainage in combination with intraluminal suction to minimize effluent flow is appropriate damage control after hemostasis to permit development of a comprehensive management plan to deal with these rare, extremely challenging injuries.

## Outcomes

> Finally, to Whipple or not to Whipple, that is the question…Though few in gross numbers, more patients are eventually salvaged by drainage, TPN, and meticulous overall care than by a desperate pancreaticoduodenectomy in a marginal patient. A. J. Walt (commentary in *The Textbook of Penetrating Trauma*, 1996) [22]

Summarizing the results of nine large series of pancreatic injuries that included >100 patients published between 1978 and 2009 demonstrated an overall mortality of 17 % (363/2,174) for these patients. Similarly, the results of seven large series of duodenal injuries published between 1977 and 2004 demonstrated an overall mortality of 17 % (227/1,344) for these patients as well. From data abstracted from the overall patient cohort, combined pancreaticoduodenal injuries demonstrated an overall mortality of 29 % (83/285). Early deaths attributable to exsanguination and central nervous system injury accounted for 74 % of deaths (105/142) [1].

## Complications

Complications are common following both pancreatic and duodenal injuries and contribute to morbidity and later mortality [23]. The high incidence of complications generally reflects the complex nature of these injuries and not inappropriate care.

### *Pancreatic Complications*

*Pancreatic fistula* is the most commonly reported pancreas-related complication following trauma, with an incidence reported as high as 38 % of cases [24]. Measurable drain output with a measured amylase level three times greater than the serum is consistent with the diagnosis. Fortunately most fistulas spontaneously close within 1–2 weeks with adequate external drainage, nutritional support, and infection control. If delivery of distal enteral nutrition increases fistula output, parenteral nutrition may be required. CT imaging confirms that the fistula is adequately drained without occult fluid accumulations that would necessitate additional drain placements. Fistulas are classified as either low (<200 mL/day) or high (>700 mL/day) output. High-output fistulas are rare and may suggest a significant ductal disruption. Persistent high output for more than a week may be an indication for ERCP/MRCP imaging of the pancreatic duct and consideration of endoscopic stenting or operative intervention.

Routine use of octreotide for the management of pancreatic fistulas is not yet validated. If prescribed, dosage begins at 50 μ(mu)g administered subcutaneously every 12 h. The dose can be progressively increased to 200 μ(mu)g every 8 h. Hyperglycemia resulting from insulin resistance should be anticipated [12].

*Post-traumatic pancreatitis and pseudocyst* develop as a consequence of unrecognized pancreatic duct injuries. Pancreatitis occurs in up to 23 % of patients and is manifested by abdominal pain, nausea, and hyperamylasemia. CT imaging excludes alternate diagnoses such as peripancreatic abscess, pseudocyst, and necrosis. Treatment is supportive. Late post-traumatic pancreatitis may be caused by pancreatic fibrosis or ductal stricture. Pseudocysts occur in up to 22 % of patients and typically present weeks to months after injury. If the underlying pancreatic duct is intact by ERCP/MRCP imaging, then percutaneous drainage is therapeutic. If the pseudocyst communicates with the pancreatic duct, then typical interventions to avoid creation of a chronic external fistula are appropriate such as endoscopic drainage, pancreatic duct stenting, and distal pancreatectomy.

## *Duodenal Complications*

*Duodenal fistula* results from failure of the suture repair and is reported to occur in up to 17 % of cases. In patients with peri-duodenal drains, the presence of bilious drainage establishes the diagnosis. In patients without drains, the clinical presentation may be one of abdominal sepsis. Initial management consists of CT imaging to confirm the diagnosis, drainage of the duodenal effluent, drainage of any associated intra-abdominal fluid collections, intravenous antibiotics, and nutritional support. If a pyloric exclusion or other duodenal diversion had been previously performed, then the fistula is an end fistula and it will usually close. If not, persistent high output beyond 2 weeks frequently necessitates operative intervention for duodenal diversion.

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# 14. Stomach, Small Bowel, and Colon

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## Introduction

The intra-abdominal gastrointestinal (GI) tract includes the stomach, small bowel, and colon. Injury to these organs can result from either blunt or penetrating trauma, although they are much more common in penetrating injury. Injuries include contusions, hematomas, and partial- or full-thickness injuries and can often involve the mesentery and underlying vasculature. Unrecognized injuries to the gastrointestinal tract carry the risk of intra-abdominal contamination, infectious complications, and morbidity and mortality. A study from the Eastern Association for the Surgery of Trauma (EAST) revealed an incidence of only 0.3 % injury in more than 275,000 blunt trauma victims. In patients with any blunt abdominal trauma, 4–7 % will have hollow viscus injury. The presence of solid organ injury increases the likelihood of concomitant hollow viscus injury [1].

Gunshot wounds (GSWs) violating the peritoneal cavity have a higher incidence (70 % versus 30 %) of hollow viscus injury than stab wounds (SWs). This is not surprising due to the greater force transmitted from higher-velocity penetrating injury. Although some centers have advocated nonoperative management in these patients, our practice has been to routinely explore GSWs while offering a more selective approach in the management in SWs [2–6].

Blunt gastric rupture is relatively uncommon but can lead to large amounts of intraperitoneal contamination and intra-abdominal sepsis. This is most likely to occur as a result of high force transmittance such as when a motor vehicle strikes a pedestrian. Since the stomach is such a compliant

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organ, the force needed to cause gastric rupture is very large, and this force is also transmitted to other parts of the victim's body. Associated injuries are likely in a patient with blunt gastric rupture and should prompt a thorough exploration of the entire abdomen [7].

Motor vehicle collisions (MVC) remain the most common cause of blunt small bowel rupture. Although seat belts have clearly been shown to save lives, they are also more likely to lead to small bowel injury. In fact, studies have shown that the risk of small bowel injury is increased 4.38 times with the use of three-point restraints and up to 10 times with the use of lap belts. The classic "seat belt" sign involves an ecchymosed abdominal wall following the shape of a seat belt with or without abdominal wall embarrassment. This physical exam finding has been found to be associated with a significantly greater chance of abdominal and small bowel injury. A multi-institutional study found a 4.7 % increase in risk of small bowel perforation after MVC if a seat belt sign was present [1, 8, 9].

Lumbar spine fractures, occurring with or without a seat belt sign, can result as the force of energy is transmitted posteriorly to the spine. These Chance fractures are often associated with hollow viscus injury, involving either the small bowel or colon.

Colonic injury is commonly seen as a result of penetrating abdominal trauma but only involved in less than 5 % of blunt abdominal trauma [10]. The management of colorectal injury has significantly evolved over the past 40 years. In fact, during World War II, the Office of the Surgeon General mandated colostomy for all colonic injuries. Primary repair was not considered an option until the early 1950s, and it was only in the 1970s that mandatory colostomy was challenged. A prospective randomized study by Chaping in 1999 concluded there were no increases in complications with primary colonic repair after penetrating trauma. A meta-analysis by Nelson et al. in 2003, which included five prospective studies, also showed no differences in mortality between primary repair and colostomy for colonic injury [10, 11].

## History

Much of the early written work on GI injuries came as a result of military conflicts. Up until the late nineteenth century, the lack of adequate anesthesia, improper technique, and poor antiseptic measures often led to early patient demise.

The 25th president of the United States, William McKinley, was shot twice in the abdomen on the grounds of the Pan-American Exposition in Buffalo, New York, in late 1901. McKinley was rushed to a local hospital where he was given an injection of morphine and strychnine to ease his pain and ether for sedation. He underwent surgical exploration and was found to have an anterior and posterior gunshot wound to the stomach, which was primarily repaired. Unfortunately, he died several days later of gangrene and septic shock [12].

Improvements in mortality from GI injuries were first seen in World War II and the Korean and Vietnam wars. Triage, rapid transport, antiseptic technique, and management of specific intra-abdominal injuries all improved as a result of wartime experience and were subsequently adopted by civilian surgeons. The application of skills learned in the military arena continues today as a result of the wars in Afghanistan and Iraq [13–15].

## General Management

The initial approach to a patient with suspected gastrointestinal tract injury should begin with the primary survey. In an era of increasing dependence on radiographic imaging, the history and physical exam are often overlooked but can be helpful in guiding diagnostic and therapeutic decisions. Wounds should be noted and the abdomen inspected for signs of peritonitis. It is important to identify the anatomic location of entrance wounds and delineate between the abdomen, the flank, or the back. Visualizing the trajectory of penetrating injuries can help delineate injury pattern.

Standard lab values in the early stages of gastric, small bowel, and colonic injuries are of little diagnostic value. Markers of resuscitation, such as lactic acid and base deficit, correlate well with the adequacy of resuscitation or ongoing hemorrhage [16]. Lab values are more likely to help in the diagnosis of missed hollow viscus injury that can present after the first 24–72 h of admission. Peritonitis and hemodynamic lability are absolute indications for urgent exploratory laparotomy. If the patient's abdomen is tender but there is no peritonitis, serial examinations and radiographic studies can be considered.

The focused assessment by sonography for trauma (FAST) is now a standard diagnostic tool. It is helpful in identifying free fluid, but is not very sensitive in diagnosing hollow viscus injury [17]. FAST has supplanted diagnostic peritoneal lavage or aspirate (DPL/DPA) as an initial means to diagnose free fluid in the peritoneal cavity. However, DPL/DPA should remain in the toolbox of the acute care surgeon, especially in the setting of an equivocal FAST exam. Neither the FAST nor DPL/DPA will identify blood in the retroperitoneum. DPL findings of succus entericus, stool, and vegetable or other food matter are all signs of hollow viscus injury [18]. An alkaline phosphatase level in the DPL fluid of greater than 10 international units has a specificity of 99.8 % and sensitivity of 94.7 % for hollow viscus injury [19].

Computed tomography (CT) scan of the abdomen is used very often in patients with blunt trauma who are hemodynamically stable. Findings such as bowel wall thickening, lack of enhancement of the bowel wall on a contrast scan, mesenteric stranding or hematoma, free intraperitoneal fluid or contrast extravasation, pneumatosis, and pneumoperitoneum are all signs of possible hollow viscus injury [20–22]. The overall sensitivity and specificity of CT for bowel injury have been shown to be as high as 88.3 % and 99.4 %, respectively [23]. Free intra-abdominal fluid can be misleading as it does not always indicate bowel injury and can occur as a result of large-volume resuscitation. Fahkry et al. found that only 29 % of patients with free fluid in the abdomen had full-thickness bowel injury. Yet, another study found that 12 % of patients with normal abdominal CT were subsequently found to have bowel injury [24].

Although its utility in blunt abdominal injury is established, its role in penetrating injury is less well defined. Velmahos et al. have proposed the utility of CT scan in the selective nonoperative management of abdominal gunshot wounds [25]. In our institution, hemodynamically stable patients with penetrating abdominal wounds who do not exhibit absolute indications for surgery are scanned and observed. Missile trajectory is also used to help guide operative versus nonoperative decision making.

Finally, laparoscopy is an increasingly utilized tool in the management of GI injury and can be useful in excluding bowel injury in the setting of the presence of solid organ injury without a solid viscus injury. Several studies have shown that laparoscopy is safe in selected patients with blunt and penetrating abdominal trauma, minimizes nontherapeutic laparotomies, and allows for the minimal invasive management of selected intra-abdominal injuries. Surgeon experience and supporting hospital infrastructure are important variables to factor when considering its use [26–28].

# Organ-Specific Injury: Management and Personal Tips

## *Stomach*

The stomach is very well vascularized due to its redundant blood supply. The distended stomach is at higher risk for rupture because of direct compression or acute increase in intraluminal pressure. During initial exploration, the entire gastrointestinal tract from the gastroesophageal (GE) junction to the rectum should be visualized and injuries identified. Blunt gastric injury usually occurs as a result of a blowout-type injury and is usually found on the anterior surface of the stomach. Taking down the gastrohepatic and gastrocolic ligaments increases exposure. Care must be taken to avoid injury to the middle colic artery.

Dividing the left triangular ligament of the left lobe of the liver and placing the patient in reverse Trendelenburg position can also improve visualization.

The diaphragm should also be closely inspected to rule out injury and potential contamination of the pleural cavity. It is imperative to explore the lesser sac to expose injuries on the posterior wall of the stomach. This is done most easily by gently grasping the stomach in one hand and the transverse colon in the other and lifting it up. The lesser sac is then entered by dividing the gastrocolic omentum. Completely dividing the gastrocolic omentum and taking the short gastric vessels up to the GE junction provide ultimate exposure to the stomach (Fig. 14.1). Should the suspected gastric injury not be found by visual inspection alone, the surgeon may ask the anesthesia team to fill the stomach with saline and a small amount of methylene blue dye. Gentle occlusion of the GE junction and pylorus while simultaneously applying manual pressure to the stomach can help identify the site of gastric injury.

Gastric injuries are graded according to the American Association for the Surgery of Trauma (AAST) Organ Injury Scale (Tables 14.1, 14.2, 14.3, and 14.4). Grade I stomach injuries are contusions or hematomas or a partial-thickness laceration. A grade II stomach injury is defined as a laceration less than 2 cm at the GE junction or pylorus, less than 5 cm in the proximal one-third of the stomach, or less than 10 cm in the distal two-thirds of the stomach. A grade III stomach injury is defined as a laceration greater than 2 cm at the GE junction or pylorus, greater than 5 cm in the proximal one-third of the stomach, or greater than 10 cm in the distal two-thirds of the stomach. A grade IV stomach injury is when there is significant tissue loss or devascularization.

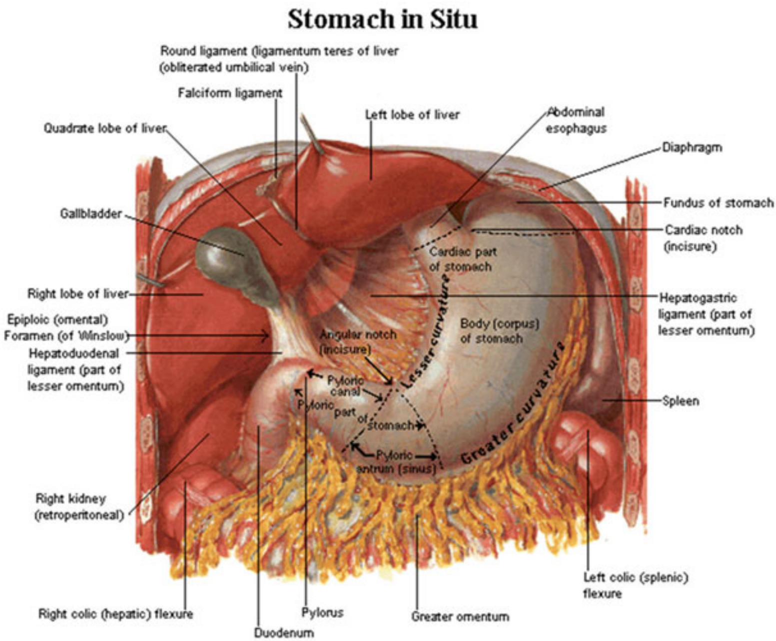


Fig. 14.1. General anatomy and exposure of the stomach.

Table 14.1. American Association for the Surgery of Trauma (AAST)—stomach injury scale.

| Stomach injury scale | | |
|---|---|---|
| Grade | Description of injury | AIS-90 |
| I | Contusion/hematoma | 2 |
| | Partial-thickness laceration | 2 |
| II | Laceration <2 cm in the GE junction or pylorus | 3 |
| | <5 cm in the proximal 1/3 of the stomach | 3 |
| | <10 cm in the distal 2/3 of the stomach | 3 |
| III | Laceration >2 cm in the GE junction or pylorus | 3 |
| | >5 cm in the proximal 1/3 of the stomach | 3 |
| | >10 cm in the distal 2/3 of the stomach | 3 |
| IV | Tissue loss or devascularization <2/3 of the stomach | 4 |
| V | Tissue loss or devascularization >2/3 of the stomach | 4 |

Table 14.2. American Association for the Surgery of Trauma (AAST)—small bowel injury scale.

| Small bowel injury scale | | | |
|---|---|---|---|
| Grade | Type of injury | Description of injury | AIS-90 |
| I | Hematoma | Contusion or hematoma without devascularization | 2 |
| | Laceration | Partial thickness, no perforation | 2 |
| II | Laceration | Laceration <50 % of circumference | 3 |
| III | Laceration | Laceration >50 % of circumference without transection | 3 |
| IV | Laceration | Transection of the small bowel | 4 |
| V | Laceration | Transection of the small bowel with segmental tissue loss | 4 |
| | Vascular | Devascularized segment | 4 |

Table 14.3. American Association for the Surgery of Trauma (AAST)—colon injury scale.

| Colon injury scale | | | |
|---|---|---|---|
| Grade | Type of injury | Description of injury | AIS-90 |
| I | Hematoma | Contusion or hematoma without devascularization | 2 |
| | Laceration | Partial thickness, no perforation | 2 |
| II | Laceration | Laceration <50 % of circumference | 3 |
| III | Laceration | Laceration ≥50 % of circumference without transection | 3 |
| IV | Laceration | Transection of the colon | 4 |
| V | Laceration | Transection of the colon with segmental tissue loss | 4 |
| | Vascular | Devascularized segment | 4 |

Once identified, surgical repair of the gastric injury is straightforward. Smaller injuries can be repaired primarily after debridement of devitalized tissue. Most grade I injuries and small perforations can be managed with interrupted silk Lembert sutures in either single- or two-layered closure. Larger perforations should be closed with a two-layered repair. The inner layer is closed with a continuous running locking absorbable suture, and the outer layer is closed with interrupted silk

Table 14.4. American Association for the Surgery of Trauma (AAST)—rectum injury scale.

| Rectum injury scale | | | |
|---|---|---|---|
| Grade | Type of injury | Description of injury | AIS-90 |
| I | Hematoma | Contusion or hematoma without devascularization | 2 |
| | Laceration | Partial-thickness laceration | 2 |
| II | Laceration | Laceration <50 % of circumference | 3 |
| III | Laceration | Laceration ≥50 % of circumference | 4 |
| IV | Laceration | Full-thickness laceration with extension into the perineum | 5 |
| V | Vascular | Devascularized segment | 5 |

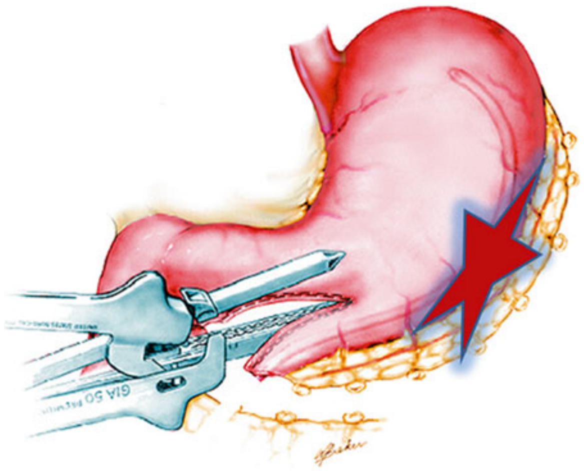


Fig. 14.2. Grade III injuries with major involvement of the greater curvature can be repaired using the gastrointestinal anastomotic (GIA) stapler.

Lembert sutures, taking imbricating seromuscular bites. Grade III injuries with major involvement of the greater curvature can be repaired using the gastrointestinal anastomotic (GIA) stapler (Fig. 14.2). Careful attention should be paid to avoid narrowing of the stomach lumen. Injuries causing damage to the pylorus may also necessitate pyloroplasty. Grade IV stomach injuries, with total loss or devascularization of greater than 2/3 of the stomach, may require major resection and either

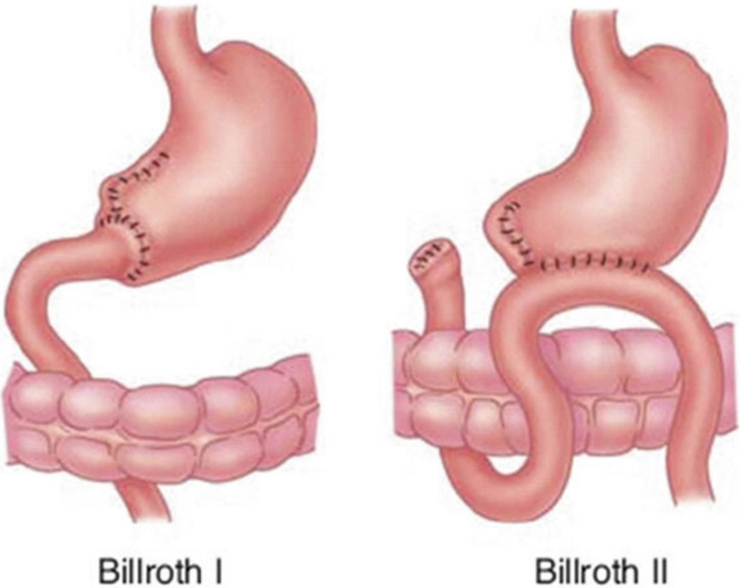


Fig. 14.3. Billroth reconstructions.

gastroduodenostomy (Billroth I) or gastrojejunostomy (Billroth 2) anastomoses (Fig. 14.3). Grade V injuries are rare and may require total gastrectomy followed by Roux-en-Y esophagojejunostomy [29–33].

Complications after gastric injury include rebleeding, gastric fistula formation, gastroparesis, anastomotic leak, and sepsis. Additionally, in patients with resection and with reconstruction, the development of postgastrectomy syndromes is possible. Symptoms include early satiety, delayed gastric emptying, Roux-en-Y stasis syndrome, early and late dumping syndrome, alkaline reflux gastritis, postvagotomy diarrhea, afferent and efferent loop syndromes, internal hernias leading to obstruction, and marginal ulcers. Management may require alterations in diet, prokinetic agents, or reconstruction of the initial anastomosis [30, 33, 34].

## *Small Bowel*

The small intestine is well vascularized and is less prone to ischemic injury compared to the colon. Distal to the ligament of Treitz, it is suspended on its mesentery with the majority of its blood supply originating from the superior mesenteric artery (SMA) along with multiple arcades. Upon entering the peritoneal cavity, the first priority of management should be hemorrhage control. Mesenteric lacerations can be a source of major hemorrhage and should be identified and controlled rapidly by systematic inspection of the small bowel starting from the ligament of Treitz to the ileocecal valve. Once hemorrhage has been controlled, controlling contamination should be the second step. This can be done with either non-penetrating clamps, simple suture repair, or stapled division. Although not our practice, skin staplers have also been described for temporary spillage control.

Particular attention should be paid to the technique of running the bowel in patients who have penetrating trauma. It is our practice to run the bowel using the index finger and middle finger of each hand. From the left-hand side of the table, the surgeon places the right-hand middle and index fingers at the ligament of Treitz and gently slides along the bowel with the index finger and middle finger of the left hand traveling a short distance. This technique helps avoid missing foreign bodies retained within the wall of the bowel, particularly helpful after a shotgun injury with multiple pellets entering the abdominal cavity (Fig. 14.4).

Careful inspection of the mesentery should be performed. Hematomas of the bowel wall should raise suspicion of underlying bowel wall injury. Grade I small bowel injuries can usually be treated by simple inversion with seromuscular sutures. Grade II bowel injuries should be debrided and managed with single- or double-layered closure with either absorbable or nonabsorbable suture. Grade III and IV injuries will more likely require bowel resection. Careful attention must be paid to avoid narrowing the small bowel lumen. Injuries should be closed transversely, and those involving a >50 % circumference should be managed with segmental resection and, if the patients' hemodynamic and acid-base status allows, primary anastomoses (Fig. 14.5). The small bowel mesentery should be closed with either interrupted or running absorbable or nonabsorbable suture after anastomoses to prevent the potential for internal hernia. Patients left in discontinuity should return to the operating room for definitive management by 72 h. Adjunctive techniques for assessing bowel viability can be used if there is any question of viability. Doppler ultrasound, fluorescence with Wood's lamp, or the newer SPY Elite® Intraoperative Perfusion Assessment System from LifeCell can all be used.

The ideal technique for small bowel anastomosis is unknown. Some prefer stapled anastomoses, while others prefer either single- or two-layered hand-sewn. There may be higher leak rates with stapled versus hand-sewn anastomoses in trauma patients. Our practice has been to

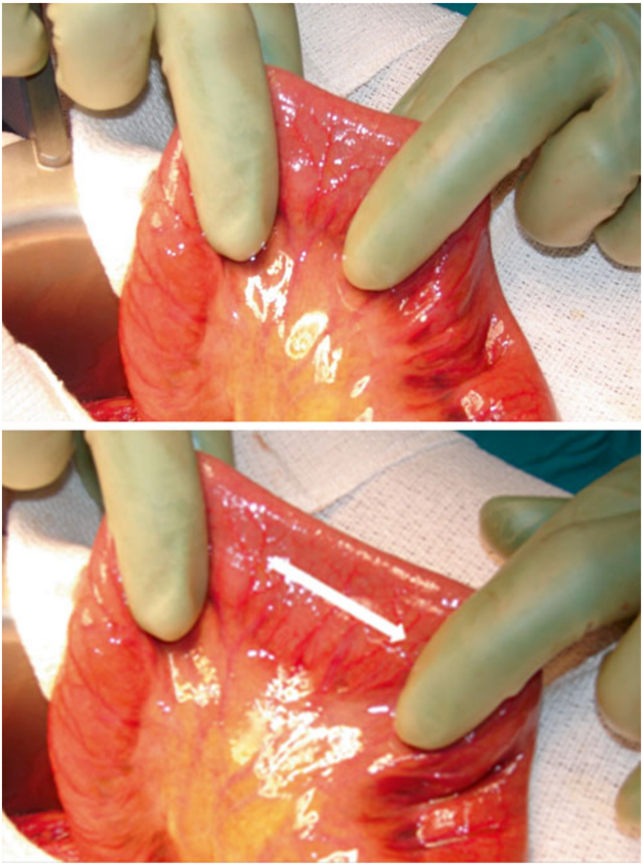

Fig. 14.4. Manual inspection of the small bowel.

perform stapled anastomoses for routine resections in non-edematous bowel and hand-sewn double-layered anastomoses, particularly in the setting of bowel edema (Fig. 14.6). Currently, the Stapled versus Handsewn: A Prospective Emergency Surgery Study (SHAPES), a multi-institutional AAST study, is being led by our institution and will aim to assess superiority of either method. Grade V injury typically involves significant tissue loss or a devascularized segment warranting resection. A delayed second-look laparotomy within 24 h to assess bowel viability prior to definitive closure may be wise. The open abdomen can be managed by a temporary wound vacuum assisted closure (VAC)

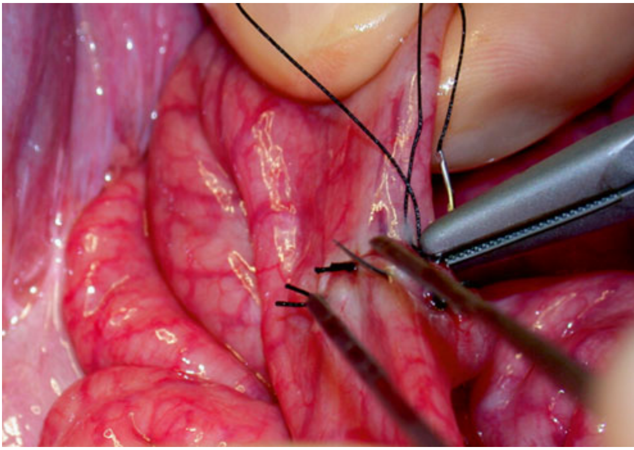

Fig. 14.5. Primary repair of small bowel injury.

