Review Article

Penetrating cardiac injury: a narrative review

Larry R. Hromalik Jr[1], Matthew J. Wall Jr[2], Kenneth L. Mattox[2], Peter I. Tsai[3]

[1]Department of Surgery, University of Hawaii at Manoa John A. Burns School of Medicine, Honolulu, HI, USA; [2]Department of Surgery, Baylor College of Medicine, Houston, TX, USA; [3]Department of Surgery, University of Hawaii at Manoa John A. Burns School of Medicine, Queen's Heart Institute, Honolulu, HI, USA

Contributions: (I) Conception and design: All authors; (II) Administrative support: All authors; (III) Provision of study materials or patients: All authors; (IV) Collection and assembly of data: All authors; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Larry R. Hromalik Jr. Department of Surgery, University of Hawaii at Manoa John A. Burns School of Medicine, Honolulu, HI, USA. Email: larryrh@hawaii.edu.

Background and Objective: Penetrating cardiac trauma is rare but can cause life-threatening complications. Survival is dependent on prompt diagnosis and treatment. Given the low incidence and life-threatening implications, it is difficult to study in large prospective studies. The current literature regarding penetrating cardiac trauma comes primarily from large, experienced trauma centers and military sources. Understanding the history, current literature and even expert opinion can help with effectively treating injury promptly to maximize survival after penetrating cardiac trauma. We aimed to review the etiology and history of penetrating cardiac trauma. We review the prehospital treatment and initial diagnostic modalities. We review the incisional approaches to treatment including anterolateral thoracotomy, median sternotomy and subxiphoid window. The repair of atrial, ventricular and coronary injuries are also addressed in our review. The purpose of this paper is to perform a narrative review to better describe the history, etiology, presentation, and management of penetrating cardiac trauma.

Methods: A narrative review was preformed synthesizing literature from MEDLINE and bibliographic review from identified publications. Studies were included based on relevance without exclusion to time of publication or original publication language.

Key Content and Findings: Sonographic identification of pericardial fluid can aid in diagnosis of patients too unstable for CT. Anterolateral thoracotomy should be used for emergent repairs and initial stabilization. A median sternotomy can be used for more stable patients with known injuries. Carefully placed mattress sutures can be useful for repair of injuries surrounding coronary vessels to avoid devascularization.

Conclusions: Penetrating cardiac trauma is life threatening and requires prompt workup and treatment. Trauma algorithms should continue to refine and be clear on which patients should undergo an emergency department (ED) thoracotomy, median sternotomy and further imaging.

Keywords: Penetrating cardiac injury; cardiac trauma; cardiac injury repair; emergency thoracotomy

Received: 10 May 2022; Accepted: 26 December 2022; Published online: 22 February 2023.

doi: 10.21037/med-22-18

View this article at: https://dx.doi.org/10.21037/med-22-18

Introduction

Cardiac injury previously was almost fatal, as described in the death of Sarpedon from an impalement of a lance to the heart in the Iliad (1). Hippocrates (2), Aristotle (3), Galen (4), Fabricius (5) and Boerhaave (6), all described such wounds to the heart as futile. While once universally fatal, penetrating cardiac trauma still has life-threatening implications. It is important to understand the how to promptly diagnose and manage these injuries to maximize survival. Despite advances in prehospital care, in-hospital protocols and surgical techniques patients can still

Table 1 The search strategy summary

Items	Specification
Date of search	03/25/2021
Databases and other sources searched	MEDLINE via PubMed, Google Scholar, University of Hawaii Libraries
Search terms used	"penetrating trauma"[MeSH]
	"polytrauma"[MeSH]
	"cardiac trauma"[MeSH]
	"penetrating cardiac trauma"[MeSH]
	"cardiac injury"[MeSH]
	"thoracic trauma"[MeSH]
	"emergency thoracotomy"[MeSH]
Timeframe	No exclusions were made based on date of publication
Inclusion and exclusion criteria	Focus was made on papers that address an aspect of history, incidence, etiology, presentation, diagnosis or treatment of penetrating cardiac injuries. Studies were excluded if they were small case studies. Studies written in primarily in English were given preference but studies with English translations were also included
Selection process	Review of articles was primarily done by Hromalik LR Jr but selection was made with approval of all authors
Any additional considerations, if applicable	Older texts found in introduction and that are not found on MEDLINE texts were found using University of Hawaii Library and Google Scholar

decompensate quickly with penetrating cardiac injuries. The purpose of this article is to better characterize the history and present treatment of penetrating cardiac trauma in the form of a narrative review. The rationale for creating this review is to combine the literature with expert experience to help guide future research and clinicians to better treat penetrating cardiac injury. We present the following article in accordance with the Narrative Review reporting checklist (available at https://med.amegroups.com/article/view/10.21037/med-22-18/rc).

