Penetrating cardiac injuries: What you need to know

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ABSTRACT: Despite significant advances in trauma surgery in recent years, patients sustaining penetrating cardiac injuries still have an overall survival rate of 19%. A substantial number of deaths occur at the scene, while approximately 40% of those reaching trauma centers survive. To increase survival, the key factor is timely intervention for bleeding control, pericardial tamponade release, and definitive repair. Asymptomatic patients sustaining precordial wounds or mediastinal gunshot wounds should be assessed with chest ultrasound to rule out cardiac injuries. Shock on admission is an immediate indication of surgery repair. Patients admitted in posttraumatic cardiac arrest may benefit from resuscitative thoracotomy. The surgical team must be assured that appropriate personnel, equipment, instruments, and blood are immediately available in the operating room. A left anterolateral thoracotomy, which can be extended to a clamshell incision, and sternotomy are the most common surgical incisions. Identification of cardiac anatomical landmarks during surgery is vital to avoid complications. There are several technical options for bleeding control, and the surgeon must be trained to use them to obtain optimal results. Ultimately, prioritizing surgical intervention and using effective resuscitation strategies are essential for improving survival rates and outcomes. (*J Trauma Acute Care Surg.* 2024;00: 00–00. Copyright © 2024 Wolters Kluwer Health, Inc. All rights reserved.)

KEY WORDS: Cardiac injuries; heart trauma; ventricular injuries; atrial injuries; pericardial tamponade.

Penetrating cardiac injuries were first mentioned in Homer's poem *Iliad*, written in the 7th century.[1] For many centuries, they were considered lethal, with no chance of survival. Block (1882) and Del Vecchio (1895) demonstrated that suturing the heart was possible.[2] The first successful repair of a cardiac wound in humans was attributed to Rehn in 1886, in Frankfurt.[2]

Rhee et al.[3] reported cardiac wounds in 1:100.000 people yearly, 1:210 trauma admissions, 1:11 penetrating thoracic injuries, and 1:56 autopsies. More than half of patients with cardiac injury (55%) died at the scene. Of those arriving alive at the trauma center, 42% ultimately survived. Considering all patients, the survival rate was 19%. Similar survival rates were reported by Naughton et al.[4] in 1989.

Penetrating injuries to the heart are caused mainly by stab wounds (SWs) and gunshot wounds (GSWs). Gunshot wound is the most frequent mechanism of injury (58%).[3] There is an important difference in survival rates when comparing these two mechanisms: 9% for GSW and 33% for SW. Higher mortality rates associated with GSW have also been reported in other series.[5–12]

The vast majority of patients who reach the hospital alive have injuries amenable to repair by a trauma surgeon without the need for cardiopulmonary bypass.[13,14] To achieve optimal results, prompt diagnosis and immediate surgical intervention are critically important, particularly for those presenting in shock.[15,16] This review aims to offer the reader the essential information to attain the best results when treating patients with penetrating cardiac wounds.

ANATOMY

A list of specific anatomical structures that must be identified during the initial operation is provided hereinafter. They should be understood as markers of safety and should be used to avoid iatrogenic injuries and poor outcomes: 1, pericardial sac and its relationship with the phrenic nerves; 2, the left anterior descending artery (LAD), also known as the anterior interventricular branch of the left coronary artery, allows for the identification of the right and left ventricles anteriorly; 3, the circumflex artery (branch of the left coronary artery) runs in the left ventricular wall, supplying blood to the left lateral and posterior ventricular wall; 4, right and left atria — their walls are paper thin and must be carefully assessed so as not to overlook minor injuries; 5, great vessels, including the aorta, pulmonary artery and its bifurcation, and the superior and inferior vena cava; and 6, the electrical system: sinoatrial node, atrioventricular node, and the left and right bundle branches. Injuries to these sites may course with significant arrhythmias eventually observed after hemorrhage control.

Correctly identifying these structures is vital to plan the best surgical approach. For example, repairing wounds close to the LAD needs special attention to avoid occluding it during repair. In addition, strategies to control active bleeding depend on the anatomic location of the wound.

The right ventricle is injured more frequently (53%), followed by the left ventricle (32%), right atrium, and left atrium.[3,6,10,17] This is far more common in victims of SW because of the anterior anatomic position of the right ventricle. Other chambers are more frequently injured following GSW. Injuries to multiple chambers carry much higher mortality rates compared with single-chamber injuries.[3]

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INJURY SEVERITY STRATIFICATION

The American Association for the Surgery of Trauma Organ Injury Scale is the preferable injury severity classification, as it correlates with mortality (https://www.aast.org/resources-detail/injury-scoring-scale#heart).[18]

CLINICAL SCENARIOS AND INITIAL APPROACH

Patients sustaining cardiac injuries may have three different clinical presentations: (1) hemodynamically stable, (2) shock upon arrival, and (3) posttraumatic cardiac arrest. Mortality is directly related to the clinical presentation. The survival rate of those admitted in shock is approximately 35%, while it reaches 90% in hemodynamically stable patients.[3]

