Emergency Cardiac Imaging

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Identifying patients with acute chest pain (ACP) presenting in the emergency department (ED), requiring hospitalization and urgent treatment, is a diagnostic challenge that is further intensified by limited resources. The goal is to improve the ultimate outcome by optimizing patient flow, decreasing costs, and appropriately investigating differential diagnosis. Diagnostic algorithms with appropriate use of cost-effective MDCT are imperative to a quicker diagnosis with superior ability to rule out acute coronary syndrome (ACS) while simultaneously providing alternative diagnoses.

ACP is one of the most common and challenging clinical problems in the ED, accounting for 7 million visits annually in the United States with related healthcare costs of between $13 billion and $15 billion [1]. Despite diagnostic algorithms, 4% of patients with ACP are mistakenly discharged, resulting in higher risk of mortality and morbidity compared with hospitalized patients and accounting for 20% of all medical malpractice claims [2, 3]. Consequently, many patients with low-to-intermediate risk ACS are admitted to acute-care hospitals, representing a major burden to the U.S. health system [4].

The first-line diagnostic tools in the assessment of suspected ACS are a detailed clinical history, 12-lead ECG findings, and measurement of biochemical cardiac markers. Usually, ECG monitoring and serial biomarker sampling is required over 12 hours to safely rule out ACS. With high-sensitivity troponin T or I assay, acute myocardial ischemia can now be detected as early as 3 hours after the initial event in patients presenting with ACP [4].

Low-risk patients with negative biomarkers and ECG findings undergo functional stress testing during the period of observation or shortly after discharge, a class I indication (level of evidence: A) according to the European Society of Cardiology guidelines and class II recommendation from the 2014 guidelines from the American Heart Association and the American College of Cardiology guidelines [5].

Cardiac CT protocols incorporated into cardiac emergency workup provide excellent spatial resolution with superior anatomic as well as functional information with blood perfused volume and stress protocols. In a meta-analysis evaluation of MDCT accuracy in acute setting, Hulten et al. [6] reported reduction in costs and length of hospital stay. In a multicenter study, patients presenting with suspected ACS and undergoing MDCT were discharged from the ED earlier than patients in the traditional care group, and an additional 6.4% were diagnosed with coronary artery disease (CAD) [7]. Recent systematic and meta-analysis of randomized controlled trials of coronary CT angiography (CTA) versus usual care triage of patients in the ED with ACS found that coronary CTA is associated with decreased length of stay and decreased costs [7, 8]. MDCT has shown exceptional negative predictive value (NPV) in another meta-analysis of 29 studies, in which Hamon et al. [9] depicted 96% sensitivity, 74% specificity, and 97% NPV compared with invasive coronary angiography (CA) [9]. The consensus is to consider the use of cardiac CT mainly in patients with low to intermediate probability, when cardiac troponin levels or ECG (or both) and functional tests are inconclusive.

Nontraumatic Emergencies

Static Imaging of Ischemic Conditions

ACS is a continuum of diagnoses including unstable angina, non–ST-segment elevation myocardial infarction (MI), and ST-segment elevation MI (STEMI) in ascending severity, with atherosclerotic plaque rupture by far the most common cause [10]. Thin-cap fibroatheromas (TCFA), which have an intact cap less than 65 µm, are vulnerable to rupture. Atherosclerotic plaque with hypodense center surrounded by a hyperdense rim, which is called the “napkin ring” sign, is highly specific with high predictive value for detecting lipid-rich and advanced plaques. Kashiwagi et al. [10] proposed that a ringlike attenuation of a plaque on coronary CTA may be a surrogate marker of TCFA.

Coronary artery imaging—CA, intravascular ultrasound, and optical coherence tomography are the reference standards for diagnosing coronary artery stenosis and offer the advantage of allowing percutaneous coronary intervention. Recent technologic and radiation-dose minimizing advancements in coronary CTA have successfully allowed accurate diagnosis and assessment of CAD. Besides

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evaluating coronary arteries, coronary CTA clearly shows myocardial perfusion defects indicating myocardial ischemia.

A recent meta-analysis investigating diagnostic accuracy of coronary CTA for obstructive luminal stenosis compared with CA described a 93% sensitivity and 96% specificity to detect stenosis of less than 50%. The most valuable aspect of coronary CTA in acute settings, however, is the NPV, which in several studies has been reported at 95–99%; this characteristic allows exclusion of CAD in a rapid, noninvasive way that is less resource-intensive than CA [11]. Additionally, studies have shown excellent prognostic value of coronary CTA with a 5-year risk of cardiovascular events of less than 5% after a normal study [12].

