Cardiac Injuries

Ulrich Linsenmaier and Lucas L. Geyer

Contents

Abstract

Cardiac injury due to penetrating or blunt thoracic trauma is relatively rare but associated with significant morbidity and mortality. Many of these injuries have not been characterized fully by diagnostic imaging so far. With the introduction of fast MDCT an established emergent diagnostic modality is now available for heart imaging, that allows the detection and characterization of a large variety of myocardial, pericardial, vascular and mediastinal injuries. Beside the established methods, like cardiac ultrasound and cardiac angiography, it allows now in the emergency setting a thorough morphologic characterization of injuries and its' potential bleeding dynamics. This article reviews the spectrum of blunt and penetrating heart injuries as well as the imaging modalities commonly used in the acute trauma setting.

1 Introduction

Cardiac injury is rare and is related with significant mortality and morbidity. Radiological imaging of cardiac injuries is relatively new, and the majority of the imaging features have not yet been fully evaluated. With the introduction of fast multidetector CT (MDCT), these injuries have increasingly come into the focus of radiology, and CT can now identify a large spectrum of

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U. Linsenmaier, MD, PhD (✉)
Director Institute for Diagnostic and Interventional Radiology, HELIOS Kliniken München West, Associate Professor of Radiology, Ludwig-Maximilians-University Munich (LMU), Past President ESER – European Society of Emergency Radiology, Munich 81737, Germany
e-mail: Ulrich.Linsenmaier@helios-kliniken.de

L.L. Geyer, MD
Institute for Clinical Radiology, LMU Ludwig-Maximilians-University Hospital Munich, Marchioninistr. 15, Munich 81377, Germany
e-mail: Lucas.Geyer@med.lmu.de

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injury patterns. In the acute trauma setting, it is crucial to recognize these findings and to initiate appropriate treatment (Mattox et al. 2012).

Cardiac injuries are caused by work accidents, explosions, falls from height, and also from CPR and assaults. In communities where there is a higher ratio of firearm ownership among the public, the likelihood of penetrating injuries to the heart is higher (Table 1) (Parmley et al. 1958; Tenzer 1985).

In many cases, injuries to the heart lead to immediate death. Typically, the myocardium, pericardium, and the coronary arteries are affected. In blunt trauma, the heart can be compressed between a flexed spine and the sternum; however, shearing forces, twisting, and deceleration trauma have also been described. The mechanically injured heart can be further damaged by hypovolemic shock, arterial hypotension, and resulting myocardial ischemia. In addition, heart function may be impaired by hypoxia from other injuries such as pulmonary contusions, pulmonary lacerations, and pneumothorax as well as multi-organ failure (MOF) (Parmley et al. 1958; Fulda et al. 1991; Orliaguet et al. 2001).

Up to 25 % of deaths from traumatic events are associated with cardiac injuries. The incidence of blunt cardiac injury has risen during the last decades, but early diagnosis and efficient, specific treatment are mandatory and are correlated with increasing survival rates. A major proportion of patients with manifest cardiac injuries die on the scene before they can reach medical treatment. In cardio surgery, new technologies are influencing outcomes, as bypass surgery and the use of intra-aortic balloon devices can assist the cardiac function and thus may help to improve the outcome (Table 2) (Mattox et al. 2012; Co et al. 2011).

Table 1 Cardiac injury – mechanism of injury

In principle, any mechanism with kinetic energy to the thoracic cage may cause blunt cardiac trauma
Typical examples:
Motor-vehicle accident (>20 mph) with compression by the steering wheel
Deceleration trauma
Accidental falls from great heights
Objects of great weight falling directly onto the sternum
Blast and direct forces applied to the chest
Increased abdominal pressure
Cardiopulmonary resuscitation

Table 2 Cardiac injury – clinical presentation

Acute findings	Subacute findings
Complete hemodynamic instability	Tenderness and pain along the anterior chest wall
Congestive heart failure	Dysrhythmias
Cardiopulmonary arrest	New heart murmur
Cardiogenic shock	Pericardial friction rub
Symptoms of pericardial tamponade	

2 Imaging Modalities

2.1 Cardiac Ultrasound (US)

Echocardiography (cardiac US) provides precise evaluation of the existence of pericardial effusions. In addition, small volumes of not more than 25 ml can be detected. Myocardial wall motion and the valvular structures can also be assessed, as well as the left ventricular function. Transesophageal echocardiography (TEE) can also be used to assess the ventricular function in cases of myocardial contusion and was deployed to evaluate the aorta for signs of aortic injury (AI) before reliable CT angiography (CTA) from advanced MDCT scanning became available (Restrepo et al. 2007, 2012). However, TEE is more time-consuming and invasive and is difficult to perform with concomitant injuries, e.g., to the face and cervical spine. Additionally, it is not always available and is operator dependent. Therefore today TEE plays only a minor role in the acute trauma setting.

US findings of acute cardiac injury comprise cardiac wall compression and pulmonary artery compression as well as paradox flow patterns, abnormalities of the ventricular septum, and abnormal swinging motion of the heart itself (Restrepo et al. 2007, 2012).

Alternatively, transthoracic cardiac US can be performed. It is rapid, noninvasive, and efficient. It is reported that even limited training in cardiac US techniques may provide an efficient means of detecting pericardial hemorrhage. Sensitivity is reported to be 90 %, specificity 97 %, and accuracy 96 %. Pericardial emergency ultrasound of the heart is an important component of FAST ultrasound (focused assessment with sonography in trauma) (Mattox et al. 2012; Co et al. 2011).

2.2 Conventional Radiography (CR) of the Chest

Supine conventional radiography (CR) of the chest is still a component of the initial trauma workup in the emergency room. However CR is limited to delineate the full spectrum of injuries to the thorax and heart as well. In many cases, however, signs of pneumopericardium, hematothorax, pneumothorax, and mediastinal widening, due to mediastinal hematoma, can be detected. Imaging quality of supine CR of the chest in the emergency setting is often limited and most of the important cardiac injury patterns cannot be detected (Mattox et al. 2012; Co et al. 2011).

2.3 Cardiac Angiography

Angiography of the coronary arteries (syn. cardiac angiography) is not an established component of a typical trauma-imaging workup in the emergency room. However, it is very sensitive and specific in imaging coronary artery injuries, and it can detect even subtle vascular lesions. In addition, it offers the entire spectrum of opportunities for immediate interventional treatments of vascular lesions. It is indicated in all cases of suspected vascular injury and also when ischemia is suspected with ECG changes after trauma, to evaluate patients for traumatic aneurysms, intima dissections, and vascular thrombosis after trauma. Most of these lesions can be detected and can undergo intermediate interventional treatment.

2.4 Multidetector CT (MDCT)

Many patients with suspected multiple trauma undergo a MDCT from head to toe, so-called whole-body CT (WBCT). MDCT is the imaging modality of choice for the evaluation of all kinds of chest trauma and is highly sensitive and specific for the evaluation of lung injuries, pneumothorax, active hemorrhage, pericardial or myocardial injury, pleural and pericardial effusions, hematothorax, and also cardiac herniation and cardiac luxation. MDCT can also depict valvular injuries and papillary muscle rupture as well as avulsion of the aortic and mitral valve (Linsenmaier et al. 2002; Mirvis).