1. Hemodynamically stable patients

This presentation is often of a patient sustaining a penetrating injury to the chest or to the thoracoabdominal area. Having a high index of suspicion for cardiac injury with some degree of pericardial tamponade is critically important. A thorough clinical examination and the use of the extended focused assessment with sonography in trauma (eFAST) are warranted.[19]

The "cardiac box" is an area usually used to identify those with a higher chance of sustaining cardiac injuries, although its relevance has not been totally accepted.[7,20–23] It is bordered by the sternal notch superiorly, the xiphoid process inferiorly, and the middle axillary lines laterally.[7,14] Kim et al.[7] compared the incidence of cardiac injuries between patients sustaining external wounds within and outside the cardiac box. The frequency of cardiac injuries was significantly higher in patients sustaining wounds within the cardiac box (13.0% vs. 2.6%), mainly because of SW (14.3% vs. 2.4%).[7] It is important to emphasize that not all cardiac injuries will have an external wound located in the precordial area, particularly in cases of GSW.[24,25]

The diagnosis of a cardiac injury in hemodynamically stable patients with anterior chest wounds is of critical importance, as these patients may be in the early stages of pericardial tamponade, and delays in diagnosis may lead to deterioration of cardiocirculatory function and sudden cardiac arrest. For many years, the standard of care was to use a pericardiac window for diagnosis.[22,23,26] The procedure is frequently performed under general anesthesia in the operating room, with all resources available for an emergency surgical intervention (sternotomy or thoracotomy). There are three different surgical approaches to the pericardial sac when performing a diagnostic pericardial window: (*a*) Subxiphoid[20,21] (Fig. 1): the pericardial sac is accessed through a 4-cm incision below the xiphoid process. After opening the linea alba, access to the pericardial sac is obtained without entering the peritoneal cavity. If the xiphoid process makes the exposure difficult, it can be resected. Two Allis clamps are used to grasp the pericardium, which is lifted, and a small incision is made with scissors or a scalpel. The exit of blood or blood-tinged fluid confirms the violation of the pericardial sac by the initial injury.[22,23] (*b*) Transdiaphragmatic: this access is used during an exploratory laparotomy when there is a high index of suspicion that the trajectory of the wounding agent may have injured the heart or the pericardial sac. Access to the pericardial sac is obtained through a 3- to 4-cm longitudinal incision made in the central tendon of the diaphragm. There are also descriptions of laparoscopic approaches to the pericardial sac, although infrequently used. [27] (*c*) Video thoracoscopic approach: this approach is an option when video thoracoscopic approach is indicated for other reasons, such as when searching for the presence of a diaphragmatic injury or if a chest tube was initially placed.[26–28]

Currently, imaging technology is believed to be the preferable method to assess stable patients with anterior thoracic wounds. The FAST has gained great acceptance by most surgeons.[19,29] With a short learning curve, it is noninvasive, repeatable, free from ionizing radiation, and widely available. This point-of-care examination, when searching for the presence of fluid in the pericardial sac, showed high accuracy in diagnosing cardiac injuries. Rozycki et al.[29] reported an accuracy of 97% in detecting cardiac injuries, with zero false-negative examinations in the early experience with FAST. A complete echocardiography is an additional option when the FAST examination is questionable or inconclusive.[30–32]

A recent meta-analysis reported that, compared with a pericardial window, chest ultrasound was 79% sensitive and 92% specific.[32] However, there are potential challenges with FAST and echocardiography.[31–34] False-negative examinations may occur, leading to delays in diagnosis. Ball et al.[34] reported 5 cases of false negatives in 228 examinations. All of those cases had a concomitant left hemothorax caused by injury on the pericardial sac communicating with the left pleural cavity, causing a hemothorax and not allowing enough blood to accumulate inside the pericardial sac to be identified by the ultrasound.

2. Shock upon admission

Hemodynamic instability in patients with cardiac injuries occurs either because of active bleeding or because of pericardial tamponade. Both are emergencies and need prompt surgical intervention. Time to bleeding control is one of the most important

Figure 1. Subxiphoid pericardial window. (*A*) Pericardium grasped between forceps, (*B*) Metzenbaum scissors opening the pericardium, and (*C*) blood exiting the pericardial sac.

prognostic factors in unstable trauma patients.[35,36] Moreno et al.[37] reported that patients with documented pericardial tamponade had a survival rate of 73%, while patients with free bleeding into the pleural cavity had a survival rate of only 11%.

Care must be taken if the decision is to intubate a hypotensive patient in the emergency department. Eventually, the blockade of the sympathetic system may trigger a cardiac arrest. Therefore, the trauma team must anticipate the need for an emergency department thoracotomy (EDT) when marked hemodynamic instability or cardiac arrest occurs during intubation. [38]

Depending on the mechanism of injury, penetrating cardiac wounds may bleed into the mediastinum, the pleural cavity, and the peritoneal cavity. Most frequently, patients sustaining massive hemothorax should undergo prompt thoracotomy, as mortality is extremely high. The key is to avoid delaying bleeding control because of other unnecessary tests. A "direct to the operating room" resuscitation approach is likely the best strategy for patients who still have signs of life.[35,36,39,40]