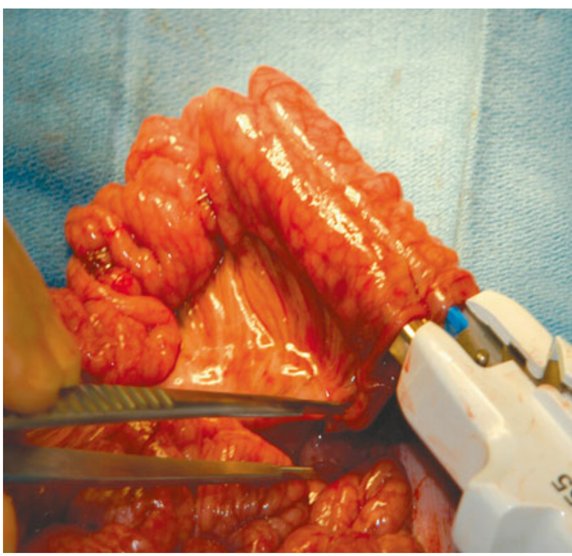

Fig. 14.6. Stapled anastomosis using GIA stapler.

using either a “1010 drape” (3M™ Steri-Drape; catalog no. 1010, 3M, St. Paul, MN), Kerlix gauze, nasogastric tubes, and an Ioban® dressing, with a traditional black sponge negative-pressure therapy KCI VAC® or the newer ABThera™ VAC [35, 36].

## Complications After Small Bowel Injury

Postoperative complications can develop in the immediate perioperative or can be delayed by several days to weeks. Bleeding, wound infection, dehiscence or evisceration, and the development of abdominal compartment syndrome can all occur within 72 h of surgery. Less common complications can include stomach or bowel ischemia, enterocutaneous fistula, and empyema.

Any surgical wound is at risk for the development of a surgical site infection. Necrotizing abdominal soft tissue infection can also develop rapidly and be fatal. Prompt aggressive surgical debridement can help lessen the degree of morbidity and mortality associated with this condition.

Intra-abdominal abscesses can develop and usually form as a result of residual contamination from the original injury, new spillage as a result of an anastomotic breakdown, or the development of a fistula. Patients exhibiting signs of fever with leukocytosis approximately a week after operation should undergo CT imaging of the abdomen and pelvis to rule out abscess formation. If found, percutaneous drainage can be performed. In a small number of cases, re-operative exploration will be required.

Diaphragmatic injury in the setting of gastric injury can occasionally result in empyema. The early use of video-assisted thoracoscopic surgery (VATS) for empyema can be helpful. A small subset of these patients may eventually require thoracotomy for debridement.

Any postoperative trauma patient with intra-abdominal injuries should be monitored for abdominal compartment syndrome in the early postoperative phase. This is especially true in cases of damage control surgery or when high-volume resuscitation was used. Particular attention should be paid to the overall hemodynamic status, abdominal distention, urine output per hour, and ventilatory difficulties. Bladder pressure can serve as a marker of intra-abdominal pressure and should be measured if there is clinical concern for intra-abdominal hypertension or abdominal compartment syndrome. Some authors have recommended the early and routine use of bladder pressure monitoring in the postoperative setting [37].

A rare but morbid complication is the short gut syndrome, which can occur after resections of large amounts of small bowel. Approximately 100 cm of small bowel is required to allow for oral nutrition without the colon. If the colon remains intact, a minimum of 50–60 cm of small bowel is needed. The ileocecal valve should be preserved if possible [38].

## *Colorectal*

Colon and rectal injuries can occur as a result of either blunt or penetrating trauma, although they are much more commonly caused by penetrating trauma. In blunt trauma, the colon can be injured by creation of a closed loop and blowout rupture due to increased intraluminal pressure, by shear injury due to tearing at the junction of the mobile and immobile colon, and by deceleration mechanisms causing mesenteric avulsion injury.

Diagnosis of colorectal injury should begin with physical examination. Close attention should be given to examination of the perineum, the anus, the rectal vault, and the prostate in men. Obvious tears of the anus, the presence of gross blood, disruption of the bony pelvis, a high-riding prostate, or an exquisite pain in the perineal region can all provide clues to a possible rectal injury. CT scan of the abdomen and pelvis looking for the presence of extra-luminal air, extravasation of contrast, colonic wall thickening, or mesenteric stranding can also be helpful. Triple contrast studies can be helpful, particularly with injuries to the flank. Patients with confirmed or suspected colorectal injury should be placed in stirrups for initial sigmoidoscope evaluation followed by exploratory laparotomy. This facilitates access to the rectal vault and concomitant sigmoidoscopic evaluation should the injury be difficult to find intra-abdominally. In the abdomen, mandatory exploration of hematomas of the colonic wall or mesentery should be performed to avoid missing underlying injury [39].

A large number of retrospective studies have concluded that direct repair is acceptable in virtually all colonic injuries. An exception to this rule is the high-velocity military-grade injuries that will likely require diversion. The “4 Ds” of rectal trauma, diversion, debridement, presacral drainage, and distal rectal washout, described by Lavenson and Cohen in the early 1970s were a result of their experience with high-energy rectal wound sustained during the Vietnam War. The routine use of this approach is no longer warranted [40–42].

Patients diagnosed with colonic injury warranting exploration should be given preoperative broad spectrum antibiotics continued for 24 h post-op. The principles of management remain the same: hemorrhage control followed by control of contamination [43]. Colonic mobilization is performed by dissecting along the white line of Toldt. The surgeon should exercise judgment in determining which patients will be best suited for primary versus colonic diversion [44]. Our practice has been to consider primary repair in patients who have no evidence of hypotension/shock based on physiologic and acid-base parameters, those with minimal stool contamination [45].

Similar to the management for small bowel injuries, colonic injuries can either be managed with stapled or hand-sewn anastomoses. Intraperitoneal rectal injuries are treated similarly to colonic injuries. Extraperitoneal colonic injuries located near the anus can be managed trans-anally. The middle and lower third rectal injuries are managed by proximal diversion.

## Complications of Colorectal Injury

The most common cause of death in patients with colorectal injury is exsanguination from the concomitant mesenteric injury. Sepsis leading to multisystem organ failure, especially in cases where an injury is missed, is the second most common cause of death. Infection complications are common in patients who sustain colorectal injury. Repeat imaging should be performed to evaluate for intra-abdominal abscesses in patients who develop signs of infection. Should they be present, percutaneous drainage is the preferred approach. Wound infections can be avoided by leaving the skin open to heal by secondary intention or the use of a wound VAC. Delayed primary closure can be considered once the initial postoperative period has passed. Delayed complications can occur as a result of suture line failure or development of fistulas. Fistula management is dependent on ensuring there is no distal obstruction, foreign body, or active inflammatory process. Localization should be performed by either CT scanning or fistulogram. Non-septic patients can usually be managed nonoperatively. In addition, these distal GI fistulas are generally low-output fistulas (<500 cc/day) and can be managed by continuing patients on an oral diet. Multiple, proximal small bowel or high-output fistulas will generally require total parenteral nutrition [46–50].

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# 15. Trauma of the Kidney, Ureter, and Bladder

*Stacy A. Shackelford, M.D.*

## Introduction

Trauma to the genitourinary (GU) tract affects 10 % of patients with abdominal trauma [1] and 0.5–3.1 % of all trauma patients [2–4]. Although not often the cause of significant shock, GU trauma frequently occurs in the setting of multi-trauma and may be overlooked, causing significant morbidity [5]. Blunt trauma accounts for 80–90 % of GU injuries [6, 7]; however, in an urban setting, penetrating trauma may cause up to 20 % of GU trauma [8]. In contrast, over three-fourths of the cases requiring surgical exploration are caused by penetrating injury [7]. In blunt trauma, 43 % of GU injuries are to the kidney, 9 % to the bladder, and 47 % to the external genitalia. Ureteral injuries are relatively rare in blunt trauma [2] and account for less than 1 % of all urologic trauma [5].

## Grading of Renal Injuries

The organ injury scale for renal trauma was first published in 1989 by the American Association for the Surgery of Trauma (AAST) (Table 15.1) [9]. A proposed revision to the AAST renal injury grading scale recommended designation of all collecting system injuries and segmental vascular injuries as Grade IV (Fig. 15.1) and limited the designation of Grade V to main renal artery and vein injuries [7]; however, this revision was not formally adopted.

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Table 15.1. AAST renal injury scale [9].

| | |
|---|---|
| Grade I | Contusion: microscopic or gross hematuria, urologic studies normal<br>Hematoma: subcapsular, nonexpanding without parenchymal laceration |
| Grade II | Hematoma: nonexpanding perirenal hematoma confined to renal retroperitoneum<br>Laceration: <1 cm parenchymal depth of renal cortex without urinary extravasation |
| Grade III | Laceration: >1 cm parenchymal depth of renal cortex without collecting system rupture or urinary extravasation |
| Grade IV | Laceration: parenchymal laceration extending through renal cortex, medulla, and collecting system<br>Vascular: main renal artery or vein injury with contained hemorrhage |
| Grade V | Laceration: completely shattered kidney<br>Vascular: avulsion of renal hilum which devascularizes kidney |

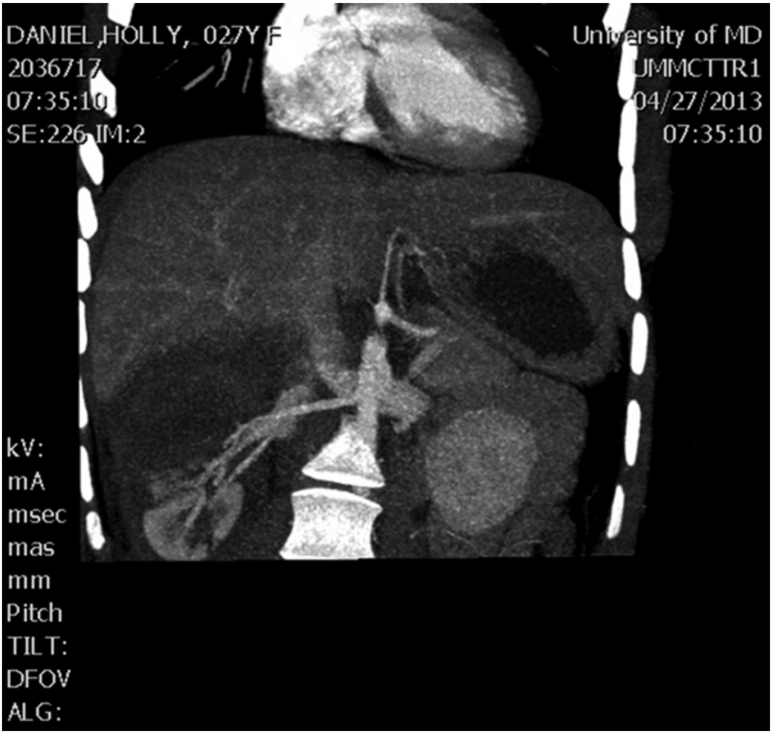


Fig. 15.1. Grade IV blunt right kidney injury with approximately 60 % devascularization.

## Imaging

Initial evaluation by computed tomography (CT) scan is indicated in cases of blunt and penetrating trauma when the patient is hemodynamically stable. For blunt trauma with injuries to the pelvic arch, it is important to look for blood at the urethral meatus. If there is no blood at the meatus, placement of a Foley catheter may be attempted. When gross hematuria is identified, then a cystogram or CT cystogram is indicated to look for injury to the bladder. Similarly, for penetrating injuries to the pelvis and suprapubic region, cystography is indicated in stable patients. CT cystogram requires instillation of 350 ml of contrast into the bladder, then clamping of the Foley for the scan. A routine CT with passive filling of the bladder is not adequate to exclude bladder injury [10–12]. When blood is present at the urethral meatus, a retrograde urethrogram must be performed prior to Foley catheter placement.

Reimaging of renal injuries should not be performed routinely but is indicated for evaluation of sepsis, flank pain, decreased hemoglobin, or persistent hematuria. Scheduled reimaging may be considered for early detection of complications in Grade V injuries [13].

## Management of Renal Injuries

Grade I–III renal injuries may be observed. Grade IV injuries require intervention by angiography or surgical exploration when there is hemodynamic instability or vascular extravasation. Grade V injuries require surgical exploration in most cases (Fig. 15.2). Not all collecting system injuries require surgical repair, and management with percutaneous nephrostomy, stenting, and Foley catheter may be preferred, particularly if there is no other indication for laparotomy. Figure 15.3 illustrates a penetrating injury to the collecting system that was managed with nephrostomy and stenting.

Technically, surgical exploration is focused on the goals of hemostasis, debridement of devitalized tissue, and repair of the collecting system. Surgical options include repair, partial nephrectomy, and total nephrectomy [14]. Many times, associated injuries will dictate the need for laparotomy.

Fig. 15.2. Nephrectomy specimen demonstrating Grade V laceration through renal hilum.

When a zone II retroperitoneal injury is discovered intraoperatively, the kidney must be explored if there is an expanding hematoma or active bleeding into the peritoneum. Exploration should be considered if there is no preoperative imaging. If the trajectory of penetrating trauma indicates that the ureter is at risk of injury, then this must be explored as well.

The surgical approach to renal injury may include control of the renal pedicle prior to opening Gerota's fascia or a lateral approach to opening Gerota's fascia without prior control of the renal pedicle. Control of the renal vessels prior to opening Gerota's fascia does not result in a higher rate of renal salvage or lower blood loss in the most recent series [15–17]; however, other authors have reported flaws in prior studies leading to ongoing controversy about the role of vascular control prior to renal exploration [18] (Fig. 15.4). Rapid control of the renal hilum en bloc adjacent to the kidney is a solution that avoids prolonged dissection of the renal artery and vein while still allowing vascular occlusion (Fig. 15.5).

The kidney can be exposed after medial mobilization of the right or left colon. A generous vertical incision should be made through Gerota's fascia, directly over the kidney. The injured kidney should not be bluntly

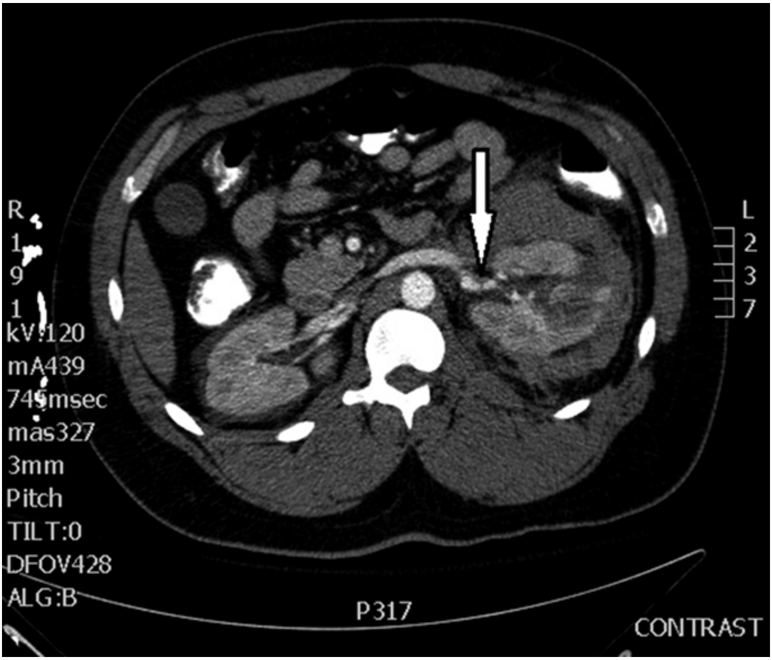


Fig. 15.3. Gunshot wound to left kidney with perinephric hematoma. *Arrow* indicates urine extravasation. The injury was managed with nephrostomy and stenting.

pulled up, as this may decapsulate the kidney or increase the injury. After evacuation of the hematoma, the renal capsule should be identified and dissected free from the surrounding areolar tissue under direct vision. Blunt dissection may be performed away from the site of the injury. After mobilizing the entire kidney, particularly the upper pole, the kidney may be rotated anteriorly. Bleeding should be controlled by compressing the injury, by compressing the renal hilum with a sponge stick, or by placing a vascular clamp across the renal pedicle.

Bleeding from the kidney may be controlled by placing large absorbable mattress sutures through the renal capsule. Topical hemostatic agents may be utilized. A limited debridement of obviously devitalized tissue should be performed; however, debridement should not be overly aggressive. Defects in the collecting system should be closed with absorbable suture (Fig. 15.6). In the event of associated colon or pancreatic injury,

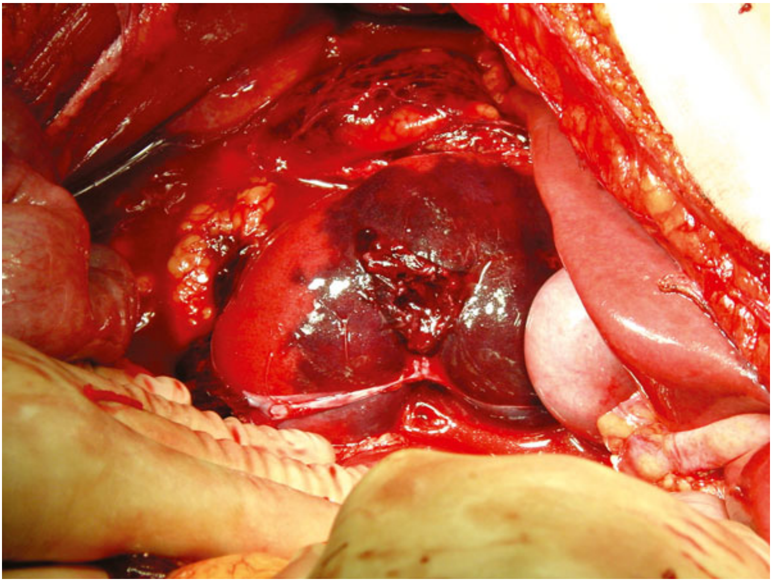

Fig. 15.4. Operative photo of right kidney gunshot wound with hilar injury and devascularization of upper pole. Control of the renal hilum will facilitate repair.

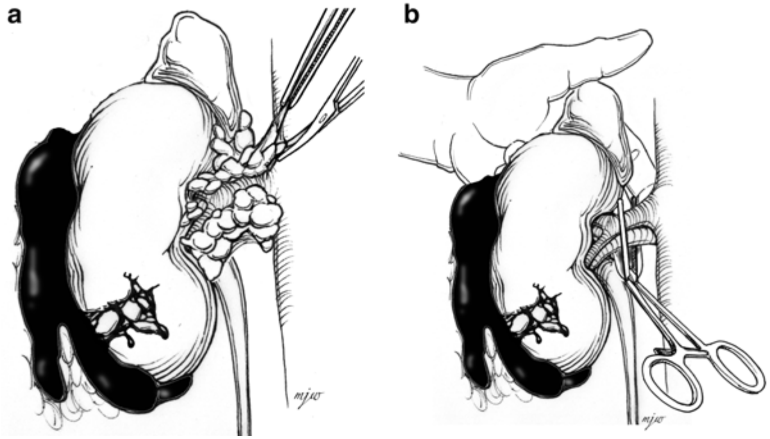


Fig. 15.5. **(a, b)** Control of the renal hilum. Prior to exploration of the injured kidney, rapid control of the hilum may be obtained by encircling the hilar vessels en bloc. Prolonged dissection of the renal vessels is not needed.

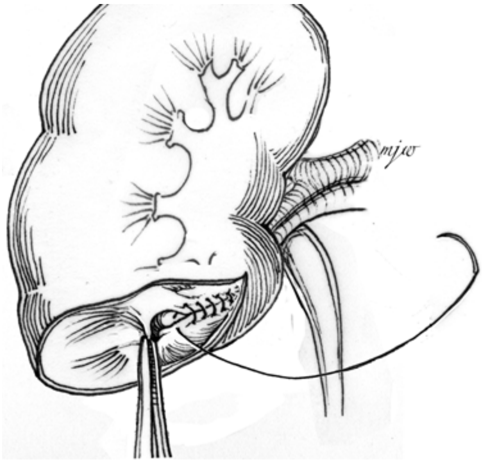


Fig. 15.6. Defects in the renal collecting system should be closed separately with absorbable suture. Bleeding may then be controlled using large absorbable mattress sutures, topical hemostatics, or cautery.

viable tissue should be interposed between the injured kidney and colon or pancreas. If there is concern for a urine leak, a drain should be placed adjacent to the injury. If an urgent nephrectomy is required, palpation of a normal size contralateral kidney is adequate assurance of renal function.

## Angiography

Angiography is a useful adjunct for management of renal injuries and may be indicated for initial management of hemorrhage, stenting of an intimal injury of the renal artery, or delayed occlusion of a pseudoaneurysm. Angioembolization may improve renal salvage rates compared to surgical exploration (Fig. 15.7). There are no standardized indications for angiography; however, active contrast extravasation on CT scan and perinephric hematoma rim greater than 2.5 cm predict a high likelihood of therapeutic embolization in Grade III and IV renal trauma [19–21]. Importantly, the failure rate for patients who require angioembolization for active hemorrhage is 27 %, frequently requiring laparotomy for treatment [22], although repeat angioembolization is also an option and has been reported to have a 97 % success rate [23]. Angiographic embolization of Grade V renal injuries is not generally recommended due to

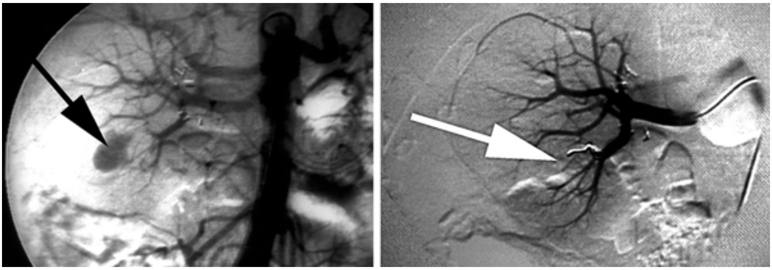

Fig. 15.7. Renal angiogram showing extravasation of contrast from injured lower pole artery and post coil placement.

an excessively high failure rate [24]; however, recent series have demonstrated success in managing select Grade V injuries with an aggressive angiographic approach including repeat embolization after initial failure [23, 25].

## Management of Ureteral Injuries

The majority of ureteral injuries are caused by penetrating trauma. A high index of suspicion must be maintained based on injuries in proximity to the ureter. Gross hematuria is not a reliable indicator and is absent in about one-third of cases; CT scan may miss up to two-thirds of ureteral injuries [26, 27]. A missed ureteral injury is a cause of significant morbidity and may present as a prolonged ileus, urine leakage from the abdominal wound, oliguria, sepsis, or uremia.

Ureteral injuries are managed by surgical repair. It is important to be aware of the blood supply to the ureter: The upper ureter is supplied by segmental branches from the renal, gonadal, and common iliac arteries entering the ureter from the medial side. After crossing the pelvic brim, the ureter is supplied by branches of the hypogastric artery, entering from the lateral side. The blood supply should be preserved to the greatest extent possible when mobilizing the ureter.

Debridement should be conservative to allow the simplest repair. When possible, the ureter should be mobilized to allow a tension-free end-to-end repair with fine absorbable suture over a ureteral stent (Fig. 15.8). A distal ureteral injury may be managed by reimplantation into the bladder, using a psoas hitch if necessary to avoid tension. More complex reconstruction with a Boari flap or ileal conduit may be required for more proximal ureteral injuries that cannot be repaired primarily.

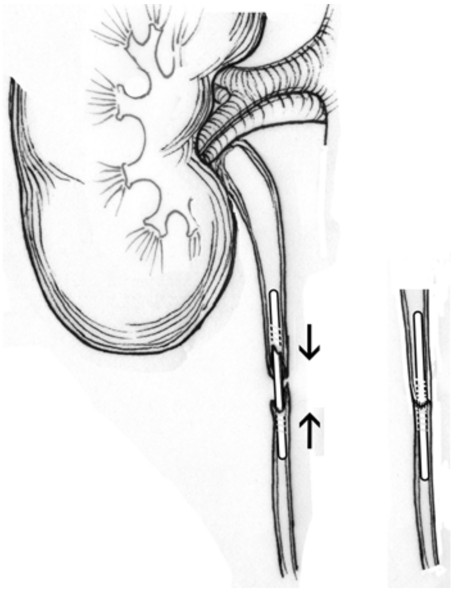

Fig. 15.8. Repair of the ureter over a stent. When possible, the ureter should be mobilized for a tension-free end-to-end repair.

A transureteroureterostomy may be considered with caution, as anastomosis to the uninjured ureter may cause a stricture affecting both kidneys (Fig. 15.9). Ureteral injuries are also easily managed with damage control techniques by inserting a single J stent or pediatric feeding tube up the injured ureter into the renal pelvis, tying the distal ureter over the stent, and exteriorizing the drain through a lateral stab incision in the abdominal wall; this will allow for delayed reconstruction [14] (Fig. 15.10).

Postoperatively, ureteral stents should be maintained for 6 weeks. Bladder drainage should be continued with a Foley catheter for at least 7 days.

## Management of Bladder Injuries

Bladder injuries may be caused by blunt or penetrating trauma; 85–94 % will have associated injuries [28, 29]. Pelvic fractures are the most common associated injury, present in 83–88 % of bladder injuries [28, 29]. Injury of the bladder may occur as an overpressure burst injury from high energy transfer to the abdomen or a tear at the point of the

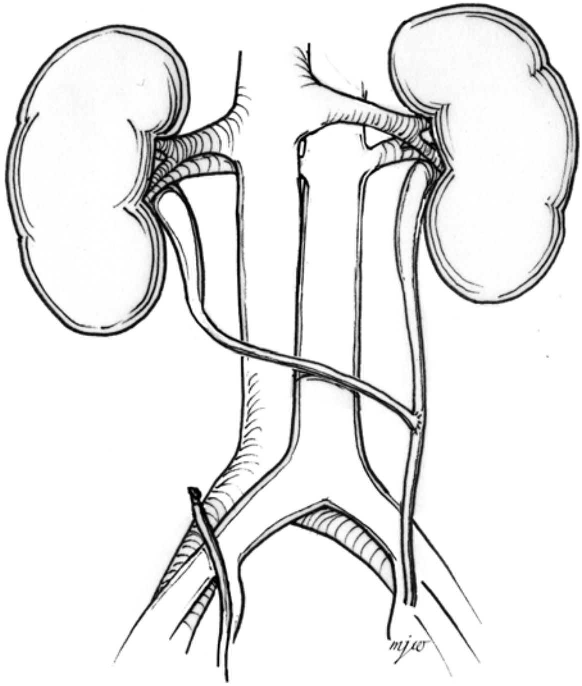


Fig. 15.9. Transureteroureterostomy should be considered with caution in cases of ureteral injury as a stricture may affect both kidneys.

fascial attachments resulting from pelvic disruption or from direct laceration by bone fragments or penetrating injuries. Bladder rupture presents with hematuria in 95 % of cases [30, 31], and the combination of gross hematuria and pelvic fracture predicts a 29 % incidence of bladder rupture [32]. Due to its location deep in the pelvis, bladder rupture may occur on either the intraperitoneal portion, with free perforation into the peritoneal cavity, or below the peritoneal reflection where the perforation is contained within the extraperitoneal space.

Intraperitoneal bladder injury is associated with free fluid in the abdomen. This cannot be distinguished from intraperitoneal bleeding on focused assessment with sonography for trauma (FAST) exam and should be recognized as a potential confounder [33]. Surgical repair is required in all cases of intraperitoneal bladder rupture, although management of pelvic hemorrhage will take priority in the hypotensive patient. Gunshot wounds are the most frequent cause of penetrating

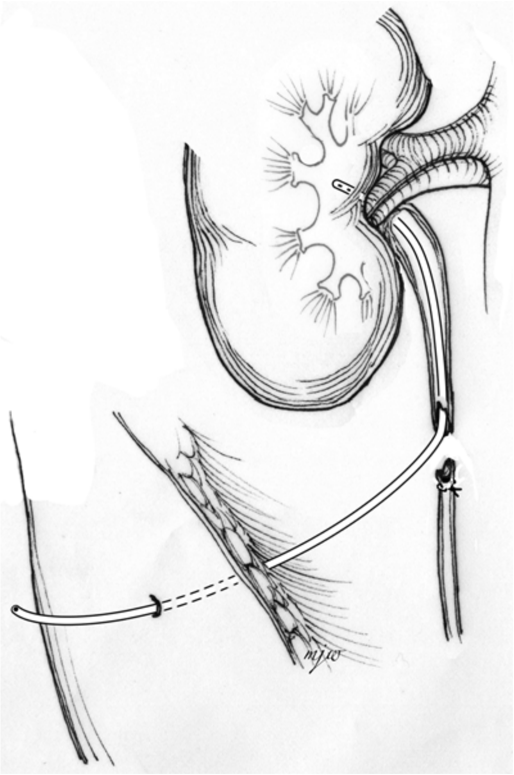


Fig. 15.10. Damage control technique for managing ureteral trauma. A drain is passed through the injured ureter into the renal pelvis, tied over the ureter, and exteriorized through the abdominal wall.

bladder trauma. Surgical exploration is indicated for gunshot wounds to the bladder; 82 % have a concomitant injury to the intestine; 90 % have two sites of transmural bladder injury necessitating a thorough examination of the bladder and bladder neck specifically looking for two sites of bladder injury [34].

