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Penetrating cardiac trauma

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Abstract

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This chapter summarizes approaches to hemorrhage control in penetrating cardiac trauma, an injury that is a true test of trauma systems integration, trauma center readiness, teamwork, decision-making, technical excellence, and multidisciplinary trauma care.

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Physiologic considerations. As little as 100 mL of blood accumulating in the pericardial space after a PCI can impair venous return to the heart, compromise ventricular filling, and result in diminished cardiac output and coronary perfusion, and, eventually, circulatory collapse. Early resuscitation efforts should prioritize the establishment of wide bore vascular access (14 or 16 G peripheral lines or 8.5 F cordis central venous catheters) and initiation of massive transfusion, in order to maintain ventricular filling during diastole. The use of inotropic agents or pressors can transiently augment compensatory sympathetic responses and maintain cardiac output. Intubation and the initiation of positive pressure ventilation, with an associated incremental decrease in venous return to the right atrium, can tip cardiac tamponade into cardiac arrest. In patients with associated lung injuries, positive pressure ventilation that exceeds pulmonary venous pressure, can promote air embolism, adding further obstructive shock and coronary occlusion to an already dire situation. Delaying intubation until surgical intervention is ready to go, may avoid or minimize the duration of cardiovascular collapse. But these are just temporizing measures – ultimately, the definitive restoration of ventricular filling and cardiac output requires anatomic approaches to relieve tamponade physiology and address cardiac hemorrhage.

Anatomic considerations. Knowledge of the surface anatomy of the mediastinum and the position of the PCI can give the trauma team an idea of trajectory and injury pattern, and the key to rapid exposure, decompression, and control.

Mediastinal wounds should be suspected with any clinical evidence of trauma to the ‘cardiac box’ (i.e. the space bordered by the midclavicular lines, clavicles, and costal margins – Fig. 2). However,
Fig. 1. Initial strategies for penetrating cardiac injury.

Fig. 2. The box.
the observation that a higher mortality rate has been reported for cardiac trauma associated with wounds outside the precordium highlights the importance of maintaining a high index of suspicion for any penetrating chest injury [1]. Special attention to gunshot injuries is also particularly important, as high energy bullets have a wider path of destruction than their entry wounds might suggest [2].

The palpable sternomambral joint is a good landmark to locate the second rib and, below it, the corresponding second intercostal space. The joint roughly overlies the superior border of the heart, the origin of the aorta and pulmonary artery, and the first part of the descending aorta. The manubrium resides cephalad to this joint, and below it, the main sternal body overlies a large portion of the anterior heart. The most commonly injured chamber of the heart (over 50% of PCLs) is the right ventricle due to its anterior location, which spans vertically between the third costal cartilages and the inferior cardiac border at the xiphisternal joint. The right heart border, which consists mostly of the right atrium between the vena cavae, lies parasternally between the third and sixth costal cartilages. The left heart border is formed mainly by the left ventricle, descending from the second parasternal intercostal space to the fifth intercostal space at the midclavicular line. Injuries to the left lateral mediastinal border are highly lethal due to the high-pressure system it encloses [3]. An oblique line between the medial portion of the left third intercostal space and the cardiac apex roughly traces the anterior interventricular groove where the left anterior descending artery resides (often within a fat pad). Injuries to this region mandate further planning and assessment for a potentially lacerated coronary artery and associated myocardial ischemia. The posterior surface of the heart begins at the T4/T5 intervertebral level where the arch of the aorta resides, as well as the trachea bifurcates. The heart then extends caudally across the mediastinum to the T8/T9 intervertebral level where it rests on the diaphragm.

Preparation. The trauma team in the opening scenario has the benefit of a few minutes of preparation time, during which it can don personal protective equipment, anticipate worst case scenarios (e.g. trauma arrest), designate team members for specific tasks (e.g. primary survey, airway interventions, extended FAST exam, intravenous access, coordination of blood transfusion, resuscitative thoracotomy, right chest tube, extended FAST exam). Those minutes can be used to harness resources and to keep them at the ready (e.g. resuscitative thoracotomy tray (Fig. 3), massive transfusion, OR on standby).

The patient arrives in the trauma bay and is met by the team. He is awake, but tachypneic (30 breaths/min), pale, tachycardic (120/min), and hypotensive (85/60). He has a stab wound to the right of the sternum. What is the best diagnostic strategy?

Diagnostics

Initial assessment. All penetrating thoracic injuries should trigger a high degree of suspicion for PCI. The classic findings of cardiac tamponade such as Beck’s triad (muffled heart sounds, jugular venous distention, and hypotension), electrical alternans, and pulsus paradoxus (a fall in systolic pressure of greater than 10 mmHg during inspiration), have been eclipsed as diagnostic tools by FAST ultrasound findings of pericardial fluid, often supplemented by extended-FAST correlates such as inferior vena cava distention. If the initial assessment is suggestive of PCI, the patient’s hemodynamic status determines the location and invasiveness of subsequent diagnostic and therapeutic efforts, which can range from subxiphoid pericardial window (SXPW) or urgent operative exploration in the OR, to resuscitative thoracotomy in the emergency department. (Fig. 1).