A small amount of blood in the pericardial sac, when accumulated rapidly, is enough to create pericardial tamponade. Khaitan et al.[14] described the patient with pericardial tamponade as having a "dusky or death-like" appearance, with extreme anxiety ("I am going to die"), a sense of pressure in the chest, inability to lie flat, a progressive rise in central venous pressure if the diagnosis is delayed, and a late precipitous fall in blood pressure. Beck's triad (hypotension, muffled heart sounds, and jugular vein distention) is not easily recognized in the trauma resuscitation area, but when present, it helps in the diagnosis of pericardial tamponade, which is then confirmed by the eFAST examination demonstrating pericardial separation from the heart greater than 1 cm, dilated inferior vena cava, cardiac septal deviation to the right, and paradoxical movements in the right chambers. These signs are relevant in either stable or unstable patients.[29,30]

Pericardiocentesis should be avoided if surgical resources are available to evacuate pericardial blood and perform a formal cardiac repair. In cases of pericardial tamponade and significant hemodynamic instability, when the resources for definitive repair are unavailable, pericardiocentesis under ultrasound guidance may be a lifesaving procedure while resources are mobilized and the transfer process is arranged.

3. Posttraumatic cardiac arrest

Most patients with a penetrating injury to the chest presenting in cardiac arrest should be considered for an EDT, also known as resuscitative thoracotomy. [41] Factors such as duration of cardiopulmonary resuscitation, presence of a definitive airway, and signs of life must be considered when deciding to perform an EDT. The best outcomes are achieved in patients who arrested in the trauma resuscitation area or who had a short period of prehospital cardiopulmonary resuscitation (<10 minutes).[42–44]

In patients sustaining cardiac arrest secondary to a cardiac wound, EDT is indicated to release pericardial tamponade, hemorrhage control, aortic cross-clamping, prevention of air embolism, and open cardiac massage. Emergency department thoracotomy should also be performed in patients in extremis who are prearrest.[42–44]

Rohman et al.,[45] in 1983, described a physiologic classification of critical trauma patients in four groups to facilitate the decision to perform an EDT (Table 1). In their study, no patients classified as "dead on arrival" survived. Survival was approximately 30% in those considered "fatal" or "agonal and 40% in the "profound shock" group. The authors suggested that EDT was the best option for all "fatal" and "agonal," as well as for "profound shock" patients who did not improve rapidly with resuscitation. Coimbra et al.,[8] in 1995, reported different mortality rates using this same classification system: profound shock (45%), agonal (70%), fatal (100%), and dead on arrival (100%).

Rhee et al.,[46] in 2000, reviewed 24 studies for a total of 4,620 patients undergoing EDT for both blunt and penetrating trauma over a period of 25 years. Overall survival was 7.4%, with good neurologic outcomes in 92% of the survivors. Significant differences were observed among subgroups of patients. Penetrating injuries had 8.8% survival compared with 1.2% following blunt trauma. Stab wound had higher survival when compared with GSW (16.8% vs. 4.3%). Patients sustaining thoracic trauma had a survival of 10.7% compared with 4.5% in those sustaining abdominal injuries and 0.7% in polytrauma patients. The highest survival following EDT was observed in cardiac injuries (19.4%). The presence of signs of life on hospital admission was also accompanied by better survival rates (11.5%).

The American College of Surgeons Committee on Trauma, in 2001, defined signs of life as the presence of any of the following: pupillary response, spontaneous ventilation, presence of carotid pulse, measurable or palpable blood pressure, extremity movement, or cardiac electrical activity.[47] The absence of signs of life at the scene is associated with worse outcomes.[41,45,46]

An Eastern Association for the Surgery of Trauma practice management guideline regarding patient selection for EDT was published in 2015.[41] They strongly recommended EDT in patients presenting pulseless with signs of life after penetrating thoracic injury and conditionally recommended EDT for patients presenting pulseless and without signs of life.

The use of resuscitative endovascular balloon occlusion of the aorta (REBOA) in traumatic cardiac arrest has been controversial. In 2022, the Western Trauma Association published an algorithm delineating the indications for using REBOA.[48] They recommended against the use of REBOA if there is a considerable risk of thoracic vascular injury. At this moment, and until additional new data are reported, REBOA in the setting of cardiac tamponade and cardiac arrest due to a penetrating or blunt cardiac injury is not supported by evidence, and it should be avoided.

TABLE 1. Admission Physiologic Status Classification[45]

	Characteristics	Survival
Death on arrival	No signs of life in transit	0
Fatal	Unconscious No vital signs No spontaneous respiration No spontaneous physical activity Signs of life present in transit	32%
Agonal	Semiconscious Thready pulse Gasping respiration	33%
Profound Shock	Conscious Measurable systolic blood pressure (<70 mm Hg)	40%

RESUSCITATION ADJUNCTS

In parallel with the repair of anatomic injuries, it is essential to prevent, identify, and correct the physiologic derangements accompanying major hemorrhage, particularly trauma-induced coagulopathy.[49–53]

Trauma-induced coagulopathy occurs early after severe injury.[51,54] Therefore, modern resuscitation strategies should start in the prehospital phase of care. Recent data suggest that whole blood and blood component administration, including plasma in the prehospital setting, is accompanied by increased survival and less severe coagulopathy upon arrival to the hospital.[51,55–59]

