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PENETRATING CARDIAC INJURIES. COMPLEX INJURIES AND DIFFICULT CHALLENGES

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INTRODUCTION

The heart is a unique organ, vital and constant it's tireless function, working 24 hours a day during the entire life time of an individual. It has inspired many talented poets, writers and musicians throughout the ages. The first description of a cardiac injury is found is Homer's poetic description of the death of Sarpedon from the classical Greek epic The Iliad (1,2).

Cardiac injuries remain amongst the most challenging of all injuries seen in the field of trauma surgery. Their management often requires immediate surgical intervention, excellent surgical technique and the ability to provide excellent surgical critical care to these patients postoperatively.

HISTORICAL PERSPECTIVE

Cardiac injuries have been well described throughout the times. The history of the management of these injuries is fascinating. However, it would take a separate paper to just detail the history. The earliest description of cardiac injuries appear in the Iliad (1,2) which contains specific references to exsanguination as a cause of death and weapons piercing the heart. Other earlier descriptions of penetrating chest wounds can be found in the Edwin Smith Papyrus (3) written around 3,000 BC.

Beck (4) classifies the history of cardiac injuries according to three historical periods. First, the period of mysticism, in which wounds of the heart were described but were considered to be uniformly fatal. This period extended into the 17^{th} century. This is followed by the period of observation and experimentation, culminating in the period of suture, which had its beginnings in 1882. It is in this period that definitive repair and many of the current surgical techniques of we know today were developed.

Hippocrates (5), stated that all wounds of the heart were deadly. Ovid, Celsus, Pliny, Aristotle, and Galen (6-10) regarded all cardiac wounds as fatal. Paulus Aegineta (11) described the venting of the pericardial tamponade. Fallopius (12) described the difference between wounds of the right and left ventricles. None other Ambrose Pare (13) described the presenting signs for cardiac injuries. Similarly, Pare (14) also described in his classic masterpiece the Apologie and Treatise, the prognosis of cardiac wounds. He described autopsy results of patients sustaining injuries to the heart (15). Fabricius (16) and Boerhaave (17) also wrote extensively describing the futility of the management of these injuries.

However, in the 17^{th} Century, the stronghold of these firmly entrenched concepts was broken by Hollerius (18), a French surgeon who was first to advance the idea that wounds of the heart can heal and are not all necessary fatal. Wolf (19) in 1642, described a healed wound to the heart. His observation remained forgotten for over a century until Senac (20) arrived at the same conclusion. Morgagni (21) in 1761 described the effects of compression to the heart due to hemorrhage into the pericardium. Larrey (22) in 1810 was first to describe the approach and surgical technique to deal with a pericardial effusion. In 1829 Larrey (23) described a case of a wound of the pericardium in patient that recovered which he treated by passing a catheter into the stab wound of the chest.

Dupuytren (24) was a strong advocate of venisection to deal with cardiac injuries. Jobert (25) in 1839 observed that the life span of a cardiac wound is related to the amount of blood contained in the pericardium. With this observation, the advocated passage of sounds and catheters to evacuate blood from the pericardium. During this period of time, numerous case reports began to appear in the literature, as well as the first attempts to collect these cases. For the first time authors studied the presentation of cardiac injuries and reviewed post-mortem studies. Purple (26) in 1850 compiled a total of 42 cases. Fischer (27) in 1868 collected 452 cases and reported a 10% survival rate from the literature.

During this period of time no less a prominent figure in the european surgical stage than Billroth (28) expressed strong disagreement with any surgeon attempting to repair cardiac injuries. In 1875 he made his strong views well known to the surgical world "Paracentesis of the pericardium is an operation which, in my opinion, approaches very closely to the kind of intervention which some surgeons would term a prostitution of the surgical act and other madness." Billroth (29), for reasons unknown continued to proclaim his opposition to cardiac injury repair. In 1883 he pronounced at a surgical meeting "the surgeon who should attempt to suture a wound of the heart would lose the respect of his colleagues." Furthermore, another statement attributed to him is "let no man dare to operate upon the heart (28). It is not known why a man of his stature in the surgical field would be so adamant against this life saving intervention (30,31).

However, other surgeons emerged to challenge Billroth. Roberts (32) in 1881 suggested the possibility that cardiac injuries could be sutured but did not attempt to do so. The period of suture had its beginnings in the animal experiments by Block (33), who in 1882 utilizing a rabbit model, created cardiac wounds and was successful in repairing them, thus demonstrating successful recovery of the animals and suggesting that the same techniques could applicable in humans. Nevertheless, other surgeons continued to support Billroth and his negative view of surgeons who would attempt to repair cardiac injuries. Riedinger (34) in 1882 dismissed anyone who would attempt to suture heart. Paget (35) states in his classical textbook, Surgery of the Chest: "Surgery of the heart has probably reached limits set by nature to all surgery." Still others were not deterred. Del Vecchio (36) followed the footsteps of Block (33) and created a canine model in which he sutured the heart.

The first attempt at repairing a cardiac injury was by Cappelen (37) in 1896 in Christiania (the old name for Oslo). He repaired a laceration of the left ventricle and ligated the distal left anterior descending coronary artery. The patient succumbed in the immediate postoperative period. Also in 1896, Farina (38) of Rome attempted the unsuccessful repair of a left ventricular stab wound. The first successful attempt is credited to Rehn (39) of Frankfurt, Germany, who also in 1896 successfully repaired a wound of the right ventricle resulting in the patient's survival. From this moment on the era of cardiac surgery was born.