Subxiphoid pericardial window. In patients with suspected PCI, the FAST examination, which screens for pericardial fluid, has been shown to have superb test performance, while also improving both the time to definitive care and overall survival [4]. However, the sensitivity of bedside ultrasonography in detecting pericardial fluid can be limited by concomitant hemopneumothorax, synchronous lacerations to the pericardial tissue/pleura, subcutaneous emphysema, or operator inexperience. Although SXPW is a traditional test with vanishing indications (for stable patients with suspected PCI and equivocal FAST exams), it remains a powerful and definitive diagnostic adjunct. Furthermore, a recent randomized trial involving stable patients with suspected PCI and ultrasound-detected hemopericardium, which compared an approach using SXPW, gentle pericardial irrigation, and pericardial drain placement followed by median sternotomy for patients with ongoing hemorrhage, with immediate median sternotomy, confirmed that the SXPW approach is safe and effective [5]. Thus, performance of a SXPW still has a specific and important role in the management of PCIs that do not mandate immediate sternotomy.

The SXPW can be performed in the emergency department, the OR, or even the intensive care unit. A 5 to 6 cm vertical, midline incision is centered over the xiphoid process. Deeper tissues are then separated by electrocautery or a spreading technique with scissors. Placing larger patients in the Trendelenburg position will assist in facilitating exposure to the xiphisternum and pericardium [6]. The linea alba is carefully

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**Fig. 3. The set.**
incised without breaching the peritoneal cavity. Xiphoidectomy is completed by releasing the tissue around the xiphoid process with either electrocautery or Mayo scissors. Alternatively, the xiphoid can be hinged upwards (i.e. similar to opening the hood of a vehicle). The distal sternum is retracted anteriorly and careful dissection is engaged towards the pericardiophrenic junction. It may occasionally be necessary to divide some of the anterior diaphragm before the pericardium can be identified. When initial visualization is poor despite dissection of the surrounding tissue, which is often, digital palpation of the cardiac impulse can be used as a guide to locate the pericardium. Use of a sponge stick to push the precordial fat out of the way laterally in a cork-screw movement is also very helpful. The heart is further revealed by pushing down the inferior diaphragm. The pericardium is then grasped tautly with two long Allis clamps. A vertical 1 to 2 cm incision is made in-between the two clamps with a #15 scalpel blade (or sharp scissors) to reveal, in the absence of PCI, a trace of clear pericardial fluid and the underlying epicardium. It is essential to ensure a completely bloodless field (ideally with white surgical sponges) prior to violating the pericardium. A false positive result secondary to contaminated blood from outside the pericardial space is suboptimal. A positive window for hemopericardium is noted by the evacuation of clot or blood staining within the pericardial fluid. The pericardial sac is then irrigated with warm saline to confirm any active bleeding. Communication with anesthesia is pertinent since drainage can immediately reduce preload and trigger hemodynamic collapse in some patients. Progressive deterioration during the procedure may mandate emergency sternotomy or thoracotomy. A positive window is classically followed by a median sternotomy and pericardiectomy.

If a concurrent laparotomy has been initiated, a pericardial window can also be performed through the central tendon of the diaphragm. This can be accomplished by extending the abdominal incision cephalad to the xiphoid, tracing the falciform ligament to the diaphragm, identifying an area of diaphragm to the left of the falciform, grasping and elevating the diaphragm between two Allis clamps, incising the peritoneum in a vertical direction, and, finally, feathering through the central tendon with a scalpel until the pericardial space is, most gratifyingly, entered.

The patient remains profoundly hypotensive and increasingly obtunded during the rapid initiation of a massive transfusion protocol. A FAST ultrasound confirms the presence of pericardial fluid. The trauma team agrees that urgent intervention for cardiac tamponade is indicated. **What is the best exposure and technique?**

**Surgical exposure**

**Left anterolateral thoracotomy and clamshell thoracotomy.** Hemo-dynamically unstable or pulseless patients with PCI (i.e. despite fluid resuscitation and/or CPR for less than 15 minutes) require resuscitative thoracotomy, often via a left anterolateral thoracotomy (LAT) [7]. The LAT approach offers rapid access to the heart and left thoracic structures. This also allows for timely decompression of cardiac tamponade, cardiac hemorrhage control, cardiac massage, aortic cross clamping, and prevention or control of air embolism. Concurrent induction of anesthesia and application of positive pressure ventilation in the setting of tamponade physiology can reduce preload to an extent that may result in profound hemodynamic instability. Resuscitation with blood products must be initiated and the thoracic operative field must be prepared and surgeon-ready prior to induction. Penetrating bodies found in situ are generally left in place until the chest is opened in case of concomitant vascular and solid organ injuries [8,9].

With the arms of the supine patient abducted to 90 degrees on arm boards and the breast retracted cephalad, an incision using a #10 scalpel is made from the left sternal border of the fourth or fifth intercostal space to the left posterior axillary line along the curve of the rib (Fig. 4). The inframammary fold is a reliable visual landmark for this space. The intercostal muscles and pleura are subsequently transected with curved scissors along the superior margin of the rib below. A Finochietto retractor is then placed with the instrument joint on the lateral side of the incision. Before spreading the ribs, large surgical sponges may be used to cover the incised edges to avoid injury from rib spikes. Once opened, the incision can be extended medially for further exposure. To improve exposure and protect the pleural surface during the procedure, ventilation to the left lung can be reduced by temporary right mainstem bronchial intubation. Even as they focus on maneuvers in the left chest, surgeons must remain vigilant about possible concurrent right thoracic injuries – LAT can be supplemented by a right sided chest tube to screen for a right hemopneumothorax that may be contributing to hemodynamic instability and that may warrant exploration.