In the hospital setting, rapid hemorrhage control; damage-control hemostatic resuscitation; permissive hypotension; early use of whole blood or blood components in a 1:1:1 ratio of packed red cells, plasma, and platelets (as defined in the institutional massive transfusion protocol); and aggressive warming are the first steps.[51,54,60] The use of viscoelastic tests (thormboelastography/rotational thromboelastometry) may help guide the use of blood components and adjuncts (prothrombin complex concentrate, tranexamic acid, and fibrinogen).[61,62] Aggressive resuscitation and bleeding control should improve metabolic acidosis. Similarly, adequate oxygen delivery should be reestablished, as intravascular volume expansion is achieved with blood transfusion, and oxygenation and ventilation are optimized by mechanical ventilation.

Despite being uncommon, arrhythmias may complicate the management of patients with cardiac injuries, especially in hypotensive, acidotic, and hypothermic patients. The management of arrhythmias should follow the current advanced cardiac life support protocols, although the management of hypothermia and acidosis is critical for antiarrhythmic drugs to work properly.[17] With the aging population, it is not rare to find patients taking medications that affect their hemodynamic status. Elderly patients are more prone to hemodynamic collapse due to cardiac failure associated with profound hypovolemia.[63–65] A point-of-care cardiac ultrasound may help differentiate between the need for additional volume expansion and inotropes.[19,66]

SURGICAL MANAGEMENT OF CARDIAC INJURIES IN THE OPERATING ROOM

The surgical team must be assured that appropriate personnel, equipment, instruments, and blood are immediately available in the operating room. Foley catheters, staplers, adequate suture material (2-0, 3-0, and 4-0 polypropylene sutures on tapered 3/8 circumference needles), a Finochietto retractor, Duval lung forceps, vascular clamps (DeBakey for aortic cross-clamping and a Satinsky clamp), one pair of long Russian forceps, hemostats, one pair of long scissors, and one pair of suture scissors should be immediately available. The thoracotomy trauma tray should also include a power sternal saw, a Lebsche knife with a hammer, and a bone cutter. An internal defibrillator and all equipment for internal and external pacemaker placement are essential and should be at hand. In addition, the presence of a pharmacist is extremely helpful if drugs and infusion solutions are needed in cases of hemodynamic decompensation, arrhythmias, and cardiac arrest. The Cell Saver equipment, to allow reinfusion of shed blood, is critically important in patients who are coagulopathic and bleeding massively.

A clear surgical plan should be quickly discussed with the nursing and anesthesia teams while the patient is being prepped. The trauma surgeon must lead the resuscitation team while performing the cardiac repair. Communication between surgeons and anesthesiologists is crucial at all times. Surgeons must be informed when vasopressors and inotropes are used.[16,17,67]

A trauma surgeon should be able to deal with most acute cardiac injuries. The use of cardiopulmonary bypass in the acute setting is uncommon and not accompanied by better outcomes than primary repair.[14] Although large ventricular injuries and injuries to the proximal coronary vessels may benefit from the expertise of a cardiac surgeon and cardiopulmonary bypass, by the time the resources are mobilized and the team is assembled, it is usually too late.

Most atrial and ventricular defects are repaired primarily. The trauma surgeon must have a high index of suspicion, based on trajectory, for most valvular and septal injuries, which must be investigated by a transesophageal echocardiogram intraoperatively or by a transthoracic echocardiogram as soon as the initial operation is completed, and the patient is transported to the surgical intensive care unit.

SURGICAL ACCESS AND ANATOMICAL EXPOSURE

The patient should be positioned supine with both arms out. The type of incision depends on the hemodynamic condition of the patient, potential associated injuries, the need for aortic cross-clamping, the (probable) anatomical site of the cardiac injury, equipment availability (especially those necessary for sternotomy), and team training.[14,16,67–69] The skin should be prepared from the neck to the groins. Cardiac monitoring leads are usually placed on the back of the patient.

LEFT ANTEROLATERAL THORACOTOMY

A left anterolateral thoracotomy (LALT) through the fourth or fifth intercostal space can be accomplished rapidly. The inframammary fold is a reliable landmark following the costal margin toward the scapula.[16] If there is no time for hemostasis, the surgeon can incise all the muscles (pectoralis major and pectoralis minor anteriorly and serratus anterior muscle posteriorly) to access the thoracic cavity using an electrocautery or a scalpel. Hemostasis may be obtained temporarily using laparotomy pads applied on the wound edges. Only large arterial bleeders from the chest wall should be ligated at this time. Definitive hemostasis of the chest wall is obtained after the cardiac repair is completed. A pleural incision should be made close to the rib's cranial (superior) border to avoid additional injury to the neurovascular bundle, which runs on the inferior border of the rib. The distal aspect of the arms of the Finochietto retractor should face the sternum. If the exposure of the left chest cavity is not adequate, intentionally detaching one or two ribs from the sternum may increase exposure.