Other important contributions to this field were made by Duval (40), who in 1897 described the median sternotomy incision. The ingenuity needed to overcome the surgical inabilities in draining and restoring negative intrathoracic pressure after opening the chest resulted in the development of different surgical approaches to the heart. This included the quadrangular flap with an external hinge, which included two of five cartilages developed in 1900 by Fontan (41). Hill (42), an american surgeon was the first to successfully repair a stab wound to the left ventricle in 1902. Dalton (43) and Williams44 in 1895 and 1897 respectively reported pericardial operations. Spangaro (45) an italian surgeon described in 1906 the left anterolateral thoracotomy. While Sauerbruch (46) in 1907 described a technique for controlling hemorrhage from wounds of the heart by obstructing flow of blood that compression of his bace.

Matas (47) described the dangers of rapidly relieving a pericardial tamponade, which could result in exsanguinating hemorrhage. Peck (48) in 1909 described a series of cardiac injuries collected from the literature and also described many of the surgical techniques of cardiorrhaphy that are still widely used today. Pool (49) in 1912 also collected additional cases and his own series and fully described surgical techniques in the management of cardiac injuries concluding that; "the treatment of heart wounds should be surgical." Borchardt (50) provided evidence that the classical syndrome of pericardial tamponade was often absent from the clinical presentation of these injuries.

Other important contributions made to cardiac injury management were by Ballance (51) in 1920, whom delivered the Bradshaw lecture on surgery of the heart, which to this day remains one of the most comprehensive treatises in cardiac injury management. Smith (52) in 1923 developed a comprehensive plan for cardiac injury management and for the first time pointed out the dangers of disrhythmias during cardiac manipulation. He also described the use of an Allis clamp near the apex to stabilize and hold the heart while sutures were being placed. He was first to tabulate and analyze the mortality of cardiac injuries stratified to the chambers injured (52).

Beck (4) in 1926 described the physiology of cardiac tamponade and reported the results of animal studies. Similarly, Shoenfeld (53) in 1928, and Bigger (54) in 1939 reported their collective experiences in the management of cardiac injuries. Elkin (55) in 1941 recommended the use of fluoroscopy to assess cardiac motion and alerted surgeons to the danger of ice pick injuries while describing the advantages and disadvantages of the median sternotomy and the left anterolateral thoracotomy. Furthermore, he described the use of a clamp to control hemorrhage from atrial wounds. Beck (56) in 1942 pointed to the necessity of sparing ligation of coronary arteries in wounds adjacent to these structures. Turner (57) in 1942, after reviewing the experience for cardiac injury management during World War I pointed to the need of emergency treatment of cardiac injuries.

Griswold (58) in 1942 described his experience and pointed to the cause of death in cardiac injuries as either exsanguination or tamponade. Perhaps his most important recommendation was that every large hospital should have available an operating room and instruments at all times. This set the stage for the development of modern day trauma centers. Blalock and Ravitch (59) in 1943 described the use of pericardiocentesis for the management of cardiac injuries during World War II and observed that some wounds of the heart may seal and stop bleeding spontaneously. Elkin (60) in 1944 recommended the administration of intravenous infusions prior to operation and pointed to the beneficial effects of increasing blood volume and thus cardiac output, while Harken (61) in 1946 drawing upon his experience the management of thoracic injuries during World War II described techniques to remove foreign bodies adjacent to the heart and major blood vessels.

CLINICAL PRESENTATION OF CARDIAC INJURIES

The clinical presentations of penetrating cardiac injuries range from complete hemodynamic stability to acute cardiovascular collapse and frank cardiopulmonary arrest. The clinical presentation can also be related to several factors, including the wounding mechanism; the length of time elapsed prior to arrival in a trauma center; the extent of the injury, which if sufficiently large, causes exsanguinating hemorrhage into the left hemithoracic cavity; whether blood loss exceeds 40 to 50% of the intravascular blood volume, resulting in cessation of cardiac function and whether a pericardial tamponade is present or absent (62).

Beck's Triad (4) represents the classical presentation of the patient arriving in the emergency department with a full blown pericardial tamponade. Kussmaul's sign originally described as jugular venous distention upon expiration is another classic sign attributed to pericardial tamponade. In reality, the presence of either Beck's Triad4 or Kussmaul sign represent the exception rather than the rule. Most importantly, the trauma surgeon must be cognizant that cardiac injuries can be extremely deceptive in their clinical presentation, particularly thoracoabdominal injuries which can be quite lethal (63).

Patients sustaining high velocity missile injuries with massive tissue destruction; patients who arrive late in the trauma center, those that have experienced cardiopulmonary arrest for prolong periods of time and those that lose the majority of their blood volume into the left hemithoracic cavity invariably develop cardiopulmonary arrest with little chance for survival (62).

The physiology of pericardial tamponade is related to the fibrous nature of the pericardium, which renders it relatively inelastic and non-compliant to any sudden increases and intrapericardial pressure. Sudden acute losses of intracardiac blood volume lead to acute intrapericardial rises of pressure and compression of the thin walled right ventricle. This decreases it's ability to fill resulting in a subsequent decrease in left ventricular filling and ejection fraction, thus effectively decreasing cardiac output and stroke volume (64). Cardiac work also increases, as does myocardial wall tension, increasing energy demands in the heart which, owing to the increased workload, has already developed a greater oxygen demand that cannot be met, resulting in hypoxemia, oxygen debt and lactic acidosis (65).