An initial right thoracotomy may be preferred for patients with right-sided chest injuries [10]. Otherwise, the LAT incision can be carried into the contralateral thorax as a bilateral anterior thoracotomy (clamshell) incision by cutting the sternum with either heavy scissors, Lebsche knife, or a Gigli saw. Using one or two retractors, the clamshell is opened for further exposure by extending the thoracotomy posterolaterally. In desperate scenarios, a gloved assistant can manually hold the incision open [11]. Approximately 1 cm from the lateral edges of the sternum (with a variable course), the internal mammary arteries can be indentified in a vertical plane. Rarely, they may be ligated as the incision is extended across the sternum. Although these vessels do not often initially bleed due to vascular spasm, they must eventually be ligated at both the proximal and distal ends before final closure. LAT is employed as the classic approach to resuscitative thoracotomy, but the clamshell incision provides access and improved visualization in poor lighting to every thoracic structure, except the posterior diaphragm and superior esophagus. LAT with clamshell extension is often the incision of choice where wide exposures are required for injury control and repair [11–13].

**Median sternotomy.** Hemodynamically stable patients with injuries to the cardiac box can be assessed with immediate sternotomy and exploration in the OR [14]. Although sternotomy requires technical precision and attention to detail (i.e. to avoid postoperative complications), it also affords excellent visualization of the anterior heart and great vessels, and therefore the deployment of multiple operative techniques. A sandbag positioner can be applied posteriorly between the shoulder blades to better expose the midline (particularly for obese patients) [15]. The suprasternal notch and xiphoid process are first identified to prepare the incision between these two points. The initial skin incision is deepened to the sternal bone with cautery which is then used to trace the midline and divide the interclavicular ligament found at the superior aspect of the manubrium. This prevents subsequent binding and failure of the sternum saw. The jugular venous arch may require ligation or catherization if closely approximated to the sternal notch. Blunt digital dissection is then engaged to rapidly separate the xiphoid process and manubrium from the underlying mediastinal structures. Opening up the retrosternal space provides additional safety from saw-associated trauma. Osteotomy is generally initiated from the caudal end, rather than the top, as extra steps may otherwise be needed to cut the sternoclavicular ligaments and develop an adequate retromanubrial space to insert the saw [16]. It is critical to keep the saw within the midline of the sternum to avoid shearing into either side of the chest. This is particularly important in the lower sternum because it is thinner and more vulnerable to saw deviation than the top portion [17]. If an electric or pneumatic saw is unavailable, a large straight bone cutter can be applied upward from the xiphisternum instead [18]. The anesthetist ideally holds patient ventilation, and the osteotome proceeds with the saw angled upwards to avoid any injury to the underlying pleura and mediastinum. With towels/sponges covering the cut sternal edges to control bleeding, the retractor is then placed into the sternum. The retractor blades should ideally contact the distal manubrium to minimize any additional fractures upon rapid thoracic distraction [17]. The mediastinal fat can be dissected, and pleurae are pushed aside. It should be
noted, that in general a median sternotomy should be reserved for patients with anterior thoracic stab wounds only. Procedures required posterior to the heart can be particularly challenging to perform with efficacy through this incision (therefore, a bilateral thoracotomy is preferred for all gunshot wounds and most other penetrating injuries, particularly outside of the cardiac box).

Pericardiotomy. From a LAT, the pericardium is elevated and punctured with a blade 1 to 2 cm anterior to the phrenic nerve. It is then extended parallel to the nerve with scissors. The phrenic nerve lies on the pericardial surface and is immediately anterior to the pulmonary hilum. Care should be taken to avoid damaging the phrenic nerve by dividing it, or by cutting the pericardium too closely and causing a retraction injury to the nerve. After releasing a cardiac tamponade, open cardiac massage can be initiated against the sternum with one palm on the posterior aspect of the heart [19].

From a median sternotomy, after the sternal halves are retracted, the pericardium is grasped between two mosquito forceps (or Allis clamps) and a small incision is created with a #10 scalpel blade along the midline. Forceps will be unhelpful in the context of a tight, fluid filled pericardial space. Damage to the underlying epicardium can be avoided by simply maintaining the blade at an oblique angle. The resulting defect is extended longitudinally with Metzenbaum scissors and T extensions are created along the aortic and diaphragmatic reflections. Cautery can also be used to open the pericardium as long as care is taken to avoid direct application to the myocardium, which can initiate rapid wide-complex tachyarrhythmias (i.e. ventricular tachycardia or fibrillation). Likewise, the thymic tissue can be divided with cautery, or pushed...
away to expose the pericardium covering the ascending aorta. Access to the heart must be large enough to allow the insertion of two hands to perform internal cardiac massage when indicated. A simple pericardial sling is created by tautly suturing the open edges to the skin or wound towels, and therefore preventing retraction from dehydration [6]. The hemopericardium should be evacuated, and the cardiac rhythm noted for potential cardiac massage and/or defibrillation. Attention to a sudden change in arterial pressure upon opening of the pericardium (in the presence of a tamponade) is essential, as there will be an initial rise in the arterial pressure. If a continuous intrapericardial bleed is present, this rise will be followed by a drop in arterial pressure due to the continuous blood loss.