Recently, the Coronary Artery Disease Reporting and Data System (CAD-RADS) classification was developed to create a standardized method to communicate findings of coronary CTA to facilitate decision-making regarding patient management [13]. It represents the highest-grade coronary artery lesion documented by coronary CTA and ranges from CAD-RADS category 0 for the complete absence of stenosis and plaque to CAD-RADS category 5 for the presence of at least one totally occluded coronary artery (Table 1). Awareness of CAD-RADS allows reading radiologists to help triage patients to the appropriate management.

Coronary artery disease versus spontaneous coronary artery dissection—Spontaneous coronary artery dissection (SCAD) is the separation of coronary artery wall layers, creating a false lumen and intramural hematoma. Patients present with myocardial ischemia, infarction, or ventricular arrhythmias [14]. Predisposing factors include young age in female patients, peripartum state, recent extreme exertional or emotional stress, and presence of fibromuscular dysplasia or connective tissue disorders [15]. CA has been the reference standard for the diagnosis of SCAD. In the acute setting, cardiac CT can be used to distinguish SCAD from atherosclerotic disease, thus significantly aiding in determining treatment options [16] (Fig. 1).

Static Imaging of Nonischemic Conditions

Infective endocarditis—Infective endocarditis (IE) is an infection of the endocardium or prosthetic material surfaces in the heart that has a 40% mortality rate [17]. Patients present in the ED with heart failure, abscess formation, and embolization [18]. Transthoracic echocardiography (TTE) or transesophageal echocardiography (TEE) is the most frequently used imaging modality, but it is limited and inadequate in the assessment of complications, including prosthetic valve endocarditis, prosthetic material infections, and complex abscesses. A baseline study comparing MDCT and TEE in the diagnosis of IE reported a sensitivity and specificity of 97% and 88%, respectively [18]. Additionally, studies have shown that coronary CTA, when compared with TEE and MRI, is least affected by prosthetic material, valves, and calcifications [19].

Imaging findings include hypoattenuating filling defects of vegetative lesions as well as valve tissue destruction, perivalvular extension with abscess formation, and pseudoaneurysm or fistula formation. Therefore, although echocardiography is the initial test of choice, MDCT is particularly helpful in visualizing valvular vegetation and paravalvular involvement, precise surgical planning, and assessing CAD preoperatively to avoid the risk of embolization with CA.

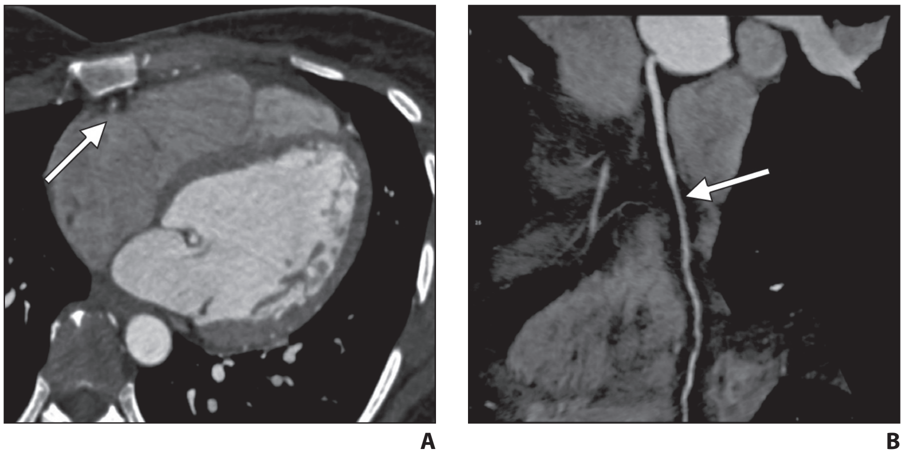
Nonbacterial thrombotic endocarditis—Nonbacterial thrombotic endocarditis (NBTE), also known as marantic endocarditis, is seen in patients with advanced-stage malignancies and often does not present with specific signs or symptoms. In the appropriate setting of multisystemic emboli with no identifiable source, a high degree of suspicion for NBTE is appropriate. As with bacterial endocarditis, vegetation on cardiac valves can be seen on cardiac CT (Fig. 2).

Cardiac tamponade—Cardiac tamponade is a life-threatening condition caused by acute accumulation of blood, fluid, pus, or gas in the pericardial sac, which may lead to

TABLE 1: SCCT Grading Scale for Stenosis Severity

CAD-RADS Category	Degree of Maximal Stenosis (%)	Likelihood of ACS	Management
0	0	Highly unlikely	No further evaluation of ACS is needed.
1	1–24	Highly unlikely	Consider cause other than ACS if troponin levels and ECG findings are normal.
2	25–49	Unlikely	Consider cause other than ACS if troponin levels and ECG findings are normal. If clinical suspicion of ACS is high, consider hospital admission with cardiology consultation.
3	50–69	Possible	Consider hospital admission and cardiology consultation, functional testing, ICA, or some combination of those for evaluation.
4			
A	70–99	Likely	Consider hospital admission with cardiology consultation. Conduct further evaluation with ICA.
B	Left main > 50% or obstructive disease in three vessels	Likely	Consider hospital admission with cardiology consultation. Conduct further evaluation with ICA.
5	100	Very likely	Consider expedited ICA on a timely basis and revascularization.
N	Nondiagnostic study	Cannot be excluded	Additional or alternative evaluation for ACS is needed.