This incision guarantees access to the anterior, left, and posterior aspects of the heart. It also allows aortic cross-clamping, which is essential in severely hypotensive patients or in those in cardiac arrest. Furthermore, the extension to the contralateral side (clamshell thoracotomy) through a transverse sternotomy gives access to the right chest and provides excellent exposure to both thoracic cavities and the mediastinum. These advantages make a LALT the best choice for hemodynamically unstable patients or those in cardiac arrest.[14,16,68,69]

EXTENSION OF LALT TO CLAMSHELL THORACOTOMY

A LALT may not adequately expose the right side of the heart. In cases of confirmed or suspected injuries of the right atrium and the lateral and posterior right ventricle, a clamshell thoracotomy is indicated. In addition, this incision is extremely useful in cases where there is suspicion of associated mediastinal vessel and pulmonary hilar injuries.[14,16] The sternum may be cut with heavy scissors, a Lebsche knife, or a Gigli saw.[16] Care must be taken to identify and ligate the internal thoracic arteries (internal mammary artery) bilaterally. These arteries run parallel to the sternum and usually are a source of unnecessary additional bleeding.

MEDIAN STERNOTOMY

A median sternotomy is an ideal incision for stable patients sustaining a precordial SW.[16,68,69] In these cases, associated injuries are not expected, and aortic cross-clamping is not usually necessary. Median sternotomy is associated with better postoperative pulmonary function and shorter hospital stay when compared with a LALT.[70] With adequate instruments, a median sternotomy can be completed rather quickly. This incision has also been selectively used in patients with hemodynamic instability.

A few relevant technical aspects of this incision are worth mentioning: (*a*) placement of a roll, beanbag, or pillow positioned posteriorly between the shoulder blades allows better exposure of the anterior chest wall; (*b*) the incision should extend at least for 3 to 4 cm cranially to the sternum; (*c*) the sternal notch must be completely cleared and separated from the interclavicular ligaments to allow for safe blunt dissection of the space posterior to the sternum; (*d*) prior to cutting the sternum with an electrical sternal saw or with a Lebsche knife, the index finger of the surgeon must clear the posterior wall of the sternum superiorly and inferiorly, and anterior traction must be applied to the sternum to avoid iatrogenic injuries to mediastinal structures; and (*e*) as the sternum is opened, it is advisable to ask the anesthesiologist to use low-volume ventilation or to hold ventilation in the expiratory phase to decrease lung expansion.[70]

Adequate closure of the sternum at the end of the operation is critical. Bone wax may be used to achieve hemostasis of the sternal edges, which are approximated tightly using wire sutures in a figure-of-eight fashion. The presternal fascia should also be closed tightly.

PERICARDIUM OPENING

In cases of a LALT, after identification of the left phrenic nerve, the pericardial sac can be grasped by two hemostats placed anteriorly to the nerve and then opened longitudinally. The right phrenic nerve should not be forgotten, but it is more distant. Injury to the phrenic nerve causes diaphragmatic paralysis and should be avoided.

In cases where a median sternotomy is performed for mediastinal access, a pericardial incision is made anteriorly and distant from both phrenic nerves.

INJURY ASSESSMENT AND BLEEDING CONTROL

After opening the pericardium, if there is considerable bleeding from the wound, bleeding control may be obtained by placing the index finger or a "sponge on a stick" over the laceration, followed by a swift repair using a series of pledgeted or unpledgeted U-type stitches of 3-0 or 4-0 polypropylene sutures.[14]

If, after the initial repair, the patient develops cardiac arrest, cross-clamping of the descending aorta, cardiac compressions, and intravenous or intracardiac drugs (1 mg epinephrine, repeated after 2 minutes) should be performed. Internal defibrillation should be used when ventricular fibrillation or pulseless ventricular tachycardia occurs. Internal paddles should be placed anteriorly and posteriorly to the heart, and shocks at 10 to 50 J are deployed.[67] After restoration of cardiac rhythm, the use of intravenous lidocaine or amiodarone should be considered. The participation of the anesthesia team in managing the reversal of metabolic acidosis is critically important. In cases of asystole or pulseless electrical activity, internal cardiac massage should be continued, and epinephrine, 1 mg intravenously every 3 to 5 minutes, should be given.[14]

The surgeon must address the extent of heart injuries by examining all cardiac chambers anteriorly and posteriorly. The examination of the posterior aspect of the heart must be done carefully, as lifting the heart toward its base may lead to sudden cardiac arrest due to kinking of the vena cava, which must be treated with intravenous or intracardiac epinephrine (1 mg) and cardiac massage immediately after repair of the cardiac injury and repositioning the heart to its natural position. In most circumstances, the examination of the posterior wall of the heart may be simply accomplished by applying a surgical pad to the lateral wall of the left ventricle and gently rotating it anteriorly, allowing palpation and direct examination. Another alternative is to use a Satinsky clamp applied to the tip of the right ventricle without occluding the distal portion of the LAD. The clamp is then used to gently lift the heart from its normal anatomical position in the pericardial sac.[71]

Of note, in cases of large or complex anterior or posterior ventricular injuries, the surgeon may use inflow occlusion by cross-clamping the vena cava to rapidly induce severe bradycardia and cardiac arrest, which may allow a quick repair before the heart is restarted with the same pharmacologic approach described previously. Alternatively, the use of 3 to 12 mg of intravenous adenosine will also cause asystole 30 seconds after drug administration, which will last less than a minute and can be used to either repair complex cardiac lacerations or examine the posterior aspect of the heart. Additional doses of adenosine may be necessary to complete a complex repair.[14,72–75]

The identification of the coronary arteries and their proximity to the injury is critically important to plan a safe repair without the risk of occluding the vessel. In GSW cases, the bullet may be inside the heart or may have already caused distal embolization. This is particularly probable in cases where just one heart wound is found.