It should be noted that when a thoracotomy is performed for trauma, the pericardium must always be opened. External inspection of the pericardium is not sensitive for intrapericardial blood, even in the presence of tamponade.

The patient loses pulses within minutes of arriving in the trauma bay, and intubation and left anterolateral thoracotomy are simultaneously undertaken (double set up). Pericardiectomy releases torrential hemorrhage, but once the blood is cleared, the heart is seen to be empty and fibrillating, with a 3 cm laceration of the right ventricle. Massive transfusion is ongoing, mainly via a right subclavian cordis line. The patient is also receiving intravenous calcium chloride (1 g), magnesium sulfate (5 g), amiodarone (300 mg), and epinephrine (1 mg). What is the sequence of the next steps?

Cardiac hemorrhage control

Light digital pressure may be adequate for the initial control of cardiac injuries. When faced with multiple cardiac lacerations, stapling (6-mm-wide skin staples (Auto Suture 35 W, United States Surgical Corporation, Norwalk, CT)) can be employed for temporary bleeding control. While some clinicians reinforce the stapled closure with sutures, they can alternatively be left in place without reinforcement when necessary/pREFERRED. Unfortunately, some injuries, such as large caliber gunshot wounds or injuries proximate to the coronary arteries, cannot be appropriately managed via cardiac stapling [20]. Balloon occlusion with a clamped Foley catheter, or cuffed endotracheal tube, may address larger defects by inflating the balloon with saline inside the chamber and gently withdrawing it against the wall. Excessive traction can enlarge the laceration further and create a fatal disaster. With the balloon inflated and extremely gentle traction applied to the catheter, Teflon-pledged sutures can then be passed through the ventricle from side to side over the balloon. The thin wall of the right ventricle puts the inflated balloon at significant risk of puncture as each suture is placed. Pushing the catheter and balloon into the ventricle with each bite of the suture will mitigate this complication, although blood loss may be significant. An alternative option is to employ a cuffed endotracheal tube. This provides the advantage of increased manual stability while sewing. It must be re-emphasized however, that excessive traction on either device can enlarge the initial laceration and lead to death. Conveniently, direct venous access may be obtained through the Foley catheter itself for medication boluses (i.e. connect intravenous fluid tubing). A novel hemostatic vacuum device, which consists of a central pillar (CPB). Patients will immediately become hypotensive when the vena cavae are occluded. Curved aortic or angled vascular clamps are first applied to the superior and inferior vena cavae. The inferior vena cava can be accessed either within the pericardium or between the liver and diaphragm if the surgeon is familiar with this area. As the heartbeat slows, horizontal mattress sutures are inserted rapidly on either side of the defect and then crossed to control hemorrhage. A continuous suture is placed to close the defect and before it is tied down, air is vented out of the elevated ventricle by releasing the clamps on the cavae. This cardiac response also occurs with compression of the right ventricle and pulmonary artery. Internal paddles and other resuscitation tools should be readily available. This technique must be limited to short intervals of occlusion with repeated relief, or successful rhythm restoration is unlikely after approximately 3 minutes [25]. For injuries to more vulnerable or friable myocardium, manually compressing the right atrium will result in the partial inflow occlusion necessary to repair the ventricle [19]. Injuries involving the lateral wall of the left ventricle, left pulmonary veins, left atrial appendage, or the left pulmonary artery are accessed through a “capping” maneuver to lift the ventricles out from the pericardial well. This should be performed fairly slowly by running the fingers of the right hand between the diaphragm and the right ventricle, and then sweeping them posteriorly and cephalad. The hand cups the apex of the left ventricle, which is subsequently elevated anteriorly out of the pericardial well. This nuanced sequence will avoid rapid subsequent hypotension. Meanwhile, placing several pericardial retraction sutures in the posterior part of the pericardium is also helpful to maximize exposure.

It should be noted that as procedures such as inflow occlusion are considered and/or engaged, additional (and early) consultation with our perfusionist (i.e. heart-lung machine) and cardiac surgical colleagues becomes increasingly important. Scenarios such as ventricular septal punctures or acquired ventricular septal defects, are nuanced and mandate bypass.

Cardiac repair

Once temporary hemostasis is achieved (often with a delicate single finger), patients with signs of life should proceed to the OR for definitive repair. Optimization of technical conditions (lighting, field organization, operative exposure, instrumentation, suture availability) are essential, both to avoid iatrogenic injury and create a precise and enduring repair. The specific reconstruction technique depends upon the characteristics of the injury, the resources available to the resuscitation area or OR, as well as the operator’s experience and preference.