Surgical exploration for bladder injury requires a thorough search for associated injuries. The bladder perforation should then be extended across the dome of the bladder to allow a full inspection and repair of all injuries from within the bladder. The orifice of each ureter should be identified by visualizing the urine jet entering the bladder prior to placing any sutures. The bladder should then be repaired in two layers of absorbable suture (Fig. 15.11).

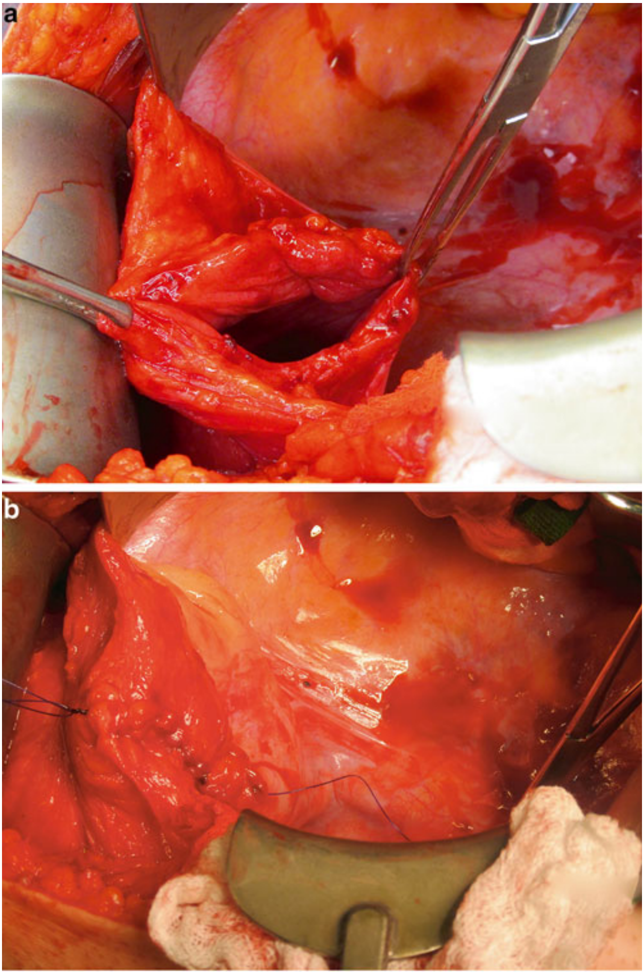

Fig. 15.11. **(a)** Operative photo of intraperitoneal bladder rupture from blunt trauma and **(b)** post repair image.

Extraperitoneal bladder rupture is highly associated with pelvic fracture. Associated urethral injury occurs in 10–29 % and should be suspected when there is blood at the urethral meatus or when a Foley catheter does not easily pass [35]. Uncomplicated extraperitoneal bladder ruptures can be managed by simple Foley catheter drainage [36–38].

Complicating features include concomitant vaginal or rectal injury, bladder neck injuries, bone fragments projecting into the bladder, open pelvic fractures, and need for internal fixation of pelvic fractures. Such injuries have a lower incidence of complications of incontinence, fistula, stricture, and sepsis when managed with surgical repair [39].

## Complications

Complications of renal injury may include secondary hemorrhage, urinoma, perinephric abscess, arteriovenous fistula, hypertension, and renal failure [18, 35]. Rebleeding from the kidney can be managed with surgical exploration or angioembolization, depending on hemodynamic stability. The majority of urinomas can be managed expectantly and will resolve. In cases of large urinoma or abscess, percutaneous drainage is usually an adequate treatment. The risk of perinephric abscess is increased when there are associated pancreatic or colon injuries or segments of devitalized kidney. Arteriovenous fistula is treated by interventional radiology techniques, potentially stenting for hilar fistulas or angioembolization for more distal lesions. Renovascular hypertension is caused by renin release by ischemic or damaged renal tissue; the incidence is approximately 5 % or less. Hypertension may be medically managed. If renal artery stenosis is present, stenting may be considered. Nephrectomy for renovascular hypertension is indicated if there is a significantly decreased function of the injured kidney as demonstrated by renal scintigraphy [18].

Urine leak may occur from a missed injury to the collecting system, ureter, or bladder, after dehiscence of a repair, or from a high-grade kidney injury managed nonoperatively. Urine leak may present in many ways including acidosis, uremia, fever, sepsis, low urine output, peritonitis, ileus, urinary ascites, or respiratory difficulty. Small urine leaks will frequently seal without further treatment. Missed injuries that are diagnosed within the first week may be repaired primarily if the patient's condition will allow. Urine leaks diagnosed after the first week or any complicated leak typically requires urinary diversion, as the tissue may become too friable to allow repair. Urinary diversion may be accomplished using minimally invasive techniques in most cases, including percutaneous nephrostomy, ureteral stenting, Foley catheter, and percutaneous drainage of abscess/urinoma [5, 18, 35].

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# 16. Traumatic Injuries and Common Surgical Emergencies of the External Genitalia and Urethra

*Richard C. Bryson, M.D., Meagan Dunne, and Andrew Kramer, M.D.*

## Traumatic Injuries

### *Amputation*

Penile amputation is usually the result of self-inflicted injury or mutilation (Fig. 16.1). Psychiatric evaluation should be considered in all cases given the high rate of comorbid underlying psychiatric illness. Ideally, the severed portion of the penis should be wrapped in saline-soaked gauze and double-bagged in ice. Reanastomosis is possible with a cold ischemia time of up to 16 h or warm ischemia up to 6 h. If the severed piece is unavailable, a penile stump should be created in a similar fashion to a distal penectomy with corporal closure and formation of a spatulated urethral neomeatus. A microvascular approach to reattachment yields significantly greater functional and sensory outcomes as compared to a strictly macrovascular approach. However, either technique yields satisfactory erectile function in greater than 50 % of cases. Loss of sensation, skin necrosis, and urethral stricture can also occur as a result of the amputation or repair, and such complications are more common after macrovascular repair. Adjuvant therapy to surgical reattachment includes hyperbaric oxygen treatment and leeches to encourage healing and blood flow [1, 2].

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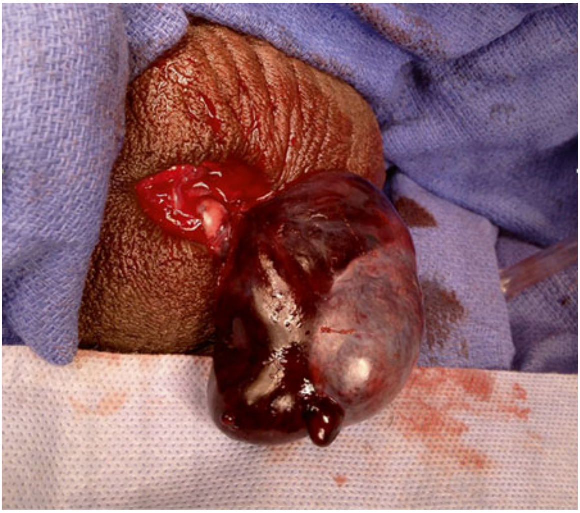

Fig. 16.1. Traumatic amputation of the penis.

## *Zipper Injury*

Zipper injury is most commonly encountered in the adolescent and adult inebriated population. Before manipulation, lubrication and a penile block should be administered. A single attempt at unzipping the retained skin should be performed before further intervention. Cutting the cloth in between each of the zipper teeth may release the entrapped portion of the penis. Using a bone cutter to sever the median bar of the zipper may also allow for release [1].

## *Constricting Devices*

The most common causes for strangulation injury are hair, rubber band, and string-related constriction. As the majority of cases are seen in children, child abuse should always be considered. In the adult population, strangulation is often a result of sexual practices. Patients will typically present with penile edema and voiding symptoms from an either visible or non-visible source (i.e., hair). Presentation may be delayed due to patient embarrassment. Initial management should be aimed at decompression of the penis. Adequate lubrication should be administered before attempted direct removal of the constricting device. A distal tourniquet or glandular puncture can be utilized in an attempt to decrease swelling. Consider suprapubic tube placement if the patient is unable to void for an extended period of time. Plastic and nonmetal devices can be excised with a scalpel or cast saw. Removal of metal objects may require the use of industrial-strength equipment with the patient under anesthesia. Prolonged constriction may lead to skin necrosis requiring possible reconstruction with skin grafts [1].

## *Penetrating Injuries*

Gunshot wounds account for most penetrating injuries to the penis. Up to 80 % of cases present in the context of major injury to surrounding structures such as the abdomen, pelvis, and lower extremity [3]. Potentially fatal injuries must be searched for and treated prior to exploration of the genitalia. Almost all penetrating penile injuries require surgical exploration. Immediate management often leads to an excellent prognosis. Exploration with extensive irrigation, removal of foreign material, and debridement of necrotic tissue with added antibiotic prophylaxis can lead to good functional and cosmetic results. The most common approach is through a circumcising incision in which the penis is degloved to provide optimal exposure [4]. Absorbable sutures are used to repair injuries to the corpora. Nonviable tissue is removed, the tunica albuginea is closed tightly, and the overlying skin is then loosely closed. An artificial erection can be used to detect any penile curvature that may result from the repair of a corporal injury. Plication techniques can then be used to straighten the erect penis. Other potential complications include sexual and voiding dysfunction.

Up to 50 % of penile gunshot wounds will have associated urethral injury [4]. Blood at the meatus, voiding difficulty, or obvious injury near the urethra are indications that retrograde urethrography and/or intraoperative cystoscopy should be performed to evaluate for urethral injury. Absence of blood at the meatus can be misleading, and urethral damage may still be present. In the setting of urethral injury, primary closure is possible via standard urethroplasty with great functional outcomes. In cases of more extensive injury, suprapubic catheter placement and staged urethroplasty may be necessary [1].

## *Testicular Trauma*

The testes are subject to both blunt and penetrating trauma. Blunt trauma is more common and is most often related to sports injury, motor vehicle accidents, and assault. Penetrating trauma can result in bilateral

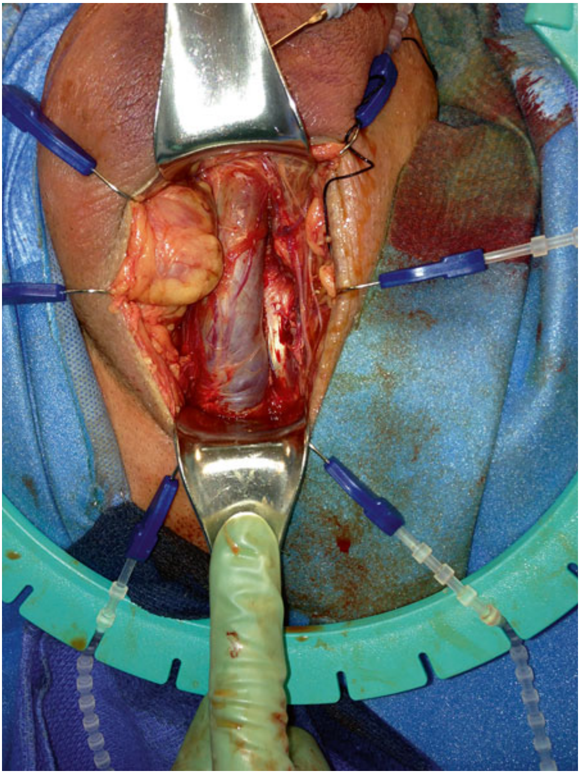

Fig. 16.2. Penetrating trauma to the scrotum.

injury involving adjacent structures which typically requires surgical exploration (Fig. 16.2). Regardless of suspected bullet trajectory or physical findings, both testes should be explored [1].

Differential diagnosis considerations for testicular trauma include hematoma, torsion (Fig. 16.3), fracture, and dislocation. Initial workup of blunt testicular trauma should include physical examination and ultrasound. Although edema and ecchymosis are commonly seen, these findings do not necessarily correlate with the degree of underlying injury to the testicle. Ultrasound can be used to evaluate vascular integrity and for testicular fracture. Heterogeneous echogenicity of the testes is diagnostic of fracture. If ultrasound results are equivocal, surgical exploration should be performed emergently based on physical exam findings alone and should not be delayed. Management is aimed at salvage of viable testicular tissue. Nonviable tissue is debrided and the tunica albuginea is

Fig. 16.3. Testicular torsion.

closed primarily. If the defect is too wide, a free graft of tunica vaginalis can be used [5]. Even in the absence of proven fracture, large intratesticular hematomas and hematoceles should be managed operatively. Drainage of the hematoma has been shown to prevent pressure necrosis and delayed orchiectomy. In addition, 80 % of significant hematoceles are caused by underlying testicular rupture. Delaying surgical exploration and testicular salvage for greater than 3 days significantly increases the morbidity associated with the trauma. Potential complications of conservative nonoperative management include infection, necrosis, chronic pain, and delayed orchiectomy. Ruptured testes that were explored before 72 h have a salvage rate of 90 % compared to 45 % of those explored beyond that window [1].

## Common Surgical Emergencies

Although not necessarily traumatic in origin, both priapism and infections of the external genitalia may require emergent surgical intervention and are therefore worthy of further discussion.

## *Priapism*

Priapism is a full or partial erection that continues more than 4 h beyond sexual stimulation and orgasm or is unrelated to sexual stimulation. There are two types of priapism: ischemic (low-flow) and nonischemic (high-flow, arterial) priapism.

Nonischemic (high-flow) priapism is caused by unregulated cavernous arterial inflow resulting in a non-painful and partially rigid erection which is not associated with hypoxia or acidosis and does not require emergent intervention. Nonischemic priapism is most commonly traumatic in origin, often resulting from a straddle injury or pelvic fracture that leads to disruption of a cavernous artery. High-flow priapism can develop immediately following trauma or days later, and Doppler ultrasound can usually identify a cavernosal artery fistula. Treatment is not an emergency, and approximately 62 % of cases will resolve without intervention.

In contrast to nonischemic priapism, ischemic or low-flow priapism requires emergent surgical intervention aimed at detumescence and the preservation of erectile function. Ischemic priapism is a persistent erection marked by rigidity of the corpora cavernosa and little or no cavernous arterial inflow which results in progressive hypoxia, acidosis, and a painful, fully rigid erection. On examination, both the glans and corpus spongiosum are soft, and the corporal bodies are rigid and tender to palpation. Left untreated, resolution may take days, and interventions beyond 48–72 h may help to relieve pain but will have little benefit in preserving erectile function.

The goal of the immediate workup for priapism is differentiation of ischemic versus nonischemic etiologies. Ischemic and nonischemic subtypes can typically be differentiated on physical examination alone; however, cavernosal blood gas and/or color Doppler ultrasonography is definitive. After having made the presumptive diagnosis of ischemic priapism based on presentation and examination, we obtain a cavernosal blood gas as the first step when beginning cavernosal aspiration and irrigation. Characteristic blood gas findings for both types of priapism are displayed in Table 16.1 [6].

The goal in the immediate management of ischemic priapism is achieving detumescence and preservation of erectile function. While draining the corpora and creating cavernosal-spongiosal shunts can create de novo erectile dysfunction, it is felt that it preserves the corpora by eliminating the acute ischemia and relieving the pain of the priapism.

Table 16.1. Typical blood gas values.

| Source | $PO_2$ (mmHg) | $PCO_2$ (mmHg) | pH |
|---|---|---|---|
| Normal arterial blood (room air) | >90 | <40 | 7.40 |
| Normal mixed venous blood (room air) | 40 | 50 | 7.35 |
| Ischemic priapism (first corporal aspirate) | <30 | >60 | <7.25 |

Montague DK, Jarow J, Broderick GA, et al. AUA guideline on the management of priapism. J Urol 2003;170:1318–24

Thus, the goal is to determine if the priapism could be causing ischemia to the corpora: if it does, surgical intervention of some kind is necessary. Oral systemic therapies (pseudoephedrine) and conservative measures including prostate massage and application of ice packs are not recommended by the AUA guideline panel [7].

Surgical management of priapism typically takes the form of diverting blood from the corpus cavernosum to the corpus spongiosum given that the venous drainage is discrete and separate between these two entities. Creation of a shunt provides an outlet to the trapped blood. Shunts vary from simple bedside procedures to more permanent intraoperative shunts. The most basic is a Winter's shunt, which is simply passing a needle through the glans and extending it through to the corpus cavernosa, effectively shunting the two through a small opening that remains only temporarily patent. A Quackles shunt is an example of a more extreme intervention in which the urethra and the corpora are approached proximally and an anastomosis between the two is created such that blood drains from the corpora into the spongiosum (Fig. 16.4). Such a procedure is permanent, associated with high risk of erectile dysfunction, and requires the resources of an operating room to perform.

## *Penile Fracture*

Penile fracture occurs most commonly where the erect penis is buckled traumatically, often during vigorous sexual intercourse, and the corpus cavernosum is opened (Fig. 16.5). The spongy smooth muscle within the corpus cavernosum can extrude out, cause bleeding within the penis, and cause a large hematoma. The site of rupture can be anywhere along the shaft of the penis, and a history of rapid tumescence and hematoma during the sexual act is typically enough to warrant surgical exploration.

Fig. 16.4. Priapism with proximal approach (Quackles) for corporospongiosal shunt.

In many cases, there is associated urethral injury, so if there is hematuria, a cystoscopy and urethral catheterization would be required. MRI can also make the diagnosis of penile fracture, showing a discontinuity of the tunica albuginea overlying the corpus cavernosum.

Surgically, a circumferential circumcising incision can be made, and the penis degloved such that the tunical laceration can be identified. A scrotal approach can also be taken, where the tunica injury is approached through a lower incision. Once the injury is identified, interrupted closure with Vicryl sutures is carried out, making sure the closure is watertight. A good closure is required to stop the acute bleeding, as well as to ensure that the trapping mechanism for the patient's future erections is still intact.

Immediate versus delayed exploration has been debated, but the most logical approach is to explore by 36 h. With immediate repair, the goal is prevention of future Peyronie's disease and erectile dysfunction by mitigat-

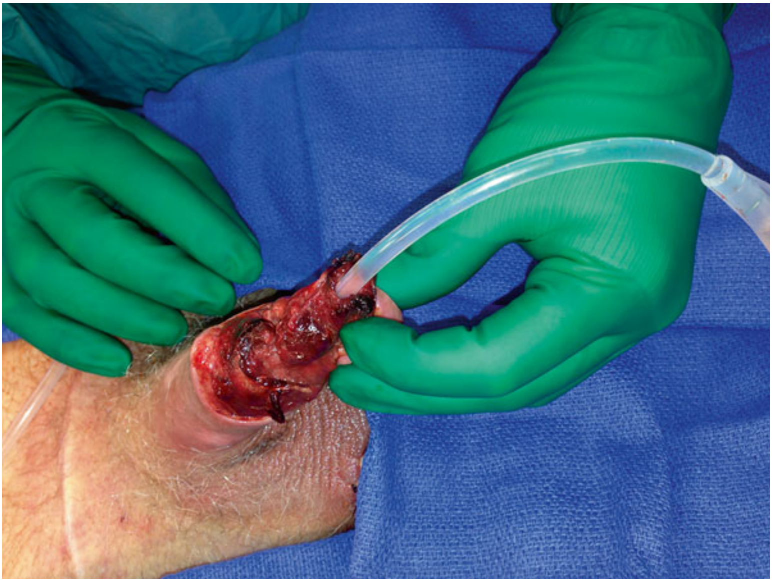

Fig. 16.5. Acute penile fracture.

ing the scar tissue that would invariably form at the site of the tunical injury. The rate of penile curvature with immediate repair is less than 5 %, whereas those with delayed repair experience curvature at a rate of greater than 10 %, with abscess or debilitating plaque in 25–30 % [1].

## *Penile Implant Infections*

Infection associated with a penile implant has classically been managed with complete explantation (Figs. 16.6, 16.7, and 16.8). Attempts at using antibiotics to clear the implant infection have proven futile due to the presence of poorly vascularized scar tissue surrounding the device and the presence of a biofilm which impedes the diffusion of antibiotics. Many bacteria produce a mucopolysaccharide matrix called a biofilm which not only impairs the host's ability to clear infection but also establishes a favorable environment for bacterial growth. Following explantation of an infected device, a minimum of 2 months should be allowed for clearance of infection and healing prior to placing a new implant. Delayed replacement of an implant results in scar formation within the

Fig. 16.6. Infected and eroded penile implant.

Fig. 16.7. Post debridement from penile implant infection.

Fig. 16.8. Erosion of penile implant through urethral meatus.

corporal bodies which can dramatically increase the difficulty of surgery and potentially compromise a successful outcome [8]. Alternatively, a more aggressive approach was described whereby the infected device is removed and a new implant is replaced after a seven-step irrigation and lavage procedure. Success rates of 84 % in achieving infection-free reimplantation were described in a set of 101 patients who underwent this salvage procedure [9]. A middle ground between these two extremes has also been described in which a salvage procedure is performed by replacing the implant with a semirigid device and with the option of reimplantation of an inflatable device in a delayed fashion [10]. Fortunately, the evolution of both preoperative and intraoperative techniques for reducing the risk of infection has significantly reduced the need for aggressive salvage procedures.

Infection associated with placement of a penile prosthesis has become a less common occurrence with the application of certain measures including skin preparation with chlorhexidine-alcohol solution, antimicrobial prophylaxis, "no-touch" techniques, and antibiotic-coated devices. Although required infrequently, salvage procedures have been developed in which the implant is removed and ultimately replaced at the same procedure, providing patients with the possibility of preserving erectile ability.

### *Artificial Urethral Sphincters*

An artificial urethral (or urinary) sphincter (AUS) is a device used to treat male stress urinary incontinence which typically occurs in men who have undergone radical prostatectomy for the treatment of prostate cancer. The AUS device consists of an inflatable cuff that surrounds the proximal urethra and a reservoir that cycles fluid in and out of the cuff so a man can void spontaneously but also remain dry between voids. This device can create a surgical challenge in scenarios where the cuff erodes into the urethra. Erosion may occur due to infection, normal wear and tear of the device, or when one attempts to place a urethral catheter in these patients without deactivating the cuff. One must take care in the trauma setting to obtain a good history and/or examine patients for the possibility of an AUS. If there is one, the sphincter needs to be inactivated with a button on the scrotal pump prior to placement of a urethral catheter. Cystoscopy is required to evaluate whether a device has eroded into the urinary tract. Regardless, erosion of any component of the device requires explantation of the device [11]. Associated urethral injuries can be managed with placement of either a urethral catheter or suprapubic cystostomy tube for urinary drainage.

## Urethral Injuries

### *Catheter-Induced Trauma: Acute and Chronic*

Urethral injury secondary to catheterization can occur in the inpatient or trauma setting via both acute and chronic mechanisms. Acute Foley trauma can occur in any patient in whom a catheter is placed. Due to altered mental status or simply by accident, some patients pull on a catheter or part of the urinary drainage tubing and traumatize the urethra. This can cause severe urethral bleeding and hematuria, especially when the bladder neck or prostate is traumatized. The treatment is typically replacement of the catheter if possible. Cystoscopic guidance may be required to replace the catheter, and, if necessary, cauterization of active bleeding can be performed endoscopically.

Chronic catheters can cause what is described as a traumatic hypospadias in which the urethra erodes due to constant pressure from the catheter. Such erosion occurs on the ventral aspect of the urethra and can extend all the way to the base of the penis if the catheter is left in for a prolonged period of time. Management involves removal of the chronic urethral catheter and placement of a suprapubic (SP) tube. In the patient who is unable to perform self-catheterization and therefore requires chronic catheterization, a suprapubic cystostomy tube is almost always preferable to a urethral catheter. Urinary diversion such as ileal conduit or ileovesicostomy is a better alternative for long-term urinary drainage, as even an SP tube is suboptimal for extended periods of time.

## *Urethral Injury from Pelvic Injuries and Fractures*

The urethra can be disrupted from pelvic injuries, often resulting in a distraction defect of the posterior urethra. Concern for urethral injury based on hematuria, bleeding per urethral meatus, urinary retention, or simply by mechanism of injury should prompt further investigation with a retrograde urethrogram before any attempts at catheterization. There remains controversy regarding the optimal initial management of urethral injuries [12]. Primary realignment over a urethral catheter placed either blindly or with endoscopic guidance is generally considered a reasonable first approach. Endoscopic realignment of the urethra does not appear to compromise the results of formal urethroplasty in the event that such an intervention is required in the future for treatment of severe urethral stricture or a large distraction defect [13]. While scar tissue will almost invariably occur at the site of injury, immediate realignment seems to provide a better chance of long-term urethral integrity at our institution. We have found that development of stricture following primary endoscopic realignment can often be managed endoscopically in the patient who is able to perform intermittent self-catheterization.

Occasionally primary endoscopic realignment of a urethral injury is not feasible. On imaging, the bladder may appear to be completely disconnected from the proximal urethra, resulting in the classic "pie in the sky" bladder. Placement of an SPT can provide urinary drainage, and delayed repair of the injury with urethroplasty can be performed. Alternatively, we have found immediate open repair to be a reasonable approach especially when the patient requires surgical intervention for other injuries. In this situation, a low midline incision is made, the bladder neck identified, and a catheter inserted on the field and placed directly into the open bladder neck. Anastomotic sutures can be placed; however, this is often not possible given poor visualization and the presence of traumatized tissue. Long-term catheterization is required, and a suprapubic catheter is often placed for auxiliary drainage.

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# Part V
# Techniques in Vascular Trauma

# 17. Cervical Vascular Injuries

*Joseph DuBose, M.D.*

## Introduction of the Problem

The complex anatomical relationships within a small area make the diagnosis and management of both penetrating (PNVI) and blunt neck vascular injuries (BNVI) challenging. Radiographic evaluation continues to evolve, with a shift from invasive to noninvasive diagnostics. Despite advances in both diagnosis and therapeutics, the optimal management of neck injuries remains a matter of active investigation.

The epidemiology of penetrating and blunt vascular injuries to the neck is distinctly different. Among penetrating injuries, firearms are responsible for about 43 %, stab wounds for about 40 %, shotguns for about 4 %, and other weapons for about 12 % [1]. Overall, about 35 % of all gunshot wounds (GSWs) and 20 % of stab wounds (SWs) to the neck cause significant injuries, but only 16 % of GSWs and 10 % SWs require surgical therapy. Even though transcervical GSWs cause significant injuries in 73 % of victims, only 21 % require surgery [2].

Blunt vascular injury to the neck follows a distinctly different epidemiology. Although BNVI is common, when cervical spine injuries are excluded, injuries to the remaining structures are rare. Though uncommon, blunt cerebrovascular injuries to the vertebral and carotid arteries can be associated with significant lethality. With increased appreciation and availability of noninvasive diagnostics, the rates of these injuries are now between 1.0 and 2.0 % [3–10].

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## History of Care

Historically, open surgical techniques were utilized for both diagnosis and treatment of cervical vascular injuries. In this context, the division of the cervical region into three anatomical zones facilitated algorithms for evaluation and operative planning (Fig. 17.1). Zone I comprises the area between the clavicles and the cricoid cartilage. Critical structures include the innominate vessels, the origin of the common carotid artery, the subclavian vessels and the vertebral artery, the brachial plexus, the trachea, the esophagus, the apex of the lung, and the thoracic duct. Surgical exposure in zone I can be difficult because of the presence of the clavicle and bony structures of the thoracic inlet. Zone II comprises the area between the cricoid cartilage and the angle of the mandible and contains the carotid and vertebral arteries, internal jugular veins, trachea, and esophagus. This zone is more accessible to clinical exam and surgical exploration than the other zones. Zone III extends between the angle of the mandible and the base of the skull and includes the distal carotid and vertebral arteries and the pharynx. The proximity to the skull base makes zone III structures less amenable to physical exam and difficult to explore. Overall, zone II is the most commonly injured area (47 %) after PNI, followed by zone III (19 %) and I (18 %) [1]. In 16 %, injuries will involve more than one zone [1].