Methods

A narrative review was preformed synthesizing literature from MEDLINE and bibliographic review from identified publications as seen in the reference section. The search strategy is summarized in *Table 1*. Medical Subject Headings (MeSH) terms were used. Search terms included: penetrating trauma OR polytrauma OR cardiac trauma OR penetrating cardiac trauma OR cardiac injury OR thoracic trauma OR emergency thoracotomy. All abstracts were further screened by primary author Hromalik LR Jr. and qualitatively analyzed to include articles with penetrating cardiac injury. A focus was made on articles that presented an aspect of the history, incidence, etiology, presentation, diagnosis or treatment of penetrating cardiac injury. Papers were primarily in English but other texts were reviewed if there was an English translation available. Older texts and translations cited in the 'Introduction' and 'History' that are not primarily medical research were found utilizing Google Scholar and with review of texts at University of Hawaii Libraries.

History

The earliest interventions were described by Morgagni (7) in 1761 who described the compressive effects of blood by the heart. Larrey (8) was credited for pioneering the technique of a pericardial window. Ludwig Rehn performed the first successful repair of a cardiac injury on September 9, 1896 in Frankfurt (9). Exposure of the heart after penetrating trauma evolved at the turn of the century when Duval (10) first described the median sternotomy incision, while Spangaro (11) in 1906 described the left anterolateral thoracotomy incision. The diagnosis of cardiac injury evolved in 1926 when Beck described the Triad physiology

of cardiac tamponade. He also described an important repair technique that is still used today. This technique involves placing mattress sutures under the coronary vessels to spare ligation for lacerations to the heart (12,13). Treatment was then further developed by Harken (14) in 1946 who described the removal of foreign bodies adjacent to the heart and great vessels. Treatment was then extended beyond the operating room by Beall (15-18) who first described emergency department thoracotomy (EDT) and along with Cooley (17) who reported the potential benefits for cardiopulmonary bypass in the management of selected intracardiac injuries. Mattox (19-21) further protocolized the use of EDT and cardiorrhaphy including emergency cardiopulmonary bypass.

Incidence

Penetrating cardiac injuries are uncommon and represent a small fraction of penetrating trauma overall. Penetrating cardiac trauma is often described in high volume urban trauma centers (22-30). Iatrogenic penetrating cardiac injury can be also seen in any clinic or hospital, following procedures. Iatrogenic penetrating cardiac trauma is most often seen following pericardiocentesis. The true incidence of injury overall is difficult to quantify but various centers have described their experiences. Feliciano (22) described in a one-year experience 48 cardiac injuries at Ben Taub Hospital in Houston. Mattox (23) in 1989 described a 30-year experience from the same institution, reporting 539 cardiac injuries. Asensio (24,31) reported a total of 165 cardiac injuries within a 3-year period at LA County/USC hospital in Los Angeles. Tyburski (32) in 2000 reported an 18-year experience of 302 patients with penetrating heart injuries undergoing emergency thoracotomy. Seamon (26) described 207 cardiac injuries over 7 years between Temple University Hospital and the Hospital of the University of Pennsylvania. Clarke (28) described 206 cardiac injuries in South Africa over a 3-year period. The overall incidence varies by geographic location and is also influenced by violent crimes involving the use of firearms or penetrating objects (22-32).

Etiology

In the civilian setting, penetrating cardiac injuries are usually seen as a result of gunshot wounds and stab wounds. A subset of cardiac injuries are seen from iatrogenic needles, trocars, and catheters (33-39).

In the military setting, most patients do not survive cardiac injuries from high velocity automatic rifles in battle. The majority military reported injuries are from fragments of grenades or shrapnel. Rich (40) reported such injuries in 96 patients from the Vietnam conflict, arriving at treatment facilities. Hughes (41) describes over 2,000 thoracic injuries over 10 years during the Afghanistan and Iraq conflicts.

Clinical presentation

Most cardiac injuries from stab wounds will follow the trajectory of the insult. Gunshot wounds are different because they can cause injury from precordial and extra-precordial entrance sites (42). Hirshberg (43) described 26% associated cardiac injuries in 41 patients presenting with combined thoracoabdominal injuries, while Asensio (44) reported a 44% incidence of associated penetrating cardiac injuries in his series of 73 patients who sustained thoracoabdominal injuries.

Penetrating injuries to any of the cardiac chambers may quickly lead to acute cardiac tamponade and death. Hemorrhage through a lacerated pericardial injury will flow into the hemithorax and will lead to death. The pericardium can therefore prevent fatal exsanguination and allow patients survive long enough to reach the trauma center alive. They may have varying degrees of hemodynamic instability secondary to pericardial tamponade (24,31). Interestingly, the classic presentation of Beck's Triad (muffled heart sounds, jugular venous distension and hypotension) or Kussmaul's sign (jugular venous distension with inspiration) are only present in 10% of patients who present with pericardial tamponade (42).