High-quality MDCT is today available in all major trauma centers, it is widely accepted, and MDCT is today the core imaging modality in the major trauma setting. In thoracic and cardiac imaging, MDCT can detect penetrating foreign bodies, it also depicts the track of penetrating objects, and it allows for initiation of a targeted treatment. MDCT has a high sensitivity and accuracy in the detection of pleural and pericardial effusions or pericardial hemorrhage and tamponade. It detects pericardial and myocardial lacerations and also active hemorrhage from the heart. It also depicts luxation and displacement of the heart and has also a high sensitivity for concomitant mediastinal vascular and lung injuries. Due to its high spatial and timely resolution, it delivers isotropic voxel allowing for the calculation of high-resolution multiplanar reconstructions (MPRs). Today small motion and flow artifacts are now much reduced from prior scanner generations. ECG-gated MDCT scanning is an adjunct to the initial whole-body CT (WBCT) in the acute trauma setting. Contrast medium (CM) is administered in all studies, and an extended CM bolus allows for a contrast filling of the right and left heart and the vascular in- and outflow at the same time. Primary axial reconstruction is performed with the thinnest possible slice thickness (ST) of 0.5–0.625 mm; diagnostic axial images are reconstructed at 1–1.5 mm and coronal and sagittal MPRs at 2–3 mm and VRT as well (Fig. 1) (Mirvis; Korner et al. 2009).

2.5 Cardiac Magnetic Resonance Imaging (MR)

Cardiac magnetic resonance imaging (MR) has the ability to assess cardiac anatomy as well as cardiac function; it can visualize signs of myocardial ischemia and myocardial infarction (MI). In myocar-

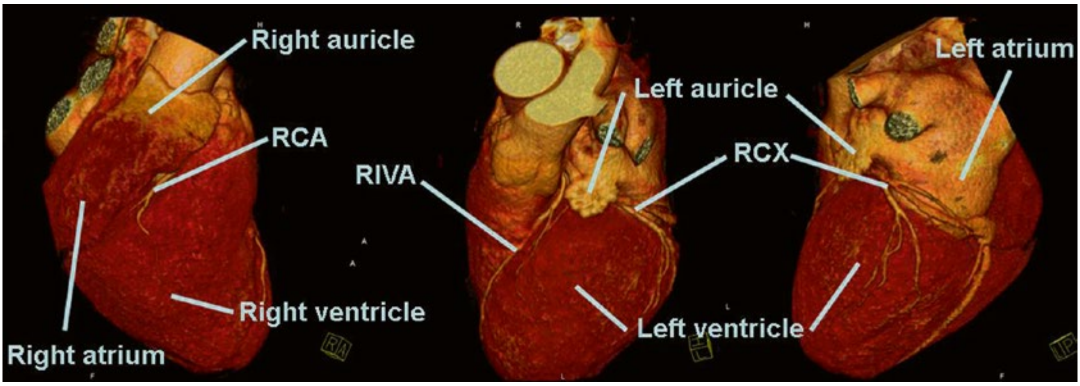

Fig. 1 CT anatomy of the heart ECG-gated cardiac CT in a volume-rendering technique (VRT) for radial display

dial contusions, it can depict abnormal cardiac wall motion and abnormal valve function and can detect edema and ischemia of the myocardium. MRI is not useful in the early and acute trauma workup as availability of 24 h/7 days is limited, the exam is complex to be performed, and the patient monitoring is difficult at the same time. However, if indications are given, it is a valuable noninvasive imaging method in addition to MDCT of the acute setting (Co et al. 2011; Korner et al. 2009).

3 Blunt Cardiac Injuries

Minor injuries are so-called myocardial contusions (syn. cardiac contusion); more severe injuries comprise ruptures of the pupillary muscles, valve injuries, injuries to the coronary arteries, and septal and myocardial injuries as well as cardiac rupture. Most common causes of blunt cardiac injury are high-speed motor-vehicle accidents (MVAs), crush or blast injuries, falls from height, and less common, direct violence or direct impact to the chest or abdomen. Also iatrogenic injuries are reported due to cardiopulmonary resuscitation (CPR). A clinical algorithm is available for management of patients after blunt cardiac trauma (Fig. 2).

3.1 Myocardial Contusion

Myocardial contusion is best defined as motion changes of the cardiac wall when myocardial infarction (MI) could be ruled out. Clinically it can be suspected in cases of significant chest trauma and persistent arterial hypotension despite volume therapy (Embrey; Kaye and O’Sullivan).

Myocardial contusion has to be differentiated from myocardial infarction which can be clinically difficult to distinguish. In myocardial infarction (MI), symptoms are related to a vascular territory, and the tissue at the risk shows a transition zone when in myocardial contusion the tissue at risk is more confined and has a distinct edge. The incidence of myocardial contusion is reported in a wide range with 10–75 %, probably due to inconsistent findings, and a scientific standard for diagnosis is still missing (Mattox et al. 2012; Co et al. 2011; Symbas; Tenzer).

These injuries are also named under the term myocardial contusion (alternatively, myocardial concussion) and are usually best diagnosed by laboratory testing of isoenzyme MB of creatine phosphokinase (CPK-MB), echocardiography, and ECG. The troponin test is an additional laboratory test (CTNI and CTNT >0.1 µg/l), with increased levels of the protein troponin usually observed in patients with cardiac contusions. Typically, patients only undergo monitoring on intermediate care units (Table 3) (Mattox et al. 2012; Co et al. 2011; Symbas; Tenzer).

The introduction of the diagnosis cardiac contusion is controversial as clinical importance, incidence, and morbidity and mortality remained controversial. It is accepted that younger patients with ECG abnormalities after trauma should

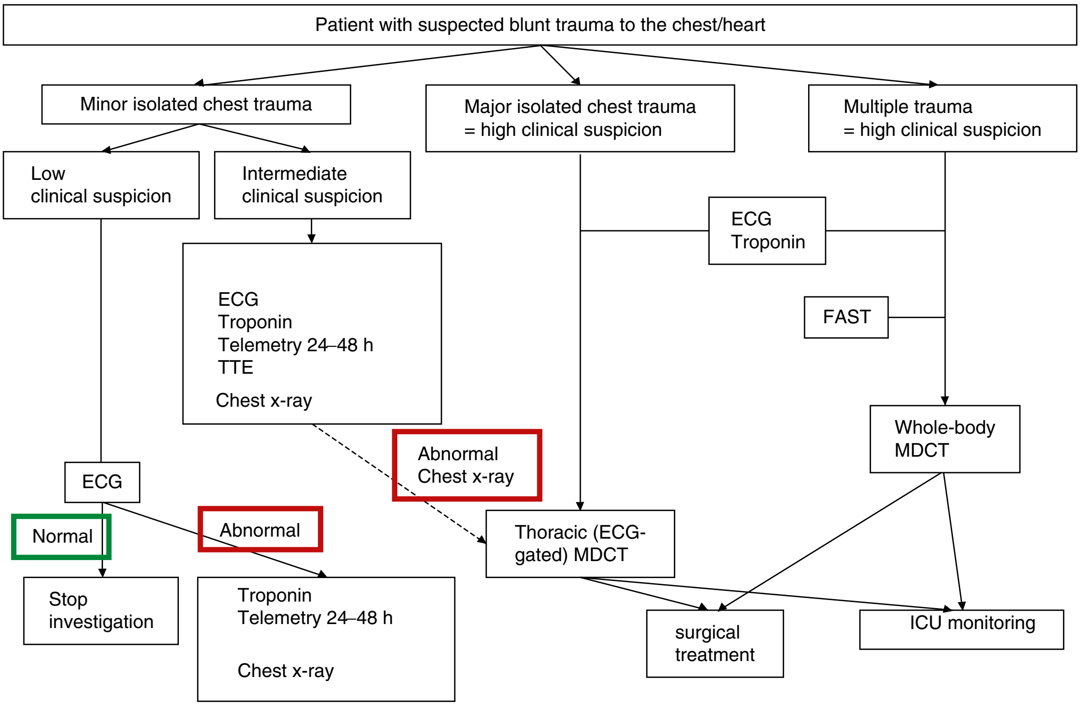

Fig. 2 Clinical algorithm for management of patient with suspected blunt trauma to the heart. The algorithm distinguishes minor isolated chest trauma from major isolated chest trauma and multiple trauma (El-Chami et al. 2008)