The pericardium is able to accommodate gradual accumulations of blood if the bleeding is not rapid enough to cause acute rises in intrapericardial pressures which exceed the right ventricular pressure, and subsequently the left ventricle's ability to fill (52,62,66). A slow and gradual hemorrhage is much better tolerated as it can be gradually accommodated by the pericardium. It is thus clear, that pericardial tamponade can have both a deleterious and a protective affect. The protective effect can limit extra pericardial bleeding into the left hemithoracic cavity, thus preventing exsanguinating hemorrhage and allowing the patient to reach a trauma center alive. The deleterious effect can lead to rapid cardiopulmonary arrest (62).

Moreno (67) in a retrospective study strongly supports the presence of a pericardial tamponade as a critical determinant for survival in penetrating cardiac injuries. In these series, the authors reviewed 100 consecutive unselected patients presenting with acute cardiac injuries; 57 sustained stab wounds and 43 gunshot wounds, and 77 patients presented with pericardial tamponade. Overall, 31% survived including 27 (47% of 57) patients with stab wounds and 4 (9% of 43) with gunshot wounds. In this study the authors concluded that patients with pericardial tamponade experienced a higher survival rate, 73% compared versus 11% survival rate in those without it's protective effect. The presence of tamponade improved survival following stab wounds - 77% versus 29%; gunshot wounds - 57% versus none; right heart wounds - 79% versus 28%; left heart wounds - 71% versus 12% and overall in patients arriving with vital signs - 96% versus 50%. These findings were statistically significant, leading the authors to conclude that pericardial tamponade is a critical independent factor in patient's survival, and suggested that it is more influential than presenting vital signs in determining outcomes.

The findings of the above mentioned study which was retrospective have not been confirmed. Buckman and Asensio (68) in the first prospective study of penetrating cardiac injuries in the literature could not find pericardial tamponade to be a critical independent factor in survival. Similarly, Asensio (62) (unpublished data), in a study of 97 patients subjected to ED thoracotomy, did not find pericardial tamponade to be a critical independent factor in survival. Asensio (69) in one year prospective preliminary study of 60 penetrating cardiac wounds with an overall survival of 37% and a 16% survival for patients undergoing ED thoracotomy did not find, after statistical analysis, pericardial tamponade to be a critical independent factor for survival. Asensio (70) in the third and largest prospective study of penetrating cardiac injuries again could not find on the presence pericardial tamponade a critical independent predictive factor for outcome.

What is clear, is that despite the differences between the Moreno (67) study and the other studies cited, (68-70) that the answer lies somewhere in between; there appears to be a period of time in which pericardial tamponade provides a protective affect and thus leads to an increases survival rate. What remains undefined is that period of time, after which this protective effect is lost, resulting in an adverse effect in cardiac function (62,68,69,70).

METHODS OF EVALUATION

A. Sub-xiphoid Pericardial Window

The original technique to create a pericardial window was described by Larrey in the 1800's (22). Remarkably enough, only small variations in the original technique have been added to this procedure. It still remains the gold standard of all procedures for the diagnosis of cardiac injury; however, it requires that the patient be subjected to general anesthesia, and is an invasive procedure. In trauma centers with availability of ultrasound this technique it has been relegated to a second line of evaluation. It is indicated for any patient that sustains a penetrating injury in the area inferior to the clavicles, superior to the costal margins and medial to the midclavicular lines (62).

The subxiphoid pericardial window should be performed in a operating room under general anesthesia. As it is routine with all trauma patients, the patients entire torso prepped from neck to midsize. A 10 cm incision is made in the midline over the xiphoid process. This incision is carried through the skin and subcutaneous tissue, and hemostasis is achieved utilizing electrocautery. Electrocautery is also used to dissect around the xiphoid. The xiphoid is then separated, dissected and grasped by an Allis or Kocher clamp and displaced cephalad, it is then transected. Blunt dissection with a Kittner dissector separates the adipose tissue beneath the xiphoid. A combination of blunt and sharp dissection after digitally palpating the transmitted cardiac impulse is used to locate the pericardium which is grasped between Allis clamps (62).

Once the pericardium has been firmly grasped, a longitudinal incision measuring approximately 1cm is made in the pericardium sharply, with meticulous care taken not to lacerate the underlying epicardium. After making this aperture, the field is either flooded with clear straw-colored pericardial fluid, signifying a negative window, or with blood, which is indicative of a positive window and thus a cardiac injury. Finally, the field may remain dry if blood has clotted within the pericardium. We then recommend passing a suction catheter through the previously made aperture when this situation arises. This maneuver, may liberate clot and allow blood to escape through the aperture, in which case the window is positive and the surgeon should proceed immediately to a median sternotomy and cardiorraphy (62).

Numerous studies have confirmed the reliability and diagnostic potential of the subxiphoid pericardial window. Trinkle (71,72), Arom (73), Garrison (74), Miller (75), Brewster (76) and Duncan (77) have recommended this technique as a safe, expeditious and accurate method of identifying cardiac injuries (78). The advantages of this technique are safety and reliability in detecting a hemopericardium. It is a relatively simple surgical technique that belongs in the surgical armamentarium of every trauma surgeon. Its advantages consist of having to subject a patient to a general anesthetic and a surgical procedure. It's role has been progressively diminished as a diagnostic tool as echocardiography has emerged (62).

B. Two-dimensional echocardiography.

Echocardiography has clearly emerged as the newest technique for the diagnosis of penetrating cardiac injuries. Feigenbaum (79-81) Moss (82) and Goldberg (83) began to define echocardiography as a valuable technique in diagnosing pericardial infusions beginning in 1965. Horowitz (84) in 1974 defined the limits of sensitivity and specificity for this technique and concluded that a minimum of 50 mls of pericardial fluid is necessary before echocardiography can reliably demonstrate an effusion. Subsequently, Weiss (85), Miller (86), Choo (87), Lopez (88), Hassett (89), Robinson (90), DePriest (91) and Freshman (92) began to utilize this technique to establish the diagnoses of penetrating cardiac injuries.