Moreno (45) did a retrospective study that looked at 100 patients with penetrating cardiac injuries and reported higher survival 77% *vs.* 11% in patients who present with pericardial tamponade. Moreno also showed that right-sided chamber injuries confer a higher survival 79% *vs.* left-sided chamber injuries of 28% survival.

Diagnosis

The clinician should always be concerned for cardiac injury when patients present after sustaining any penetrating injury. If the patient is hemodynamically stable and has a widened mediastinum on chest X-ray the clinician should also have a high suspicion for cardiac injury. Sonography is an excellent tool that can determine the presence of

pericardial fluid. Physical exam findings of Beck's triad or Kussmaul's sign can also be supportive but not always present. Any injury with a concern of direct trajectory towards the heart should prompt preparation for a possible emergent bedside anterolateral thoracotomy should the patient acutely decompensate.

Subxiphoid pericardial window

The reliability of subxiphoid pericardial window technique *vs.* pericardiocentesis has been controversial in the evaluation and treatment of penetrating cardiac injury (46-54). These techniques may be useful in the absence of two-dimensional echocardiography. While these techniques might demonstrate hemopericardium, they are time consuming. In addition, a pericardial window may result in exposing a cardiac injury through a very small incision and may need a larger secondary thoracic operation. A transdiaphragmatic pericardial exploration at the time of a laparotomy (55) has been described in cases where patients have sustained combined thoracoabdominal injuries. Laparoscopic transdiaphragmatic pericardial window also has been described for more stable patients (56-58). However, if there is an injury found, they still may need a larger secondary operation for optimal exposure of the heart and treatment.

Two-dimensional echocardiography

Echocardiography has now become the gold standard in the initial diagnosis and evaluation of patients with penetrating thoracic injury. The diagnosis is made by looking for hemopericardium. It is fast, and easily reproducible (42,55,59-61). Governatori (61) performed a review of multiple studies that show echocardiography has a high accuracy up to 96–97% with sensitivity and specificity reaching near 100%. Echocardiography can also be used to further delineate some intramyocardial foreign bodies *vs.* missiles located within the cardiac chambers (62-64). We recommend use of sonography to look for pericardial fluid in all patients with concern for penetrating cardiac injury because it is fast, reproducible and can influence operative management.

Management

Patients with penetrating cardiac injury may have a fatal outcome regardless prehospital intervention. In the select group that are stable enough for transport to the trauma center, the time between initial injury and release of cardiac tamponade is of utmost importance. This prehospital course is marked by certain surrogate parameters for either improved or dire prognosis.

Under no circumstances should EMS personnel delay transport by insertion of intravenous lines—this should be carried out during transport. Concomitant notification of the trauma center to activate the trauma team is also of paramount importance (42). Gervin (65) demonstrated a survival advantage if patients are transported to the trauma center is within 9 minutes, while all patients succumbed when transport was greater than 25 minutes. Mattox (66) found no survivors in 100 patients who had received external cardiac compression for more than 3 minutes in the prehospital period and were not intubated. Lorenz (67) associated better survival if patients had systolic blood pressures of 60 mmHg or more in the field and upon arrival in the emergency department. Durham (68) showed the average survival was seen with 5 minutes or less of cardiopulmonary resuscitation, but this time improved to 9 minutes when prehospital intubation was performed.

Upon arrival to the emergency department, the trauma team should be ready to perform advanced trauma life support or immediately transport patients from the ambulance bay to the operating room (69). Patients can be grouped into multiple categories based on stability. The hemodynamically stable patient can allow time for expedited yet detailed workup. The unstable patient that responds to initial fluid resuscitation may have the opportunity to be transported to the operating room for a life-saving operation. Patients who present or go into cardiopulmonary arrest will require EDT (24,31,42,70,71). EDT, if performed under strict indications for cardiac injuries, has been shown to improve survival rate as much as 31% (72). Rhee (73) preformed a large systematic review looking survival after EDT with respects to location, mechanism of injury and signs of life on arrival. It was shown that patients with penetrating cardiac injury and with signs of life on arrival yielded the highest survival among those who underwent EDT. Seamon *et al.* (74) reviewed 72 studies of patients undergoing EDT. They compared outcomes by presentation for location, mechanism, pulse status, and signs of life. Signs of life were defined as: pupillary response, spontaneous ventilation, presence of carotid pulse, measurable or palpable blood pressure, extremity movement or cardiac electrical activity. They strongly recommend that EDT should be performed in patients who present pulseless

with signs of life after penetrating thoracic injury.