Large lacerations may allow air to enter the ventricles causing coronary artery air embolism. This is easily diagnosed by the presence of bubbles of air in the coronary arteries and requires immediately positioning the patient in the Trendelemburg position and aspirating air from the ventricle, as this condition is usually fatal.[14]

A few additional technical aspects are worth mentioning. Open cardiac massage should be done with two hands, one placed anteriorly and the other posteriorly to the heart. Gentle rhythmic compressions between the two hands from the apex to the base of the heart, allowing time for the heart to fill, are usually effective. Care must be taken to avoid additional injury to the heart, enlarging the traumatic lacerations, and damaging the initial repair.

Epicardial pacing should be used when bradycardia unresponsive to multiple doses of atropine occurs, likely because of an atrioventricular block. The epicardial pacing wires should be placed in the upper part of the anterior wall of the right ventricle (one at the top and the other 1 cm below). The maximal current output of 10 mA is used.[67]

TEMPORARY MEASURES TO ACHIEVE BLEEDING CONTROL

The best tool to stop bleeding from a small cardiac wound is the surgeon's index finger. In larger wounds, there are other options. Much has been written and discussed about inserting a Foley catheter through the wound, insufflating the balloon, applying gentle traction, and pulling the balloon against the cardiac wall to temporarily control the bleeding. Although effective, this maneuver is accompanied by complications. The cardiac wall may become enlarged if traction of the catheter is excessive and the inflated balloon pops out of the heart. In addition, at every stitch placed in the heart, the balloon must be further inserted inside the ventricle to avoid rupture of the balloon by the needle or having the catheter caught in the suture line.[14]

Staplers with 6-mm staples may be used to rapidly close bleeding wounds both in the atria or ventricles, particularly during an EDT.[76–78] In those circumstances, some surgeons advocate performing definitive repair with sutures in the operating room and removing the staples, while others suggest that the staples can be left in place without problems.[16,77]

Crossed horizontal mattress sutures are also used to control bleeding in ventricular injuries. They are placed parallel to the ventricular wound, on both sides, while the index finger occludes the laceration. The sutures then cross against each other to occlude the wound, allowing a continuous permanent suture or staples to be placed as definitive repair.[14]

In atrial/auricular injuries, bleeding control may be successfully obtained by placing a Satinsky clamp under the laceration area. Alternatively, using sequential Allis clamps in atrial wounds when the Satinsky clamp cannot be placed is also effective in controlling bleeding and aligning the edges of the laceration for suture repair.[14]

DEFINITIVE MANAGEMENT

Atrial wounds are usually repaired using running 4-0 polypropylene sutures placed 5 mm beyond the edges of the wound (Fig. 2).[14,69] Pledgets are not required because of the low pressure of these chambers. Ventricular wounds are commonly repaired by full-thickness 3-0 polypropylene U-type sutures (Fig. 3). The atraumatic needle should be large enough to be inserted in one side of the wound and retrieved on the other in one pass, placed approximately 1 cm away from the edge of the wound. Small "bites" may tear the muscle, enlarging the wound and worsening the situation. Large lacerations may benefit from pledgets to reinforce the suture line and avoid tearing through the cardiac muscle. In cases of cardiac arrest, a pledgeted repair is advised before internal cardiac massage is performed. 5 mm Teflon pledgets are usually utilized, but small pieces of pericardium can also be used (Fig. 3).

The most common way to place sutures in a beating heart involves the coordinated participation of the operating surgeon and the first assistant. The surgeon compresses the wound with the tip of the index finger of the nondominant hand, stopping the bleeding. A full-thickness stitch is passed underneath the finger. The first assistant is responsible for limiting the heart movement by holding the heart firmly with two hands when the suture is being placed and grasping the tip of the needle as it passes through the opposite edge of the wound. Eventually, the cardiac muscle around the wound can be grasped between the thumb and the index finger of the surgeon's nondominant hand, decreasing the bleed, and allowing a safer suture. Partial thickness