Jimenez (93) prospectively compared hemodynamically stable patients admitted with penetrating chest wounds located within the precordial boundaries and concluded that echocardiography had a 90% accuracy, 97% specificity and a 90% sensitivity in detecting penetrating cardiac injuries. These findings were also confirmed by Plummer (94) and Aaland (95).

Meyer (96) in what is perhaps the most comprehensive study in the literature prospectively evaluated 105 hemodynamically stable patients sustaining thoracic injuries for the presence of occult cardiac injuries. All patients underwent two dimensional echocardiography followed by subxiphoid pericardial window. For the entire group, the subxiphoid window revealed a sensitivity of 100% and specificity and accuracy of 92% versus echocardiography with a reported sensitivity of 56%, specificity of 96% and accuracy of 90%. However, when the subxiphoid pericardial window was compared with echocardiography in patients without an associated hemopneumothorax , their sensitivity (100% versus 100%) specificity (89% versus 91%), and accuracy (90% versus 91%) were comparable.

From these data the author (96) concluded that echocardiography has significant limitations and identifying serious cardiac injuries in patients with associated hemopneumothoraces; however, in patients without, echocardiography missed no significant injuries and is an acceptable diagnostic option for detecting significant cardiac injuries. At the Los Angeles County/ Southern California Trauma Center, echocardiography is employed aggressively in both hemodynamically stable and unstable patients, allowing trauma surgeons to proceed directly to median sternotomy and in a significant number of cases eliminates the need for a subxiphoid pericardial window (62).

EMERGENCY DEPARTMENT THORACOTOMY

Emergency Department thoracotomy (EDT) remains a formidable tool within the trauma surgeon's armamentarium. Since its introduction during the 1960's, the use of this procedure has ranged from sparing to liberal. In many urban trauma centers this procedure has found a niche as part of the resuscitative process. Because of great improvements in emergency medical services (EMS) systems, many patients arrive in either impending or full cardiopulmonary arrest. The arrival of these critically injured patients in "extremis" has prompted many trauma surgeons to attempt this procedure with the hopes of salvaging some of these patients. This technically complex and challenging procedure should only be performed by surgeons who are familiar with the management of penetrating cardiothoracic injuries (62).

Indications for the use of the emergency department thoracotomy in the literature range from vague to quite specific. It has been used in a variety of settings including penetrating and blunt thoracic and/or thoracoabdominal injuries, cardiac and exsanguinating abdominal vascular injuries. It has also been used in exsanguinating peripheral vascular injuries arriving in cardiopulmonary arrest and in pediatric trauma. Many studies in the literature have also reported its use in patients presenting in cardiopulmonary arrest secondary to blunt trauma (62).

Emergency department thoracotomy is best indicated for the management of penetrating cardiac injuries with immediate cardiorrhaphy along with aortic cross clamping and open cardiopulmonary massage. In this setting, it is successful in salvaging approximately 10% of all penetrating cardiac injuries. Open cardiopulmonary massage after definitive repair of penetrating cardiac injuries is more effective in producing a greater ejection fraction (EF). If a definitive repair cannot be accomplished, temporary control of the injury, along with the use of adjunct measures, such as balloon tamponade can also be effectively accomplished, similarly, lacerations of major thoracic blood vessels can also be controlled by vascular clamps (62)

Pre-hospital factors predictive of poor outcome include absence of vital signs, fixed and dilated pupils, absence of cardiac rhythm, and absence of motion in the extremities. Similarly, the absence of a palpable pulse in the presence of cardiopulmonary arrest is also predictive of poor outcome. ED thoracotomy should be performed simultaneously with the initial assessment, evaluation and resuscitation, using the Advanced Trauma Life Support (ATLS) protocols of the American College of Surgeons (ACS). Similarly, immediate venous access with simultaneous use of rapid infusion techniques complements the resuscitative process (62).

Patients are generally transferred to the ED gurney upon arrival. The left arm is elevated and the entire thorax is prepped rapidly with an antiseptic solution. A left anterolateral thoracotomy commencing at the lateral border of the left sternocostal junction and inferior to the nipple is carried out and extended laterally to the latissimus dorsi. In females, the breast is retracted cephalad. This incision is rapidly carried through skin and subcutaneous tissue and the serratus anterior until the intercostal muscles have been reached. The three layers of these interdigitated muscles are sharply transected with Metzenbaum scissors. Occasionally, the left, fourth or fifth costochondral cartilages are transected to provide greater exposure. A Finochietto retractor it then placed to separate the ribs. Evaluation of the extent of hemorrhage present within the left hemithoracic cavity is then carried out. An exsanguinating hemorrhage with an almost complete loss of the patient's intravascular volume is a reliable indicator of poor outcome (62,68-70,97-105).

The left lung is then elevated medially and the thoracic aorta is located immediately as it enters the abdomen via the aortic hiatus. The aorta should then be palpated to assess the status of the remaining blood volume within the vasculature. It can also be temporarily occluded digitally against the bodies of the thoracic vertebrae until it can be cross clamped (62,68-70,97-105).

To cross clamp the aorta, a combination of sharp and blunt dissection commencing at both the superior and inferior borders of the aorta is performed, so that the aorta may be encircled between the thumb and index fingers, in order for the aortic cross clamp be safely placed. We prefer the Crafoord-DeBakey clamp. Inexperienced surgeons often mistakenly cross clamp the esophagus, which is located superior to the aorta. A nasogastric tube previously placed can serve as a useful guide in differentiating the esophagus from an often somewhat empty thoracic aorta (62,68-70,97-105).