Table 3 Cardiac injury – laboratory and ECG diagnosis

Laboratory findings/cardiac enzymes	ECG findings
Cardiac markers are biomarkers measured to assess heart dysfunction: Myoglobin, LDH-1 isozyme, glycogen phosphorylase isoenzyme BB (GPBB), creatine kinase MB, troponin T and I *Creatine kinase* MB (CK MB) has turned out to be nonspecific *Troponin T*: very specific marker for cardiac injury (91 %), but with low sensitivity (31 %) *Troponin I* shows the best correlation of sensitivity and specificity in different trials. In combination with EKG abnormalities, it exhibits 100 % sensitivity for detection of clinically significant blunt cardiac trauma such as cardiogenic shock, dysrhythmias requiring treatment, or structural cardiac abnormalities related to trauma Levels <1.05 μg/L in asymptomatic trauma patients, indicative of cardiac injuries Levels >1.05 μg/L associated with ventricular dysrhythmias and left ventricular dysfunction The remaining cardiac parameters are not relevant for trauma monitoring	The important role of ECG bases on the fact that electrical instability is an important indicator for blunt cardiac trauma ECG is a quickly available tool for the first survey: Hemodynamically stable patients with normal EKG need no further monitoring Significant electrical disorders are suggestive of cardiac injuries especially the presence of any new bundle branch block Other typical findings: persistent sinus tachycardia (most often), atrial fibrillation, ST depression, ST elevation Limitation: present abnormalities are not pathognomonic markers for diagnostic correlations

undergo further evaluation. ECG is a clinical indicator in multiple injured patients as significant cardiac disease is relatively rare in young patients after trauma.

When ECG abnormalities occur, they are significant and need further evaluation. Clinical recommendations comprise that patients after thoracic trauma, as long as they are symptom-free, do not need any surveillance or monitoring; in symptomatic patients, intermediate care or telemetry monitoring is considered to be sufficient (Cachecho et al.; Fabian et al.; McLean et al.).

Pathophysiologically there is a wide range of tissue damage in myocardial contusions, from transmural hemorrhage and tissue necrosis to superficial contusions with different extend of tissue loss. The resulting perfusion defects and myocardial dysfunction most likely result from focal contusion and tissue edema when coronary artery disease is not present. The right heart is more affected due to its position next dorsal to the sternum. Clinical findings comprise ECG changes and elevated cardiac enzymes (creatine phosphokinase and serum cardiac troponin) (Allen and Liedtke; Ghersin et al.).

Clinical symptoms can mimic myocardial infarction, including dyspnea and chest pain; the ECG changes are variable and most cases are uncomplicated. However, a progress to an arrhythmia, cardiac dysfunction, hypotension, and low-output failure as well as myocardial rupture can be observed leading to life-threatening cardiac failure.

Abnormal cardiac wall motion is best diagnosed with echocardiography. In the setting of whole-body computed tomography after trauma (WBCT), there are no specific imaging features reported for myocardial contusion so far. Advanced ECG-gated MDCT enables an anatomic workup including CT angiography (CTA) of the coronary arteries. In addition, it allows for a functional assessment of the heart including assessment of the cardiac wall motion in 4D technique and initial reports on myocardial perfusion. Concomitant injuries of the thorax and mediastinum are present in many cases and can deteriorate the clinical situation (Fig. 3) (Embrey; Kaye and O'Sullivan).

Cardiac MR and positron emission tomography (PET) can delineate the possible extend of the hypoperfused myocardium and can be used for further workup if myocardial contusion is suspected (Co et al. 2011; Kaye and O'Sullivan).

3.2 Injuries to the Pericardium

Pericardial tears can differ in size from millimeters to an extent over the entire pericardium. They are most common at the diaphragmatic surface and the left-sided pericardium. Typically they are

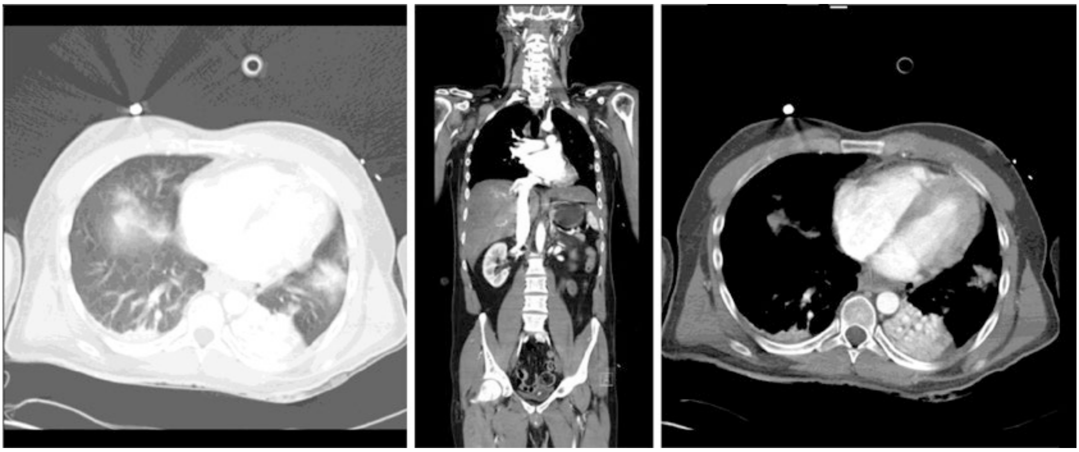

Fig. 3 Myocardial contusion: ungated MDCT of the whole body showing heart dilatation of the right atrium and ventricle, pulmonary contusion and hematothorax, and atelectasis of the left lower lobe. A contrast reflux with retrograde paradox flow in the inferior vena cava (IVC)

result of an increased intra-abdominal pressure or the direct impact to the chest and mediastinum (Fulda et al. 1991; Parmley et al.).

Conventional radiography (CR) may show air in the pericardium (pneumopericardium); pericardial injuries can be complicated by diaphragmatic rupture and cardiac herniation from resulting in severe cardiac failure. However CT findings are by far more sensitive and specific.

Pericardial tears and ruptures are rare injuries, with an incidence of only 0.3–0.5 %. They occur with severe deceleration forces or are due to osseous fragment perforation by fractures to the sternum or the ribs. Pneumopericardium is a complication of pericardial rupture; an air collection is located ventral to the myocardium in the pericardial sac. Pneumopericardium is a sign for pericardial injury. The tear itself can be detected by irregular margins of the pericardium, discontinuity, and interposition of fat or long parenchyma. This can be further complicated by cardiac tamponade and compression. Pneumopericardium is always a sign for pericardial injury; the pericardial tear itself can be detected by irregular margins or discontinuity of the pericardium, but also by interposition of fat or lung parenchyma (Restrepo et al. 2007; Farhataziz and Landay) (Fig. 4).

After pericardial injury MDCT can be used to depict pericardial effusions. In the acute trauma setting, every pericardial effusion has to be evaluated for hemorrhage; MDCT can measure the density of effusions in Hounsfield units (HU) and confirm pericardial hemorrhage and tamponade (Restrepo et al. 2007).

Further complications include the displacement of the heart through the pericardial rupture into the mediastinum or thoracic cavity, showing an empty air-filled pericardium on MDCT. As the vascular structures are stretched or also rotated (also described as volvulus), this can lead to immediate compression of the heart and obstruction of the vascular system. Cardiac luxation describes herniation and compression of the heart, which can result in obstruction of the upper venous inflow over the superior vena cava (SVC). Luxation can occur in up to 28 % of pericardial ruptures, and there is a high associated mortality rate of up to 67 %. An ECG allows observation of a change of the heart axis. Cardiac US is of limited value only. MDCT can be used to diagnose heart displacement as well as the compression and deviation of the myocardium and the heart chambers (Fig. 5) (Moront et al.; Bruschi et al.).