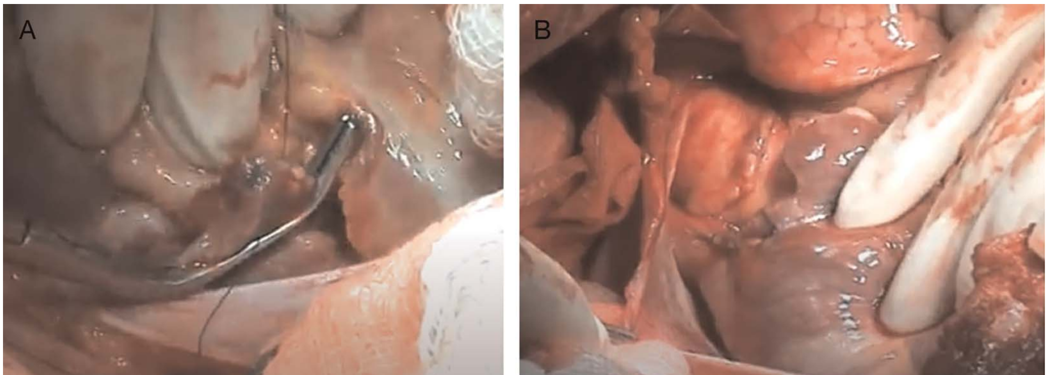

Figure 2. Repair of atrial injuries. (*A*) Satinsky clamp placed under a left atrial laceration; (*B*) running suture with 4-0 polypropylene occluding an injury in the right atrium and superior vena cava.

Figure 3. Repair of ventricular injuries. (*A*) Full-thickness left ventricular wounds (2): one repaired with 3-0 polypropylene U-type pledgeted sutures and the other with staples, (*B*) partial-thickness injury of the left ventricle, and (*C*) repair with Teflon reinforcement.

wounds should be repaired to prevent ventricular pseudoaneurysms.[14] Frances et al.[79] reported that 7% of left ventricular pseudoaneurysms were due to trauma.

If the wound is too close to a coronary artery, U-type stitches should be placed under the vessel. Sometimes, the injury is so close to the coronary artery that simple traction would occlude it. In these cases, a sutureless approach can be used by the application of a collagen mesh covered with fibrin glue.[80] Distal coronary artery injuries may be ligated, but all proximal injuries must be repaired, which constitutes an indication for consultation with the cardiovascular team. Wall et al.[81] reported mortality above 60% in coronary artery injuries, depending on the location and treatment. The decision about repairing a coronary artery injury under cardiopulmonary bypass is complex and should be made together with the cardiac surgeon. Myocardial revascularization can be accomplished off-pump, depending on the experience of the cardiac surgeon.[82,83]

Posterior wounds are more difficult to manage. As previously mentioned, the exposure is challenging because elevating the heart may obstruct the blood inflow or cause caval kinking, as well as entry of air into the injured ventricle, resulting in an airlock or even coronary air embolism in hypovolemic patients.[14] When normovolemia is restored, it is possible to elevate the heart with a Duval or a Satinky clamp applied to the apex of the heart.[71] The surgeon can alternate elevating the heart for a moment, placing a stitch, and putting the heart in its anatomic position, repeating the procedure until the wound is completely closed. Laparotomy pads can be placed posteriorly to the heart, helping to expose the injured area.

CLOSURE OF THE CHEST

We do not recommend closing the pericardium, unless the left pleura is open and the heart "herniates" into the left pleural cavity. Mediastinal and pleural drains (if the pleura was opened) are routinely used. Conventional closure of the thoracotomy incision by layers after obtaining adequate hemostasis and closure of a median sternotomy with figure-of-eight stitches using wire sutures are recommended.

POSTREPAIR MANAGEMENT

When there is suspicion of an intracardiac injury, a transesophageal echocardiogram is indicated before the chest is closed.[84,85] If a thrill is not felt on careful heart palpation, the rhythm is normal, and the patient is hemodynamically stable, a mandatory postoperative complete echocardiogram should be obtained while the patient is in the intensive care unit.

A summary list of critical decisions, options, and tips and tricks in the management of penetrating cardiac injuries is presented in Table 2.

CURRENT CONTROVERSIES: NONOPERATIVE/ MINIMALLY INVASIVE MANAGEMENT

During the last decades, surgeons assumed that a positive pericardial window in patients sustaining precordial wounds demanded surgical exploration of the heart via sternotomy or thoracotomy. Currently, a paradigm shift is being proposed by some authors.[49,86–89]

Navsaria and Nicol,[87] in 2005, analyzed 14 stable patients with hemopericardium diagnosed by pericardial window who subsequently underwent a sternotomy. Of those, 10 (71%) with American Association for the Surgery of Trauma grades I to III had nontherapeutic sternotomies. With this knowledge, they treated the next seven patients with pericardial window and irrigation only. If there was no active bleeding after irrigation of the pericardial sac, a drain was placed, and the patient was admitted to the intensive care unit for close monitoring. There were no complications related to the procedure. Thorson et al.,[89] in 2012, found that 38% of the patients with positive pericardial windows had no repairable cardiac or great vessel injury.

Nicol et al.,[86] in 2014, published a randomized controlled trial including hemodynamically stable patients with hemopericardium confirmed by subxiphoid pericardial window without active bleeding. Fifty-five patients underwent sternotomy, and 56 were treated by pericardial window and drainage only. In the sternotomy group, 93% of the patients had no cardiac injury or tangential wounds. The authors suggest that a pericardial window and drainage are a safe choice for stable patients with penetrating injuries and hemopericardium.[86] In 2018, Chestovich et al.[88] reported 21 stable patients with hemopericardium diagnosed by a pericardial window. Of those, 16 underwent sternotomy, and 5 were treated by pericardial irrigation and drainage. No complications or rebleeding were observed in those treated conservatively, and none required surgical exploration.[88] More recently, Selvakumar et al.[23] reviewed the diagnostic and therapeutic role of a pericardial window. The authors concluded that a pericardial window can be an effective therapeutic modality in stable patients.