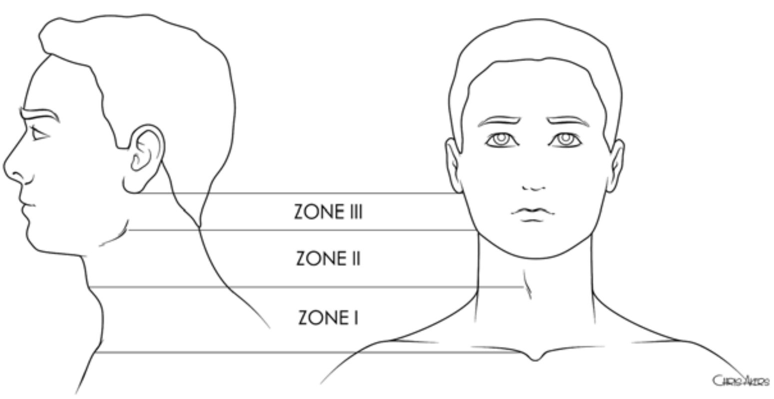


Fig. 17.1. Surgical zones of the neck: zone I is between the clavicle and the cricoid, zone II is between the cricoid and the angle of the mandible, and zone III is between the angle of the mandible and the base of the skull.

Table 17.1. Hard and soft signs of injury after penetrating neck trauma.

| Hard signs of injury | Soft signs of injury |
|---|---|
| Active arterial hemorrhage | Stable hematoma |
| Absent peripheral pulse on affected side | Trajectory |
| Expanding hematoma | Dysphagia |
| Air or saliva from wound | Pulse abnormality on affected side |
| Bruit | Nerve deficit |
| Hemoptysis | |

Using these zone categorizations to guide operative planning, for many years mandatory operation for all patients with penetrating injuries of the neck that violated the platysma was standard. The rationale was that clinical examination was not reliable. In addition, it has been suggested that routine operation avoided expensive investigations and does not prolong hospital stay [11]. Routine surgical exploration is associated with an unacceptably high incidence of unnecessary operations, however, ranging from 30 to 89 % [11, 12]. Improved appreciation of the reliability of physical exam and "hard" and "soft" (Table 17.1) signs of vascular injury, combined with noninvasive diagnostic capabilities that can be utilized to investigate patients with "soft" signs of injury, has resulted in the use of selective nonoperative management at most centers [1, 13, 14].

GSWs are associated with a higher incidence of significant injuries requiring operation than SWs. However, more than 80 % of GSWs to the neck do not require an operation, and there is strong evidence that these patients can be identified and spared an unnecessary operation [1, 13–16].

Transcervical GSWs are associated with a much higher incidence of significant injuries than GSWs that have not crossed the midline (73 % vs. 31 %) [17]. It has been suggested that all such patients undergo exploration, irrespective of clinical exam [18]. However, many of these injuries, such as spinal cord or nerve injuries, do not require operation. In one prospective study of transcervical GSWs, 73 % of patients had injuries to vital structures, but only 21 % required operation [14, 17]. Several studies have demonstrated that CT angio with thin cuts can reliably identify those patients who do not need further investigation or those who might benefit from specific studies [18–23].

## Technique with Personal Tips

### *Operative Management: Carotid Injuries*

The patient is placed in slight Trendelenburg with neck extended and the head rotated away from the side of injury. The patient should be prepped from the chin down to the knees in anticipating the need for a thoracic incision or saphenous vein harvest. The most common incision for exposure of the unilateral carotid artery is a vertical oblique incision made over the anterior border of the sternocleidomastoid muscle (SCM), from the angle of the mandible to the sternoclavicular joint. Retracting the SCM laterally will expose the internal jugular vein, with the carotid artery lying medial and deep to the vein. The vagus nerve is located in the posterior carotid sheath. Division of the facial vein exposes the carotid bifurcation and allows mobilization and control of the internal and external carotids. Simple lacerations of the internal jugular vein or external carotid artery may be repaired, but in most cases veins can be ligated without sequela.

Some zone I injuries may be controlled and repaired through a cervical incision, but proximal zone I injuries may require extension inferiorly into a median sternotomy. Mobilization and superior retraction of the brachiocephalic veins will expose the aortic arch, brachiocephalic artery, and proximal common carotid arteries. Care should be taken to avoid the recurrent laryngeal nerves ascending posterior to the vessels.

Zone III carotid injuries are the most difficult to expose and get distal control. The cervical incision should be extended superiorly into the posterior auricular area and the digastric muscle divided, avoiding injury to the hypoglossal, glossopharyngeal, and facial nerves. Anterior subluxation of the mandible, and further improved by mandibular osteotomy, excision of the styloid process, and removal of the anterior clinoid process improve exposure (Fig. 17.2). Temporary control of uncontrolled zone I or III hemorrhage may be obtained by insertion of an embolectomy catheter through the arterial defect or an arteriotomy and inflation of the balloon.

Most external carotid injuries may be ligated without consequence. Ligation of the common or internal carotid artery can result in devastating neurologic sequelae if collaterals are inadequate. Carotid ligation should be reserved for patients in whom repair is not technically possible,

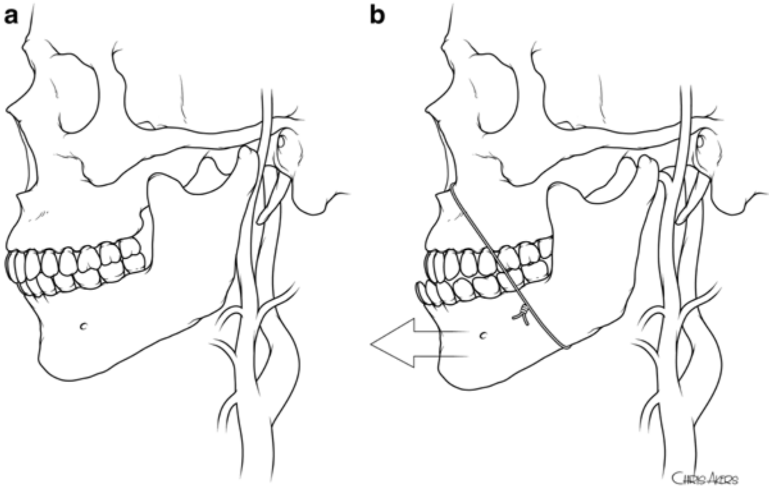


Fig. 17.2. Exposure of zone III carotid injuries.

such as injuries at the base of the skull or patients with an established anemic cerebral infarction. In unstable patients, placement of a temporary intraluminal shunt and delayed reconstruction is an option.

Intravenous heparin should be administered if there are no other sites of hemorrhage or intracranial injury, preferably before clamping the artery. Alternatively, local administration of heparin at the site of injury may be used. Adequate collateral flow may not be present. Use of an intraluminal shunt to provide antegrade flow in complex repairs requiring a graft may be wise. Small lacerations may be primarily repaired using an interrupted or running suture after adequate debridement of wound edges. If primary repair is not possible, then a vein or prosthetic patch plasty of the defect is performed. Clean transections, such as stab wounds, may be repaired by mobilization of the proximal and distal artery and primary end-to-end anastomosis if this can be achieved without stenosis or tension.

Many carotid injuries, particularly from GSWs, are not amenable to primary repair or anastomosis after debridement. Reconstruction with either a vein or prosthetic interposition graft is needed. Saphenous vein is preferred for internal carotid artery reconstruction, with some evidence of

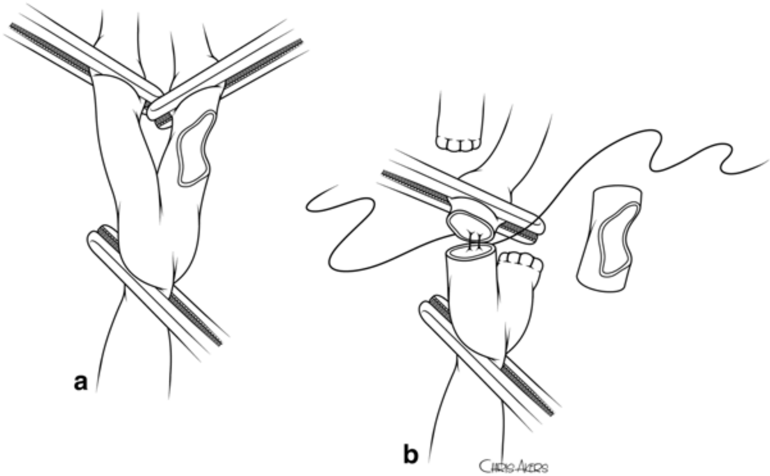


Fig. 17.3. Reconstruction of the proximal internal carotid by transecting the proximal external carotid artery and transposing it to the distal transected internal carotid.

improved patency and lower infection rates compared to prosthetic graft [24, 25]. Alternatively, reconstruction of the proximal internal carotid may be performed by transecting the proximal external carotid artery and transposing it to the distal transected internal carotid (Fig. 17.3).

Common carotid artery injuries are best repaired using a thin-walled polytetrafluoroethylene graft, which has a better size match with the native artery and excellent long-term patency. An intraluminal shunt may be used here as well. If associated injuries to the aerodigestive tract have been repaired, well-vascularized tissue such as a sternocleidomastoid muscle flap should be placed between the repairs [26].

If the injury or dissection extends into the distal internal carotid artery (zone III), exposure and repair are significantly more difficult. Ligation or catheter-assisted thrombosis of the injured vessel should be considered in the asymptomatic patient or if the appropriate expertise is not available to perform distal revascularization. Extracranial to intracranial carotid bypass may be performed but requires significant exposure of the intracranial carotid artery. Alternatively, saphenous vein bypass from the proximal internal carotid to the petrous carotid artery or middle cerebral artery has been reported. This technique avoids intracranial dissection of the carotid artery and has been associated with excellent associated long-term outcome and graft patency [24, 27].

## *Operative Management: Vertebral Arteries*

Operative management is almost always necessary when there is severe active bleeding from the vertebral artery. The head is turned away from the injured site and the neck slightly extended. A generous incision is made on the anterior border of the SCM. The fascia is incised and the SCM retracted laterally. The omohyoid muscle is divided, and the carotid sheath is exposed and retracted, while the midline structures are retracted medially. A tissue plane anterior to the prevertebral muscles is opened, taking care to avoid the ganglia of the cervical sympathetic chain. Next the anterior longitudinal ligament is incised longitudinally. The transverse processes are palpated, and the overlying longus coli and the longissimus capitis muscle should be mobilized laterally with a periosteal elevator. The anterior aspect of the vertebral foramen is then best removed with rongeurs to expose the underlying vertebral artery. The artery can then be ligated. The cervical roots are just behind the artery, and care should be taken not to injure them. Blind clamping or clipping should be avoided. Although the artery can be identified between the transverse processes, this is technically challenging. In addition, the venous plexuses can be troublesome.

Another option for rapid control of the proximal vertebral artery is to approach it at the base of the neck where it comes off the subclavian artery. One method is to extend the incision towards the clavicle and transect the SCM off the clavicle, retract the subclavian vein caudal, and transect or retract the anterior scalene muscle laterally. The first portion of the subclavian artery is medial, and it gives off the vertebral artery, the thyrocervical trunk, and the internal mammary muscle. The vertebral artery comes off the superior dorsal aspect of the ascending subclavian artery. When approaching the left vertebral artery, care should be taken not to injure the thoracic duct. The second method is to cut down directly on the clavicle and open the periosteum. The clavicle can be disarticulated at the sternal boarder and resected with towel clamps as a handle. This can be a rapid way of identifying the artery. Repair of the vertebral artery is extremely difficult and is not usually attempted. The collaterals are usually sufficient to not cause an ischemic stroke. When dealing with an active bleeding vertebral artery and obtaining vascular control is difficult, packing is an option if bleeding can be controlled in this manner [28].

## Outcomes

Many patients with cervical vascular injuries die before reaching a hospital or present to the ED in cardiac arrest. Those surviving to reach the hospital may be completely asymptomatic and have subtle findings or active arterial hemorrhage, neck hematoma, and hemodynamic instability. Associated injuries may mask blunt cerebrovascular injury, but they should be suspected in any patient with a suspicious exam (such as the seatbelt sign—Fig. 17.4) concerning mechanism or neurologic deficits or deterioration not explained by head CT.

Fig. 17.4. “Seatbelt sign” after motor vehicle accident.

It should also be appreciated that a considerable percentage of patients will be initially asymptomatic only to develop symptoms hours to days later, missing the window for intervention. In 1996, Fabian et al. found an average time to diagnosis of 53 h, with a range of 2–672 h [29]. The majority (78 %) developed neurologic deficits prior to diagnosis. After initiating screening criteria, they demonstrated reduced the mean time to diagnosis of 20 h, with 38 % of injuries diagnosed based on the screening criteria alone. Only 34 % of patients developed ischemic symptoms prior to diagnosis [28].

With the advancement of imaging capabilities, it has been suggested that the diagnosis of cervical vascular injury is increasing. While management options for these injuries include observation, anticoagulation, antiplatelet therapy, endovascular stenting, and operation, the natural history of these lesions is not well defined. Biffl et al. [7, 8] have developed a widely used grading scale that can be utilized to both guide therapy and predict outcomes (Table 17.2). These investigators found that grade I injuries healed in the majority of cases with or without anticoagulation. Only 10 % of grade II injuries healed with anticoagulation, with the majority (60 %) progressing to grade III lesions (pseudoaneurysms) on repeat angiography. Almost all grade III lesions (85 %) remained unchanged, with 1 of 13 healing with the use of IV heparin. No grade III lesion healed without treatment.

Endovascular stents were used to treat the majority of persistent grade III lesions, with an 89 % initial success rate. Grade IV injuries (occlusion) remained unchanged despite anticoagulation, but none of the patients treated with heparin developed a stroke. Grade V injuries were uniformly fatal in this series, despite attempts at angiographic embolization in two of the four patients. The authors also suggested categorizing

Table 17.2. Grading scale for cerebrovascular injuries.

| Cerebrovascular injury grades | |
|---|---|
| Grade I | Luminal irregularity or dissection/intraluminal hematoma with <25 % luminal narrowing |
| Grade II | Dissection or intraluminal hematoma of ≥25 % of the lumen |
| Grade IIa | Dissection or intraluminal hematoma of 25–50 % of the lumen |
| Grade IIb | Dissection or intraluminal hematoma of ≥50 % of the lumen or intimal flap |
| Grade III | Pseudoaneurysm |
| Grade IV | Vessel occlusion |
| Grade V | Vessel transection |

arteriovenous or carotid-cavernous fistulae as grade II (insignificant) or grade V (hemodynamically significant).

Angiographic embolization, balloon occlusion or plasty, and stents may be used as a temporizing bridge to surgical repair for definitive treatment. Angiography with possible endovascular intervention should be considered in: (1) hemodynamically stable patients with either physical exam or radiographic evidence of a distal internal carotid artery injury, (2) stable patients with evidence of an arteriovenous or carotid-cavernous sinus fistula, (3) ongoing facial or intraoral hemorrhage from external carotid branches, and (4) small intimal defects or pseudoaneurysms in surgically inaccessible locations or high-risk surgical candidates. Stent/grafts may be particularly useful in patients with posttraumatic false aneurysms, arteriovenous fistulae, or arterial stenosis. Expanding experience with the use of interventional techniques for arterial injury is likely to better elucidate the optimal indications, timing, techniques, and outcomes [30].

There is class III evidence that systemic anticoagulation or antiplatelet therapy improves survival and neurological outcome after blunt carotid injury [28, 29], although anticoagulation may be more effective in carotid dissection than pseudoaneurysms [31]. Some studies, however, failed to show any obvious benefit from systemic heparin [32].

A recent study conducted at our own institution by Stein et al. highlighted the difficulties with any approach to therapy for BCVI as nearly one third of patients were not candidates for therapy [5]. While treatment reduced the risk of infarction, strokes that did occur were not preventable. In the absence of prospective, randomized data regarding treatment, management decisions must be based on the injury pattern, associated injuries, clinical condition of the patient, and currently available literature. The algorithm for our present management approach of blunt cerebrovascular injury at R Adams Cowley Shock Trauma Center is shown in Fig. 17.5.

## Complications with Treatment

Among patients who survive their initial injury, postoperative ischemic events remain the primary concern. For patients who present with or experience stroke in the setting of medical management, optimal response in the setting of coma or dense contralateral neurologic deficits remains controversial. While some earlier reports warned against revascularization in the presence of neurologic deficits due to the concern of

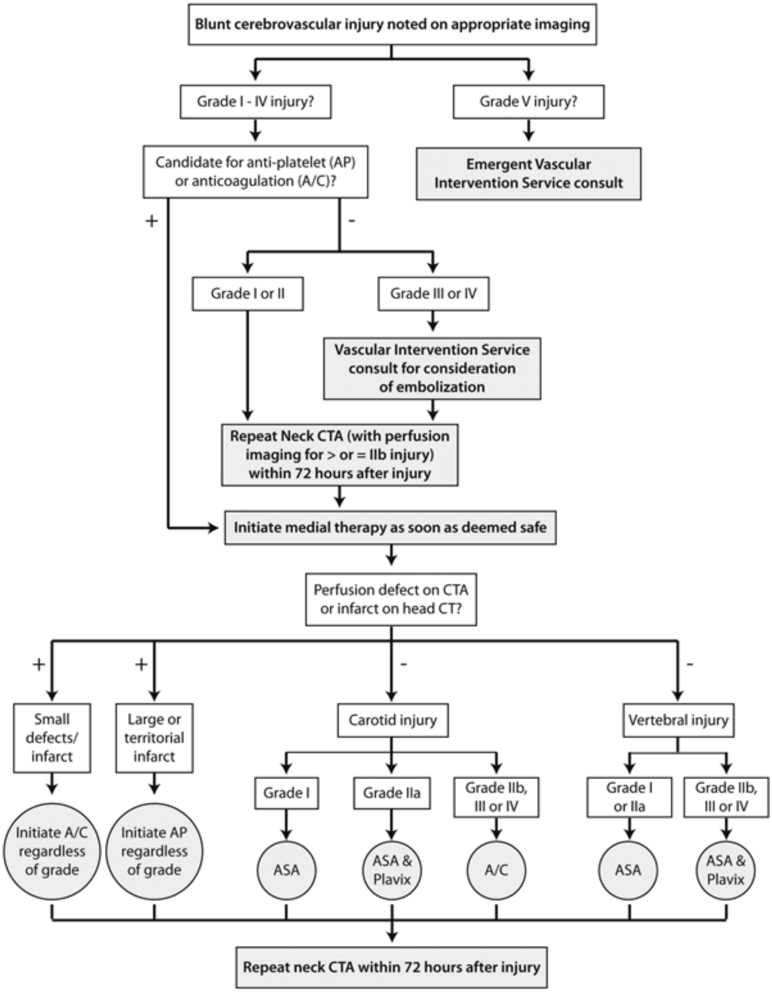


Fig. 17.5. Initial management algorithm for blunt cerebrovascular injury at R Adams Cowley Shock Trauma Center.

converting an ischemic infarct to a hemorrhagic infarct [33], subsequent studies support that the best chance for neurologic improvement is early revascularization [34]. However, patients with coma (>4 h) have an extremely poor prognosis regardless of treatment, and revascularization often exacerbates cerebral edema and intracranial hypertension [35, 36].

Among patients undergoing endovascular or open vascular treatment of cervical neck injuries, concern for postoperative stroke or bleeding complications predominates. Post-repair ischemic events, if diagnosed early, should undergo emergent revision to restore cerebral perfusion. Postoperative hemorrhage due to repair disruption is most commonly due to technical error, but coagulopathy can also contribute to the onset of significant hematoma. Any suggestion of compressive symptoms or airway compromise demands immediate action via the establishment of a secure airway and re-exploration for hematoma evacuation and to address the cause of bleeding directly.

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# 18. Thoracic Vascular Injuries

*James V. O'Connor, M.D., F.A.C.S.*

## Introduction

Thoracic vascular trauma can present a significant clinical challenge. The relative inaccessibility of the vasculature, exsanguinating hemorrhage, and lack operator experience all contribute to the difficulty in treating these infrequent but potentially lethal injuries. Early recognition, appropriate utilization of imaging, and familiarity with surgical exposure and techniques of repair will improve survival. This chapter includes a brief history of thoracic vascular trauma, the evolution of treatment, specific operative techniques, management of surgical complications, and outcomes. Emphasis will be placed on decision making, clinical judgment, and operative techniques.

## History

Although thoracic vascular trauma is not frequent, it is associated with significant mortality. The vast majority of thoracic vascular injuries are the result of penetrating trauma, all intrathoracic vessels are at risk, and the mortality is significant [1–5]. Blunt injuries most often involve the descending thoracic aorta just distal to the left subclavian artery and are also associated with high mortality [6]. Several studies report a prehospital mortality greater than 50 % following penetrating injury [1, 7] and a variable operative mortality ranging from zero to almost 40 % [8]. Parmley's landmark article described the natural history and lethality of blunt aortic injury (BAI) [6]. Unlike penetrating trauma, there have been

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major advances in the treatment and survival of BAI, including thoracic endovascular aortic repair (TEVAR), delayed operative management, and selective nonoperative management. Endovascular techniques have been less frequently employed in the treatment of penetrating vascular injuries. Improved imaging, particularly computed tomographic angiography (CTA), defines the nature, extent, and location of the vascular injury. This information influences the decision regarding nonoperative, endovascular, or open procedure. By characterizing the injury and its location, imaging will influence the choice of incision. Damage control, a widely used technique for selective abdominal and orthopedic injuries, has been successfully applied to both vascular and thoracic trauma.

## Penetrating Vascular Injury

The thorax, especially the mediastinum, contains several large arteries and veins. The aorta and its intrathoracic branches and the innominate, subclavian, and proximal carotids can all be injured from blunt or penetrating injury. Intrathoracic venous structures including the superior and inferior vena cavae and right and left innominate, subclavian, proximal internal jugular, and azygos veins are all at risk. The pulmonary artery and veins may also be injured, especially at the pulmonary hilum.

The vast majority of the thoracic great vessel injuries result from penetrating trauma, and many victims die before reaching definitive care [9]. Patients arriving with suspected great vessel injury demand rapid assessment and evaluation. Not surprising, those presenting in shock generally have a higher mortality, reinforcing its lethality. This subset of patients requires an immediate operation; only stable patients should undergo advanced imaging.

### *Initial Evaluation*

All patients presenting with penetrating thoracic trauma are at risk for great vessel injury and undergo the standard ABCs of trauma care. Vital signs, arterial saturation, and a rapid yet thorough physical exam, with particular attention to external bleeding, expanding hematomas, and upper extremity pulse differential, should be performed. Direct digital pressure should be applied to external bleeding. An absent radial pulse suggests an arterial injury, and an extremity neurologic deficit may be the result of a brachial plexus injury. A FAST examination including abdominal and pericardial views will detect hemoperitoneum and hemopericardium. A portable chest radiograph yields valuable information including hemothorax, pneumothorax, or widened mediastinum. A type and cross match and lactate and arterial blood gas should be included with the admission laboratory tests. With these data the clinician must make a judgment regarding hemodynamic stability, shock, and depth of shock. Hypotension, generally defined as a systolic blood pressure <90 mmHg, is an ominous sign with resultant shock and acidosis. A normal blood pressure on admission may represent a compensated shock state, which should be considered in the presence of tachycardia and a narrow pulse pressure. Lactate and base deficit are excellent markers for the presence and depth of shock.

The initial determination of shock and hemodynamic instability is the crucial first decision in the patient's management. Unstable patients require immediate operative intervention. Additional diagnostic studies and imaging should only be performed in stable patients. This point cannot be overemphasized; penetrating thoracic trauma with hemodynamic instability and shock requires surgery.

Hemodynamically stable patients, however, may benefit from additional imaging. CTA has supplanted angiography as the imaging modality of choice for both blunt and penetrating chest trauma. It defines the nature, extent, and exact location of the injury. Information gleaned influences open versus endovascular approach and, choice of incision if an open repair is indicated. CTA accurately diagnoses penetrating great vessel injuries, altering the operative approach in 25 % of patients [8]. Chest CTA has been shown to be the definite imaging study for penetrating mediastinal injuries, which historically required angiography, bronchoscopy, esophagoscopy, and esophagram to exclude an injury [10]. Blunt aortic injury is also accurately diagnosed with CTA [11].

## *Surgical Approach*

The choice of the incision ("the incision decision") requires sound surgical judgment and is influenced by the patient's hemodynamics. Unlike abdominal exploration, which is almost always performed through a laparotomy incision, there are several surgical approaches to the thorax, each with advantages and disadvantages. Irrespective of the choice of incision, it must provide adequate surgical exposure and be versatile. The thorax can be explored through an anterolateral incision, which can be extended across the midline as a bilateral thoracotomy or

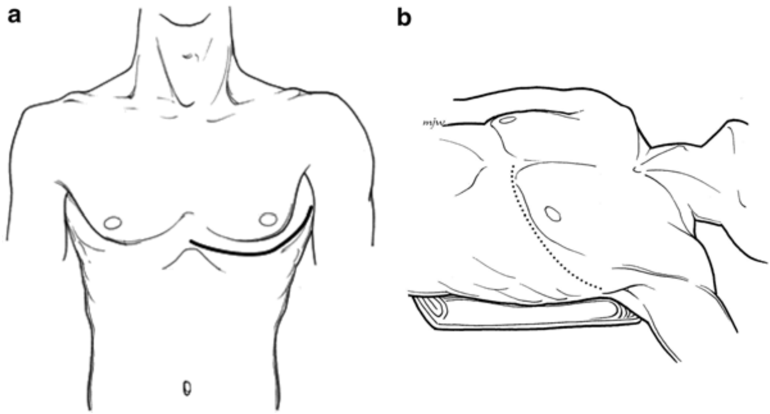


Fig. 18.1. (**a** and **b**) Anterolateral thoracotomy. The bump and extended ipsilateral arm greatly improves exposure of the pleural space. The incision can be extended across the sternum as a bilateral anterolateral thoracotomy ("clamshell").

"clamshell" (Figs. 18.1 and 18.2). This offers several advantages; it is rapid, allows excellent exposure of the anterior mediastinum and pleural spaces, and is an incision familiar to trauma surgeons. With the patient supine, a laparotomy can be easily performed. The disadvantages include inadequate access to posterior structures, and, if a clamshell is performed, the incision across the sternum may be placed too caudal, limiting superior mediastinal exposure. Placing a bump under the back and extending the ipsilateral arm improve exposure. When performing a clamshell thoracotomy, remember to ligate the internal mammary arteries. With profound hypotension they may not initially be bleeding but certainly will once blood pressure is restored.

Median sternotomy is an excellent choice for mediastinal exposure (Fig. 18.3). It is ideal for cardiac and great vessel injury, can be extended for neck or periclavicular exposure, and allows a laparotomy to be easily performed. A surgeon familiar with this incision can rapidly perform it, but less experienced operators may prefer the clamshell approach. As with the anterior lateral incision, sternotomy provides poor visualization of posterior structures. One area of controversy is the approach to the proximal left subclavian artery. While the right subclavian is exposed through a sternotomy with periclavicular extension, the optimal exposure of the left subclavian artery has been debated. Conventional wisdom favors a periclavicular incision coupled with a third or fourth

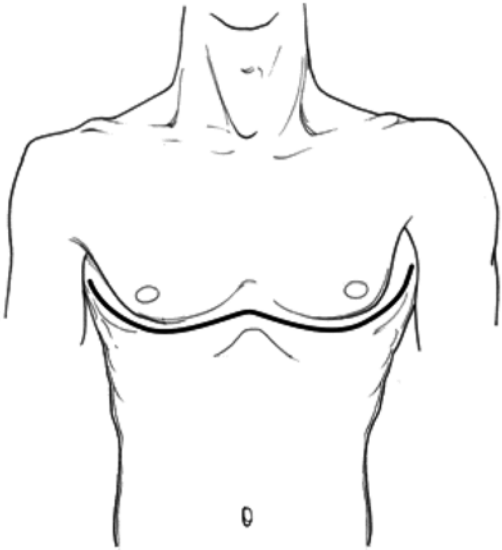

Fig. 18.2. Anterolateral thoracotomy extended as a clamshell. For optimal exposure the sternum must be divided as shown. Placing the incision more inferiorly will transect the xiphoid thereby limiting exposure to the superior mediastinum.