Following pericardiectomy, the heart produces an additional lateral rocking motion without the pericardium holding it in place. This movement can be safely minimized by an assistant’s Satinsky clamp on the acute anteroinferior angle of the right ventricle [26]. This technique is often more straightforward in a heart that is less filled with blood. Use of the Octopus tissue stabilizer (Medtronic, Dublin, Ireland) is also a reasonable alternative, if available. Simple ventricular laceration repair involves passing 4–0 SH or 3–0 MH polypropylene sutures (double armed) under the digital occlusion and out the other side in one pass. The two ends of the sutures are gently pulled to approximate the lacerated edges from bleeding, and the needle is reinserted across the finger and back out the other side. This completes a figure-of-eight stitch as the finger is subsequently withdrawn. These steps are repeated along the defect as needed. A potentially safer alternative is to employ pledgeted polypropylene sutures with a horizontal mattress technique when possible to reduce the risk of tearing the heart tissue. Although Teflon pledgets are sometimes unnecessary on a thick and robust myocardium, they can be helpful for a friable and edematous heart, right ventricle, or areas with surrounding contusion and hemorrhage. This technique generally provides additional seal and protection [19,27,28] (Fig. 5).

It is important to highlight that the principles of suturing cardiac muscle are similar to sewing other soft structures such as the liver and...
tire curve of the needle for insertion and egress, tying small pledgets are required for vascular anastomoses and repairs. This simple technique is also especially useful when particular size, and the two ends are pulled. The second pledget is apposed out the opposite pericardial edge. Pledgets are cut and fashioned into a through the pericardial sling on one side, then across the laceration, and tress sutures \[29\]. Two needles from a double-ended suture are passed readily available, small pieces of the pericardium can also be used to but- underneath. If the atrium is especially dilated, pledget reinforcement may wounded edges together with subsequently prepare for a mattress repair is then passed through the opposite edge of the laceration. Timing the needle entry to diastole can also prevent inadvertent slashing of the car- diac musculature. Furthermore, if a Foley catheter is employed to con- trol the bleeding, the catheter can be carefully pushed into the chamber each time the needle is inserted, thereby preventing perfora- tion of the balloon. Larger defects, including gunshot wounds, may be closed with interrupted horizontal mattress sutures instead \[6\]. Which- ever strategy is employed, adequate suture bites through the myocar- dium must be ensured to lower the risk of tissue tearing. This is particu- larly important for the thinner right ventricle. As previously noted, the selection of needle size is critical to success.

Atrial defects are repaired by placing a vascular clamp under the perfo- ration. Preventing additional traction to the atrial wall is essential to avoid lacerating it. Subsequently, simple, continuous stitches with 5–0 polypropylene sutures on an RB needle can be utilized. Alternatively, a 6–0 polypropylene suture may be employed if the atrial tissue is exceptionally thin. Running horizontal mattress stitches may be more appropriate for thin atrial walls which require a technique that spreads tension along the entire wound edge \[6\]. When the injury cannot be controlled with a single clamp, multiple Allis clamps can be engaged in a row to pinch the wounded edges together with subsequently prepare for a mattress repair underneath. If the atrium is especially dilated, pledget reinforcement may be required. When time is limited, or such bioprosthetic materials are not readily available, small pieces of the pericardium can also be used to but- tress sutures \[29\]. Two needles from a double-ended suture are passed through the pericardial sling on one side, then across the laceration, and out the opposite pericardial edge. Pledgets are cut and fashioned into a particular size, and the two ends are pulled. The second pledget is apposed to the ventricular wound by irrigation, and then the sutures are tied to complete the stitch. This simple technique is also especially useful when small pledgets are required for vascular anastomoses and repairs.

As mentioned, the beating heart often presents a challenge for accurate suture placement, posing a risk of needle-stick injury during digital occlusion. Intravenous administration of adenosine has therefore been employed to induce a brief asystole and thereby facilitate repairs on the stationary heart \[30–32\]. Low doses of adenosine (3 to 12 mg) stop the heart for 10 to 30 seconds, during which repair and compre- hensive inspection are completed. Adverse effects, including atrioven- tricular block and hypotension, usually resolve when the drug is discontinued, making adenosine a reliable adjunct to repair \[30\].

Alongside adenosine infusion, several additional maneuvers for the inspection and repair of challenging cardiac injuries are relevant. Man- agement of wounds to the posterior aspect of the heart require special care, as lifting the heart kinks the great vessels, causing bradycardia, hy- potension, and arrest. To access the posterior heart however, it must often be ‘flipped up’ prior to suture repair. Close communication with the anesthesiologist and rapid surgical technique are essential, given the typical induction of complete cardiac arrest after positioning. As a result, intermittent restoration of the heart back into its natural position is required for cardiac relief during prolonged repairs. Alternatively, gentle lifting of the heart by gradually stacking one to three folded laparotomy pads provides time for the heart to adapt to the planned displacement. Depending on their availability, off-pump cardiac stabiliz- ation devices are also an option to gain safe elevation and rotation for cardiac exposure \[33\]. In desperate cases, it may ultimately be necessary to elevate an atraumatic clamp applied to the acute anterior-inferior margin of the right ventricle and repair the wound as quickly as possible \[26\].

Defects adjacent to the coronary arteries also warrant additional comment as coronary blood flow can be inadvertently compromised during the repair. Interrupted, horizontal mattress sutures are placed beneath the bed of the coronary vessel to prevent vascular constriction. Pledgets may be omitted unless the sutures are likely to tear through the myocardium and vessel. Accordingly, suturing alongside a coronary artery is guided by monitoring for ST segment changes or Q waves. If these occur, urgent stitch removal and re-suturing may be required.