Techniques for cardiac injury repair

Incisions

Median sternotomy and left anterolateral thoracotomy are the two incisions of choice for cardiac injuries. The median sternotomy is preferred in patients who are treated for anterior stab wounds to the chest, and for those who arrive in some degree of hemodynamic instability, but stable enough for work up with sonographic or chest x-ray imaging. The left anterolateral thoracotomy is the incision of choice in the management of patients that arrive in extremis. This incision is also used as EDT for emergent resuscitative purposes (24,31,42,70,75). A bilateral transsternal anterolateral thoracotomy can provide optimal exposure of the mediastinum and both hemi-thoracic cavities if necessary.

Adjunct maneuvers

Exposure of the heart to repair posterior injuries can be accomplished in several ways. The Heart can be retracted using sutures. Temporary pledgeted sutures can be placed on the apex of the heart with the sutures cut long in order to slowly retract the apex superiorly to gain access to the posterior injury. Alternatively, a Satinsky clamp can also be used on the right ventricular angle to achieve the same exposure (76). A simple option that we recommend is to place folded wet towels sequentially behind the heart in order to gradually lift the heart up to provide exposure without causing the heart to go into an arrhythmia. Stabilizing devices can also be used to help provide exposure but require time to set up. It is important to be careful with placement of repair stitches on laceration injuries to avoid causing further tear injury.

Total inflow occlusion of the heart can also be performed by placing clamps on the intrapericardial location to isolate and repair injuries at the level of atriocaval junction. This will often cause the heart to fibrillate, requiring paddle defibrillation and pharmacologic intervention (42,75). It is important to remember that the heart should be intermittently compressed as cardiorrhaphy is performed in case defibrillation is necessary. Failure to decompress the heart before defibrillation can cause further injury to the heart.

Repair of atrial injuries

Exposure of atrial injuries is relatively straight forward. Right atrial injuries can usually be stabilized and controlled with a Satinsky clamp (77,78) followed by repair using 4-0 non-pledgeted polypropylene monofilament sutures. The atrium is thin walled and tears easily, so it is important to be gentle with traction of sutures to avoid further injury or tearing.

Repair of ventricular injuries

Blast injuries resulting from gun shots to the ventricle can damage the epicardium and myocardium making them more friable and unforgiving with standard suture repair. The repair can be further complicated by tachycardia or high-pressured bleeding. Left ventricle injuries will also have higher. Depending on the size of the injury, 2-0, 3-0 or 4-0 polypropylene can be used for repair. Many surgeons suggest that pledgeted sutures should be used for repair however they have not been demonstrated to have any benefit over a carefully placed suture in the horizontal mattress fashion. Commercial brand fibrin sealant (78,79) are also often recommended but have also not been proven to add any value or benefit over suture repair.

Coronary artery injuries

Direct coronary artery injuries can be challenging to repair. Proximal injuries will require cardiopulmonary bypass, especially if there is gross evidence of cardiac ventricular dysfunction. Distal coronary artery injuries can potentially be ligated. Specifically, if the distal third of the vessel is injured/lacerated there may be little benefit in bypass. Bypass may not be necessary if the heart remains without ventricular dysfunction and tolerates ligation. Off-pump bypass can also be an option in select patients (80). Cardiac injuries in close proximity to coronary arteries may be managed with carefully placed horizontal mattress sutures underneath the coronary vessel for safe repair, taking care not to narrow or occlude the coronary artery in the process (42,70,77,81-83).

Complex and combined injuries

These can be defined as penetrating cardiac injury in addition to associated thoracic, thoracic-vascular, neck, abdominal and abdominal-vascular, or peripheral vascular injuries. Priority should be given to treatment of injury with the greatest risk of blood loss or is most life-threatening (42,70,77,84-89).

Wall and Mattox (90) described complex cardiac injuries as those beyond lacerations of the myocardium. These injuries often include concomitant coronary artery injuries, cardiac valvular injuries, intracardiac fistulas, ventricular

false aneurysms and coronary sinus injuries. These may be addressed by the cardiac surgeon once the other life-threatening injuries are temporized and dealt with. Priority should always be limiting blood loss and stabilizing patient before definitive repair is undertaken.

Limitations

There are many limitations to this narrative review. First, this is not a systematic review of all research regarding penetrating cardiac trauma, and we do not specifically compare the overall quality of research included in our review. We have included relevant literature regarding the history, incidence, etiology, diagnosis, and treatment to provide guidance in the care of patients with penetrating cardiac injury.