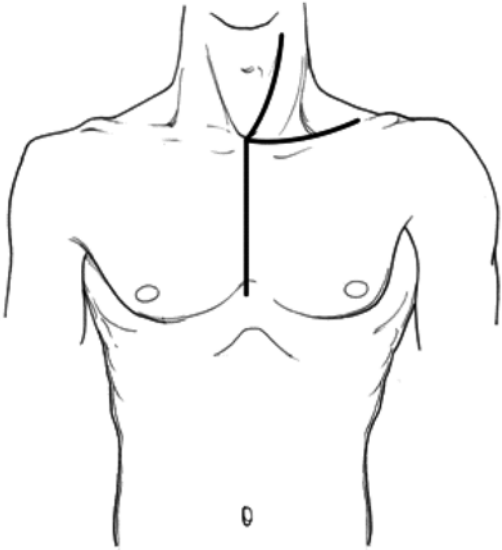

Fig. 18.3. Median sternotomy. It is the ideal approach to the heart and great vessels. This is a versatile incision as it can be extended to the neck or clavicle.

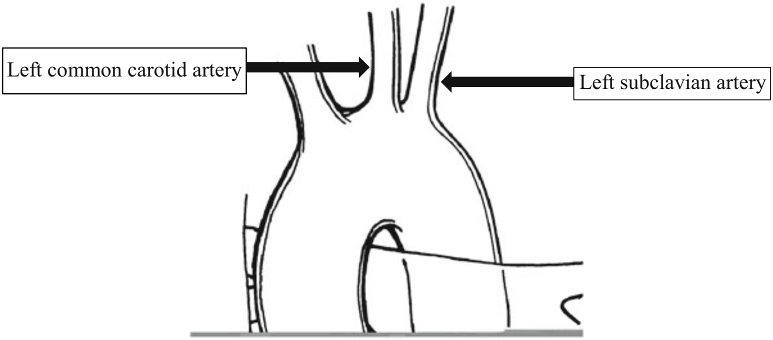


Fig. 18.4. Aortic arch and branches. The left subclavian artery is adjacent to the left common carotid and can be exposed through a sternotomy with left periclavicular extension. This is the authors' preferred approach.

interspace left anterior thoracotomy. This is curious since the operative approach to the proximal left carotid artery is median sternotomy and the left subclavian vessel is adjacent (Fig. 18.4). Combining sternotomy with a left supraclavicular extension provides excellent exposure of the left subclavian artery [12]. We have used this approach exclusively for left subclavian injuries, and clavicular resection is rarely needed [8]. Hemodynamically unstable patients require rapid evaluation, a thoughtful choice of incision and prompt surgical exploration. Anterolateral thoracotomy, clamshell, and sternotomy are all acceptable incisions in the hemodynamically unstable patients [8].

There are more options for surgical exposure in the hemodynamically stable patient with a great vessel injury. As opposed to an emergent operation, which is commonly exploratory in nature, imaging studies will have defined the location and nature of the vascular injury. The operation is performed to repair a definitive injury, thus allowing a more tailored approach. In addition to anterolateral thoracotomy (unilateral or clamshell) and sternotomy, periclavicular, partial sternotomy and posterolateral thoracotomy approaches can be used. The choice of incision depends on the specific injury, and each has its inherent advantages and disadvantages.

A periclavicular incision has the advantage of being rapidly performed and is versatile, as it can be extended to a sternotomy or for a neck exploration (Fig. 18.5). The main disadvantage is limited exposure, and clavicular resection is necessary and may prove more challenging than anticipated, especially for those with limited experience with the technique.

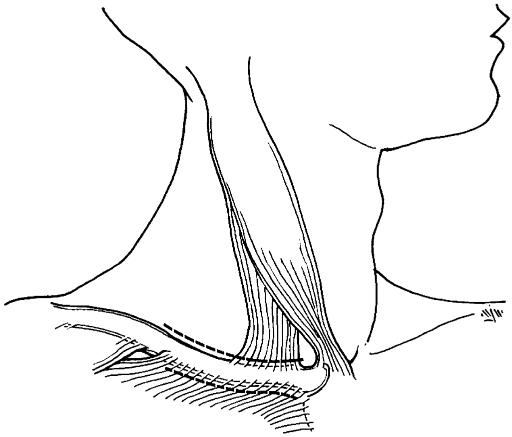

Fig. 18.5. Periclavicular incision. Either supra- or infraclavicular approach can be used. Resecting the clavicle may be challenging and take more time than expected. Unroofing a hematoma with proximal control can be problematic.

Posterolateral thoracotomy allows excellent visualization of the pleural space with the exception of the anterior mediastinum and is the preferred incision for elective thoracic surgery (Fig. 18.6). Disadvantages, in addition to the limited anterior exposure, include lack of versatility. Also hypotension may be exacerbated with lateral positioning. Single-lung ventilation will allow for excellent visualization of the pleural space. In stable patients partial sternotomy is an attractive option for superior mediastinal exposure (Fig. 18.7). The manubrium is divided in the midline from the sternal notch passed the angle of Louis. It is carried laterally as a “T” of “J” and a small sternal retractor (pediatric sternal retractors work well) is placed. It affords excellent exposure of superior mediastinum and is versatile, as it can be extended to the neck and clavicle or continued as a full sternotomy. The ultimate choice of incision for exploring the hemodynamically stable patient will depend on the location of the injury, experience, and surgical judgment.

## *Intraoperative Management*

Operative management of intrathoracic vascular trauma depends on the specific vessel injured and the patient’s clinical condition. Damage control is an attractive option in the hypotensive, acidotic, hypothermic,

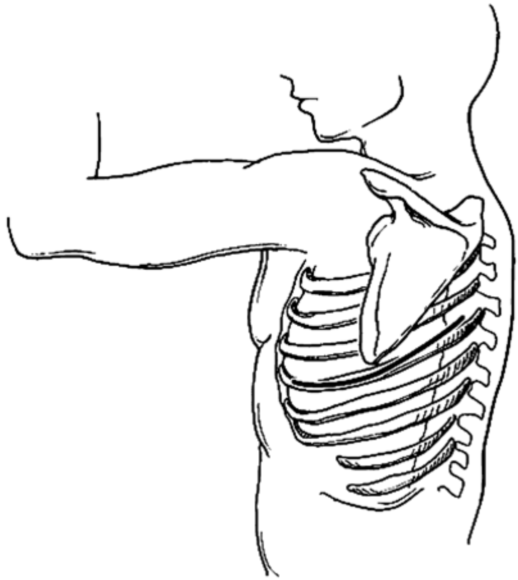

Fig. 18.6. A posterolateral approach is preferred for elective thoracic operations. Limited exposure of the anterior mediastinum and lack of versatility are its disadvantages. Exposure of the hemithorax is greatly improved with double lumen tube and lung isolation.

and coagulopathic patient. Hemorrhage is controlled, the thorax is packed, and resuscitation continues in the ICU. Following restoration of normal physiology, planned re-exploration and closure can be performed [13]. Proximal and distal vessel control is a fundamental tenant of vascular surgery; the previous section discussed the various operative approaches to accomplish this. With the expanding role of catheter-based therapy, a sophisticated option is proximal balloon occlusion. This is an excellent, though underutilized, technique to achieve inflow control without extensive dissection in a challenging anatomic location. Its role will expand as catheter-based therapies gain more popularity.

Although thoracic venous injuries may be repaired, it can be time consuming, often results in venous thrombosis and possible embolization. With the crucial exception of the superior and inferior vena cavae, which are repaired without lumen compromise, thoracic veins can be ligated with little clinical consequence. If ligation is performed, indwelling venous catheters must be removed prior to venous ligation.

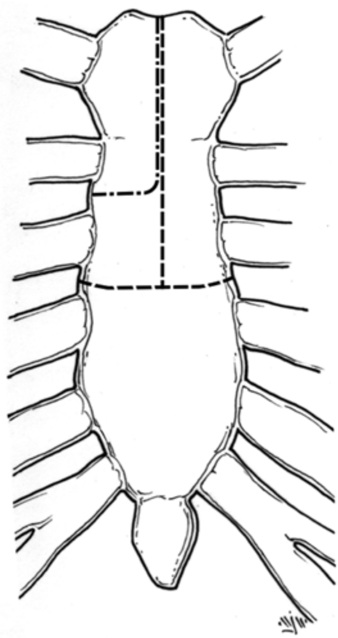

Fig. 18.7. Partial sternotomy. This is an attractive option in stable patients. Carrying the sternotomy distal to the angle of Louis generally provides excellent exposure to the superior mediastinum. Either a "T" or "J" lateral division of the sternum can be utilized. This incision is versatile as it can be extended to the neck and clavicle or continued as a full median sternotomy.

Facial or extremity edema is the sequela of venous ligation, which is managed by elevation and generally resolves within days.

With few exceptions arterial injuries should be repaired, with ligation only performed as life-saving measure for uncontrollable ensanguining hemorrhage. There are multiple options for arterial repair, and the trauma surgeon should be familiar with all of them. They include primary repair, patch angioplasty, graft interposition, and temporary shunting with delayed repair. Stab wounds can often be repaired primarily, with or without resection as indicated. Patch angioplasty can be accomplished with autologous vein or prosthetic material. Gunshot wounds result in significant tissue injury and generally necessitate resection and end-to-end interposition graft. Contrary to the use of bypass grafting for diffuse atherosclerotic disease, penetrating injuries are localized and amenable to graft interposition. Either autologous vein or prosthetic graft can be used. Size match and wound contamination will influence the choice of conduit. Vein is the preferred conduit in a grossly contaminated wound or if the graft traverses a joint.

The principles of damage control surgery have been successfully applied to vascular trauma [14]. Performing an arterial reconstruction in the face of profound acidosis, hypothermia, and coagulopathy may be ill advised. The alternative approach is placing a temporary vascular shunt, physiologic resuscitation in the intensive care unit, and a delayed definitive arterial reconstruction. Once physiologic depletion has been corrected, a planned vascular repair can be performed.

Preoperative planning, adherence to established principles, and a precisely performed technical repair are all crucial to a successful outcome. Patients should be widely prepped and draped, including the torso and extremities for vein harvesting. As discussed in the previous section, the choice of incision is extremely important. Vascular control is obtained directly or using proximal balloon occlusion. Once the injury is isolated, devitalized tissue is excised; this is particularly important when treating gunshot wounds. Visualizing normal intima is imperative; a repair to damaged intima will fail. Next, inflow and back-bleeding must be assessed, and, if inadequate, a thrombectomy should be performed. Since most individuals with penetrating trauma are young, inadequate inflow cannot be the result of atherosclerotic lesions, and a proximal thrombus must be sought. Back-bleeding may be more difficult to assess, and if poor a thrombectomy should be performed. If back-bleeding is still inadequate, an intraoperative angiogram will define the distal anatomy. Performing the angiogram at this stage will assist in planning the remainder of the operation. If the distal vessels are patent, poor retrograde flow is secondary to the lack of collateral vessels, and arterial reconstruction may proceed. If, however, the distal vessels are occluded, additional procedures, such as distal vessel exploration and thrombectomy, are warranted. Whichever technique is chosen for arterial repair, it is imperative that the anastomosis be tension free. At the conclusion of the arterial repair, vessel patency must be confirmed. While interrogation with a Doppler is often performed, the presence of a palpable distal pulse will confirm a patent vessel. An absent palpable pulse should prompt an intraoperative angiogram and, if abnormal, will allow for the rapid correction of any technical problem. It is often stated that following arterial reconstruction one should leave the operating room with "a pulse or a picture."

The role of anticoagulation in the management of vascular trauma is debated, particularly among those with head trauma or blunt mechanism with significant associated injuries. It is preferable to systemically anticoagulate prior to applying vascular clamps. If systemic anticoagulation is contraindicated, flushing the arterial tree with heparinized saline is an option. Systemic anticoagulation is not reversed. Similarly, the role of postoperative antiplatelet agents is not known. It is our practice, if there is no contraindication, to keep the patient on low-dose aspirin for 1 month postoperatively.

The role of endovascular treatment of thoracic vascular trauma is evolving rapidly. Although these techniques are more commonly used in the treatment of blunt injuries, which are discussed below, there is a limited but growing application to penetrating vascular trauma. Pseudoaneurysms, arterial-venous fistulae, occlusion, and transection, resulting from penetrating trauma, have all been successfully treated using endovascular techniques [15]. The advantages are obvious, definitive treatment without thoracotomy or sternotomy, thereby avoiding the associated operative complications. There is, however, attendant morbidity with endovascular therapy; the two most common are endoleaks and insertion site vascular complications. These will be discussed in more detail below. It can be anticipated that the role of endovascular therapies in the treatment of penetrating vascular injuries will expand as devices improve and more experience is gained using this modality.

## Personal Tips for Specific Vascular Injuries

The intercostal arteries are commonly injured arteries with penetrating trauma. Surgery to control hemorrhage from intercostal injury is the most common indication for thoracotomy following penetrating injury. The intercostal vascular bundle runs on the inferior border of the rib. Thus, it may be hard to isolate and ligate them. Our preferred method to control these is placing a suture, usually 0 or #1 Vicryl suture, around the rib and reenter the chest at the top of the lower rib, similar to a pericostal suture for chest closure. When the suture is tied down, the intercostal artery and vein are cinched up against the rib and ligated. It is important to ligate both proximally and distally from the point of injury, as the distal may bleed from collaterals if not ligated. If this is difficult, exposure may be enhanced by simply opening the entrance wound and dissecting down onto the chest wall. The suture can be passed from the chest out into the wound and then back again into the chest with a greater degree of accuracy. If hemostasis is being attempted using a thoracoscopic approach, using a suture passer can be helpful to occlude the intercostal artery. We prefer using the orthopedic passer. Intercostal artery injuries located posteriorly may be exceedingly difficult to control. The rib space is narrow, and the entire area posteriorly is difficult to approach from an anterior exposure. In that case, temporizing and attempting angiographic embolization may be helpful. Finally, bleeding from an intercostal artery may stop when compressed following placement of a chest or sternal retractor. Removing the retractor and establishing exposure using hand held retractors is a very helpful technique, which allows visualization of the bleeding vessel.

Internal mammary arteries are also under systemic pressure and bleed accordingly. One of the most common reasons internal mammary arteries bleed is they are divided during a clamshell thoracotomy. As these patients are often in extremis, the internal mammary arteries may not bleed with arterial pressure. If resuscitation is successful, these arteries can bleed impressively as do the intercostals. Bleeding from the internal mammary may be minimized by placement of a sternal retractor. It is important to exam these with the retractor removed. As with the intercostals, treatment for a mammary artery is ligation.

Bleeding from the large mediastinal arteries can produce exsanguinating hemorrhage. Regardless of the exposure used, control can be difficult. Initial control with digital pressure can be very helpful until formal control can be obtained. A side biting vascular clamp may also be helpful, in temporarily controlling arterial hemorrhage until the vessels can be dissected free. The innominate and right subclavian arteries are best exposed through a sternotomy with clavicular extension if necessary. It is important to maintain flow via the right carotid artery, if at all possible, during dissection to avoid cerebral hypoperfusion. Injuries to the pulmonary artery and pulmonary vein are fortunately relatively rare, but the bleeding is impressive. Because the pulmonary circuit is a low pressure system, hemorrhage from the pulmonary artery acts more like bleeding from a major vein. There is limited muscle in the wall. Thus, neither of these vessels develop vasospasm. Several of the techniques mentioned in the vascular chapter can be helpful. In particular, injuries to the side of these vessels can often be controlled with intestinal Allis clamps. The clamps can be used to control hemorrhage from the injury without occluding the pulmonary artery or vein. The injury can then be repaired under the clamps. Inflow control for pulmonary artery or venous injuries may be expedited by opening the pericardium. Controlling the vessels within the pericardium allows the surgeon to gain inflow control without attempting to expose the area of injury.

# Blunt Vascular Injury

One area which has seen a dramatic change in both diagnosis and management is blunt aortic injury (BAI). Historically this highly lethal injury was suspected by mechanism, such as a motor vehicle collision with rapid horizontal deceleration, and a wide mediastinum on plain chest radiograph, and the diagnosis confirmed by aortography. Except in special circumstances, such as associated severe head injury, the treatment was operative repair with cardiopulmonary support or without cardiopulmonary using the "clamp and sew" technique.

In the current era, CTA is the screening modality of choice, and a more selective management is warranted. Options include medical management without operative intervention, delayed intervention, and the use of thoracic endovascular aortic repair (TEVAR) and open repair. This shift in practice is dramatically demonstrated by two studies, a decade apart, from the American Association for the Surgery of Trauma (AAST). In the first study published in 1997, no patient had a TEVAR, 65 % had repair performed with cardiopulmonary support, and the remainder had the "clamp and sew" technique. Overall morality was 31 % with a paraplegia rate of 8.7 % [16]. The second AAST report in 2008 revealed a dramatic change in practice. Almost two-thirds of patients had TEVAR; the remainder were managed by open repair, and of those, 80 % were performed with cardiopulmonary bypass support. Mortality and paraplegia were 13 % and 1.6 %, respectively [17]. While these data are encouraging, long-term data on TEVAR are lacking. This is particularly pertinent in the trauma population, as many patients undergoing TEVAR are young and the long-term durability of the endograft is unknown.

The evaluation, management, and operative therapy for BAI will be thoroughly addressed in Chap. 19. In brief, the landmark study by Parmley defined the lethality of BAI [6]. Operative management with or without cardiopulmonary support was the accepted treatment. Subsequent studies describing initial medical management for blood pressure and heart rate control followed by delayed aortic repair showed improved outcomes [18]. This concept has expanded to include medical management alone for the management of minimal BAI [19–21]. Determining which injuries can be successful, medical management requires high-grade imaging and sound surgical judgment. Blunt aortic injury in the multiply injured patient presents a challenge as there may be competing priorities. Higher-resolution CT scans now detect small aortic injuries not previously detected with older technology. Grading systems have been developed which guide the clinician [19, 21, 22]. Medical management alone, medical management followed by delayed repair, and urgent or emergent intervention either open or TEVAR are all options. Endovascular repair with TEVAR is the intervention most often used, with open repair reserved for high-grade BAI [17, 18, 21]. The combination of hemodynamics, associated injuries, and CT imaging will help guide a sound clinical decision.

The main concern with medical management is the risk of aortic rupture. In one report, no mortality resulted from the aortic injury but rather was secondary to associated injuries [21]. Complications associated with open repair are those common to any operation. A dreaded complication specific to the procedure is paraplegia, which is decreased when cardiopulmonary bypass or left atrial to femoral bypass is employed. Complications related to TEVAR can be divided into those which are device related, such as endoleaks, and vascular complications related to catheter insertion [19, 21].

While there is a larger experience with endovascular techniques to treat BAI, the same modality has been applied to traumatic injuries to peripheral arteries. Some published reports compare results of endovascular to open treatment [23, 24]. Care must be taken when comparing these non-randomized reports, since there is a selection bias. Unstable patients are more likely to undergo open repair with catheter-based approach used in the stable patient. Alternatively, there are observational studies describing the use of endovascular techniques [15, 25]. The promising results with endovascular therapy and the increasing experienced gained in treating traumatic vascular injuries will lead to an expanded role for this modality.

## Complications

Complications associated with the operative management of thoracic vascular trauma can be divided into those related to any operation and those specific to the individual procedure. Complications related to the former include bleeding, respiratory and renal failure, atelectasis, and urinary tract infection. Persistent chest tube drainage is an indication for re-exploration. Wound infections can be considered as a procedure-specific complication. Multiple sources of chest wall vasculature make thoracotomy infections infrequent and generally managed by local wound care. The management of sternal wound infections and sternal dehiscence depends on the clinical setting. Dehiscence without a sternal infection may not require operative repair unless symptoms persist. Superficial sternal infections, without dehiscence, can be managed by local wound care and antibiotics. Deep sternal infections present a more difficult problem. Reoperation, debridement of nonviable tissue including the sternum, culture-specific antibiotics, and wound care are appropriate. Vacuum-assisted wound care (VAC) has been used with excellent results, either as definitive therapy or as an intermediate step prior to muscle flap coverage [26]. The pectoralis is ideal if muscle flap coverage is needed [27].

Empyema, while infrequent, is a serious complication following thoracotomy. The diagnosis is suspected in the postoperative patient with fever, leukocytosis, a persistent opacity on chest radiograph, and difficulty weaning from the ventilator. Enhancing parietal pleura on chest CT is suggestive of an empyema. The diagnosis is confirmed by thoracentesis and cultures, which guide antibiotic therapy. Interventional catheter-based techniques or decortication with VATS may be useful for early stage empyema. The more advanced organized stages more often require thoracotomy and decortication [28]. Whichever technique is chosen, the principles of complete drainage, decortication, full lung expansion, and appropriate antibiotics are the principles to be followed.

Edema resulting from venous ligation is self-limiting and managed by elevation. Serious complications related to arterial repair include bleeding, which if severe demands re-exploration, and limb ischemia resulting from vessel thrombosis. Frequent vascular checks are essential, and any decrease in pulse should be investigated with an imaging CTA, arterial duplex, or angiography, particularly if a catheter-based therapy is contemplated. An absent pulse and a threatened limb require intervention including lytic therapy, catheter-based therapy, and, more frequently, exploration and revision. Infections involving the vessel conduit can result in life-threatening hemorrhage. Pseudoaneurysm formation and anastomotic dehiscence are the dreaded sequela of infection. Vein grafts are more resistant, but not immune, to infection. Thorough debridement of devitalized tissue, adequate hemostasis, and covering the graft with viable tissue will lessen the chance of infection. Arterial duplex surveillance of the graft will detect a pseudoaneurysm.

In addition to the complications associated with an invasive procedure, catheter-based therapies have specific complications. A comprehensive discussion is found in Chap. 19, with a more limited review here. Endovascular complications may occur during the procedure or post-procedure. Endoleaks and access complications are among the more common morbidities encountered. Endoleaks may be an early or late complication and are classified as Type 1, incomplete proximal or distal sealing of the graft; Type 2, flow from collateral vessels; Type 3, rupture of graft fabric or junctional separation; and Type 4, graft porosity. Access complications are commonly discovered intraoperatively or shortly thereafter and require an open operative repair [29]. Complications should decrease over time as devices become more sophisticated and clinicians gain more experience with this modality.

## Conclusions

Trauma to thoracic vessels presents a formidable challenge. Life-threatening hemorrhage, the relative inaccessibility of the vessels, and difficulty obtaining adequate exposure culminate in a daunting clinical problem. The clinician is faced with several crucial decisions, which have a profound impact on the patient's outcome. First is determining hemodynamically instability and the presence of shock. While the presence of hypotension is an ominous finding, tissue hypoperfusion and shock may occur in its absence. In addition to initial vital signs, serum lactate and base deficit measurements are critically important. Hemodynamic instability or shock should prompt emergent exploration. Only those patients who are stable are suitable for advanced imaging. Once the determination is made for surgical exploration, the next important decision is the optimal incision ("the incision decision"). The surgeon must be familiar with all surgical approaches, their attendant advantages and disadvantages, and, given the clinical situation, choose the appropriate incision. Having obtained appropriate exposure and identifying the vascular trauma, the next decision is the management of the specific injury. Again the surgeon must understand the multiple options available and, in the context of the patient's overall clinical condition, determine which is best. In the patient in extremis, a damage control procedure may be optimal. Additionally, the surgeon must be familiar with endovascular techniques and their indications. Complications will not be infrequent among this patient population. Sound clinical judgment and adherence to fundamental surgical principles will improve survival and decrease morbidity.

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# 19. Endovascular Therapy in Trauma

*Megan L. Brenner and Melanie Hoehn*

## Introduction

The use of interventional procedures in trauma has increased steadily over the past 10 years. An analysis of the National Trauma Data Bank (NTDB) reported that 8.1 % of acute arterial injuries in 2003 were treated with endovascular therapy, compared to only 2.1 % in 1994. Nearly an equal number of blunt (55 %) and penetrating (45 %) injuries were treated with endovascular therapy [1]. A more recent study, also using NTDB data, reported that 16 % of traumatic vascular injuries were treated with endovascular therapy, including 20 % who were hypotensive at the time of intervention. The authors report decreased mortality with the increased use of endovascular intervention [2]. With advancements in both imaging and device technology, the use of endovascular techniques has become part of the treatment algorithm for the injury.

Endovascular therapy in trauma involves a minimally invasive, catheter-based approach. Sheaths, catheters, and guidewires are universal instruments, regardless of procedure. Devices passed over guidewires form the basis of diagnosis and treatment.

## Thoracic Aortic Injury

### *History of Care*

Prior to the endovascular era, care of thoracic aortic injury had been open repair. Early aortic stent grafting was based on treatment of thoracic aortic disease. These devices were not tailored to the younger, disease-free aorta of most trauma patients. As a result, many device-related complications occurred in the early stages of the endovascular era.

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## *Assessment and Operative Technique*

Immediate assessment of the patient with suspected blunt thoracic aortic injury (BTAI) includes imaging studies if hemodynamics allow. Once the diagnosis is confirmed, aggressive beta-blockade is highly recommended in the absence of contraindications. The decision regarding endovascular versus open repair is made largely on the position of the lesion relative to arch vessels. Traditionally, a proximal landing zone of 2 cm was considered acceptable, although newer devices have been used successfully with a proximal neck length of 1.5 cm. Aortic injuries are usually shorter than lesions due to aortic disease, negating the need for a preoperative spinal drain.

Injuries to the thoracic aorta that are within proximity to the major branch vessels present a challenge when the proximal or distal landing zones for the device include the take-off of major branch vessels. Coverage of the left subclavian artery (LSCA) has been routinely performed with minimal morbidity. Close observation is usually sufficient; in the event that symptoms develop and progress, a carotid-subclavian bypass is required. Other situations, such as prior cardiac surgery, may necessitate a bypass procedure prior to stent-graft placement. Careful preoperative assessment of vertebral artery patency, dominance, and flow direction must be performed in the event that the LSCA origin needs to be covered. Intraoperative neuromonitoring can provide immediate information regarding cerebral flow after coverage of the LSCA. Cerebral angiography may also be performed if absolutely needed.

Bilateral femoral artery cutdown or percutaneous cannulation is obtained. Access sheaths for wires, catheters, and sheaths are advanced under fluoroscopy. Pre-procedural planning can significantly decrease the amount of contrast used, particularly in patients with concomitant injuries. If uncertainties regarding the lesion exist with angiography, the intravascular ultrasound (IVUS) is used to more accurately assess the injury, as well as to confirm the proximal landing zone and stent apposition and rule out endoleak.

## *Outcomes*

Thoracic endovascular aortic repair (TEVAR) is currently the most studied endovascular intervention in trauma. The short-term data suggests that aortic stent grafting is comparable to open repair, citing lower rates of paraplegia, blood loss, and complications and shorter hospital stays [3–5]. While many have embraced its use, it suffers from a lack of long-term data. The relationship of the aging stent graft to the aging aorta is unknown.

## *Complications*

Complications of TEVAR include stent collapse and “bird beaking” (the proximal portion of the stent graft does not oppose to the aortic wall) due to size mismatching and/or a small arch radius and may ultimately require additional endovascular or open repair. The American Association for the Surgery of Trauma (AAST) multi-institutional trials have documented the complication rates of TEVAR [3]. Many industry-sponsored multi-institutional trials are currently investigating devices with improved deployment systems and conformability, particularly suitable for small arch radius aortas seen in younger patients. Ongoing trials for branched and fenestrated grafts (Fig. 19.1) will allow devices suitable for coverage across arch vessels to be available if proven safe and effective.