CONCLUSION

Cardiac injuries are highly lethal. The surgical team must be trained to rapidly diagnose and achieve hemostasis, release cardiac tamponade, and accomplish definitive repair. There must be well-established processes for immediate access to the

TABLE 2. Critical Decisions in the Management of Penetrating Cardiac Injuries

Critical Decision	Options	Tips and Tricks
Incisions	– LALT – Clamshell thoracotomy – Sternotomy	– Use LALT for unstable patients and/or patients with suspected associated injuries (mediastinal GSW) – Uses sternotomy in stable patients and when suspicious for associated hilar or major vascular injury – Cardiac monitoring; place electrocardiogram leads on the back – OR table positioning: supine with arms out – Prep skin from chin to knees – Check equipment/materials/surgical trays/blood – Correct hypothermia
Pericardium opening and initial injury assessment	– Longitudinal pericardial incision, anterior to phrenic nerve – Aspirate blood, evacuate clots, examine the heart thoroughly – Assess the cardiac rhythm – Injury assessment: number, location, anatomy, and presence of active bleeding – If in cardiac arrest: repair the injury first, cross-clamp the aorta, internal cardiac massage, drugs – Consider internal defibrillation if indicated	– Inform surgical plan to the anesthesiologist – Open the pericardium widely – Examine the heart anteriorly and posteriorly, and the great vessels – Try to determine the missile trajectory – If GSW and only one hole found, consider bullet embolism – Be prepared to defibrillate if necessary
Bleeding control	Ventricular wounds: – Surgeon's index finger, Foley catheter, staples, crossed mattress sutures. – If injury is too large and bleeding cannot be controlled: Atrial injuries: – Use Satinsky or sequential Allis clamps	– After bleeding control, develop a plan for definitive repair – Confirm that hemostatic resuscitation is being delivered – Address and treat coagulopathy aggressively – If bleeding control is not possible, consider inducing temporary cardiac arrest by venous inflow or IV adenosine (see text)
Surgical exposure	– Right side injuries: consider extension to clamshell – Posterior injuries: elevate the apex by applying a Duval or Satinsky clamp and/or positioning surgical packs to gently rotate the heart	– Assure the best exposure before starting the repair – The first assistant stabilizes the beating heart by holding and compressing the area around the laceration with both hands
Injury repair	Ventricular wounds: – U-type interrupted stitches – Figure-of-eight horizontal mattress – Running suture – Staples (usually used during EDT) Atrial injuries: – Running sutures under Satinsky or Allis clamps	– Use nonabsorbable sutures (polypropylene) on a large, tapered needle – Use pledgeted sutures in larger wounds (>5 mm) located in higher pressure chambers or when cardiac massage is necessary – Identify the coronary arteries in the proximity of lacerations – Be careful not to enlarge the laceration. The needle must move with the heart. Tie gently.
Postrepair reassessment	– If oozing from the wound is observed after suturing, consider local hemostatic agents – If arrhythmia is present, try to identify the cause: Ischemia? Metabolic? Internal injury? Consider epicardial pacemaker placement in severe bradycardia in the OR. – If a heart thrill is identified after the initial repair, consider the presence of an internal injury. Diagnose with transesophageal echocardiogram. If confirmed, consult cardiac surgery. – Identify and ligate a transected internal mammary artery prior to closing the chest – If the patient is in critical clinical condition after the repair, consider damage-control surgery, leaving the chest open	– If the patient remains unstable after initial cardiac repair, assess for additional injuries elsewhere – Diffuse bleeding indicating that ongoing coagulopathy may require packing the chest and chest wall
Chest closure	– The pericardium does not need to be routinely closed – If the patient is in critical clinical condition after the repair, consider damage-control surgery, leaving the chest open and use temporary closure (vacuum pack)	– After internal cardiac massage, the heart can enlarge considerably. Do not close the pericardium. If the heart “herniates” into the left chest, approximate the edges of the pericardial sac loosely to keep the heart in its anatomical position.

IV, intravenous; OR, operating room.

operating room, hemostatic resuscitation, and aggressive treatment of coagulopathy. Specific surgical equipment and materials must be readily available. Blood in the pericardium must be ruled out by eFAST in stable patients presenting with a penetrating injury in the anterior chest. The best approach for stable patients with hemopericardium (sternotomy, pericardial drainage, or nonoperative management) is still under investigation. Hemodynamically unstable patients should be transported immediately to the operating room. Patients sustaining prehospital cardiac arrest may benefit from an EDT if transport time is short or if the arrest occurred upon admission to the trauma center.

AUTHORSHIP

R.C. contributed in the conception and study design. R.C. and J.G.P. contributed in the literature review. J.G.P. contributed in the drafting of the manuscript. R.C. and J.G.P. contributed in the critical revision.

DISCLOSURE

Conflicts of Interest: Author Disclosure forms have been supplied and are provided as Supplemental Digital Content (http://links.lww.com/TA/E138).

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