Conclusions

Penetrating cardiac injury should prompt a quick comprehensive workup. Workup should include a sonographic exam that is useful to diagnose pericardial fluid indicating the need for operative treatment. In the hemodynamically stable patient, the workup can be more extensive and include CT imaging studies. An anterolateral thoracotomy can be used in the emergent setting to cross clamp the descending aorta in order to perform necessary cardiac repairs. A median sternotomy should be used in a more stable patient with identified cardiac injuries to optimize exposure and perform definitive repair. Our recommendations for exposure and repair techniques should be considered to optimize survival in all penetrating cardiac traumatic injuries. Future studies and policies should focus on refining trauma algorithms to include optimizing prehospital care and transport. Future research and policy should be driven with collaboration between high-volume, urban trauma centers that routinely care for penetrating cardiac injuries.

Acknowledgments

Larry R. Hromalik Jr, MD, would like to thank Peter I. Tsai, MD, FACS (Professor of Surgery, JABSOM, University of Hawaii), Matthew J. Wall, Jr., MD, FACS (Professor of Surgery, Baylor College of Medicine, TX) and Kenneth L. Mattox, MD, FACS (Distinguished Service Professor Emeritus, Baylor College of Medicine, TX) for their mentorship, patience, contribution of knowledge and combined vast experience that enabled the completion of this project.

Funding: None.

Footnote

Provenance and Peer Review: This article was commissioned by the Guest Editor (Simon R. Turner) for the series "Traumatic Injuries of the Mediastinum" published in *Mediastinum*. The article has undergone external peer review.

Reporting Checklist: The authors have completed the Narrative Review reporting checklist. Available at https://med.amegroups.com/article/view/10.21037/med-22-18/rc

Peer Review File: Available at https://med.amegroups.com/article/view/10.21037/med-22-18/prf

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://med.amegroups.com/article/view/10.21037/med-22-18/coif). The series "Traumatic Injuries of the Mediastinum" was commissioned by the editorial office without any funding or sponsorship. The authors have no other conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

References

1. Homer. The Iliad, Vol XIII, line 442. New York: McMillan & Co., 1992:259. Translated by Lang, Leaf and Myers.
2. Hippocrates. The genuine works of Hippocrates, Vol 2,

Aphorism 18. New York: William Wood & Co., 1886:252. Translated by Francis Adams.
3. Aristotole. The Partibus Animalim. Lib III. Chap 4: Opera Edidt Academia Regia Borrusca, Vol 3, 328. As quoted by Beck CS: Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
4. Galen. Medicorun Graecorum Opera, Vol VIII, Lipsiae Prostat in officina Libraria Car. Cuoblochii 1824, De Locis Affectis. Edited by Kuhn DC: Tome VIII, Lib V, Chap 2, 304. As quoted by Beck CS. Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
5. Fabricius ab Aquadependente. Opera Chirurgica, Chap 21. Patavii, 1666:144. As quoted by Beck CS. Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
6. Boerhaave. De vulnere in Genere, Aphorismi de Cognoscendis et. Curandis Morbis, Aphorim 170, 43. As quoted by Beck CS: Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
7. Morgagni JB. De sedibus et causes morborum. Lipsiae sumptibus Leopoldii vossiim, 1829. As quoted by Beck CS. Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