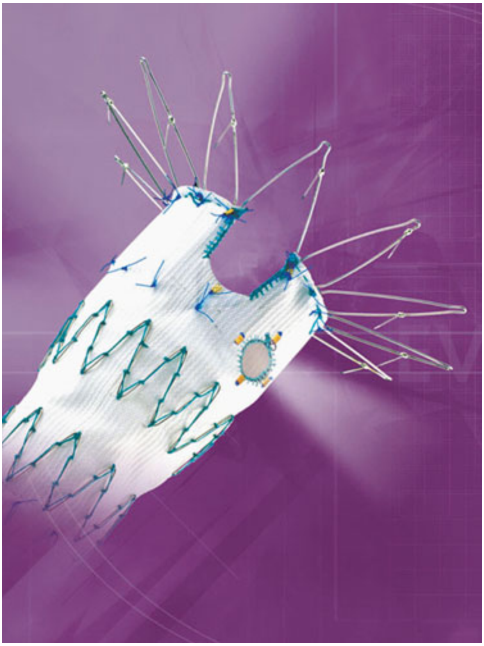

Fig. 19.1. Fenestrated aortic stent graft. For use only in approved trials in the USA.

# Abdominal Aorta

## *Introduction*

Abdominal aortic injury (BAAI) occurs from the biomechanical direct and indirect forces applied to the aorta while it is tethered between the spinal column, the peritoneum, and the abdominal viscera. The most frequent force causing abdominal aorta injury is compressive, associated with deceleration [6]. Indirect forces occur when the aortic wall is directly stretched and compressed against a high-pressure column of blood leading to intimal tears, pseudoaneurysm, rupture, or thrombosis. Atherosclerotic changes of the aorta have been associated with a weakening of the intima in addition to the loss of elasticity and compliance and thus thought to increase the risk of aortic injury [7, 8]. These forces can occur during motor vehicle collisions when the aorta is compressed by the seat belt thus termed "seat belt aorta" [6]. Other mechanisms include long-distance falls from heights, direct compression of the aorta, and penetrating injuries.

The underlying pathologic lesion of BAAI is the disruption of the intima. Depending on the magnitude of force, BAAI presents as a spectrum of disease ranging from a minimal aortic injury (MAI) to free rupture of the aorta. With increasing use of computed tomography angiography (CTA) for diagnosis of BAAI, there have been increasing numbers of MAI diagnosed [9]. Traumatic intimal tears can occur and manifest as intimal flaps or dissection. Furthermore, these can be complicated by thrombosis [10] and acute arterial insufficiency [11–13]. Injuries involving the adventitia lead to pseudoaneurysm formation (Fig. 19.2) or even rupture of the aortic wall. Rupture of the aortic wall can also be due to branch vessel avulsion.

The majority of BAAI occur inferior to the renal arteries. They are classified based on the presence of aortic contour abnormality and presence of free rupture [14]. This classification is based on experience with BTAI [15]. Intimal tears/flaps are not associated with external aortic contour abnormality. A pseudoaneurysm presents as a contained rupture and is clearly associated with an aortic contour abnormality. The most common associated injuries are small bowel injuries (38 %) and thoracolumbar spine injuries (25 %). The most common reported BAAI are intimal tears/flaps (41 %) followed by pseudoaneurysms (29 %) [14].

Fig. 19.2. Traumatic aortic pseudoaneurysm.

## *Assessment*

The initial presentation is dependent on the presence or absence of free rupture of the abdominal aorta, branch vessel avulsion, or concomitant inferior vena cava injury [16]. Those typically present with hemorrhagic shock. In a recent series, all such patients were hemodynamically unstable, and 75 % had cardiac arrest in the emergency department with 38 % receiving an ED thoracotomy [14].

Tamponade is usually associated with retroperitoneal hematoma and allows a temporary period of hemodynamic stability increasing survival [17]. Abdominal wall ecchymosis (seat belt sign) is seen in one-third of the cases of BAAI and should raise suspicion for hollow viscus and aortic injuries [14].

## *Initial Management*

Management of aortic injury varies and risk of mortality rises with the severity of the pathologic lesion. In a recent review of the NTDB of 436 patients with BAAI from 180 centers between 2007 and 2009, 90 % were managed nonoperatively. Of those who underwent operative repair, 69 % underwent endovascular repair, with the remainder undergoing open aortic repair and two extra-anatomic bypasses [18]. In general, cases of BAAI with uncomplicated intimal flaps are managed nonoperatively with beta-blockers and antiplatelet (aspirin) therapy and close follow-up. The natural history in these cases is a decrease in size and complete resolution [19]. Cases of aortic pseudoaneurysm require operative repair to prevent rupture, but this can be managed on a semi-elective basis during the initial hospitalization. Cases complicated by thrombosis, acute arterial insufficiency, and free ruptures require repair. The timing of repair also depends on associated injuries. Patients with pulse and neurologic deficits, an expanding hematoma, and concomitant intra-abdominal injuries require emergent repair. Otherwise, treatment can be individualized in the hemodynamically stable multisystem trauma patient.

## *Operative Techniques*

Endovascular stent placement for BAAI is an attractive alternative for patients with both isolated BAAI and multisystem trauma in a manner similar to that of BTAI (Fig. 19.3). Most of the literature is limited to case reports and small case series where endovascular stents, aortic extension cuffs, and limb extensions have all been used. Indications include cases with associated gross contamination from hollow viscus injury that can jeopardize aortic grafts due to risk of infection or management of injuries difficult to expose by open exploration. Endovascular interventions can be used as a stabilizing measure for critically ill patients and a bridge to open definitive repair.

Abdominal aorta zones of injury can be classified [14] based on feasibility of endovascular approach as follows: Zone I injuries from diaphragmatic hiatus to the superior mesenteric artery (SMA). Zone II injuries are between the SMA and renal arteries. Zone III injuries are inferior to the renal arteries to the aortic bifurcation. Zone I and III injuries are amenable to endovascular repair, whereas Zone II lesions are not

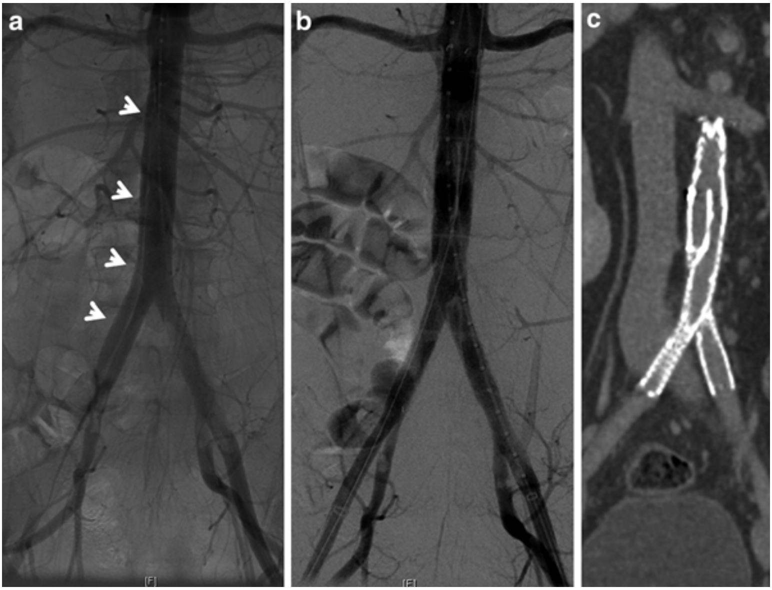


Fig. 19.3. Infrarenal blunt abdominal aortic dissection. (**a**) An intraoperative arteriogram showing the dissection flap (*arrows*) in the infrarenal aorta and extending to the right common iliac artery. (**b**) Arteriogram post-endovascular stent graft placement. (**c**) Coronal view of CT angiography 6 weeks post repair.

without fenestration for the SMA and renal arteries. The timing of the repair is dependent on the patient's hemodynamic status and the presence of acute limb ischemia.

In the abdominal aorta, major injuries near the visceral and renal vessels are not amenable to stent placement. Technologic advancements such as fenestrated (Fig. 19.1) or branched grafts are only used in the USA in trials for elective aortic surgery, but have been used with success in other countries. They may be available in the future for off-label use in the injured aorta. Additionally, the chimney technique, in which the branch vessels are stented along with the aorta, may be an option for select patients. Unfortunately, this technique is time consuming and requires a high degree of experience. Rarely, an aortic injury occurs where the proximal and distal landing zones do not place branch vessels at risk, and a stent is an excellent and minimally invasive treatment option (Fig. 19.4) [20].

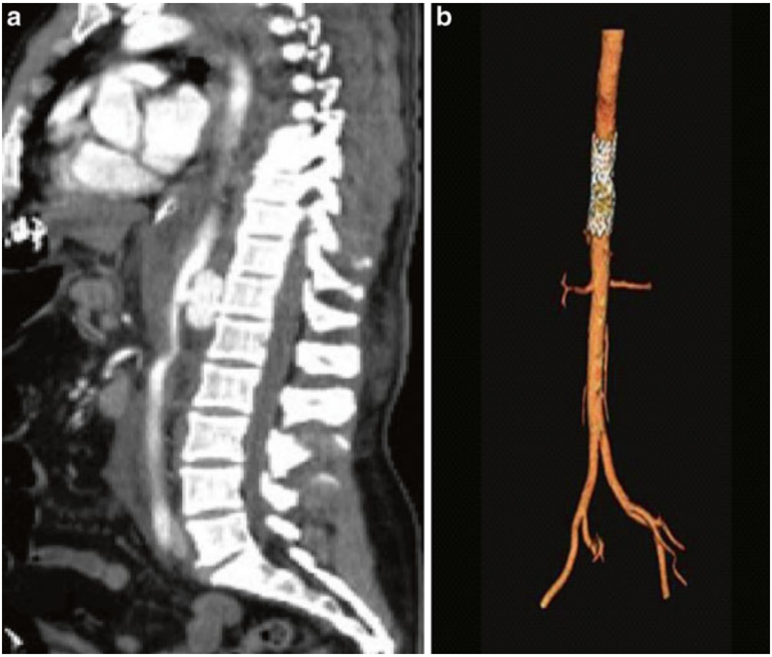


Fig. 19.4. Distal thoracic aortic injury (**a**) repaired with aortic stent graft seen on postoperative CTA with reconstruction (**b**).

## *Outcomes*

BAAI is highly lethal. Among those who survive the transport to the hospital mortality rates range from 32 to 78 % with hemorrhagic shock being the most common cause of mortality [16, 21, 22]. Outcomes in cases requiring a resuscitative thoracotomy remain poor [23, 24]. In BAAI, mortality varies by the type of aortic injury. When minimal aortic injuries, dissections of the aorta, and pseudoaneurysms are included, aggregate mortality is 11 % [14]. In cases treated by endovascular repair, the long-term durability of aortic endografts for abdominal aortic trauma has not been well described. Clearly long-term follow-up will be required in these cases. The ongoing AAST multi-institutional PROOVIT and AORTA trials will provide some answers in the near future.

# Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)

## *History*

The most common cause of death from aortic trauma remains hemorrhagic shock compounded by ongoing coagulopathy; thus, early proximal control of the aorta is a life-saving maneuver [14, 16, 21, 22]. The intra-aortic occlusive balloon placed through an open approach was first described for controlling major aortic hemorrhage in the Korean War [25]. Reports of use for control of bleeding during pelvic surgery [26, 27], hepatobiliary surgery [28], orthopedic surgery [29], postpartum hemorrhage [30], and repair of ruptured AAA [31, 32] suggest that resuscitative endovascular balloon occlusion of the aorta (REBOA) is a life-saving measure. Physiologic parameters such as serum lactate, pH, $pCO_2$, and central, cerebral, and coronary perfusion in animal models of hemorrhagic shock have been shown to improve with the REBOA [33–36]. Descriptions of its use for trauma are few [14, 37–39], but indications include control of noncompressible torso hemorrhage in the abdomen and pelvis.

## *Operative Technique*

The use of REBOA to obtain proximal control at the level of the diaphragm prior to entering the abdomen may have a role in early control of hemorrhage from the injured aorta. Placement of the REBOA can be done expeditiously and would not delay the laparotomy as demonstrated in proximal control of the aorta in cases of ruptured abdominal aortic aneurysms [40]. Currently, indications for REBOA in our institution include persistent hypotension with hemorrhage below the diaphragm and severe pelvic hemorrhage (Fig. 19.5). Contraindications for REBOA include suspected vascular injury above the diaphragm. The technique of REBOA begins with standard cannulation of the common femoral artery approximately 2 cm below the inguinal ligament. Ultrasound utilization is ideal, but landmarks, fluoroscopy, blind placement, or cutdown on the common femoral artery can be utilized. An Amplatz wire is advanced into the catheter to the level approximating the second rib space (measured externally prior to insertion). In the absence of fluoroscopy, an X-ray demonstrating wire position must be obtained to confirm

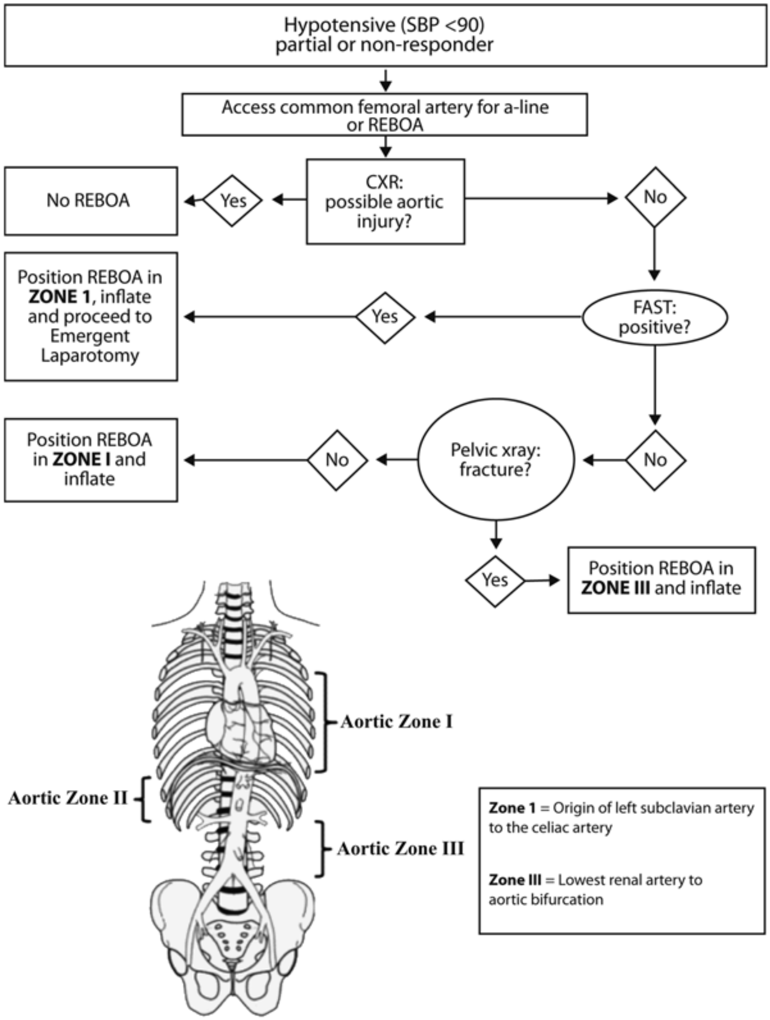


Fig. 19.5. STC clinical algorithm for REBOA.

placement. Marking of the wire at its end point on a draped end table helps to keep wire position during the procedure. The catheter is removed after enlarging the skin incision, and the 12 Fr sheath is inserted to a level approximating the proximal iliac artery (measured externally to the umbilicus). The dilator is removed, and the CODA 32 mm balloon catheter is advanced over the wire to Zone 1 (external landmark: xiphoid) or to Zone 3 (external landmark: above the umbilicus). A 30 cc syringe filled with 10 cc of contrast and 20 cc of normal saline is used to inflate the balloon quickly to a point not beyond high resistance. An X-ray may be obtained to confirm balloon placement. An immediate increase in SBP should be noticed if the REBOA technique is successful. Transportation to definitive treatment can occur with the REBOA in place. Once aortic occlusion is no longer necessary, open repair of the common femoral artery is required. Careful attention should be paid to distal pulses, as any deficit may be due to prolonged cannulation and/or thromboembolism.

Our earliest experience with REBOA in the clinical setting demonstrates this procedure to be a potentially life-saving technique [39]. Currently the procedure uses US Food and Drug Administration (FDA)-approved devices not well suited for the trauma population. Lower-profile devices are in development (Pryor Medical) and will be available in the near future.

## Endovascular Ultrasound

The intravascular ultrasound (IVUS) takes the concept of ultrasound and applies it to a "view from the inside" approach. The miniature ultrasound transducer is mounted on a catheter tip, and the ultrasound beam rotates around the axis of the catheter to give a 360° axial view of the vessel. The IVUS is the most sophisticated diagnostic tool available as it is able to visualize all three vessel layers simultaneously. It can measure lumen diameter to accurately size stent grafts and examine wall thickness, lesion shape, size, and type, as well as the position of the lesion within the vessel lumen. The IVUS can distinguish intimal flaps, dissections, pseudoaneurysms, and transections as well as visualizing blood flow with the color-flow mode (Fig. 19.6). There are no additional risks of using the IVUS if performed as part of angiography, and risks of use without angiography include contrast exposure and access site complications. Several reports in the literature have solidified the utility of IVUS in the diagnosis of vascular trauma by both changing the diagnosis and ruling out injuries previously equivocal on angiogram [41]. Furthermore, a comparison of CT, angiography, and IVUS studies in BTAI reported an unmatched sensitivity and specificity (100 %) of the IVUS compared to all other modalities [9]. The IVUS has been used to place IVC filters at the bedside when IV contrast and/or traveling outside the intensive care unit is unsafe.

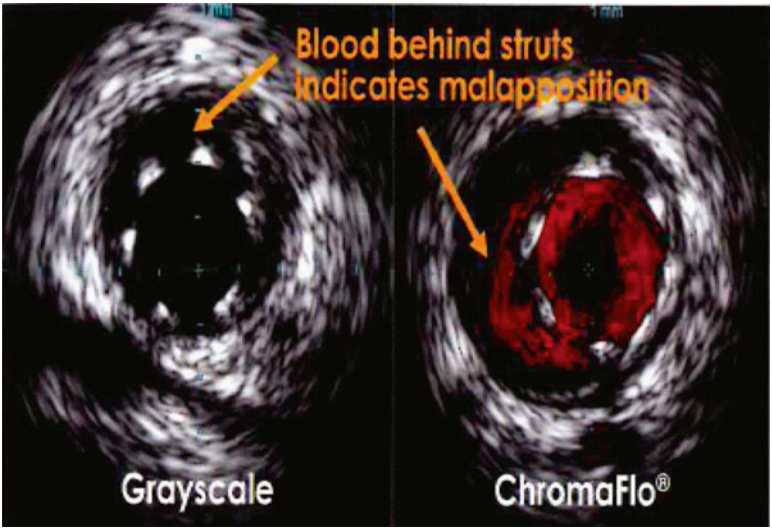


Fig. 19.6. Intravascular ultrasound (IVUS, Volcano Corp) can be used for both diagnosis and treatment, as well as confirmation of stent apposition post deployment.

The IVUS can differentiate chronic from acute injuries, rule out injuries deemed indeterminate by other modalities, and determine candidates for endovascular therapy. The IVUS may be used as a screening tool, for follow-up of minor injuries, or in lieu of CTA or angiogram when contrast is contraindicated.

## Endovascular Damage Control

Hemodynamic instability should not itself necessitate an open operation. The REBOA can be advanced quickly up a guidewire to the aorta or branch vessel to provide proximal vascular control (Fig. 19.7). This can remain in place throughout the operation regardless of whether the repair is performed open or not. The balloon can be deflated, readjusted, and reinflated for optimal positioning, which may change throughout the procedure. A recently published case series from our own institution [39] suggests the life-saving role of REBOA for noncompressible truncal hemorrhage.

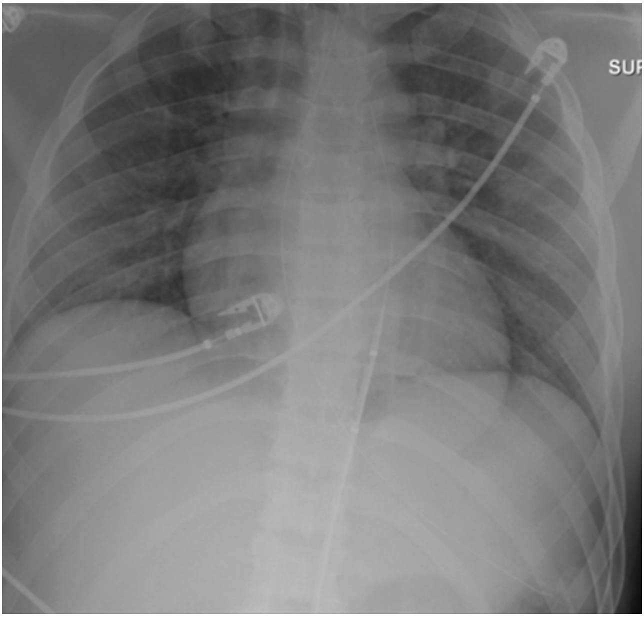


Fig. 19.7. Chest X-ray confirmation of placement of REBOA at Zone I. The CODA balloon is seen inflated at the level of the diaphragm providing proximal aortic control of exsanguinating intra-abdominal hemorrhage.

Angiography may also be used for diagnostic purposes, particularly in the multi-trauma patient whose body habitus or hemodynamic instability prevents travel to the CT scanner. Endovascular control of splenic, hepatic, pelvic, carotid, and intercostal artery injuries has occurred for decades. Technology has advanced from simple coils to gelfoam and plug devices that can be used to stop hemorrhage in these locations. Angiographic embolization has gained tremendous success in the control of hemorrhage in locations such as the pelvis where direct access is problematic.

Endovascular therapy as damage control can also be used as a bridge to open repair. Stent grafts may be used temporarily or permanently to cover partial- or full-thickness injuries, particularly in major vascular injury that cannot be easily or rapidly accessed with surgical exposure. Placing a stent across a full-thickness injury may save the physiologically devastated patient from prolonged illness by decreasing blood loss and ensuing coagulopathy.

# Hybrid Trauma OR

A hybrid trauma operating and angiography suite—where the table itself is amenable to fluoroscopy and the available equipment, devices, and experienced staff are available within minutes and are located only a few feet from the trauma admitting area—allows the team to perform multiple procedures almost simultaneously (e.g., a laparotomy and an extremity angiogram) without change in location or time delay.

A fluoroscopy table, C-arm, monitors, lights, as well as anesthesia, surgical, and endovascular supplies form the basis of the hybrid trauma suite (Fig. 19.8). Additional instruments such as a TEE, RISS, IVUS, as well as bypass and dialysis pumps may be needed. Advancements in c-arm technology have led to the production of a CT/C-arm hybrid machine, the Artis Zeego by Siemens, which combines high-resolution angiography with CT fluoroscopy. This "CT" is not as sensitive as the 64-slice helical CT but can give excellent quality three-dimensional

Fig. 19.8. Trauma hybrid operating room at RA Cowley Shock Trauma Center. Angiography capability is provided by Siemens Artis Zeego system whose C-arm is advanced into the operating field when needed and returns to its stored position away from the table during open procedures.

views to supplement two-dimensional angiography. This allows the team to obtain CT images without travel and additional contrast use and acquires sensitive information such as endoleaks, which are not seen or poorly visualized on angiography.

The technology for a hybrid OR is costly, approximately $3–9 million total for the room and $1.5–5 million for just the fluoroscopic equipment. In addition, the OR staff need to be comfortable with the acquisition, preparation, use, and billing of devices. A competent radiation technologist is essential to help provide images critical to decision making and treatment. Radiation safety should also be practiced with vigilance.

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# Part VI
# Techniques for Bony and Soft Tissue Injury

# 20. Timing of Fracture Fixation

*Robert V. O'Toole, M.D.*

## Introduction of the Problem

The ideal timing for the treatment of fractures remains controversial. In general, earlier treatment of fractures is advantageous because it facilitates mobilization of the patient, decreases the pain and systemic inflammatory response syndrome (SIRS) associated with unstable fractures, and simplifies care by removing splints, traction, and other limitations placed on the patient before surgery. However, this must be balanced with the potential danger of "second hit" fracture surgery that in itself could produce SIRS and poor outcomes.

This chapter attempts to briefly summarize the current state of the literature and one center's typical care for six of the more common orthopedic trauma issues. These six issues are treatment of fractures in the patient with polytrauma (with emphasis on timing of femoral nail insertion), open fractures, compartment syndrome, acetabular fracture surgery, hip fractures (both high energy and geriatrics), and flap coverage of mangled wounds.

## The Patient with Polytrauma: Damage Control Orthopedics (DCO) or Early Total Care (ETC)?

### *History of Care*

During the past decades, substantial changes have occurred in approach to the timing of fracture fixation in patients with polytrauma, as detailed in reviews on the topic from the author's institution [1, 2]. Much of the research has focused on femoral shaft fracture fixation with

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nails, because femoral shaft fractures are independently associated with an increased risk of death after trauma. Treatment involves reaming the intramedullary canal, which intravasates marrow and showers the lungs with embolic contents that potentially increase the chance of developing acute respiratory distress syndrome (ARDS) and other devastating lung outcomes.

In the 1950s, femoral fractures were treated with traction. This resulted in high union rates but poor functional outcomes and mortality. Bone et al. [3] showed that respiratory outcomes improved with early (<24 h) fixation of femoral fractures in patients with Injury Severity Scores >17. The control group consisted of those treated >48 h after injury. Timing had no effect on isolated femoral shaft fractures, and the study, of course, could not comment on treatment at time points between 24 and 48 h. Although early treatment of femoral fractures in patients with polytrauma seemed beneficial, the treatment is potentially harmful to some patients because of SIRS and the insult of marrow contents on the lung [1].

Damage control orthopedics (DCO), a concept first described at the author's institution, strikes a compromise that allows the benefit of early stabilization of fractures with less danger of systemic effects by initially placing an external fixator and converting to a nail later [4]. External fixators have pins that are placed percutaneously into the bone on each side of the fracture and a method to connect these pins with bars that can hold the fracture stable in reasonable alignment. The procedure is quick (typically half an hour or less per fracture) and has almost no associated blood loss. The approach is safe and yields a low infection rate at later time points when the external fixator is converted to an intramedullary nail [5]. Work from our institution also demonstrates that reamed femoral nail insertion is safe for most patients with polytrauma that includes lung injuries [6, 7]. What remains controversial is which patients should be treated with DCO and which with ETC, with which fractures are fixed definitively as early as possible (Fig. 20.1).

## *Technique with Personal Tips*

Our general approach to femoral shaft fracture fixation has yielded good outcomes and a low rate (1.5 %) of ARDS [7] despite a relatively low rate of DCO. Only 13 % of patients with polytrauma that includes femoral fractures receive DCO, and none of the isolated femora are treated in this manner. This success has been achieved at other North American centers [7].

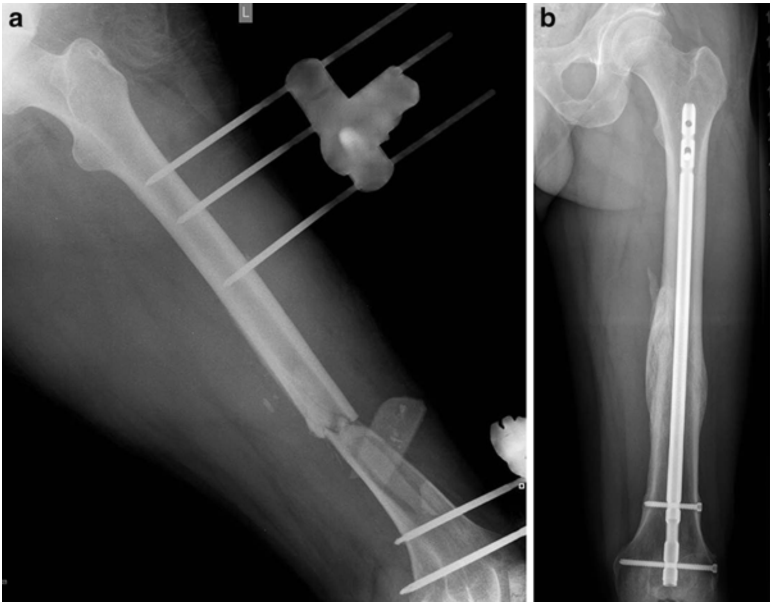


Fig. 20.1. Common clinical question for a patient with polytrauma: Should the patient initially undergo external fixation, (**a**) damage control orthopedics, or definitive reamed intramedullary nail insertion, (**b**) early total care?.