3.3 Injuries to the Heart Valves, Papillary Muscles, Chorda Tendinea, and Septum

Blunt cardiac trauma can result in ruptures of the myocardial septum, the valves, and the papillary muscles. Patients with preexisting heart disease and disorders of these structures are more prone to this type of trauma.

Clinically, these injuries can be associated with acute left ventricular failure and atypical systolic murmurs. Systolic murmur is a sign of valve injury and papillary muscle injuries. In the case of

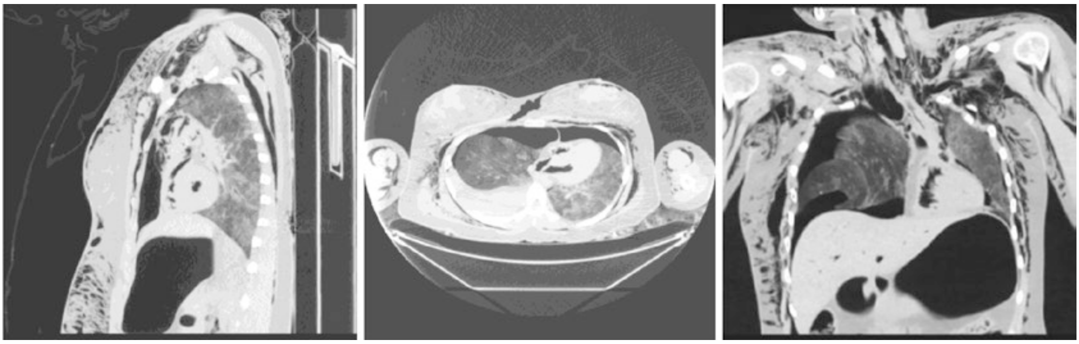

Fig. 4 Pneumopericardium: ungated MDCT showing a pneumopericardium on post-mortem CT (PM CT). There is pathological air collection in the chambers of the heart, pneumomediastinum, soft tissue emphysema, pneumothorax, gastric hyperinflation, and hematothorax

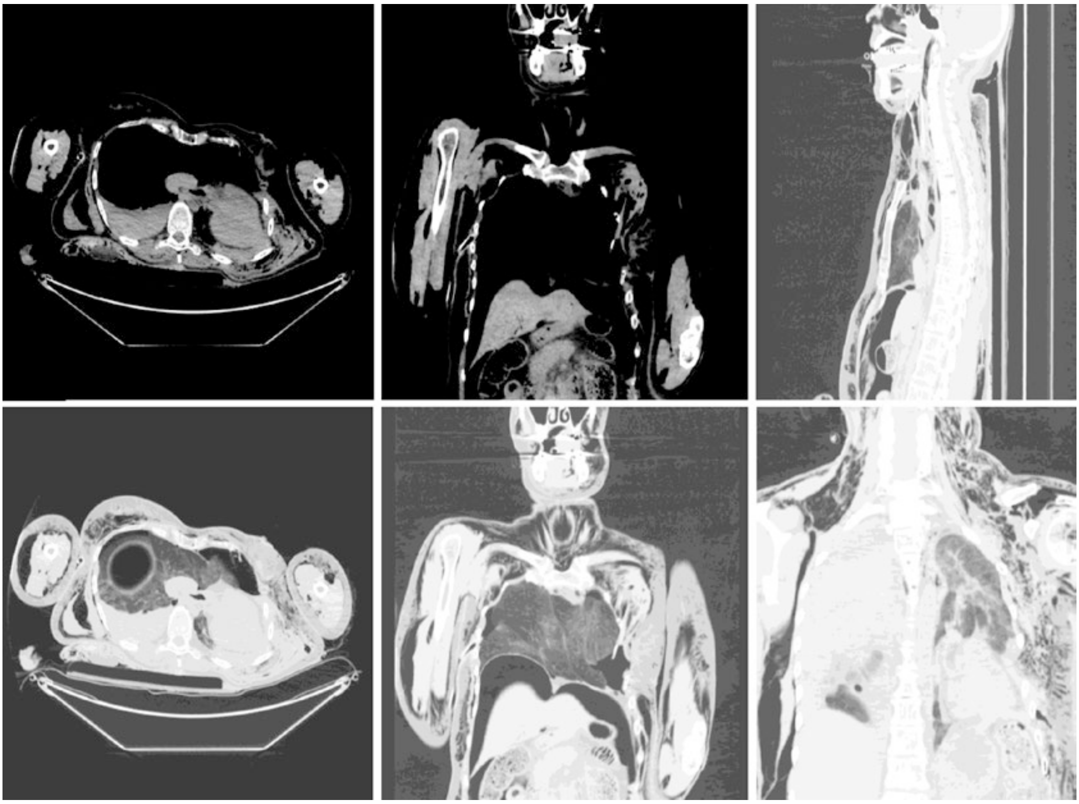

Fig. 5 Cardiac luxation: ungated MDCT case of cardiac herniation where the heart is dislocated from its anatomical position into the left thoracic cavity, lateral to the spine. The so-called black hole in the soft tissue window and "kissing lungs" due to the displacement of the entire heart can be observed in the lung window

severe ventricular failure, operative treatment is mandatory. Injuries to the septum can also result in atypical murmurs. Ruptures of the septum can result in left-right blood shunts, with the clinical symptoms dependent on the extent of the lesion caused. Operative interventions with regard to these injuries are determined by the individual case. Small septal injuries may be treated conservatively; larger defects are subject to surgical repair (Mattox et al. 2012; Moront et al.).

Moront et al. reported a case of injury of the tricuspid valve and the intraventricular septum days after blunt injury, and the patient underwent operative treatment. The ventricular septum ruptures were observed in the muscular septum close to the apex of the heart (Moront et al.).

Parmely et al. reported a series of 546 cases of blunt cardiac trauma and described a 9% incidence of injuries to the valves. In their series mitral, aortic, and tricuspid valves were involved (Parmley et al. 1958).

An injury of the heart valve and traumatic valvular dysfunction is rare. It can be suspected if pulmonary edema is present after chest trauma. Commonly affected is the aortic valve as common as the mitral and tricuspid valves. The underlying mechanism is an excessive elevation of blood pressure in the heart, but also an elevated intra-abdominal pressure can be transmitted to the heart and affect the cardiac valve and papillary muscles. Commonly observed are injuries of the mitral valve, including rupture of the chorda tendinea and the papillary muscles and aortic valve injuries (Bruschi et al.; Kan and Yang).

Imaging workup comprises usually echocardiography, TEE, and cardiac angiography. But early reports also suggest that MDCT can detect some of these injuries (Lee et al.).

3.4 Injuries to the Coronary Arteries

Intima dissection of the coronary arteries can result in thrombosis and occlusion and subsequent myocardial ischemia. In an elder population with preexisting coronary artery disease (CAD), it may be difficult to distinguish a traumatic occlusion from a non-trauma-associated arteriosclerotic occlusion of the vessel. As a complication arteriovenous (AV) fistulas as well as atrioventricular fistulas of the coronary arteries were described as result of blunt injury; however they are very rare (Mattox et al. 2012).

Diagnostic imaging with MDCT is now possible, and even in non-gated MDCT after trauma, the occlusions of the left coronary artery could be depicted. This is much dependent on the heart frequency and the timely resolution of the non-gated MDCT scanner. And not always the coronary artery main stems can be depicted on non-gated MDCT. The addition of ECG-gated MDCT studies and contrast CTA of the coronary arteries may be an option. However in the emergency setting, gated MDCT of the chest is not a primary choice.

Diagnostic imaging typically comprises card angiography, and interventional recanalization can be intended; revascularization and stent implantation are interventional treatment options.