8. Larrey DJ. Relation, historical and surgical, of the expedition of the Army of the Orient, in Egypt and in Syria. Mil Surg 1946;99:323; 790; passim.
9. Rehn L. Ueber penetrierende Herzwunden und Herznaht. Arch f klin Chir 1897;55:315-29.
10. Duval P. Le incision median thoraco-laparotomie. Bull Mem Soc Chir Paris 1907;33:15. As quoted by Ballana C. Bradshaw Lecture: The surgery of the heart. Lancet 1920;CXCVIII:73.
11. Spangaro S. Sulla tecnica da seguirenegli interventi chirurgici er ferrite del cuore e su di un nuovo processo di toracotomia. Clin Chir 1906;14:227. As quoted by Beck CS. Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
12. Beck CS. Wounds of the heart: the technique of suture. Arch Surg 1926;13:205.
13. Beck CS. Further observations on stab wounds of the heart. Ann Surg 1942;115:698-704.
14. Harken DE. Foreign bodies in, and in relation to the thoracic blood vessels and heart. Surg Gynecol Obstet 1946;83:117-25.
15. Beall AC Jr, Diethrich EB, Crawford HW, et al. Surgical management of penetrating cardiac injuries. Am J Surg 1966;112:686-92.
16. Beall AC Jr, Gasior RM, Bricker DL. Gunshot wounds of the heart. Changing patterns of surgical management. Ann Thorac Surg 1971;11:523-31.
17. Beall AC Jr, Morris GC Jr, Cooley DA. Temporary cardiopulmonary bypass in the management of penetrating wounds of the heart. Surgery 1962;52:330-7.
18. Beall AC Jr, Ochsner JL, Morris GC Jr, et al. Penetrating wounds of the heart. J Trauma 1961;1:195-207.
19. Mattox KL, Espada R, Beall AC, et al. Performing thoracotomy in the emergency center. J Am Coll Emerg Phys 1974;3:13.
20. Mattox KL, Beall AC, Jordan GL, et al. Cardiorrpahy in the emergency center. J Thorac Cardiovasc Surg 1974;68:886.
21. Mattox KL, Limacher MC, Feliciano DV, et al. Cardiac evaluation following heart injury. J Trauma 1985;25:758-65.
22. Feliciano DV, Bitondo CG, Mattox KL, et al. Civilian trauma in 1980's. A 1-year experience with 456 vascular and cardiac injuries. Ann Surg 1984;199:717-24.
23. Mattox KL, Feliciano DV, Burch J, et al. Five thousand seven hundred sixty cardiovascular injuries in 4459 patients. Epidemiologic evolution 1958 to 1987. Ann Surg 1989;209:698-705; discussion 706-7.
24. Asensio JA, Murray J, Demetriades D, et al. Penetrating cardiac injuries; Prospective one-year preliminary report: an analysis of variables predicting outcome. J Am Coll Surg 1998;186:24.
25. Kim JS, Inaba K, de Leon LA, et al. Penetrating injury to the cardiac box. J Trauma Acute Care Surg 2020;89:482-7.
26. Seamon MJ, Shiroff AM, Franco M, et al. Emergency department thoracotomy for penetrating injuries of the heart and great vessels: an appraisal of 283 consecutive cases from two urban trauma centers. J Trauma 2009;67:1250-7; discussion 1257-8.
27. Stranch EW, Zarzaur BL, Savage SA. Thinking outside the box: re-evaluating the approach to penetrating cardiac injuries. Eur J Trauma Emerg Surg 2017;43:617-22.
28. Clarke DL, Quazi MA, Reddy K, et al. Emergency operation for penetrating thoracic trauma in a metropolitan surgical service in South Africa. J Thorac Cardiovasc Surg 2011;142:563-8.
29. Isaza-Restrepo A, Bolívar-Sáenz DJ, Tarazona-Lara M, et al. Penetrating cardiac trauma: analysis of 240 cases from a hospital in Bogota, Colombia. World J Emerg Surg 2017;12:26.
30. Mina MJ, Jhunjhunwala R, Gelbard RB, et al. Factors affecting mortality after penetrating cardiac injuries: 10-year experience at urban level I trauma center. Am J Surg 2017;213:1109-15.
31. Asensio JA, Berne JD, Demetriades D, et al. One