Note—SCCT = Society of Cardiovascular Computed Tomography, CAD-RADS = Coronary Artery Disease Reporting and Data System, ACS = acute coronary syndrome, ICA = invasive coronary angiography.



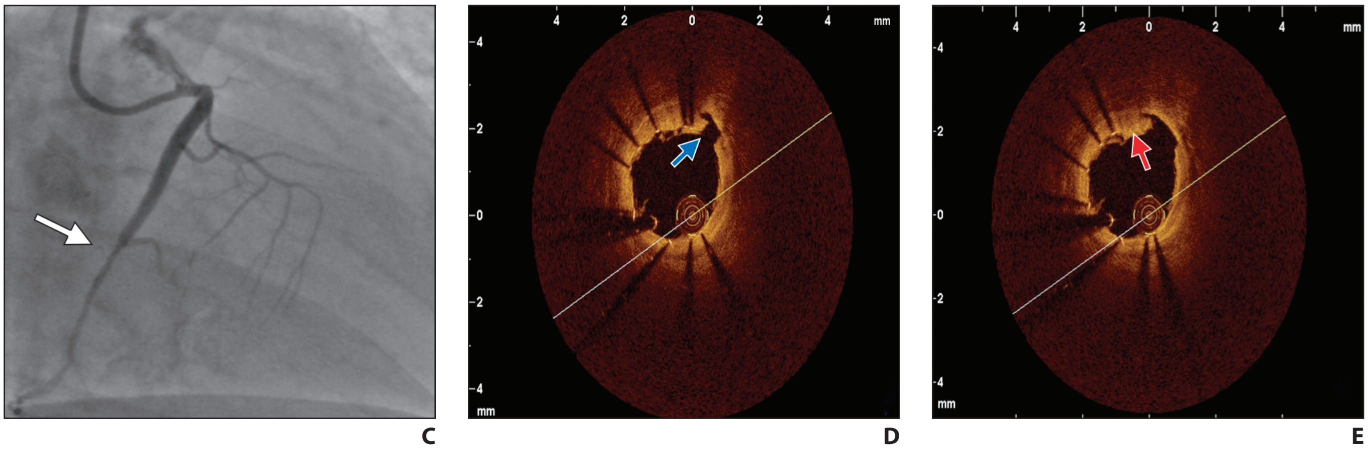


Fig. 1—Spontaneous coronary artery dissection in 35-year-old woman with no modifiable cardiovascular risk factors, presenting in emergency department with acute severe chest pain and elevated troponin level.
A and **B,** Axial cardiac CT (**A**) and curved multiplanar reformatted (**B**) images show abrupt transition in caliber (*arrows*) of mid right coronary artery with surrounding soft-tissue thickening suggesting intramural hematoma.
C, Invasive coronary angiogram shows 80% reduction in cross-sectional diameter (*arrow*).
D and **E,** Optical coherence tomography images after stent placement show intimal tear (*blue arrow*) and thrombus (*red arrow*). Streak artifacts caused by stent wires.