Coronary artery injuries are relatively rare and account for 2% of all thoracic injuries. As multiple injuries have been described, the left anterior descending artery (LAD) is most likely affected, also due to its immediate retrosternal location. Clinically signs of myocardial infarction (MI) can be observed in ECG, which can result in hypotension and arrhythmia. Intima dissection and thrombosis are more common, but vascular ruptures with free hemorrhage have also been reported. In ungated MDCT imaging using high spatial and timely resolution, diagnosis can be made; however this is based on single-case reports. If injuries to the coronary arteries are suspected, ECG-gated MDCT with CTA of the coronary arteries is indicated and also the use of triple rule out (TRO) protocols can be used. Immediate interventional treatment is carried out by coronary angiography recanalization and stent treatment (Pretre and Chilcott; Sheikh et al.) (Figs. 6 and 7).

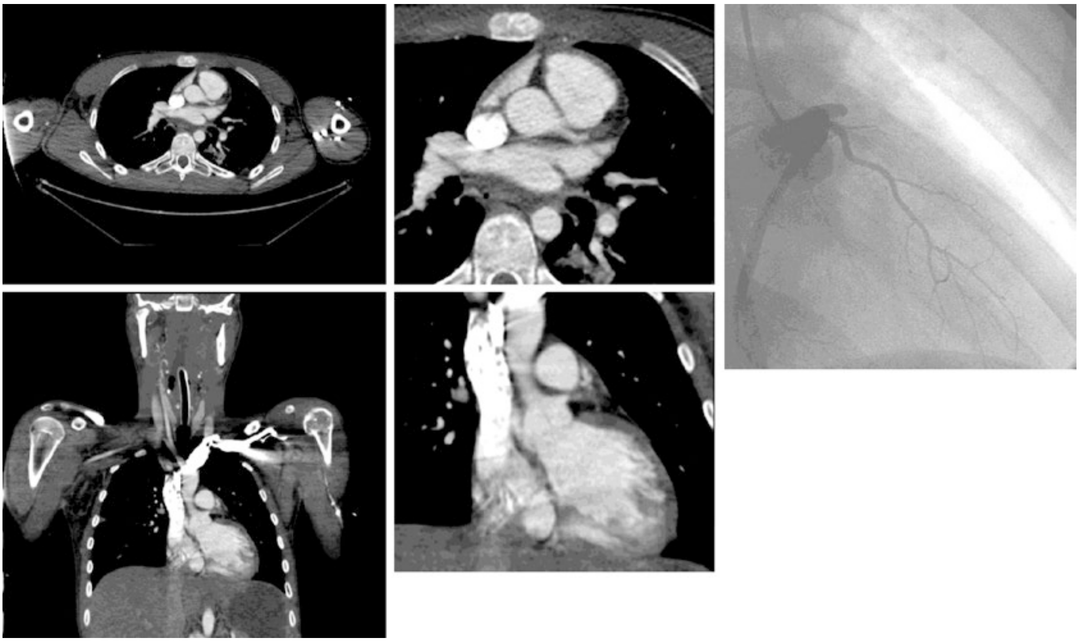

Fig. 6 Injury to the left coronary artery: Dissection of the LAD. Ungated MDCT/WBCT in a patient after polytrauma. Two centimeters from the main stem, an occlusion of LAD can be observed; the interruption of the CM-enhanced LAD with little downstream effusion, coronary angiography confirmed the diagnosis

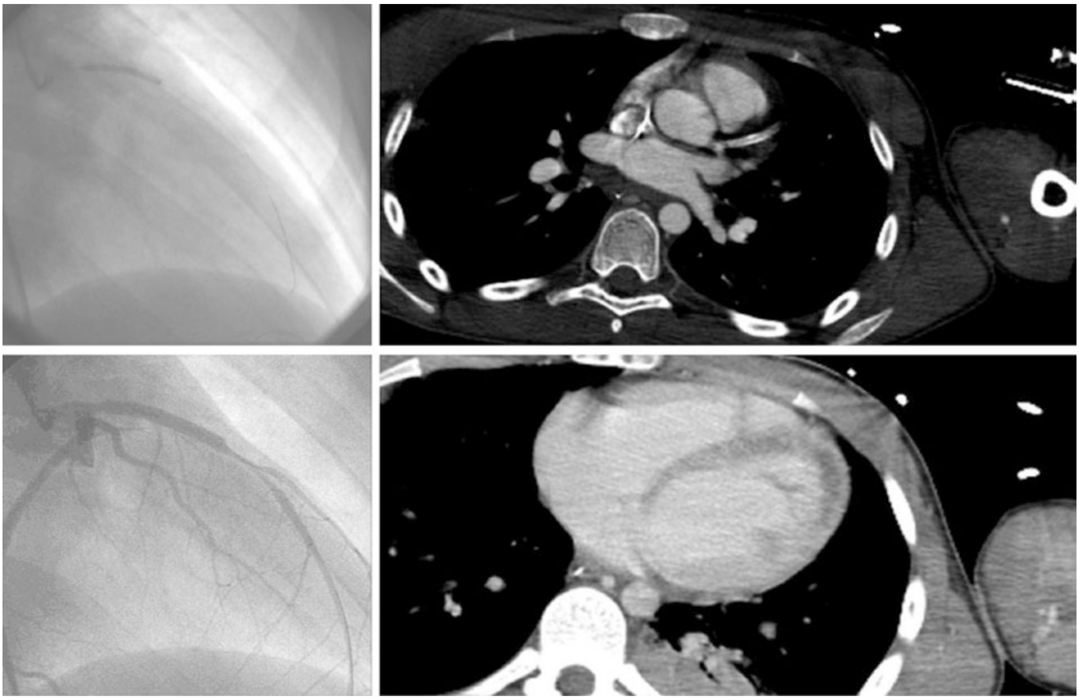

Fig. 7 Recanalization of LAD and stent-graft placement in the LAD, and follow-up CT with hypodense subendocardial rim of the myocardium which is as a correlate of myocardial infarction

Penetrating injuries of the coronary arteries most likely occur in the left anterior descending, coronary artery (LAD) resulting in myocardial dysfunction. However, the majority of coronary artery injuries are more distal. Proximal injuries can be treated by emergent coronary artery bypass surgery and smaller vessels with diameters of less than 1 mm and can result in small infarcts.

3.5 Cardiac Rupture

Cardiac rupture is typically the result of the severe thoracic trauma mostly associated with MVA as well as falls from height and direct blast injuries to the chest. The underlying mechanism of injury has been described as direct force to the chest with increased thoracic pressure and transmission to the heart. Decelerating forces typically affect the borders of mobile and fixed anatomic structures of the heart, also explaining arterial and caval tears. Additionally, severe trauma to the abdomen can be transmitted via vascular structures such as the inferior vena cava (IVC) to the right heart, causing rupture of the heart. Cardiac rupture also occurs as a result of myocardial contusion, traumatic myocardial necrosis, and formation of pseudoaneurysms. Direct force from sternal or costal fractures with penetrating bone fragments can directly perforate the cardiac walls (Mattox et al. 2012).

Many patients have no cardiac function on admission, due to cardiac tamponade, severe hemorrhage, or pericardial tamponade. Diagnosis can be delayed in patients who are stable, and in a series of 24 cases, 16 were delayed by up to 1 h (Patton et al.). In addition, polytrauma and associated injuries make the diagnosis difficult. ECG can show a bundle branch block or deviation of the heart axis in cases of cardiac herniation.

Echocardiography (syn. cardiac ultrasound) can depict pericardial hemorrhage, and it is recommended to decompress the pericardium immediately even under cardiac arrest.

Ultrasound-guided pericardial puncture is an option to confirm the diagnosis.