Patients can be grouped into three broad categories: stable, borderline, and unstable. Stable patients should receive early total care (ETC) when possible. Those unstable (or in extremis) should receive DCO. Authors have proposed multiple criteria with which to identify "borderline" patients [8], and debate continues regarding which borderline patients are best served by DCO versus ETC.

At our center, patients receive DCO for three common reasons: (1) ongoing cardiopulmonary distress, (2) traumatic brain injury (TBI), and (3) failure to respond to resuscitation as measured by parameters such as lactate [1]. Patients, on average, undergo fixation approximately 13 h from presentation at the institution [7], and emerging data indicate that fixation within 12 h, particularly for those with abdominal injuries, increases mortality [9]. We think that patients should not be "rushed" to the operating room before adequate resuscitation has been achieved, even recognizing resuscitation continues in the operating room.

There are no firm rules regarding any of these parameters, and careful clinical judgment is needed in evaluating the totality of the patient.

Regarding the cardiopulmonary status of the patient, we argue against placing a nail in any patient who is currently hypotensive or requiring massive transfusion, and we typically would not place a nail in a patient requiring pressors before surgery. Further, although we commonly place reamed nails in patients with lung injuries, we will not do so in the subset of patients with high oxygen requirements on airway pressures indicating poor lung function that might be worsened by nail placement.

Determining which TBI can be treated is complex, and high-level conversation often is required to facilitate initial placement of external fixation to receive the proposed pulmonary benefit of DCO. We use failure to respond to indicate lactate trending toward 2.5 [7, 10], although recent work has shown that a value of 4.0 might be more reasonable [11].

Most work on DCO focuses on femoral shaft fractures, but the general concepts can be extrapolated to other fractures. Patients who are deemed appropriate to receive DCO are treated with external fixation for certain fractures (femoral shaft, mechanically unstable pelvis) and splint fixation for other fractures (humeral shaft, distal radius, closed tibial shaft). Open fractures undergo débridement, and the compartments are released as needed.

Patients with multiple fractures require continuous reevaluation in the operating room to assess whether the original plan for ETC is still safe. We typically develop "break points" in the surgery at which we reevaluate how the patient is doing before continuing. If the patient's status changes, a decision is made to change to DCO. This approach requires thoughtful planning by the orthopedic team regarding the sequence of fracture fixation and close coordination between the orthopedics and anesthesia teams (and possibly consultation with a general surgery team) to ensure the safest approach.

Once the decision to use DCO has been made, the timing of definitive fixation is guided by the rationale for DCO. If the decision was because of TBI or failure to respond to resuscitation, we proceed once resuscitation is complete and/or the TBI stabilizes. For patients who receive DCO because of persistent shock or pulmonary issues, we are more conservative and tend to wait a longer time period. Some argue that the inflammatory cascade resulting from nail insertion is lessened in patients who are treated >5 days after injury [12]; however, we do not strictly adhere to this argument. We prefer to have a patient's respiratory status improved to the level of being near extubation before proceeding with procedures such as femoral nail insertion that might place the lungs at additional risk of damage.

When in doubt, a DCO approach should be used. Although the overuse of DCO leads to unnecessary surgery and likely delays discharge, underuse of DCO could lead to death. For this reason, if the clinician is unsure, we recommend DCO.

### *Outcomes*

Outcome data indicate that our general approach to femoral shaft fractures in patients with polytrauma yields low rates of death (2 %) and ARDS (1.5 %) [7], despite the high-energy nature of the mechanisms of injury in our patient cohort. Several explanations exist for our center's relative improved performance over German studies on the topic [7], and one possibility is differences in ventilator management [13]. Complication rates of late conversion to nails after initial external fixation seem to be low [5]. Other centers have reported good outcomes with similar algorithms for a broader range of fractures, including an "early appropriate care" algorithm for pelvic and acetabular fractures [11].

### *Complications with Treatment*

The dreaded complications associated with the inappropriate timing of fracture fixation in patients with polytrauma are ARDS, SIRS, and death. The severity of the sequelae of errors in this decision heightens the importance of all clinicians being aware of these issues.

DCO is not associated with particular complications except soft tissue issues related to external fixation. Prolonged external fixation of femora does not seem to incur risk of subsequent infection; however, surgeons are hesitant to insert a nail to treat a tibial fracture that has been in an external fixator for more than 2 weeks because of the concern regarding infection.

## Timing of Open Fracture Treatment

### *History of Care*

Open fractures (Fig. 20.2) traditionally were thought to require emergent débridement within 6 h of injury to reduce the risk of osteomyelitis. This "6-hour rule" seems to have been derived largely from guinea pig

Fig. 20.2. Timing of débridement remains controversial, but the 6-h rule for débridement of fractures, even high-energy fractures such as a femoral fracture after an industrial accident, as shown, has not stood the test of time.

studies in abdominal surgery in the 1800s before the advent of antibiotics. Multiple studies and systematic reviews of the literature have failed to establish the validity of this link [14]. Even in high-energy lower extremity fractures thought to be at highest risk of infection, time to the operating room was not predictive of infection risk [15]. Interestingly, time to the definitive treatment center is predictive of infection rates, and Pollak et al. [15] theorized that this time is a marker for time to definitive resuscitation.

## *Technique with Personal Tips*

At our center, we do not rush open fractures to the operating room. Time is allowed for adequate resuscitation before débridement as needed. We almost always treat open fractures within 24 h after injury and more often within 12 h but typically not within 6 h [14, 15].

There is, however, a subset of open fractures that we tend to treat with more emergent débridement. These fractures are the rare high-grade open fractures with gross contamination that typically require multiple débridement procedures. The wounds are so contaminated that every effort should be made to quickly decrease the bacterial load. No data are currently available to support this practice, but we are less inclined to let these fractures wait until the morning.

Attempts at treating all open fractures in a more emergent manner have some potential downsides. Allowing time to pass allows borderline tissue to declare itself better and increases the effectiveness of the initial débridement. Considering that many lower energy fractures are closed definitively, the quality of this initial débridement is likely important. Further, resources needed for emergent treatment of open fractures, which typically occur in the middle of the night, might not be in-house at all trauma centers. Expending resources in an effort that is not clinically indicated is not globally beneficial.

Some patients are so ill or have such concerning TBI that fracture care for more than 24 h is appropriate. Our policy is to maintain antibiotics until the patient is treated. Specific data regarding these rare patients is not available, but evidence that preoperative antibiotics reduce infection rates in open fractures is strong [16], so it is our practice to make every attempt to continue antibiotics at least until débridement can be performed.

## *Outcomes*

The outcomes of fractures that are treated outside the 6-h window from injury seem to be similar to those of fractures treated within that window [14, 15]. No level I studies are available, and none are likely to emerge. Available retrospective studies suffer from selection biases that might skew the results in either direction. A much more powerful predictor of the infection rate is the open fracture grade [17], which shows markedly increasing infection rates as the grade increases from type I to IIIC.

## *Complications with Treatment*

Infection and osteomyelitis potentially result from delayed débridement. Osteomyelitis in the setting of fractures can require many surgical procedures to "cure" the disease, if this is even possible, and results in amputation in some cases. Considering the severity of this complication, for patients who cannot undergo débridement within 24 h after injury, every effort is made to perform débridement as soon as possible.

# Timing of Compartment Syndrome Treatment

## *History of Care*

Although controversy continues regarding the diagnosis of compartment syndrome [18], almost no controversy exists regarding the ideal timing of treatment. Both animal [19–22] and clinical [23, 24] studies support emergent treatment with fasciotomy. The window of time after which outcomes substantially decline is approximately 6–12 h after injury [19–24].

## *Technique with Personal Tips*

Compartment syndrome is a true emergency that should be treated in the operating room as quickly as possible. There is no known or theoretic benefit to delay. The surgery is simple (Fig. 20.3) and can be performed with almost no equipment in any operating room by any well-trained surgeon. The leg is the most common site of compartment syndrome, and the treatment procedure is described in detail in a recent chapter on the topic from this institution [25].

We recommend a two-incision fasciotomy technique that releases all four compartments of the lower leg. One incision is parallel to the fibula but centered approximately 1 cm anterior to it. This wound allows release of both anterior and lateral compartments. The superficial peroneal nerve should be identified and avoided, if possible. The second incision is located 1 cm posterior to the medial border of the tibia and allows release of both the superficial and deep posterior compartments. The posterior border of the tibia should be exposed, which indicates that the deep posterior compartment has been released. Skin incisions typically are at least 20 cm in length.

Two common errors are to make the incisions too small and to fail to release all four compartments. More muscle mass is present proximally in the leg, so adequate proximal releases are particularly important.

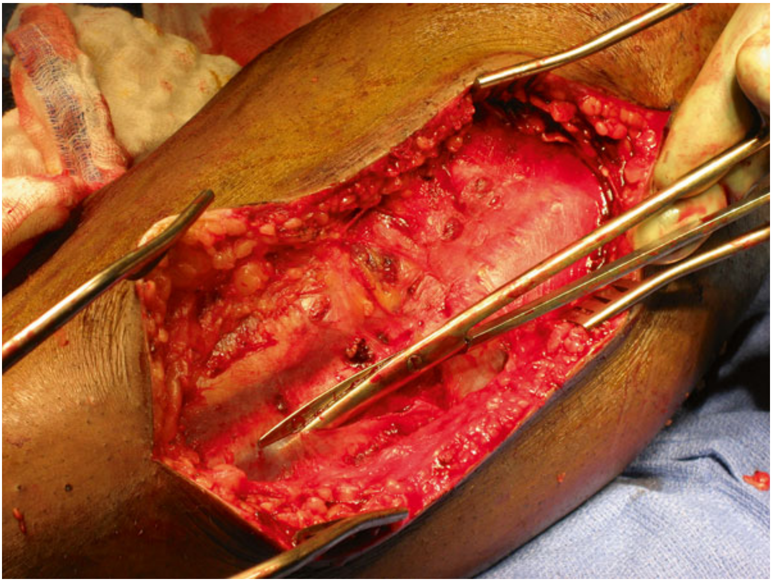

Fig. 20.3. Strong data support that compartment syndrome should be treated with emergent fasciotomy, such as that shown, which is being performed in the anterior and lateral compartment of the leg.

Wounds often are initially managed with vacuum-assisted closure unless there is a concern for hemostasis. The wounds typically are treated with a second look 3 or 4 days later, with attempts at closing the medial wound at each return trip to the operating room. The lateral wound often requires split-thickness skin grafting approximately 1 week after surgery.

## *Outcomes*

Patients who undergo fasciotomy more than 6–12 h after onset of symptoms have significantly worse outcomes ($P<0.05$). Outcomes of delayed treatment or, even worse, missed compartment syndrome can be devastating. Loss of muscle function and foot drop are common. Complete loss of muscle function, renal damage from rhabdomyolysis, and amputation can occur.

### *Complications with Treatment*

Treatment delay leads to poor outcomes, as noted previously. No complications are associated with earlier treatment.

## Timing of Acetabular Fracture Fixation

### *History of Care*

The ideal timing of acetabular fracture fixation is controversial. Delay of treatment beyond 2 weeks from injury is associated with poor hip outcomes and high rates of posttraumatic arthritis [26]. However, it is unclear how early acetabular fractures should be treated. It is thought that bleeding is increased with early treatment, perhaps leading to increased risk of mortality and prolonged stay in the intensive care unit. However, early treatment, analogous to the approach described previously for patients with polytrauma, might get the patient out of bed sooner and reduce the risk of respiratory and other systemic complications.

### *Technique with Personal Tips*

We divide acetabular fractures into "high-risk" and "low-risk" categories in terms of bleeding. Low-risk acetabular fractures include simple fractures that can be fixed relatively quickly with lower blood loss, such as "posterior wall" [27] acetabular fractures (Fig. 20.4a). High-risk acetabular fractures are complex fracture types (e.g., "associated both columns") (Fig. 20.4b, c). Fracture and patient specifics help define risk of bleeding. Earlier treatment is thought to be safe in healthier patients. We delay fixation in older patients who can tolerate blood loss more poorly to allow clot to solidify. Blood loss for complex cases can reach 3,000 mL or more.

Low-risk fractures are treated as soon as the patient has been deemed appropriate for surgery. High-risk fracture patient combinations are delayed 2–3 days in traction. Acetabular fractures are not good "night and weekend" cases because they can require significant resources from surgical and anesthetic teams.

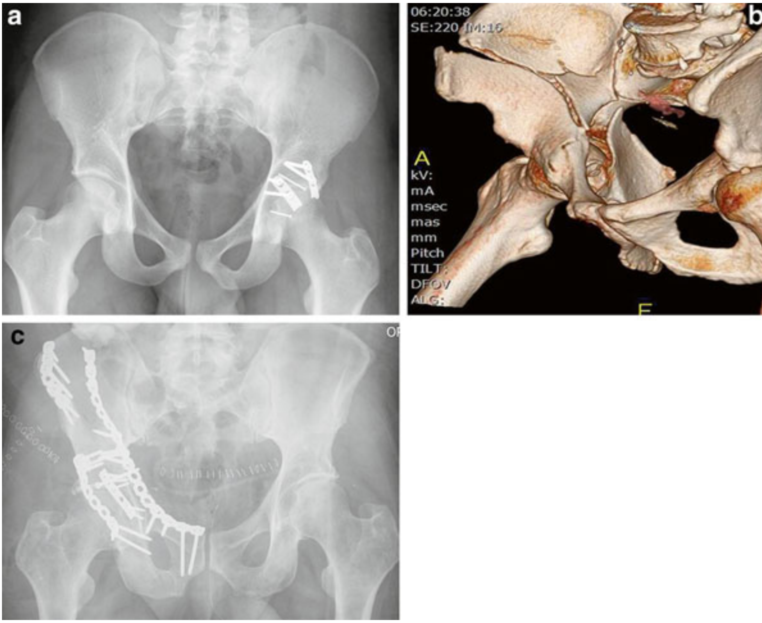


Fig. 20.4. Simple acetabular fractures, such as posterior wall fractures (**a**) in healthy patients, can typically be treated safely with immediate fixation. More complex patterns that require more extensive approaches and surgery should be delayed a few days from injury (**b** and **c**), particularly in elderly patients or other patients who cannot tolerate significant blood loss.

## *Outcomes*

Early treatment of posterior wall fractures seems to be safe and is not associated with clinically important increase in blood loss [27]. Based on anecdotal evidence, early treatment of complex fractures is associated with increased risk of bleeding and is not important in younger patients but is likely important in geriatric or sicker patients. We rarely proceed early with patients who are at high risk of bleeding, thus limiting our ability to assess the danger of early surgery in these patients [28].

## *Complications with Treatment*

When performed too early, surgery can result in increased bleeding. Unnecessary delay can be associated with prolonged bed rest and traction that delays mobilization and discharge.

# Timing of Hip Fracture Fixation

## *History of Care*

### Geriatric Hip Fractures

The timing of hip fracture treatment (Fig. 20.5a, b) is controversial. Geriatric hip fractures dominate this issue. More and more data exist suggesting that delay in fixation beyond 48 h is associated with increased mortality, even when controlling for risk factors for death [29, 30].

### High-Energy Displaced Femoral Neck in the Young

Another issue exists regarding the timing of treatment of displaced intra-articular hip fractures in young patients (Fig. 20.5c, d). Historically, these fractures have been labeled orthopedic emergencies in an effort to reduce the risk of avascular necrosis of the femoral head. The fragile blood supply to the femoral head can become kinked and is not restored until better alignment is obtained. Emergent capsulotomy to reduce hematoma in the hip capsule that might also be compromising blood flow has been advocated.

More recent literature has questioned this rationale, and the literature supporting it is of lower quality [31]. The most consistent predictor of outcome is quality of reduction, and some surgeons argue that a complex case is more likely to have a good radiographic outcome when performed in daylight than in a nonideal setting.

## *Technique with Personal Tips*

### Geriatric Hip Fractures

We proceed with fracture fixation as soon as appropriate. Well-established protocols exist regarding the need for cardiology consult and advanced imaging, such as echocardiography [32–34]. Considering that delay is associated with increased mortality, care should be taken before ordering consults and tests that are unlikely to change care. Many centers have "clearance" protocols to help speed the patients' path to the operating room. Surgery for these patients is not typically performed in the middle of the night, partially because of concern that these sicker patients are better treated when more anesthesia resources are available.

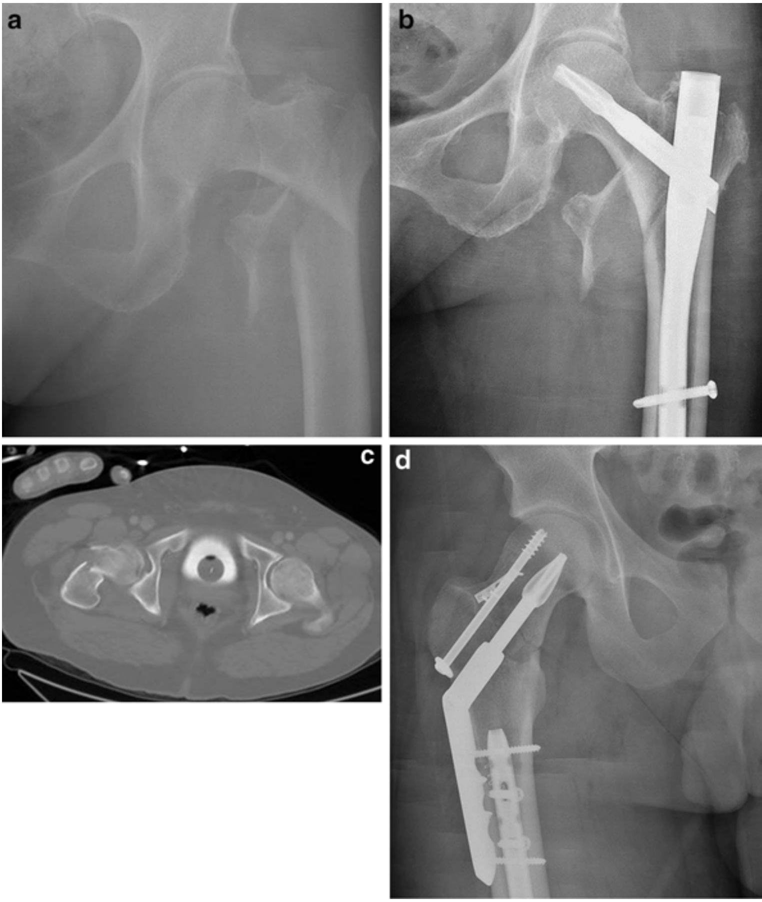


Fig. 20.5. Low-energy geriatric hip fractures (**a**) should be fixed (**b**) within 48 h to limit mortality. Timing of high-energy displaced femoral neck fractures in young patients (**c**) is more controversial, with some surgeons recommending emergent treatment to limit the risk of avascular necrosis of the femoral head and others treating urgently in the light of day to optimize surgical reduction (**d**).

## High-Energy Displaced Femoral Neck in the Young

In general, we tend to proceed with fixation of displaced femoral neck fractures urgently but not emergently. We think accurate reduction is key to outcome, and accurate reduction is less likely to be achieved if this complex multi-hour surgery starts in the middle of the night. This practice is controversial, and surgeons nationally fall on both sides of the issue.

### *Outcomes*

#### Geriatric Hip Fractures

Mortality increases when fracture fixation is delayed beyond 48 h [29, 30]. Surgery is performed to allow early mobilization and decrease the risk of mortality. One-year death rates are still approximately 25 %, so every attempt should be made to proceed to surgery in a reasonable time frame.

#### High-Energy Displaced Femoral Neck in the Young

The link between outcomes and timing of surgery is not clear and remains controversial. The outcome at question is avascular necrosis leading to posttraumatic arthritis requiring a hip replacement in a young patient. This remains an active area of research.

### *Complications with Treatment*

#### Geriatric Hip Fractures

Death is associated with excessive delay of fracture fixation (Fig. 20.5a, b) [29, 30].

#### High-Energy Displaced Femoral Neck in the Young

Controversy exists regarding the link between femoral head necrosis and time to operative fixation (Fig. 20.5c, d).

## Timing of Flap Coverage of Mangled Extremity

### *History of Care*

Infection and complications increase as number of days to flap coverage of open fractures increases (Fig. 20.6) [35–44]. However, the data are flawed with selection bias in that the worse injuries with higher risk of complication are covered late and less severe injuries covered earlier.

Fig. 20.6. Controversy remains regarding the role of timing in the development of complication after flap coverage of a mangled extremity, such as that shown. Recent data indicate that coverage after 7 days might be an independent risk factor for complication such as deep infection.

Few studies have attempted to address the timing issue using statistical methods that control for risk of complication. The first two to do so found no relationship between complication rate and timing of coverage [15, 45]. More recent work from our institution noted markedly increased risk when flap coverage is delayed beyond 7 days after injury, even after controlling for risk factors for infection [46].

## *Technique with Personal Tips*

Every attempt is made to obtain coverage within the first week. This requires close collaboration between the fracture and flap surgeons. Additionally, resources must be made available to the flap service to allow timely coverage.

### *Outcomes*

The link between outcomes and the timing of flap coverage remains controversial. The results from higher-quality studies remain mixed, with some studies showing no link [45, 47] and more recent work from this center showing a relatively profound link between delay and increased complications [46].

### *Complications with Treatment*

The complications that are theorized to occur because of delay beyond the 7-day time frame are deep infections and flap-related complications. These deep infections require multiple surgical procedures and can even lead to amputation. Because this complication is severe and relatively common (our published infection rate in tibiae requiring flaps is 30 %) [46], great interest has been shown in attempting to reduce this complication.

## Timing of Treatment of Pilon, Tibial Plateau, and Calcaneus Fixation

### *History of Care*

Early treatment of high-energy pilon fractures has been associated with high rates of complication, including osteomyelitis and amputation [48]. Protocols for initial external fixation (with or without fibular fixation) and definitive fixation after swelling have resolved in 10–14 days lead to better results [48].

### *Technique with Personal Tips*

High-energy pilon fractures are treated with initial external fixation with or without fibular fixation (Fig. 20.7). Lower-energy pilon fractures with minimal swelling are sometimes treated at presentation because they are more like ankle fractures and likely have less risk of wound breakdown and infection. Open pilon fractures are sometimes treated with limited joint fixation through the open wound with the thought that


Fig. 20.7. Definitive treatment of high-energy pilon (**a**), tibial plateau, and calcaneus fractures is typically delayed by 7–14 days to reduce the risk of infection. Temporary external fixators are used for pilon (**b**) and plateau fractures, whereas a splint is used for calcaneus fractures awaiting definitive surgery.

the wound will not be able to be approached for a considerable amount of time after closure because the wounds tend to be slow healing.

The same approach is used for both calcaneus fractures and high-energy tibial plateau fractures with significant swelling. Calcaneus fractures are initially placed in a well-padded splint, elevated, and operated on 7–14 days later, once swelling has resolved. Many tibial plateau fractures result from low-energy injuries and can be treated at the time of injury. However, the subset of these fractures resulting from high-energy mechanisms typically is initially treated with spanning external fixation and later with definitive fixation (7–14 days later, once swelling has resolved) (Fig. 20.7). Some high-energy fracture types require longer periods for swelling to resolve, which increases the difficulty of the reconstruction.

## *Outcomes*

The timing of operative treatment is thought to affect the complication rate of operative fixation of pilon, tibial plateau, and calcaneus injuries and in particular to reduce the rate of surgical site infection.

Rates in the literature have varied widely. A recently completed prospective study at our center of more than 200 patients with these fractures reported an overall deep infection rate of 11.5 % for the high-energy injuries using the above described protocol, which is within the expected range [49].

## *Complications with Treatment*

Delay in fixation to reduce infection rates has not been reported to be associated with any complications, but concern remains that use of an external fixator could increase risk of surgical site infection by having colonized frames or pin tracts. Our protocol is to either remove the frames completely at the time of surgery or use a standardized preparation protocol that has been shown to have relatively high efficacy in sterilizing the frames [50].

As with other fractures in orthopedics, the complication of surgical site infection worsens patients' outcomes, typically requires multiple débridement procedures with or without device exchange, and substantially increases the cost of care. For this reason, the added cost and inconvenience of delayed fixation is thought to be worthwhile.

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# 21. Treatment of Pelvic Fractures

*Matthew J. Bradley and William C. Chiu*

## Pelvic Fractures

### *Introduction to the Problem*

Significant force is needed to fracture a pelvis. Pelvic fractures can be associated with serious retroperitoneal injuries including vascular, gastrointestinal, and genitourinary trauma. Frequently traumatic brain, intrathoracic, intra-abdominal, and other musculoskeletal injuries accompany pelvic fractures.

Unfortunately, there is no single, straightforward algorithm for managing pelvic fractures. Outcomes depend on good judgment by the surgeon, a firm understanding of the physiology of the injury, and coordination of the appropriate therapies. Knowledge of anatomy and a high index of suspicion are key factors for optimal management. Timely and appropriate decision-making, while not easy, will be lifesaving.

### *History*

As far back as the Civil War, surgeons were conscious of the high morbidity and mortality associated with pelvic fractures [1]. Therapies have evolved primarily by focusing on minimizing and treating pelvic hemorrhage.

A few of these therapies stemmed from military concepts and technology. One such device, the military antishock trousers (MAST), popularized during the Vietnam War, came about from the antigravity suits (G-suits) used in World War II. These suits were worn by pilots to prevent pooling of blood in the lower extremities and thus the loss of consciousness. Like the G-suit, the MAST, or pneumatic antishock garments,

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redistributes blood from the lower extremity and pelvis and into the upper torso while also providing a tamponade effect on pelvic bleeding. The MAST have fallen out of favor due to complications such as abdominal compartment syndrome and pulmonary insufficiency. Additionally, the difficulty associated with deflating and removing the apparatus makes it suboptimal. Subsequently other devices were introduced to assist with compressing pelvic bleeding similar to the MAST. The various pelvic binders now available reduce pelvic volume thereby causing tamponade of potential bleeding. In addition, they are quick to apply and less bulky allowing for complete access to the patient's lower extremities.

First introduced over 40 years ago, catheter-directed angiographic embolization has played a crucial role in the management of pelvic fracture bleeding [2]. As the skill sets, imaging technology, and availability of the interventionalists improved, so has our success with pelvic hemorrhage hemostasis.

Finally, the evolution of fracture care has had a substantial impact on patient outcomes. Timing of definitive internal fixation has been a point of debate with more recent reports suggesting improved outcome with early internal stabilization [3]. However, early internal fixation may not be an option in the severely injured patient with a pelvic fracture. The principles of damage control orthopedics (DCO) originating from our institution over 10 years ago stress early external fixation to rapidly stabilize fractures until the patient recovers from their physiologic insult [4].

## *Fracture Pattern and Classification*

Three main vectors of force, lateral compression (LC), anterior-posterior compression (APC), and vertical shear (VS) can cause a pelvic fracture (Fig. 21.1). Lateral compression fractures often occur from a side-impact motor vehicle collision or a pedestrian struck on the side. An anterior-posterior compression fracture can occur from a front-impact motor vehicle or motorcycle crash and crush injuries. Vertical shear injuries commonly result from a fall from a height onto a straightened lower extremity. The Young and Burgess classification of pelvic fractures is based on these vectors of force. Fractures are subcategorized by the extent of fracture involvement, amount of displacement, and degree of ligamentous disruption (Table 21.1) [5]. Their work, first described at our institution, is now the most commonly referenced pelvic

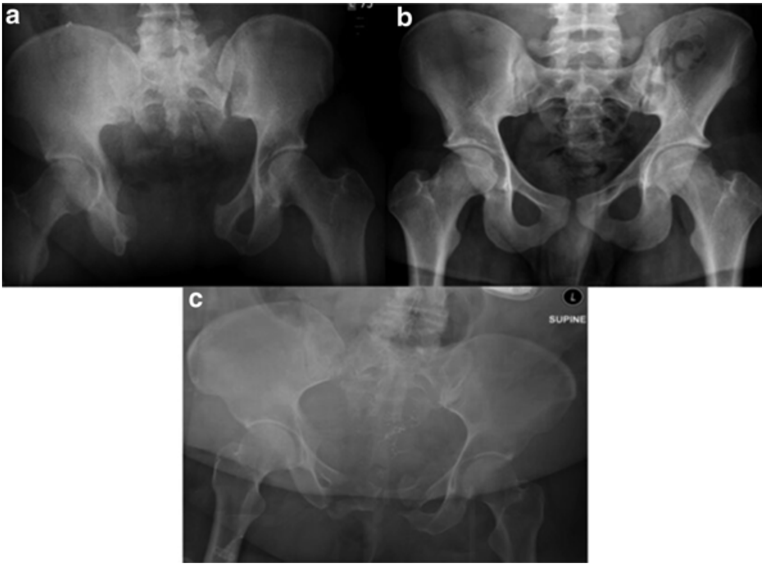


Fig. 21.1. (**a**) AP compression fracture, (**b**) left lateral compression fracture, and (**c**) AP compression fracture with vertical shear extension.

fracture classification. Pelvic fractures often are a result of a combination of vectors of force; thus, they may have elements of more than one fracture pattern.