Despite the multiple strategies that augment cardiorrhaphy, injuries adjacent to the coronary arteries may require a sutureless approach. Application of a collagen mesh dressing covered by fibrin glue to occlude a stab wound near a branch of the circumflex has previously
been reported [34]. Likewise, defects that are complex, such as large lacerations or a coronary sinus injury, may necessitate the use of autologous pericardial or synthetic patches which are subsequently strengthened by applying biologic glue agents [14,35]. When neither are available, tissue patches can be obtained from the anterior rectus fascia. Institution of CPB when bleeding is impossible to control may help further management with patch grafting, including reinforcing the seal with an omentum or muscle flap for additional protection [36].

Foreign body removal. Occasionally, trauma surgeons may encounter an in-situ cardiac foreign body. Symptoms attributable to these foreign bodies, including cardiac tamponade and arrhythmia, are considered a primary indication for removal [37,38]. Simple extraction of the offending object does however pose further risks of damage to a potentially unstable patient (e.g. a missile that approximates a coronary artery or is deeply embedded within the myocardium and tamponading the wound) [39,40]. Furthermore, manipulation of foreign bodies contained within the left heart require great care and speed due to the high risk of critical embolization [41].

When removal is indicated, embedded projectiles can be manually extracted with forceps after sewing pledged, double-armed horizontal mattress sutures around the body and slowly tightening the stitches during extraction [33]. Nails must be removed by careful twisting instead of simply pulling and risking damage to the surrounding wound edges. Alternatively, purse-string sutures may be placed at the entry site to close the defect immediately after removal. Intravenous adenosine infusion can also be considered as an adjunctive maneuver to lower contractility and facilitate safe extraction of the penetrating object [40]. The concomitant use of intraoperative transesophageal echocardiography may also be particularly helpful for visualization of a bleeding heart, reinforcing assessment of the penetrating body and guiding surgical instruments [42]. The decision to institute CPB must be balanced against its risks to the patient, but when appropriate should be triggered early in the surgical process given its clear benefit of ensuring adequate repair and/or foreign body extraction.

Coronary artery injuries and cardiopulmonary bypass. Injuries to the coronary arteries are infrequent and associated with high rates of preoperative injury, and inpatient mortality [43,44]. Decision making and the treatment (including the decision to go on CPB) can be complex and require early collaboration with cardiac surgery if possible. It must be re-emphasized again that this close relationship with our cardiac surgical colleagues is essential as their use of CPB may be more liberal and allow avoidance of prolonged inflow occlusion. The general approach to lacerated coronary arteries consists of ligating injuries to small branches or distal vessels less than 1 mm in diameter, and bypassing major arteries in patients with proximal coronary arterial wounds, although small puncture injuries can be repaired with 6–0 or 7–0 polypropylene sutures.

Ligation of a distal or narrow artery must be followed by a period of close observation for possible cardiac ischemia and/or failure. Injuries to the left anterior descending artery, which are relatively common, are close observation for possible cardiac ischemia and/or failure. Injuries to the coronary arteries are infrequent and associated with high rates of preoperative injury, and inpatient mortality [43,44]. Decision making and the treatment (including the decision to go on CPB) can be complex and require early collaboration with cardiac surgery if possible. It must be re-emphasized again that this close relationship with our cardiac surgical colleagues is essential as their use of CPB may be more liberal and allow avoidance of prolonged inflow occlusion. The general approach to lacerated coronary arteries consists of ligating injuries to small branches or distal vessels less than 1 mm in diameter, and bypassing major arteries in patients with proximal coronary arterial wounds, although small puncture injuries can be repaired with 6–0 or 7–0 polypropylene sutures.

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circulation, thereby increasing coronary perfusion and, possibly, myocardial contractility. Cross clamping may be a useful adjunct in refractory cardiac arrest or post arrest cardiogenic shock. However, the technique comes at great cost in terms of warm ischemia time, and must be limited to the time it takes to restore intravascular volume or a maximum of 30 minutes.

**Pulmonary hilar cross clamping.** Pulmonary injuries create the risk of air embolism, especially with positive pressure ventilation and low pulmonary venous pressures in the context of hemorrhagic shock. LAT and clamshell thoracotomy can provide access to the injured pulmonary hilum, which can be cross clamped at end expiration after the inferior pulmonary ligaments are partially taken down. This measure can both reduce the risk of air embolization and control ongoing pulmonary hemorrhage, until the lung injury can be controlled via tractotomy or resection.

**Extracorporeal life support.** Extracorporeal life support (ECLS) is emerging as an adjunct in the care of patients with penetrating chest trauma and refractory shock. Concerns about systemic anticoagulation had previously limited ECLS use in trauma, but have been offset by potential advantages, including rapid cannulation, and the well-documented feasibility of avoidance of therapeutic anticoagulation when heparin-bonded circuits are used [30]. Cardiopulmonary failure is managed using veno-arterial ECLS with femoral-femoral cannulation (i.e. percutaneous access with a Seldinger technique), preferably without a skin incision to prevent further bleeding. The venous cannula is positioned near the junction between the right atrium and the inferior vena cava to optimize venous drainage. The arterial cannula is directed towards the distal aorta. This will offer complete circulatory and respiratory support. ECLS enables trauma teams to control temperature at around 36 °C, which may be useful in helping to reduce secondary brain injury for patients with cerebral injuries or those who have received cardiopulmonary resuscitation. In cases where a complex cardiac operation cannot be tolerated in a resuscitated patient or where myocardial stunning results in transient cardiac shock, ECLS may serve as a bridge to recovery, or to further investigations and interventions.