Clinical treatment is comparable to that for penetrating cardiac injuries. Pericardial decompression is followed by sternotomy, and insertion of an intra-aortic balloon pump is a treatment option (Fulda et al. 1991; Calhoon et al.; Kato et al. 1988; Mattox et al. 1992). It should be considered that in these cases associated injuries are common, and the entire torso and skeleton should be diagnosed by whole-body CT (WBCT). Common associated injuries include aortic injuries, abdominal injuries (up to 43 %), head injuries (up to 51 %) and skeletal injuries (up to 40 %). The outcome is limited; Fulda et al. (Fulda et al. 1991) describe a mortality rate of 48 % in patients with cardiac arrest, and the overall mortality is reported to be up to 76 %. Kato et al. (Kato et al. 1988) report a mortality rate of more than 90 % in a cohort of 63 patients.

Myocardial rupture (cardiac rupture) is rare, and the incidence is reported as 0.1–0.3 % in patients with severe chest trauma. However, it is associated with a high mortality, accounting for 36–56 % of blunt thoracic injuries. Again, the right heart is more prone to injury due to its retrosternal position and the thinner myocardial wall of the right ventricle. In gross hemorrhage it can lead to pericardial tamponade and immediate cardiac arrest, and patient deserves cardiopulmonary resuscitation (CPR) (Co et al. 2011; Kato et al. 1988; Van Horn 2007).

Depending on the presence of a pericardial injury, the hemorrhage is contained in the pericardial sac or can procreate to the mediastinum and the thoracic cavity. The extent of the hemorrhage in an intact pericardium can lead to tamponade. Blunt myocardial rupture occurs with increased central venous pressure (CVP) in the diastole, leading to increased pressure in the ventricle when the atrioventricular valve is closed. Myocardial rupture is lethal in many cases, e.g., in a patient presenting with refractory hypotension and tachycardia (Figs. 8, 9, and 10) (Van Horn 2007).

The mortality of patients undergoing surgery is reported as high as 33 %, but where treatment is successful, a good long-term outcome is reported. MDCT has proven to be able to show complete and incomplete myocardial rupture, while active hemorrhage can be observed by the extravasation of contrast-enhanced blood into the pericardium, mediastinum, or thoracic cavity. Additional use of MR can depict myocardial disorders such as muscular thinning, formation of myocardial scars, and ischemia in cases of infarction more sensitively, but this is not appropriate in the acute setting (Mirvis; Zoni et al.).

4 Penetrating Cardiac Injury

The spectrum of penetrating injuries includes injuries to the atrium and the ventricle, injuries to the vascular structures, injuries to the trachea, bronchi, esophagus, as well as of the bony cage and the thoracic spine. Penetrating transmediastinal injury (TMI) is defined injury that transverses the mediastinum.

In a recent series of 532 penetrating injuries, the right ventricle was involved (35 %), less common are the left ventricle (25 %), right atrium (33 %), left atrium (14 %), and the aorta (14 %) (Demetriades and van der Veen). The right heart is more prone to injury due to its location dorsal to the sternum. In penetrating injuries, the extent and severity of injury depend on the caliber of the penetrating objects. The clinical symptoms can change from asymptomatic and normal ECG to unstable vital signs, hypotension, and cardiac arrest due to cardiac tamponade or active hemorrhage (Elie; Gasparri et al.; Thourani et al.).

Penetrating injury is mostly based on firearms and knives; less common is perforation by bone fragments from sternum or rip fractures. Iatrogenic injury is rare but can be related to accidental cardiac puncture, interventional procedures, or central venous access devices (Mattox et al. 2012; Asensio et al. 1996). As the right ventricle is in direct contact with the interior chest wall, it is more prone for cardiac injury. In a series of 711 patients, the authors reported a distribution of injuries to the right ventricle (40 %) and left ventricle (40 %) being more common than injuries to right atrium (24 %) and left atrium (3 %) (Wall et al. 1997).

The pathophysiology and the clinical outcome are influenced by two main factors, the severity

Fig. 8 Cardiac rupture: ungated MDCT with a cardiac chamber rupture. Missing delineation of the myocardium of the right cardiac chambers can be seen, as well as active hemorrhage from the heart to the pericardium with a compression of the heart. The corollary is that hemopericardium-associated injuries comprise hematothorax and acute aortic rupture

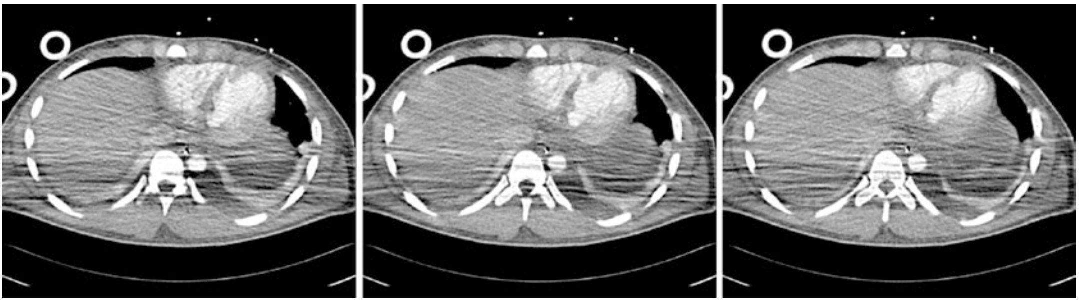

Fig. 9 Cardiac rupture: ungated MDCT whole-body CT of a patient showing a septal injury with septal rupture. The discontinuity of the cardiac septum and the transseptal hemorrhage is depicted