hundred and five penetrating cardiac injuries. A two year prospective evaluation. J Trauma 1998;44:1073-82.
32. Tyburski JG, Astra L, Wilson RF, et al. Factors affecting prognosis with penetrating wounds of the heart. J Trauma 2000;48:587-90; discussion 590-1.
33. Pang BJ, Barold SS, Mond HG. Injury to the coronary arteries and related structures by implantation of cardiac implantable electronic devices. Europace 2015;17:524-9.
34. Toufan M, Pourafkari L, Nader ND. Right ventricular perforation as a complication of fluoroscopy-guided pericardiocentesis. Rev Port Cardiol 2017;36:479-80.
35. Kunishige H, Ishbashi Y, Kawasaki M, et al. Surgical treatment of iatrogenic cardiac injury induced by pericardiocentesis; report of a case. Kyobu Geka 2011;64:419-21.
36. Patanè F, Sansone F, Centofanti P, et al. Left ventricular pseudoaneurysm after pericardiocentesis. Interact Cardiovasc Thorac Surg 2008;7:1112-3.
37. Carroll JD. Management of iatrogenic cardiac perforation "think before pulling out". Catheter Cardiovasc Interv 2007;70:60-1.
38. Rav Acha M, Rafael A, Keaney JJ, et al. The management of cardiac implantable electronic device lead perforations: a multicentre study. Europace 2019;21:937-43.
39. Asehnoune K, Azoulay D, Andreani P, et al. Cardiac perforation and tamponade during TIPS placement. Ann Fr Anesth Reanim 2006;25:899-901.
40. Rich NM, Spencer FC. Wounds of the heart. In: Rich NM, Spencer FC. editors. Vascular trauma. Philadelphia: WB Saunders, 1978:384.
41. Hughes SM, Borders CW, Aden JK, et al. Long-Term Outcomes of Thoracic Trauma in U.S. Service Members Involved in Combat Operations. Mil Med 2020;185:e2131-6.
42. Asensio JA, Stewart BM, Murray J, et al. Penetrating cardiac injuries. Surg Clin North Am 1996;76:685-724.
43. Hirshberg A, Wall MJ Jr, Allen MK, et al. Double jeopardy: thoracoabdominal injuries requiring surgical intervention in both chest and abdomen. J Trauma 1995;39:225-9; discussion 229-31.
44. Asensio JA, Arroyo H Jr, Veloz W, et al. Penetrating throacoabdominal injuries: ongoing dilemma—which cavity and when? World J Surg 2002;26:539-43.
45. Moreno C, Moore EE, Majure JA, et al. Peicardial tamponade, A critical determinant for survival following penetrating cardiac wounds. J Trauma 1986;26:821-5.
46. Arom KV, Richardson JD, Webb G, et al. Subxiphyoid pericardial window in patients with suspected traumatic pericardial tamponade. Ann Thorac Surg 1977;23:545-9.
47. Trinkle JK, Toon RS, Franz JL, et al. Affairs of the wounded heart: penetrating cardiac wounds. J Trauma 1979;19:467-72.
48. Miller FB, Bond SJ, Shumate CR, et al. Diagnostic pericardial window: a safe alternative to exploratory thoracotomy fur suspected heart injuries. Arch Surg 1987;122:605-9.
49. Brewster SA, Thirlby RC, Snyder WH 3rd. Subxiphoid pericardial window and penetrating cardiac trauma. Arch Surg 1988;123:937-41.
50. Duncan AO, Scalea TM, Sclafani SJ, et al. Evaluation of occult cardiac injuries using subxiphoid pericardial window. J Trauma 1989;29:955-9; discussion 959-60.
51. Andrade-Alegre R, Mon L. Subxiphoid pericardial window in the diagnosis of penetrating cardiac trauma. Ann Thorac Surg 1994;58:1139-41.
52. Lee TH, Ouellet JF, Cook M, et al. Pericardiocentesis in trauma: a systematic review. J Trauma Acute Care Surg 2013;75:543-9.
53. Hommes M, Nicol AJ, van der Stok J, et al. Subxiphoid pericardial window to exclude occult cardiac injury after penetrating thoracoabdominal trauma. Br J Surg 2013;100:1454-8.
54. Efron DT. Subxiphoid pericardial window to exclude occult cardiac injury after penetrating thoracoabdominal trauma (Br J Surg 2013; 100: 1454-1458). Br J Surg 2013;100:1458.
55. Garrison RN, Richardson JD, Fry DE. Diagnostic transdiaphragmatic pericardiotomy in thoracoabdominal trauma. J Trauma 1982;22:147-9.
56. Smith CA, Galante JM, Pierce JL, et al. Laparoscopic transdiaphragmatic pericardial window: getting to the heart of the matter. J Am Coll Surg 2011;213:736-42.
57. Anderson JE, Salcedo ES, Rounds KM, et al. Getting a better look: Outcomes of laparoscopic versus transdiaphragmatic pericardial window for penetrating thoracoabdominal trauma at a Level I trauma center. J Trauma Acute Care Surg 2016;81:1035-8.
58. Mayer HJ. Transdiaphragmatic pericardial window: a new approach. J Cardiovasc Surg (Torino) 1993;34:173-5.
59. Rozycki GS, Feliciano DV, Ochsner MG, et al. The role of ultrasound in patients with possible penetrating cardiac wounds: a prospective multicenter study. J Trauma 1999;46:543-51; discussion 551-2.
60. Jimenez E, Martin M, Krukenkamp I, et al. Subxiphoid pericardiotomy versus echocardiography; a prospective evaluation of the diagnosis of occult penetrating cardiac