After a brief period of resuscitation and open cardiac massage, the heart begins to contract! With time, adequate spontaneous cardiac output is confirmed by end tidal carbon dioxide and blood pressure measurements. The patient receives more calcium and magnesium, as well as intravenous bicarbonate to address anticipated effects of lower body reperfusion. He is moved from the trauma bay to the operating room for definitive hemostasis, placement of chest tubes and mediastinal drains. What are the best closure strategies?

**Closure**

**Pericardial closure.** Pericardial closure is favored in most non-trauma operations to minimize postoperative retrosternal adhesions (post sternotomy) and prevent lateral cardiac herniation (post LAT). This is especially true in cases of a repeated sternotomy, as it improves hemo-dynamics and protects against cardiac tamponade. In trauma patients however, closing the pericardium has the potential to lead to iatrogenic tamponade because of myocardial edema due to direct injury and/or re-suscitation. The risks of sealing the heart in these cases may outweigh the benefits. When primary closure is feasible, it can be performed by approximating the edges of the pericardium with a 2–0 absorbable (Vicryl) continuous stitch at 1 cm intervals beginning at the cranial end. If a reoperation is possible or intended, non-absorbable sutures may be employed to guide future re-opening. A 2 cm gap is left at the diaphragmatic end for a mediastinal drain placed anterior to the defect. When closure is still preferred despite cardiac dilation or despite a limited supply of native pericardial tissue, the defect can be conveniently covered with pericardial fat pads that are readily dissected and sutured onto the pericardial edges.

**Drains.** Proper placement of mediastinal and pleural tubes can prevent further complications from recurrent hemopneumothoraces, cardiac tamponade and/or infection. Prophylactic antibiotics are also justified for thoracostomy tubes in patients with penetrating injuries [51]. Standard 24 to 32 French chest tubes are inserted through the intercostal spaces in the midaxillary line. Although the fourth or fifth intercostal space is often used, they may not be available if a thoracotomy was performed at the same level. Drains can alternatively be placed through the lower intercostal spaces with the help of ultrasound guidance. Air drainage is best achieved by placing the drains in an anterior direction, whereas the tube can be directed posteriorly for evacuating blood. Alternatively, tube thoracostomy can proceed through epigastric incisions by ensuring they are placed laterally within the rectus fascia to prevent subsequent herniation [52]. Furthermore, mediastinal or pericardial drains can be inserted along the midline, often below the median sternotomy incision in the epigastrium (angled tubes may be particularly helpful). As previously discussed, a distal gap is left behind when closing the pericardium to facilitate drain placement. It is critical to carefully label all drains (i.e. pleural space or mediastinum or pericardial) within the thorax in the postoperative setting. Nursing needs can be complex, and suction has been inadverly placed on pericardial drains leading to negative pressure on a sutured cardiac repair.

**Median sternotomy.** Accurate sternal re-approximation and closure are key factors in preventing postoperative pain, sternal dehiscence and infection [53]. Figure-of-eight wires are often used as a fast and stable closure technique that is comparable to new sternal closure methods in regards to wound complication rates [53,54]. Four to eight stainless steel wires are passed through the manubrium and body, including one that bridges the manubriosternal joint. Before closure, a towel can be placed between the sternal halves to protect the heart. Minimal bleeding occurs when passing the needle perpendicularly through the bone, employing the needle holder between the proximal and middle third of the needle and advancing it vertically [9,52]. A concave instrument may also be positioned under the sternum to further protect the mediastinum from injury by the needle. Optimal approximation and stability are achieved by inserting wires at equal distances from the midline at the appropriate vertical level. When this is difficult, it may be better to apply the wires around the sternal body between the intercostal spaces. If this technique is preferred, extra caution is essential to avoid damaging the internal mammary arteries and causing a subsequent hemothorax. Once all the wires are in place and locked with needle drivers, the towel is gently removed, and the mediastinum is rinsed with saline. Definitive hemostasis from the sternal edges is achieved with electrocautery and/or bone wax. The wires are crossed and lifted upwards (i.e. sternal halves are approximated), and then loosely twisted and cut. The assistant can facilitate approximation by lifting forward the pectoral girdle with their palms on the scapulae. The cut ends are tightened until the two edges contact, and the wire stumps are buried entirely into the prestenral tissue. Internal sternal fixation with absorbable sternal pins can provide additional stability with the possibility of easy re-entry [55]. Alternatively, sternal wires can be placed in a simple interrupted manner, spaced 1 to 2 cm apart. They are then straightened prior to crossing in a smooth fashion to ensure adequate sternal apposition once twisted.