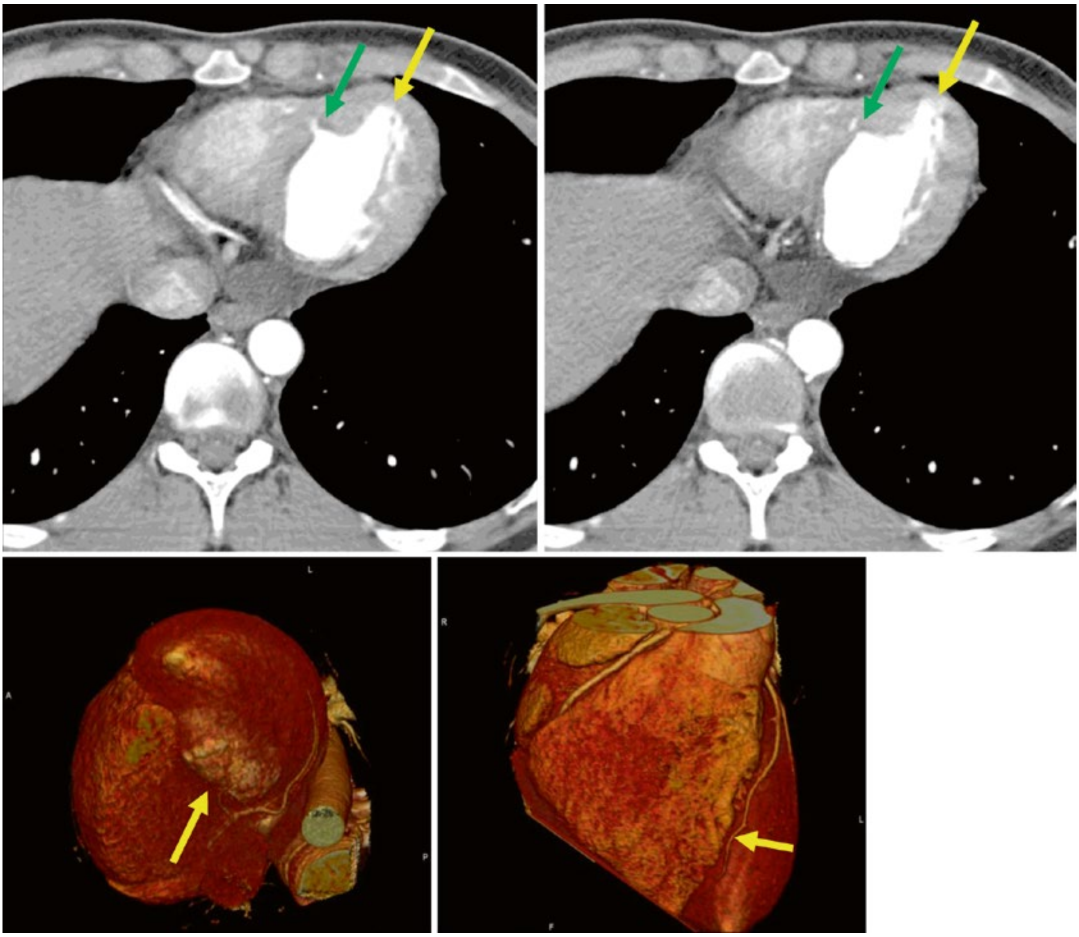

Fig. 10 ECG-gated MDCT of the heart, axial reconstructions, and VRT. The figure shows (**a**) a discontinuity of the intraventricular septum with intraseptal bleeding as a sign of incomplete rupture (*green arrows*) and (**b**) intramyocardial bleeding on the apex of the left ventricle (*yellow arrows*) as a sign of traumatic cardiac aneurysm displaying in the VRT reconstruction

and rate of bleeding and the involvement and extend of pericardial tamponade. Penetrating injuries with small knives are self-limited and can often result uncomplicated with self-healing of the laceration. Up to 90 % of patients with small object-penetrating injuries show pericardial tamponade (Symbas).

Clinically, patients present with tachycardia and increased pressure in the ventricular filling as well as paradox pulse, a high drop in systolic blood pressure during inspiration, and increased myocardial contractility. They also exhibit extended neck veins, as well as paradox inspiration and increased CVP; however, the latter can also be associated with pneumothorax, which is a differential diagnosis.

This can result in a compensated status of tamponade; however, under volume replacement the cardiac function and systemic blood pressure can still be kept within the limits. However, even a slight deterioration in pericardial tamponade can result in severe left ventricular-filling defects, immediate systemic hypotension, and cardiac output failure. The myocardial compression also results in ischemia due to compression of the coronary artery flow – leading to an uncompensated cardiac tamponade (Mattox et al. 2012).

Larger wounds or gunshot injuries result in hemorrhage from the cardiac chambers and, in many cases, associated injuries causing further blood loss and leading to clinical deterioration. Myocardial injuries to the left ventricle or right ventricle can be self-sealing, but the atrium is in greater danger, as there is less muscular substance. Direct injuries to the coronary artery can result in rapid pericardial tamponade. Penetrating injuries to the septum or the heart valves are less common.

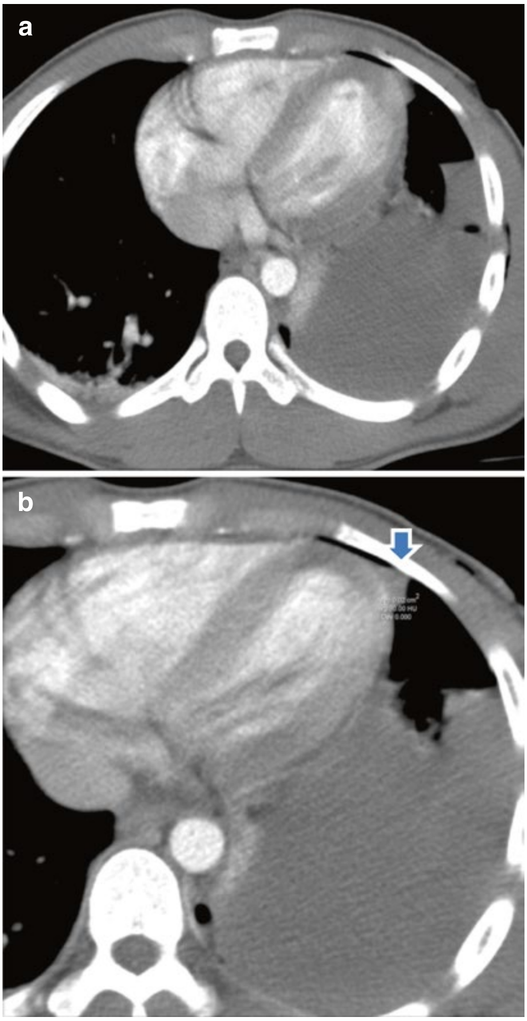

Fig. 11 Ungated MDCT of the heart, axial reconstructions. The figure shows (**a**) a stab wound to the left ventricle with perforation of the myocardium and (**b**) the bleeding site at the apex of the heart and a large left-sided hemopneumothorax (Images are courtesy of Professor Stuart Mirvis MD, University of Maryland, R Adams Cowley Shock Trauma Center, Baltimore, MD, USA ©)

Patients suffering from penetrating cardiac trauma who can be brought directly to the operating theater have a survival rate of 97 % for stab and 71 % for gunshot injuries. Of patients undergoing emergency thoracotomy, only 14 % survive; for those arriving at the hospital without cardiac function, the survival rate is only 7.8 %. Milham et al. report an overall mortality rate of 47 % in a sample of 2,253 patients (Mattox et al. 2012).

Imaging is often limited to CR of the chest if patients are hemodynamically unstable. CR can depict foreign bodies, pneumopericardium, an enlarged heart figure, and mediastinal widening, as well as concomitant lung injuries (Gunn et al. 2014).

Cardiac US is the most established imaging method; it can be quickly performed and it is repeatable to monitor hemorrhage to establish an early and quick diagnosis of penetrating cardiac injury. Cardiac ultrasound can demonstrate hemorrhage to the pericardium with or without cardiac tamponade by a subxiphoid view. Ultrasound signs of cardiac tamponade include pericardial effusion, cardiac tamponade, and diastolic compression of the atrium due to the increased pericardial pressure, dilatation of the inferior vena cava, and right ventricular diastolic collapse (Gunn et al. 2014; Gunn 2012).

In a study of 225 patients, US showed a sensitivity of 100 %, a specificity 96 %, and accuracy was 97.3 %. The average time from fast ultrasound to surgery was 12.1 ± 5 min, highlighting the importance of early and fast ultrasound in this group of patients (Rozycki et al.).

MDCT is performed whenever possible; it can show directly the entry point and the wound track of projectile-specific organ injury findings. It allows for a thorough diagnosis of the mediastinal organs including the esophagus, trachea, and the arterial and venous system as well as direct heart and lung injuries. MDCT can locate the position of foreign bodies and allow for an assessment of active bleeding in imaging (Gunn et al. 2014; Gunn 2012).

MDCT is indicated in patients who are hemodynamically stable or who recompensate after fluid resuscitation. The detection of active bleeding is usually an immediate indication for surgical treatment. In subacute findings, patients can also be further evaluated by bronchoscopy and esophagography.

Penetrating vascular injuries are located frequently in the ascending aortic arch and proximal great vessel. The mortality rate after penetrating aortic injury is 90–100 %. Patients typically undergo immediate surgery. MDCT findings include active vascular hemorrhage, formation of pseudoaneurysms, and vascular occlusions (Gunn 2012; Dosios et al. 2000). Gunn et al. recommend correlating all bullet entry points with the exit points and the number of visible bullets in the body (Gunn et al. 2014).

Projectiles can also embolize and transverse vascular structure and airways, the esophagus, and pleural cavity. Smaller projectiles have been reported to enter the aorta and embolize in the systemic circulation. Penetrating cardiac injury is often lethal, with mortality rates ranging from 3 to 81 % (Kang et al. 2009; Schmelzer et al. 1989). Again, the right heart is more prone to injury due to its anterior position.