Surgeons should then observe the pericardium and search for the presence of a pericardial laceration. Often the pericardium is tense and bluish. The phrenic nerve must also be identified and preserved. A longitudinal opening in the pericardial sac is then made anterior to the phrenic nerve and extended inferiorly and superiorly. Opening the pericardium can be quite challenging, as the sac is often quite tense. Injudicious opening with a knife may iatrogenically lacerate the underlying epicardium. Grasping the pericardium with two Allis clamps to hold it, so that a small 1 to 2 cm incision may be sharply made with a knife is prudent. This is followed by opening the pericardium with Metzenbaum scissors (62,68-70,97-105).

After opening the pericardium, clotted blood is evacuated and the surgeon should immediately note the presence and/or absence, and type of underlying cardiac rhythm, as well as the location of the penetrating injury or injuries. Immediate digital control is imperative. An attempt must be made to trace the trajectory of the wounding agent, as missiles often enter in one area and migrate to adjacent areas, such as the contralateral hemithoracic cavity. Similarly, the surgeons should also estimate the blood volume remaining within the cardiac chambers. The findings of flaccid heart devoid of any effective forward pumping motion is a predictor of poor outcome. Similarly, other reliable predictors of poor outcome are empty coronary arteries and the presence of air signifying air embolus which may be seen in the coronary veins (not the arteries) (62,68-70,97-105).

Digital control of penetrating ventricular injuries as they are simultaneously sutured prevents further hemorrhage. We recommend the use of monofilament sutures, such as 2-0 Prolene and employ mattress sutures of Halsted to repair these injuries. Lacerations of the atria can be controlled with a vascular clamp, such as Satinsky prior to definitive cardiorrhapy. If the injury or injuries are quite large, balloon tamponade utilizing a Foley catheter can temporarily arrest the hemorrhage either to allow the performance of a definitive cardiorrhapy or to gain time so that the patient may be transferred expediently to an operating room for more definitive surgical procedure (62,68-70,97-105).

We do not recommend the use of bioprosthetic materials such as Teflon patches in the emergency department, nor do we recommend the use of a skin stapler to temporarily occlude lacerations of the cardiac muscle in anticipation for definitive cardiorrhapy. We do not recommend this technique, as there is no long term follow-up in these series and in our experience, staples do not effectively control hemorrhage, tend to enlarge the original cardiac injury, and prove rather difficult to remove (62,68-70,97-105).

Although successful repairs are denoted by the cessation of bleeding and progressive filling of the cardiac chambers, they may be effectively accomplished without the heart being able to recover its rhythm. Often pharmacological manipulation coupled with direct defibrillation utilizing 20 to 50 joules is frequently needed to restore a normal sinus rhythm. If a sinus rhythm cannot be restored despite all attempts, the prognosis is grave and the outcome is invariably poor. At times a rhythm can be restored, but no effective pumping mechanism is observed. Similarly, no pulsations are detected in the descending thoracic aorta. At times the insertion of pacemaker wires may help to restore this ineffective forward pumping motion, but this is uncommon. Progressive myocardial death can be witnessed, first by dilatation of the right with ventricle and accompanying cessation of contractility and motion, followed by the same process in the left ventricle (62,68-70,97-105).

TECHNIQUES OF CARDIAC INJURY REPAIR

A. Incisions

Median sternotomy, or the Duval incision (40,62), is the incision of choice in patients admitted with penetrating precordial wounds that may harbor occult or non -hemodynamically compromising cardiac injuries. Patients admitted with some degree of hemodynamic stability may undergo limited preoperative investigation with chest radiography or echocardiography. Similarly patients that reach the operating room with some degree of stability can undergo a subxiphoid pericardial window if the diagnosis of cardiac injury needs comfirmation (62).

The left anterolateral thoracotomy or the Spangaro (45,62) incision, remains the incision of choice for the management of patients with penetrating cardiac injuries that arrive in "extremis." This incision is most often used in the emergency department for resuscitative purposes. It is also the incision of choice in patients undergoing celiotomy who deteriorate secondary to or unsuspected cardiac injuries. The left anterolateral thoracotomy can be extended across the sternum as bilateral anterolateral thoracotomies if the patient's injuries extend into the hemithoracic cavity. This is the incision of choice in a patient who is hemodynamically unstable or for injuries that have traversed the mediastinum. This incision allows full exposure of the anterior mediastinum and both hemithoracic cavities. It is important to note that upon transection of the sternum, both internal mammary arteries are sacrificed and must ligated at the completion of the procedure (62,106-109).

B. Adjunct Maneuvers

Sauerbruch (46) described a maneuver for controlling blood flow to the heart by compression of it's base. This maneuver is difficult and not easily performed via a left anterolateral thoracotomy. It is generally not used and is mentioned only for historical purposes. Total in-flow occlusion of the heart is indicated for the management of injuries to the lateral most aspect of the right atrium and/or the superior or inferior atriocaval junction. This maneuver performed by cross clamping both the superior and inferior vena cavae within their intrapericardial locations. It results in immediate emptying of the heart. The tolerance of the injured, acidotic and ischemic heart of this maneuver is quite limited (62,106-109).

Frequently, this procedure results in cardiopulmonary arrest from which a patient may not be salvaged. It is estimated that the safety period for this maneuver ranges from 1 to 3 minutes, after which the clamps must be released. If this period is exceeded, successful restoration of a normal sinus rhythm is generally not possible. The authors personal experience validates this safety period (62,106-117).