Delayed pericardial and sternal closure may be necessary if the heart enlarges from primary edema or excessive fluid administration. A temporary thoracic closure may also be required if hemodynamic compromise ensues with attempts at re-approximation. Diuresis with furosemide is a viable option if the patient’s hemodynamics will allow. Otherwise, an abdominal-type plastic covering with sterile surgical drapes, or genitourinary irrigation bag sewn onto the skin, can be temporarily employed until definitive closing is possible. It should be noted that if the sternum is left open, the patient needs to remain intubated and paralyzed, as an awake and coughing patient can cause a life-threatening laceration of the right heart by cutting the anterior
ventricular surface between the two sternal edges (Hanuman syndrome). It may also be possible to protect against this occurrence by using a Vacuum Assisted Closure (VAC) dressing with concurrent placement of a large pad between the sternal edges. VAC dressings can also be employed as an alternative to sterile draping with no apparent negative impact on cardiac and respiratory dynamics [56]. In extreme cases, where any contact between the heart and the sternal edges compromises cardiac function, sternal stenting is necessary. Two semi-rigid chest tubes, or twisted wires, can be bridged across the mediastinum and sutured against the sternal edges as a quick and simple approach to prevent an edematous heart from compression [57, 58].

**Clamshell closure.** Bilateral transverse thoracosternotomies can be closed by one or two figure-of-eight stainless steel wires that go through and cross-bridge both parts of the separated sternum. Conventional uncrossed loops into the bone do not prevent anteroposterior displacement of the sternal parts and may pose a risk to the already injured heart [59]. The transected internal mammary arteries must also be ligated prior to closure.

**Skin closure.** Consideration for sutured skin closure (versus stapled closure) is relevant in the rare scenario of massive postoperative hemorrhage requiring immediate re-entry into the chest.

Almost there! Pleural and pericardial drains are placed, and the LAT is closed. The patient is taken to the intensive care unit where he remains hypotensive, requiring norepinephrine at 11 mcg/min. **Are any further investigations needed or interventions likely?**

**Postoperative care and pitfalls**

Close postoperative evaluation is crucial to reduce the incidence of posttraumatic cardiac sequelae in patients with PCI. In-hospital postoperative care should include electrocardiogram monitoring and the liberal use of two-dimensional Doppler echocardiography. Tang and colleagues reported abnormal echocardiograms in 17.4% of penetrating cardiac trauma patients, with pericardial effusion (47%) being the most common finding (followed by wall motion abnormalities and reduced ejection fraction) [60]. Further investigation for etiologies of postoperative cardiac failure may elucidate coagulopathic tamponade, hemorrhage from the repair site, and/or acute myocardial infarction. Significant heart failure typically requires inotropic medications, and occasionally electromechanical device assists, for cardiac support. Accordingly, continuous hemodynamic monitoring is essential. Delayed hemorrhage from a traumatic or iatrogenic injury to an internal mammary artery should be considered as a cause of ongoing hypotension and prompt consideration of early re-exploration.

Posttraumatic acute myocardial infarction can be diagnosed with a combination of segmental wall motion abnormalities on echocardiography, electrocardiogram abnormalities, and serum troponin I levels. The latter two tests, however, have low specificity, as surgical and resuscitative maneuvers themselves create changes in both [61]. Subsequent cardiac assessment should incorporate differentiation of hemorrhagic, dynamic, or stenotic causes of infarction. Complete heart block and other conduction system abnormalities, which have been reported to occur in 2.8% of PCI patients, may warrant temporary placement of epicardial wires or transvenous pacing [62]. Possible symptoms, such as new murmurs or dyspnea on exertion, can alternatively indicate ventricular septal defects which are less common and can be managed conservatively in asymptomatic patients. Otherwise, transcatheter closure is preferred when possible to avoid further risks of open surgery with CPB. Similarly, other complex cardiac sequelae such as valvular injuries require close multidisciplinary communication and teamwork. Synchronous valvular injury in particular must be ruled out in cases of PCI, as 3 to 8% of patients will have a concurrent trauma to one or more heart valves.

Despite modern techniques and standard hygiene within cardiac surgery, sternal wound infections still occur at relevant rates with associated in-hospital mortality rates of up to 35% [52]. In a trauma patient, who may have undergone a rapid sternotomy with less than sterile technique in a rushed environment, special attention must be paid to postoperative infections. Although antimicrobial prophylaxis has been recommended for cardiac surgery, controversy remains over optimal dosing, duration, and timing. A combination of medical treatment and irrigation, VAC, or flap coverage should be utilized for these wound infections. Lastly, antimicrobial prophylaxis or treatment for other complications such as empyema and/or sepsis should be based upon factors such as the hospital antibiogram and specific site(s) of infection.

**Summary**

Penetrating cardiac injuries pose complex strategic, technical, and logistical challenges that test the performance of entire trauma systems. Acute care surgeons, with training and experience in the decision making and operative aspects of PCI, and with knowledge of systems of acute care, are well-positioned to lead comprehensive resuscitative and operative efforts. Technical depth and agility with respect damage control physiology and resuscitation, surgical exposure, injury control, cardiac repair, and chest closure can reduce the downstream consequences of PCI and the complications of surgery. With preparation, trauma and acute care surgeons can streamline the response to one of the most acute, time-dependent, and complex surgical crises. Early collaboration with our cardiac surgical colleagues and their perfusionist team, when available, can also be lifesaving.

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**Ethics approval**

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**Declaration of competing interest**

None of the authors have conflicts of interest related to this chapter or its subject.

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