## *Diagnosis and Management*

Motor vehicle collision accounts for the majority of pelvic fractures [6–8]. In addition, motorcycle crashes, fall from a height, pedestrians struck, and crush injuries can all cause fractures to the bony pelvis [9, 10]. History and physical findings are often relatively nonspecific. Complaints range from pelvic pain to lower abdominal pain, hip pain, and back and thigh pain. Visual inspection of the pelvis may reveal soft tissue injuries, including abrasions, lacerations, contusions, or hematomas. An important part of the initial physical exam is to assess for pelvic stability. This should be done by exerting gentle manual pressure inward on the anterior superior iliac spines (Fig. 21.2). Any motion should be interpreted as pelvic instability. Rocking the pelvis is unwise, as if the pelvis is unstable, it will cause the patient significant pain and almost

Table 21.1. Young and Burgess classification of pelvic fractures.

| | |
|---|---|
| AP compression | |
| Type I | Separation of pubic symphysis <2.5 cm and no posterior instability |
| Type II | Separation of pubic symphysis >2.5 cm and posterior instability of anterior sacroiliac complex |
| Type III | Complete disruption of sacroiliac joint involving both anterior and posterior complexes |
| Lateral compression | |
| Type I | Posterior-lateral directed force with oblique pubic rami fx. No pelvic instability |
| Type II | Anterior-lateral directed force with pivot point on anterior SI joint causing pubic rami fx, internal rotation of anterior hemipelvis, external rotation of posterior hemipelvis, and rupture of posterior SI ligaments |
| Type III | Severe ipsilateral internal hemipelvis rotation causing contralateral external rotation resulting in AP compression of contralateral side. Disruption of ipsilateral posterior SI ligaments and contralateral anterior SI, sacrotuberous, and sacrospinous ligaments |
| Vertical shear | |
| | Vertical disruptive force on one or both sides of the pelvis lateral to midline. Associated with ligamentous disruption and pelvic instability |
| Complex | |
| | At least two different vectors of force causing injury pattern |

*Source*: J W Young, A R Burgess, R J Brumback, and A Poka. Pelvic fractures: value of plain radiography in early assessment and management. Radiology August 1986 160:2 445–451

*AP* anteroposterior, *Fx* fracture, *SI* sacroiliac

certainly result in additional blood loss. An inspection of the perineum is also important. If a urethral injury is suspected based on the presence of blood at the meatus, a retrograde urethrogram can be performed (Fig. 21.3). Vaginal and rectal exams are likewise important to rule out the possibility of an open pelvic fracture.

An AP film of the pelvis should be obtained in all patients with polytrauma, regardless of hemodynamic status. While this is helpful for predicting associated injuries and predicting outcome in patients awake and alert without concerning mechanism, those without complaints or physical findings may not need a pelvic film [11–14]. Additional imaging is almost always obtained with CT scanning, though in selected cases, inlet and outlet views of the pelvis as well as Judet views may be helpful [15–19].

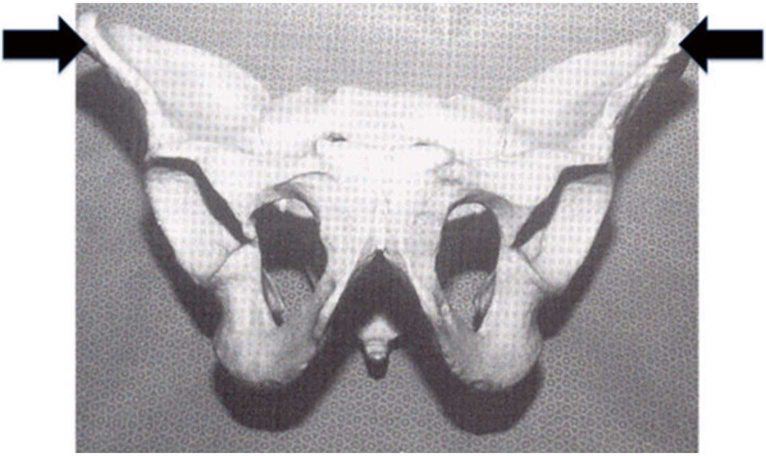

Fig. 21.2. Direction of gentle manual compression on the anterior superior iliac spines to assess for pelvic instability.

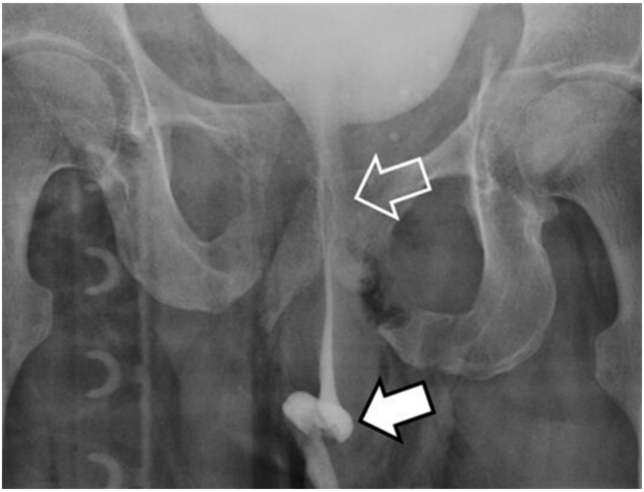

Fig. 21.3. Retrograde urethrogram demonstrating contrast extravasation from an irregular discontinuous anterior urethra (*solid arrow*) and stretch injury of the membranous and prostatic urethra (*open arrow*).

## *Management of Pelvic Fracture Hemorrhage*

Patients who present with pelvic fractures and are hemodynamically unstable can present the greatest challenge. Hemorrhage may be retroperitoneal in nature from the pelvic fracture, from other sites, or from both. Rapid assessment is important to identify all body cavities in which the patient may be losing blood. While covered elsewhere in more detail, a FAST or an eFAST may be very helpful in identifying intra-abdominal or intrathoracic hemorrhage, it will also help identify pneumothorax and/or hemopericardium, both of which can contribute to hemodynamic instability. A chest X-ray may also be helpful. Hemorrhage into muscle compartment is usually identified on physical examination and external hemorrhage is identified by history.

Patients who have a pelvic fracture and significant hemorrhage, either into the thorax or abdomen, pose a special problem. While patients with pelvic fractures are certainly at risk for retroperitoneal hemorrhage, not all of them are bleeding into their retroperitoneum. In general, patients with intra-abdominal hemorrhage, particularly if large volume on FAST, are best served with diagnostic abdominal exploration. At the time of laparotomy, the size of the pelvic hematoma can be ascertained by direct inspection.

Fracture pattern may be helpful in identifying patients more likely to be bleeding from their abdomen. A large retrospective study found that 85 % of hypotensive patients with hemoperitoneum and a stable pelvic fracture categorized as a lateral compression (LC1 or APCI) had intra-abdominal bleeding as the source of their hypotension. Conversely, 59 % of the patients with hemoperitoneum and an unstable pelvic fracture (LC2, LC3, APC2, APC3, or vertical shear) had large pelvic volume bleeding. The authors concluded that laparotomy should be performed first in the hypotensive patient with a stable fracture but consideration given to angiography before laparotomy in the patient with hemoperitoneum in an unstable pelvic fracture [20].

External compression is an important technique to control pelvic fracture hemorrhage. This can be accomplished in many ways. In a resource-poor environment, simply placing a sheet around the patient can help. It is ideal if the bedsheet is placed on the stretcher, the patient then placed on top of the bedsheet, and the sheet then crisscrossed across the patient's pelvis. This should be tied down as tightly as possible to reduce the bony elements (Fig. 21.4).

Fig. 21.4. Application of a bedsheet as an external binder with the tails of the sheet crisscrossed across the pelvis.

In the past, emergency external fixation was often used to achieve pelvic bony stability (Fig. 21.5). While this was placed in the emergency department in some institutions, more commonly, it was placed in the operating room. Thus, its use as an emergency therapy was, in some ways, negated. In certain institutions, this remains a possibility. It should be recognized that in patients with grossly unstable pelvic fractures, external fixation may reduce the anterior elements but, in fact, widen the posterior elements, causing increased hemorrhage.

In Europe, placement of a C-clamp is common (Fig. 21.6). This is not used very often in the United States. In those institutions, the C-clamp is placed blindly in the emergency department. In skilled hands, this is almost certainly safe. However, in those inexperienced, the potential visceral injury from poor placement of the pin must be recognized. Again, if this is going to be placed in the operating room under fluoroscopic control, its use as an emergency hemostatic maneuver is negated.

In the United States, virtually all of these hemostatic techniques have been replaced with the use of the pelvic binder [21–23]. The pelvic binder is a Velcro-based device which is placed around the patient's pelvis. It is important to place the device low enough over the greater

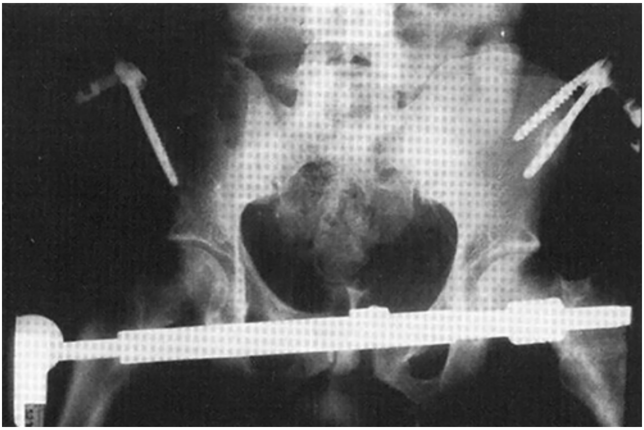

Fig. 21.5. Radiographic image of pelvic external fixator with pelvic reduction and stabilization.

Fig. 21.6. Image of a C-clamp. Note the pins required for securing the device.

trochanters of the femurs (Fig. 21.7). The binder should not be placed over the abdomen. The binder can then be laced up and even pressure placed to reduce the bony elements of the fractured pelvis. Unlike the C-clamp or external fixator, the binder is easily placed in the resuscitation bay, often, while other resuscitative maneuvers are ongoing. In addition, this reduces all portions of the pelvis equally; posterior elements cannot be displaced. The pressure exerted by the binder can be increased or reduced depending on the clinicians' wish. Physicians have

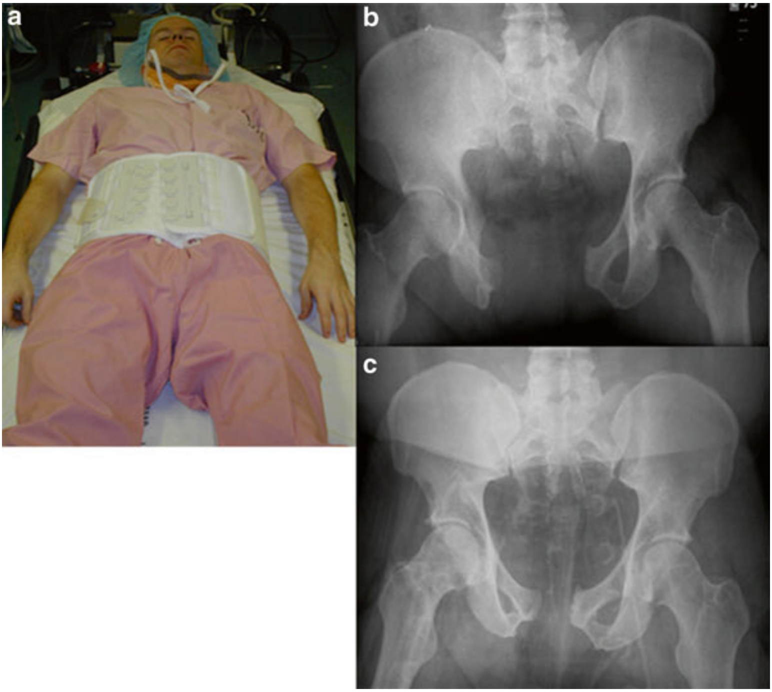


Fig. 21.7. (**a**) Pelvic binder application. Note the improperly placed binder over the abdomen instead of the greater trochanters. "Open book" AP compression fracture (**b**), with fracture reduction following proper placement of pelvic binder over the greater trochanters (**c**).

to be cognizant of the length of time that the binders have been in place, as these devices have the potential of pressure ulceration, so the skin should be routinely inspected if applied for any length of time [24].

Regardless of the method used, the most important initial hemostatic maneuver in a fractured pelvis is to reduce the bony elements. This closes down the pelvic volume and almost certainly reduces pelvic venous bleeding. In addition, if fracture fragments are reduced, bony bleeding is almost certainly reduced. External compression likely has little effect on arterial hemorrhage.

There is little downside to blanket application of the binder. Certainly in patients with badly displaced AP compression fractures (open book fractures), application of the binder can be highly efficacious and even lifesaving. The same is not true in patients with lower-grade lateral

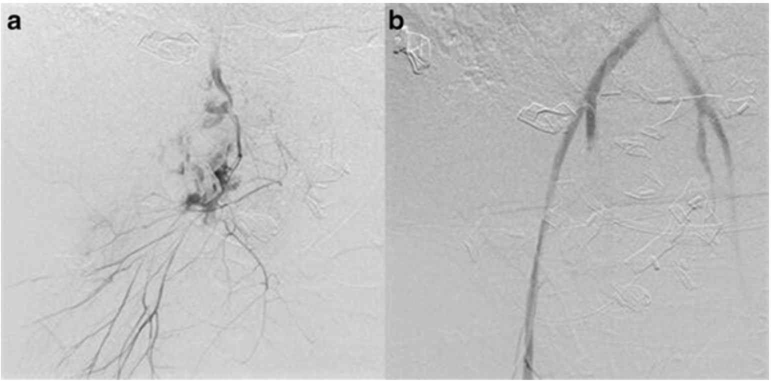


Fig. 21.8. (**a**) Contrast extravasation for right internal iliac artery and (**b**) post-angiographic embolization with resolution of extravasation.

compression or vertical shear fracture pattern. However, even in those people, there is some rationale for placing the binder. Patients with pelvic fractures commonly require transport to the hospital. Keeping the fracture fragments reduced with the binder may reduce additional bleeding when patients are transferred to and from the stretcher for various diagnostic tests and/or therapeutic maneuvers.

## *Angiographic Embolization*

For over 40 years, angiography has been used to treat pelvic fracture hemorrhage. Angiography is diagnostic and embolization therapeutic (Fig. 21.8). Patients with evidence of significant pelvic hemorrhage, particularly those who are hypotensive following pelvic stabilization or have no other identifiable source for their hemodynamic instability, should undergo immediate angiography [25, 26]. Transcatheter embolization in the unstable patient has a reported success rate of 95 % in obtaining hemorrhage control [27]. Consideration should be given for repeat angiography and persistent pelvic bleeding in patients who have continued transfusion requirements or unexplained hypotension [28].

In the hemodynamically stable patient, pelvic angiography and embolization may still have a role. Some recommend that all patients with pelvic fractures with contrast extravagation identified on CT scan undergo angiography to prevent hemorrhage [25, 29]. Other clinicians advocate a more selective approach to minimize nontherapeutic angiography in these stable patients [18, 30–32]. It would seem one clear indication for angiography should be a large pelvic hematoma (>500 cc's) because of the associated risk for pelvic bleeding [33].

It is important that the surgeon caring for the patient have full understanding of the angiographic capability and availability. If access is limited, timely transfer of a stable patient to a center with angiographic capabilities is prudent, as delays are associated with increased mortality [34]. In the unstable patient, if angiography is unavailable, other means of hemostasis must be pursued.

In our institution, angiography is the primary means of obtaining hemostasis in patients with pelvic fracture bleeding, including those that are hemodynamically unstable. We have rapid access to angiography 24 h a day, 7 days a week. In addition, all hemodynamically stable patients with a large hematoma or large volume contrast extravasation undergo diagnostic angiography. Patients with evidence of concomitant solid organ (liver and/or spleen) bleeding can undergo visceral angiography at the time of pelvic angiography and have hemostasis in all vascular beds obtained.

## *Preperitoneal Packing and New Techniques*

Unfortunately angiography may not be readily available, and in some hospitals nonexistent, so waiting for IR in the compromised patient is not an option. Preperitoneal packing as temporary, or potentially definitive, hemostasis can be lifesaving in this instance. This technique was originally described in Europe almost 20 years ago [35]. Recently this approach was modified to directly packing the anterior preperitoneal space [36]. To gain entrance to the space of Retzius, either a lower midline incision or a Pfannenstiel incision may be used. After the fascia is incised, the retroperitoneal space is bluntly dissected out laterally and posteriorly as far as possible (Fig. 21.9). While performing this maneuver, it is important not to breach the peritoneum and release its tamponade effects. This dissection is often created by the hematoma making it fairly easy to gain access to the retroperitoneum. Large clot is then evacuated and laparotomy pads are placed laterally to compress the iliac vessels. It is classically taught to place three laparotomy pads on either side; however, we place as many as needed to achieve tamponade.

Several studies have shown that preperitoneal packing directly resulted in a reduction in blood transfusion requirements and a reduction in the need for angioembolization [37, 38]. Preperitoneal packing can be combined with laparotomy in those unstable patients with both intra-abdominal and

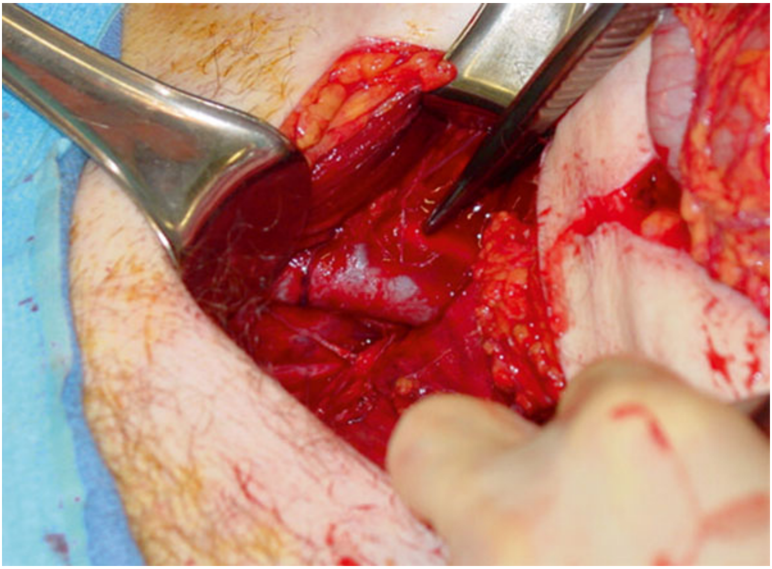

Fig. 21.9. Intraoperative exposure of the retroperitoneum. Note the identification of the iliac vessels.

retroperitoneal hemorrhage. For a combined approach, the midline laparotomy incision is stopped midway between the umbilicus and pubic symphysis. Preperitoneal packing is then done through a separate Pfannenstiel incision (Fig. 21.10).

A cutting-edge alternative for temporary hemostasis and resuscitation for the crashing blunt trauma patient is to deploy a percutaneous aortic occlusion balloon at the bedside in the emergency department. This involves placement of an endovascular balloon under fluoroscopic guidance through a femoral sheath. We have been successful in achieving hemodynamic stability for both intra-abdominal and retroperitoneal hemorrhage with this device, and in the case of pelvic hemorrhage, it has been valuable as a bridge to embolization [39]. As this technology advances, it is anticipated that this modality will become a more widespread and conventional practice for hemorrhage control and resuscitation.

The hemodynamically unstable blunt trauma victim with a pelvic fracture poses a significant dilemma. Thus, a multidisciplinary team of trauma surgeons, orthopedic surgeons, and interventional radiologists working in concert can determine the best treatment course to maximize physiologic stability and prevent further physiologic derangements [40] (Figs. 21.11 and 21.12).

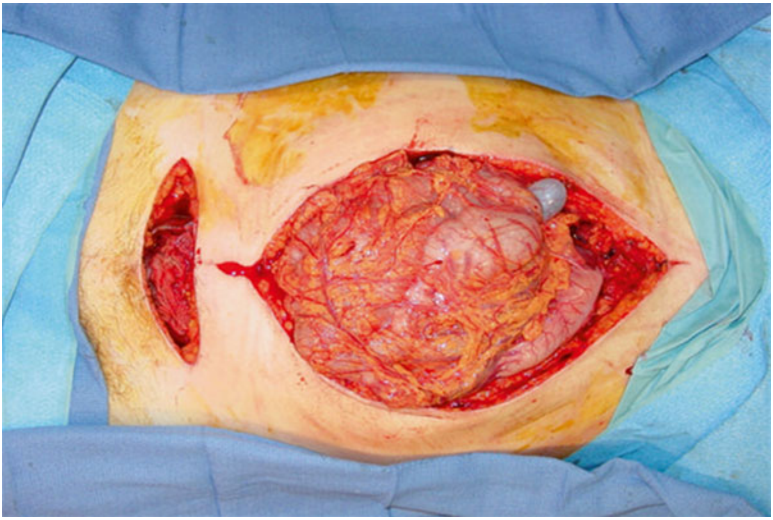

Fig. 21.10. Combined midline laparotomy for abdominal exploration and Pfannenstiel incision for preperitoneal packing.

## *Complications and Outcomes*

Morbidity associated with pelvic fractures includes increased risk for venous thromboembolism (VTE) [41, 42]. Early patient mobilization and pharmacologic prophylaxis are the best preventative therapies for VTE. Consideration for IVC filter placement is reasonable in the multi-injured, immobile patient with a pelvic fracture and in patients with a contraindication to anticoagulation [42]. Rare reports of femoral artery injury after angiography have been described [43]. Concern for gluteal necrosis and sexual dysfunction as a complication of angiography even after bilateral internal iliac artery embolization has been refuted [44, 45]. However, sexual dysfunction directly related to the pelvic fracture has been reported and has correlated to the degree of fracture displacement [46, 47]. Nerve injury and chronic pain are frequent complications of pelvic fractures, and functional recovery after nerve injury is worse in this subgroup of patients [48, 49]. Long-term disability is more common with a fractured sacrum or SI joint involvement and is directly related to the adequacy of fracture reduction [50–52]. Long-term sexual dysfunction, impotence, and dyspareunia also have been described.

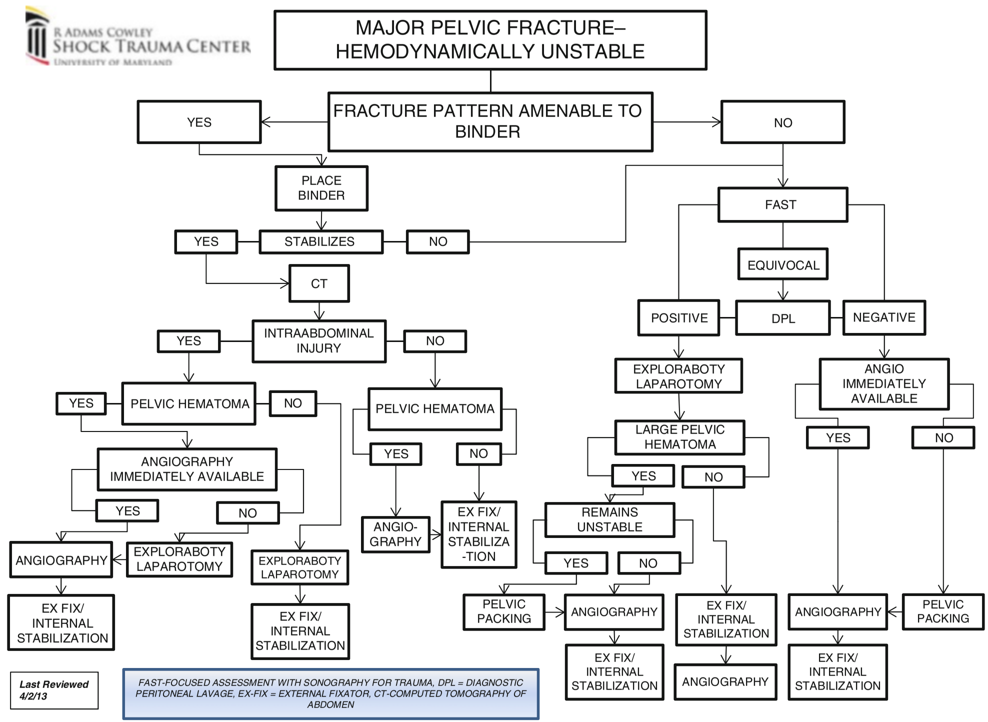


Fig. 21.11. Shock Trauma Center algorithm for the hemodynamically unstable pelvic fracture.

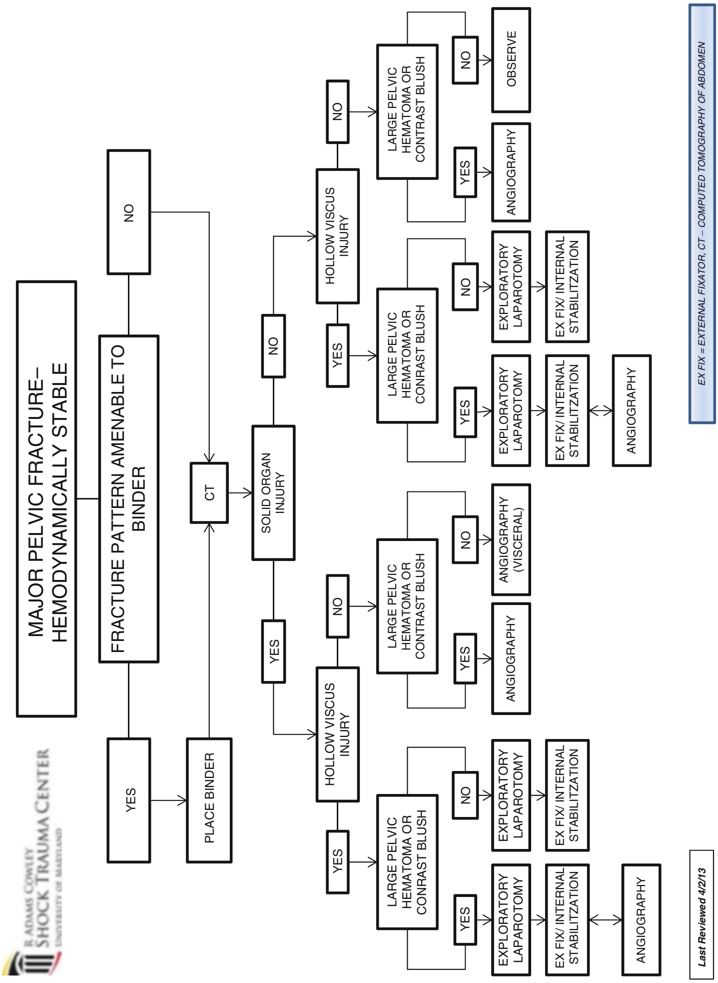


Fig. 21.12. Shock Trauma Center algorithm for the hemodynamically stable pelvic fracture.

Overall mortality associated with pelvic fractures has declined with recent estimates between 5 and 7 % [53, 54]; however, pelvic fractures remain an independent risk factor for mortality in the blunt trauma patient [55]. Death from pelvic hemorrhage has declined, while sepsis, multiple-organ failure, and associated injuries have been contributing more to mortality [56].

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