Cross clamping of the pulmonary hilum is another valuable maneuver indicated for the management of associated pulmonary injuries presenting with rapid hemorrhage. The purpose of this maneuver is to arrest hemorrhage from the lung and to prevent air emboli from reaching the systemic circulation. However, it does significantly increase the after load of the right ventricle, as half of the pulmonary circulation is no longer available for perfusion. It is recommended that sequential declamping of the pulmonary hilum be carried out as expediently as possible simultaneously with controlling the intraparenchymal pulmonary vessels responsible for the hemorrhage. This relieves the massive afterload imposed on the right ventricle. Frequently the acidotic and ischemic heart may not be able to tolerate this maneuver and fibrillates or arrests (62,106-117).

C. Repair of Atrial wounds

Atrial injuries can be controlled by partial occlusion Satinsky vascular clamp. Occlusion of the wound by this clamp will allow the trauma surgeon to perform a rapid repair utilizing a monofilament suture in either a running or interrupted fraction. We recommend 2-0 Prolene. The thin walls of the atria demand utmost care and gentleness during suturing as they can easily tear and enlarge the original wound. The use of bioprosthetic materials in the form of Teflon patches is not recommended for the management of these injuries (62,106-117).

D. Repair of Ventricular wounds

Ventricular wounds may be repaired first by digitally occluding the laceration while placing either simple interrupted or horizontal mattress sutures of Halsted. They can also be repaired with a running monofilament suture of 2-0 Prolene. Repairing cardiac injuries from stab wounds is less challenging than repairing missile injuries. Missile injuries tend to produce some degree of blast defect that causes difficulties in carrying out the repair. Injuries by missiles that have been initially sutured and controlled frequently enlarge as the damaged myocardium continues to retract secondary to the blast affect and becomes progressively more weak and friable. Frequently these injuries require multiple sutures in a desperate attempt to control massive hemorrhage. When this occurs, bioprosthetic material such as Teflon is needed to buttress the suture line (62,106-117).

E. Management of Coronary Artery Injuries

The repair of ventricular wounds adjacent to coronary arteries can be quite challenging. The trauma surgeon must always be reminded that injudicious placement of sutures may narrow or occlude a coronary artery or one of it's branches. Therefore, it is recommended that sutures be placed underneath the bed of the coronary artery.62, 118 Lacerations in proximal locations of the coronary artery may demand the use of cardiopulmonary bypass for repair, although this rarely needed. Laceration of the distal coronary arteries, particularly the distal third of the vessel, should be managed by ligation. In a desperate attempt, proximal and mid-portion coronary artery injuries are often ligated, resulting an immediate myocardial infarctions of the operating table (62,118). These patients may benefit from the immediate institution of intra-aortic balloon counterpulsation and immediate aortocoronary bypass (119).

INJURY SCALING

The American Association for the Surgery of Trauma (AAST) and its Organ Injury Scaling Committee (OIS) have developed a cardiac injury scale to uniformly describe cardiac injuries (120). (see Table 1) This scale is quite complex and although it is very comprehensive it is not user friendly in the operating room. Recently Asensio (70) validated and correlated mortality with grade of injury.

COMPLEX AND COMBINED INJURIES

As trauma surgeons develop greater expertise in the management of penetrating cardiac injuries and as patients are subjected to greater degrees of violence many patients arrive harboring multiple associated injuries, in addition to their penetrating cardiac injuries (62).

We have defined complex and combined cardiac injuries as any penetrating cardiac injury associated with either a neck, thoracic, thoracic-vascular, abdominal, or abdominal vascular injury. In addition, any extremity peripheral vascular injury can also be considered as one of these types of injuries. These injuries can be quite challenging to manage. Priority should be given to the injury causing the greatest blood loss (62).

Table 1. American Association For The Surgery Of Trauma (AAST) Organ Injury Scaling (OIS): Heart Injury Scale

Grade*	***Injury Description***
I	Blunt cardiac injury with minor electrocardiographic abnormality (nonspecific ST - or T-wave changes, premature atrial or ventricular contraction, or persistent sinus tachycardia) Blunt or penetrating pericardial wound without cardiac injury, cardiac tamponade, or cardiac herniation
II	Blunt cardiac injury with heart block (right or left bundle branch, left anterior fascicular, or atrioventricular) or ischemic changes (ST depression or T-wave inversion) without cardiac failure Penetrating tangential myocardial wound up to, but not extending through, endocardium, without tamponade
III	Blunt cardiac injury with sustained (>5 beats/min) or multifocal ventricular contractions Blunt or penetrating cardiac injury with septal rupture, pulmonary or tricuspid valvular incompetence, papillary muscle dysfunction, or distal coronary arterial occlusion without cardiac failure Blunt pericardial laceration with cardiac herniation Blunt cardiac injury with cardiac failure Penetrating tangential myocardial wound up to, but not extending Through, endocardium, with tamponade
IV	Blunt or penetrating cardiac injury with septal rupture, pulmonary or tricuspid valvular incompetence, papillary muscle dysfunction or distal Coronary arterial occlusion producing cardiac failure Blunt or penetrating cardiac injury with aortic or mitral valve Incompetence Blunt or penetrating cardiac injury of the right ventricle, right atrium, or left atrium
V	Blunt or penetrating cardiac injury with proximal coronary arterial Occlusion Blunt or penetrating left ventricular perforation Stellate wound with <50% tissue loss of the right ventricle, right atrium, or left atrium
VI	Blunt avulsion of the heart; penetrating wound producing >50% tissue loss of a chamber

*Advance one grade for multiple penetrating wounds to a single chamber or multiple chamber involvement.