injury. Surgery 1990;108:676-9; discussion 679-80.
61. Governatori NJ, Saul T, Siadecki SD, et al. Ultrasound in the evaluation of penetrating thoraco-abdominal trauma: a review of the literature. Med Ultrason 2015;17:528-34.
62. Hassett A, Moran J, Sabiston DC, et al. Utility of echocardiography in the management of patients with penetrating missile wounds of the heart. J Am Coll Cardiol 1986;7:1151-6.
63. Robison RJ, Brown JW, Caldwell R, et al. Management of asymptomatic intracardiac missiles using echocardiography. J Trauma 1988;28:1402-3.
64. Illman JE, Maleszewski JJ, Byrne SC, et al. Multimodality imaging of foreign bodies in and around the heart. Future Cardiol 2016;12:351-71.
65. Gervin AS, Fisher RP. The importance of prompt transport in salvage of patients with penetrating heart wounds. J Trauma 1982;22:443-8.
66. Mattox KL, Feliciano DV. Role of external cardiac compression in truncal trauma. J Trauma 1982;22:934-6.
67. Lorenz HP, Steinmetz B, Lieberman J, et al. Emergency thoracotomy: survival correlates with physiologic status. J Trauma 1992;32:780-5; discussion 785-8.
68. Durham LA 3rd, Richardson RJ, Wall MJ Jr, et al. Emergency center thoracotomy: impact of prehospital resuscitation. J Trauma 1992;32:775-9.
69. Advanced Trauma Life Support: Student Course Manual. Chicago, Illinois: Committee on Trauma-American College of Surgeons. 10th ed. 2018.
70. Asensio JA, Petrone P, Costa D, et al. An evidenced-based critical appraisal of emergency department thoracotomy. Evidence-Based Surgery 2003;1:11.
71. Teeter W, Haase D. Updates in Traumatic Cardiac Arrest. Emerg Med Clin North Am 2020;38:891-901.
72. Asensio JA, Wall MJ Jr, Minei J, et al. Working group, ad hoc subcommittee on outcomes. American College of Surgeons-committee on Trauma. Practice management guidelines for emergency department throacotomy. J Am Coll Surg 2001;13:303.
73. Rhee PM, Acosta J, Bridgeman A, et al. Survival after emergency department thoracotomy: review of published data from the past 25 years. J Am Coll Surg 2000;190:288-98.
74. Seamon MJ, Haut ER, Van Arendonk K, et al. An evidence-based approach to patient selection for emergency department thoracotomy: A practice management guideline from the Eastern Association for the Surgery of Trauma. J Trauma Acute Care Surg 2015;79:159-73.
75. Asensio JA, Hanpeter D, Demetriades D, et al. The futility of the liberal utilization of emergency department thoracotomy. A prospective study. Proceedings of the American Association for the Surgery of Trauma, 58th Annual Meeting, Baltimore, MD 1998:210.
76. Grabowski MW, Buckman RF Jr, Goldberg A, et al. Clamp control of the right ventricular angle to facilitate exposure and repair of cardiac wounds. Am J Surg 1995;170:399-400.
77. Asensio JA, Soto SN, Forno W, et al. Penetrating cardiac injuries: a complex challenge. Injury 2001;32:533-43.
78. Feliciano David V. Chapter 9 - Cardiac, Great Vessel, and Pulmonary Injuries,In: Rasmussen TE, Tai NRM. Editors. Rich's Vascular Trauma (Third Edition), Elsevier, 2016:71-99.
79. Agrifoglio M, Barili F, Kassem S, et al. Sutureless patch-and-glue technique for the repair of coronary sinus injuries. J Thorac Cardiovasc Surg 2007;134:522-3.
80. Karin E, Greenberg R, Avital S, et al. The management of stab wounds to the heart with laceration of the left anterior descending coronary artery. Eur J Emerg Med 2001;8:321-3.
81. Ivatury RR, Rohman M, Steichen FM, et al. Penetrating cardiac injuries: twenty-year experience. Am Surg 1987;53:310-7.
82. Moore EE, Malangoni MA, Cogbill TH, et al. Organ injury scaling. IV: Thoracic vascular, lung, cardiac, and diaphragm. J Trauma 1994;36:299-300.
83. Espada R, Whisennand HH, Mattox KL, et al. Surgical management of penetrating injuries to the coronary arteries. Surgery 1975;78:755-60.
84. Ivatury RR, Shah PM, Ito K, Ramirez-Schon G, Suarez F, Rohman M. Emergency room thoracotomy for the resuscitation of patients with "fatal" penetrating injuries of the heart. Ann Thorac Surg 1981;32:377-85.
85. Bodai BI, Smith JP, Ward RE, et al. Emergency thoracotomy in the management of trauma. JAMA 1983;249:1891-6.
86. Rohman M, Ivatury RR, Steichen FM, et al. Emergency room thoracotomy for penetrating cardiac injuries. J Trauma 1983;23:570-6.
87. Thourani VH, Feliciano DV, Cooper WA, et al. Penetrating cardiac trauma at an urban trauma center: a 22-year perspective. Am Surg 1999;65:811-6; discussion 817-8.
88. Gonzalez RP, Luterman A. Reviewer summary of "Rhee PM, Foy H, Kaufman C, et al: Penetrating cardiac injuries: a population based study. J Trauma 1998; 45:366." Current Surgery 2001;58:173.

89. Gonzalez RP, Luterman A. Reviewer summary of "Thourani VH, Feliciano DV, Cooper WA, et al: Penetrating cardiac trauma at an urban center; a 22-year perspective. Am Surg 1999; 65:811." Current Surgery 2001;58:177.
90. Wall MJ Jr, Mattox KL, Chen CD, et al. Acute management of complex cardiac injuries. J Trauma 1997;42:905-12.

doi: 10.21037/med-22-18
Cite this article as: Hromalik LR Jr, Wall MJ Jr, Mattox KL, Tsai PI. Penetrating cardiac injury: a narrative review. Mediastinum 2023;7:15.