MDCT has a reported sensitivity of 76.9 % and specificity of 99.7 % for penetrating cardiac injury where hemopericardium and pneumopericardium were observed as signs of injury; sensitivity is up to 100 %. MDCT can depict injuries to the coronary arteries, cardiac veins, valvular complex extravasation of blood, and mediastinal and lung injuries. There is evidence that MDCT is useful in the evaluation of penetrating cardiac injury (Figs. 11 and 12) (Gunn et al. 2014; Mollberg et al. 2012).

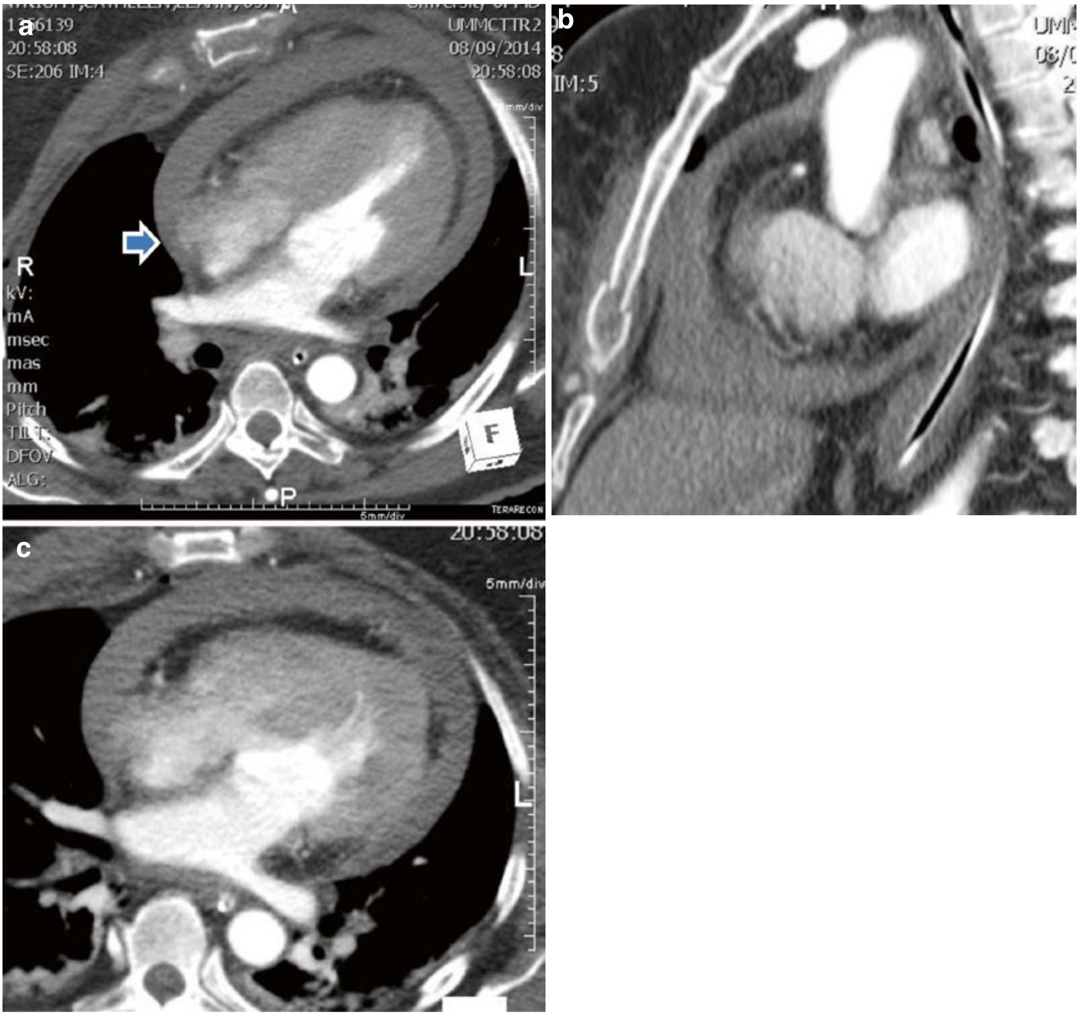

Fig. 12 Ungated MDCT of the heart, axial, and sagittal reconstructions. The figure shows (**a**, **c**) a stab wound through the sternum into the right ventricle with large pericardial hematoma and (**b**) active bleeding from the right ventricle and a heart compression by pericardial hemorrhage (Images are courtesy of Professor Stuart Mirvis MD, University of Maryland, R Adams Cowley Shock Trauma Center, Baltimore, MD, USA ©)

MR imaging has been used in stable patients to distinguish ventricular aneurysms for flow quantification of septal defects (Co et al. 2011; Plurad et al. 2013). Emergency thoracotomy should be performed in cases of prolonged resuscitation and a lack of response to volume therapy (Mattox et al. 2012).

5 Trauma Scoring

To date, no MDCT or imaging-based trauma score exists for the grading of cardiac injury.

To assess the severity of cardiac injury, clinical and anatomic parameters are evaluated, with various scoring systems in clinical practice. The most common is CVRS (cardiovascular-respiratory score), which is a predictor for the probability of survival and correlates with the severity of injury (Asensio et al. 1996; Asensio et al.). A further scoring system is the Organ Injury Scale developed by the AAST (American Association for the Surgery of Trauma), which provides a scaling of injury (severity scores) for individual organs (Table 4) (Mattox et al. 2012).

Associated injuries such as coronary artery dissections, active bleeding, and involvement of more than one heart chamber – or a delay in diagnosis and treatment – worsen the probability of survival (Table 5) (Mattox et al. 2012; Mattox et al.).

Table 4 Cardiac injury – cardiac injury organ scale

Grade I
Blunt cardiac injury with minor ECG abnormality (nonspecific ST- or T- wave changes, premature atrial or ventricular contraction or persistent sinus tachycardia)
Blunt or penetrating pericardial wound without cardiac injury, cardiac tamponade, or cardiac herniation
Grade II
Blunt cardiac injury with heart block or ischemic changes without cardiac failure
Penetrating tangential cardiac wound up to but not extending through the endocardium without tamponade
Grade III
Blunt cardiac injury with sustained or multifocal ventricular contractions
Blunt or penetrating cardiac injury with septal rupture, pulmonary or tricuspid incompetence, papillary muscle dysfunction, or distal coronary artery occlusion without cardiac failure
Blunt pericardial laceration with cardiac herniation
Blunt cardiac injury with cardiac failure
Penetrating tangential myocardial wound up to but not through the endocardium with tamponade
Grade IV
Blunt or penetrating cardiac injury with septal rupture, pulmonary or tricuspid incompetence, papillary muscle dysfunction, or distal coronary artery occlusion producing cardiac failure
Blunt or penetrating cardiac injury with aortic or mitral incompetence
Blunt or penetrating cardiac injury of the right ventricle, right or left atrium
Grade V
Blunt or penetrating cardiac injury with proximal coronary artery occlusion
Blunt or penetrating left ventricular perforation
Stellate injuries <50 % tissue loss of the right ventricle, right or left atrium
Grade VI
Blunt avulsion of the heart
Penetrating wound producing >50 % tissue loss of a chamber

Developed by the American Association for the Surgery of Trauma (AAST) (1994) (Mattox et al. 2012)

Table 5 Cardiac injury – concomitant injuries in multiple trauma

Pleural space: pneumothorax, hematothorax
Lungs: pulmonary contusion, pulmonary laceration, traumatic lung herniation
Mediastinum: pneumomediastinum
Airways: bronchial laceration, tracheal lacerations, Macklin effect
Esophagus tear
Thoracic vessels: injuries to the aorta, great thoracic vessels, and internal mammary artery
Diaphragm rupture
Chest wall: sternal, clavicular or rib fracture, flail chest, sternoclavicular dislocations
Fractures of the thoracic spine

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