This scale is quite complex and although it is very comprehensive in the description of these injuries it is difficult to utilize intraoperatively. Recently Asensio (70) validated and correlated mortality with grade of injuries.

OVERVIEW OF CURRENT PHILOSOPHIES INFLUENCING THE MANAGEMENT OF PENETRATING CARDIAC INJURIES.

Trinkle (121) has pointed out the difficulty in evaluating different series of penetrating cardiac injuries along with analyzing their results. Over the past 30 years, the literature overflows with reports dealing with these injuries, the majority of which have been retrospective reviews. Most have come from institutions treating fewer than 15 such cases annually. Many reports encompass serial and overlapping studies from the same institutions. Similarly, many of these series fail to uniformly report important data that would lead to meaningful and conclusive analysis of the results. Generally important data points are omitted (62,68-70).

Few series report pre-hospital data or transport times for these patients. Similarly, data regarding indications for the performance of ED thoracotomy, physiologic state of the patient during transport and upon arrival, and precise reporting of the anatomic areas of injuries are often missing. Few, if any series report the management of these injuries under the guidance of strict protocols. A paucity of uniform reporting of outcomes is quite noticeable. Wide variations of mortality are usually reported and appear to reflect different degrees of selection of patients who undergo attempts at resuscitation. Even less frequently reported of the results of failed resuscitative efforts (62,68-70).

The literature abounds with studies that report high survival rates but omit the physiologic status upon presentation of these critical patients. They are perhaps biased towards the reporting of patients with lesser degrees of anatomic and physiologic injury severity (62,68-70) These factors have contributed to the false perception that the lethality of cardiac injuries has diminished. This complacent attitude places limits on the development of serious scientific inquiry into this area. Similarly, fatalistic views, suggesting that surgeons abandon ED thoracotomy as ineffective, expensive, and risky procedure, may also contribute to this attitude (113).

The literature also abounds with retrospective series describing the use of emergency department thoracotomy (98-117) Great difficulties also exist in evaluating the results of these series. Overlapping studies that encompass the experience of many years, and lack of uniformity in protocols utilized, coupled with the use of physiologic parameters as predictors of outcome which have not been statistically validated regarding their predictive values render these series quite difficult to interpret (62,68-70,121) This is precisely why the need for prospective studies in the literature is necessary. Up to now there are only three prospective studies in the literature (68,-70) dealing with penetrating cardiac injuries. These studies will be cited as they provide serious scientific inquiry into penetrating cardiac injuries.

The first prospective study in the literature dealing with penetrating cardiac injuries is titled: Penetrating cardiac injuries; a prospective study of factors influencing the initial resuscitation, by Buckman and Asensio (68) In this study the authors measured the cardiovascular and respiratory elements of the trauma score (CVRS) upon admission, and prospectively analyzed 66 consecutive cardiac injuries over a two year period. In this group of patients, 44 (70%) sustained gunshot wounds, 47 (71%) were subjected to ED thoracotomy, and 54% were admitted in asystole. From these data, the authors concluded that prospective physiologic scoring was helpful in predicting outcomes. The triad of gunshot wounds, asystole and CVRS of 0 was proven to predict survival, whereas the triad of stab wounds, asystole, and CVRS of 0 could not predict survival. In this study the authors proved that the probability of successful resuscitation was significantly related to the mechanism of injury and physiologic condition upon arrival. In this study pericardial tamponade did not prove to be an independent predictor of early survival (68).

Asensio (69) in only the second prospective study on penetrating cardiac injuries in the literature titled: Penetrating cardiac injuries; a prospective study of variables predicting outcomes, studied 60 patients prospectively admitted during a one year study in a urban level I trauma center with the objectives of analyzing first the parameters measuring the physiologic condition of patients sustaining penetrating cardiac injuries in the field, during transport and upon arrival. Second, the cardiovascular respiratory score (CVRS) component of the trauma score, third the mechanism and anatomic site of injury, fourth the presence or absence of tamponade and fifth the cardiac rhythm as predictor of outcome. This study had one main intervention, which was thoracotomy for resuscitation and definitive repair of cardiac injuries. Main outcome measures were all parameters measuring the physiologic conditions of patients, CVRS, mechanism and anatomic site of injury, operative findings and maneuvers, mortality, and grade of injury (69)

The study consisting of 60 patients sustaining penetrating cardiac injuries, included 35 (58%) gunshot wounds and 25 (42%) stab wounds. The injury severity score (ISS) was greater than 30 in 22 patients; overall survival was 22 of 60 yielding wound patients survived 68%. a 36.6% overall survival rate; 5 of 35 gunshot wound patients (14%) and 17 of 25 stab Emergency department thoracotomy was performed in 37 of 60 patients (61.7%) with 6 of 37 patients surviving (16%). In this study, CVRS was a good predictor outcome with a 96% mortality reported in 25 of 26 patients admitted with a CVRS score of 0, a 67% mortality in 6 out of 9 patients when the CVRS score was in the range of 1-3 and a 25% mortality in 7 of 25 patients when the CVRS score was greater than 4 (69) ($p<0.001$).

The mechanism of injury; the presence of sinus rhythm when the pericardium was open were indeed good predictors of outcome ($p<0.001$). The anatomic site of injury and tamponade did not predict outcomes (NS). An initial attempt to validate the AAST-OIS cardiac injury scale was attempted but could only achieve statistical significance for grades IV through VI. From these data the authors concluded that parameters measuring physiologic condition, CVRS, and mechanism of injury plus initial rhythm are significant predictors of outcome in penetrating cardiac injuries. The need for aortic cross clamping and the inability to restore an organized on rhythm blood pressure after a thoracotomy were also excellent predictors of outcomes. The presence of pericardial tamponade was not (69).

Patients subjected to Emergency Department thoracotomies incurred a mortality rate of 84%, whereas those performed in the OR experienced significantly lower mortality rates (30%). Mortality was also correlated with operative findings as the mortality of patients exsanguinated was 91% ($p<0.0001$) and those with the absence of a sinus rhythm or with the presence of a disorganized rhythm when the pericardium was opened as well as those requiring aortic cross clamping experienced mortality rates greater than 90% ($p<0.0001$). Two outcome parameters measured included the ability to restore an organized rhythm a measurable blood pressure. If this was not achieved, a 100% mortality rate was uniformly noted ($p<0.0001$) (69).

In the third prospective study in the literature by Asensio (70) titled: One-hundred and five penetrating cardiac injuries; a two-year prospective evaluation. The authors analyzed the physiological parameters measured in the field, during transport, upon arrival of patients sustaining penetrating cardiac injuries, the cardiovascular respiratory (CVRS) component of the trauma score as well as other paramenters evaluated in the previous study. Similarly, the authors investigated operative characteristics and cardiac rhythms as predictors of outcome. Main interventions included thoracotomy, sternotomy or both, for resuscitation and definitive repair of cardiac injury. The main outcome measures used were parameters measuring physiologic condition of patients, CVRS, mechanism and anatomical site of injury mortality in grade of injury. Of the indications for the performance of thoracotomy, only cardiopulmonary arrest was statiscally significant. These patients had a mortality rate of 82.6% versus those that did not present in cardiopulmonary arrest, in whom the mortality rate was 33.3% ($p<0.001$) (70).

A total of 105 patients sustaining penetrating injuries were entered into the study over a two-year period. There were a 68 patients (65%) that sustained gunshot wounds and 37 patients (35%) that sustained stab wounds. The mean injury severity score was 36 denoting a severely anatomic injured patient population. Of the 105 patients, 23 (22%) sustained multiple chamber injuries. The overall survivor rate was 35 of 105 patients (33%); the survival for gunshot wound victims was 11 of 68 patients (16%) the survival rate for stab wound victims was 24 of 37 patients (65%). Emergency department thoracotomy was performed in 71 of the 105 patients (68%) with 10 survivors (14%). The CVRS score predicted a 94% mortality in 50 of 53 patients when the CVRS was equal to 0, an 89% mortality in 57 of 64 patients when the CVRS was between 0-3 and a 31% mortality in 12 of 39 patients when the CVRS was between 4 and 11 ($p<0.001$) (70).

Similarly, the presence of a sinus rhythm when the pericardium was opened predicted survival ($p<0.001$). The anatomic site of injury and the presence of a tamponade did not predict survival (NS). However, if the thoracotomy was performed in the ER for cardiopulmonary arrest, the patient was suspected of exsanguinating hemorrhage and the aorta needed to be cross clamped proved to be strong predictors of survival ($p<0.001$). Outcome oriented parameters such as restoration of an organized rhythm and a measurable blood pressure were also extremely strong predictors of survival ($p<0.001$). Stepwise logistic regression analysis identified gunshot wounds, exsanguination, and restoration of blood pressure as the most predictive variables for mortality. They produced a Max-rescaled R^2 of 0.81 and a concordance of 95%. In this study the authors were also able to correlate mortality with chamber injury (70).

The mortality for right atrial injury in this study was 62.5%, for right ventricular injuries 48.7%, left atrial injuries 80% and for left ventricular injuries 76.9%. The AAST-OIS Cardiac Injury Scale was validated. Mortality correlated with grade of injuries. In this study 99 of 105 patients (94%) sustained injuries grade IV - VI. The mortality for grades IV, V and VI was 56% of 76% and 91% respectively. In this study the authors also looked at the presence of an associated coronary artery injury as predictor of outcome. There were a total of 9 associated coronary artery injuries of which only one survived. This did not reach statiscal significance (70).

From these data the authors concluded that parameters measuring physiologic condition in the field, during transport and upon arrival, CVRS, and mechanism of injury are significant predictors of outcome in penetrating cardiac injuries. Cardiac injury grades I to III are rare in penetrating cardiac trauma in contrast with grades IV - VI which are common and these injury grades do indeed predict outcome. This is the only study published in the literature that reports the incidence of anoxic encephalopathy as a complication in survivors. Remarkably enough only 3 survivors experienced this complication. Two had Glasgow Outcome Scale (GOS) scores of 1 and needed only minimal help to perform most of their daily living activities while the other patient who had a Glasgow Outcome Scale (GOS) score of 2 needed only moderate help (70)

Similarly, there is only one prospective study in the literature dealing with emergency department thoracotomy (122). This study was reported by Asensio (122) during a two-year prospective series reporting 215 patients subjected to emergency department thoracotomy. In this study the authors reported a 10% an overall survival rate. In this series the only survivors experienced penetrating cardiac injuries. None of the patients subjected to emergency department thoracotomy for blunt cardiopulmonary, non-cardiac thoracic injuries or exsanguinating abdominal vascular injuries survived (122).

It is apparent from these and other studies that much remains to be done in terms of anatomic and physiologic injury assessment. It is clear that better selection of patients through the use of physiologic indices such as the CVRS score to undergo ED thoracotomy and cardiorraphy will lead to improved survival. Only with serious scientific inquiry based on prospective collection and analysis of data can we extend the frontiers in the management of devastating injuries, much like Cappelen, Farina and Rehn did over 100 years ago (62,68,69,70,122).

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