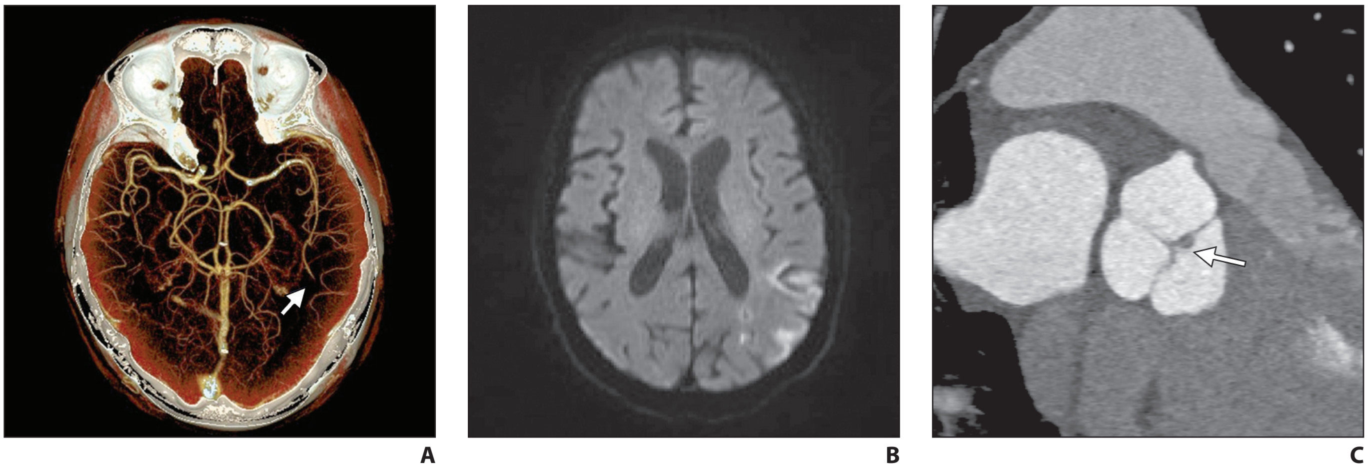


Fig. 2—Marantic endocarditis in 81-year-old man with known metastatic pancreatic cancer.
A, Maximum-intensity-projection CT angiography image shows complete cutoff (*arrow*) of distal M3 middle cerebral artery branch.
B, Single axial DW image shows hyperintense signal in left parietal cortex consistent with infarct.
C, Short axis cardiac CT image of aortic valve shows vegetation (*arrow*) at left aortic cusp.

cardiac chamber compression and progress to cardiogenic shock and death if not treated promptly [20]. Diagnosis has traditionally been based on clinical findings and confirmed with echocardiography in the acute setting. In the acute setting, CT and MRI have generally had a limited role. In cases of loculated or complex effusions, however, cardiac CT may help to plan percutaneous pericardiocentesis [21]. CT provides higher spatial resolution with additional regional information because of its larger FOV.

An enlarged cardiac silhouette with or without an epicardial fat pad sign will be seen on conventional radiographs. However, chest radiographs may be negative in patients with small pericardial effusion (< 200 mL), and patients with acute cardiac tamponade after blunt chest trauma can have a normal heart size on chest radiographs.

Imaging findings on echocardiography include presence of pericardial effusion with cardiac chamber compression, Doppler flow velocity paradoxus, swinging motion of the heart in the pericardial sac, compression of the pulmonary trunk and thoracic inferior vena cava, and paradoxic motion of the interventricular septum on echocardiography. However, pleural effusions, lower lobe atelectasis, and pericardial and intracardiac masses can simulate pericardial effusion on echocardiography.

CT will show pericardial effusion with measurements of attenuation coefficients to identify the possible nature of fluid; distention of the superior vena cava (SVC) to a diameter similar to or greater than that of the adjacent thoracic aorta; distention of the inferior vena cava (IVC) to a diameter twice that of the adjacent abdominal aorta; reflux of contrast medium within the IVC, the azygous vein, or both; angulation or bowing of the interventricular septum (due to paradoxic movement); and flattening of anterior surface of heart with decreased anteroposterior diameter (flattened heart sign) with concave chamber deformity in severe cases. Imaging findings seen on CT in isolation are not specific for cardiac tamponade.

Dynamic Imaging of Valvular Abnormalities

Mitral valve prolapse—Mitral valve prolapse (MVP) affects 2–3% of the general population and can present acutely with mitral regurgitation leading to heart failure and death if not surgically treated [22]. TTE remains the reference standard for evaluating valvular function. Technologic advances and dose minimization strategies have allowed use of MDCT, in addition to echocardiography, showing 95% diagnostic accuracy, 96% sensitivity, and 93% specificity in patients with TTE-proven MVP [23] (Fig. 3).

Imaging findings include bowing (billowing leaflet) and free leaflet (flail leaflet) showing systolic bowing of at least 2 mm above the mitral annulus toward the left atrium.

Wall motion abnormalities—Myocardial stunning is defined as myocardial dysfunction after MI despite restoration of myocardial perfusion [24]. With this condition, decreased myocardial contrast enhancement in a specific coronary artery distribution is seen as well as hypokinesia of the infarcted myocardium on functional MDCT and cine cardiovascular MRI.

Takotsubo cardiomyopathy (TTC) is a rare entity characterized by transient left ventricular wall dysfunction that extends beyond the vascular bed of any single coronary vessel in the absence of obstructive CAD [25]. Clinical presentation can mimic MI in 70–80% of patients, preceded by a triggering emotional stressor. A strong female predominance is present, with 90% of cases affecting women between 60 and 75 years old [26]. With > 95% NPV for CAD, cardiac CT is the imaging modality of choice in the ED to rule out a culprit obstructive lesion in suspected TTC (Fig. 4).

Imaging findings of TTC include hypokinesis, akinesis, or dyskinesis in the left ventricular mid segments with or without apical involvement; regional wall motion abnormalities extending beyond a single epicardial vascular distribution; absence of obstructive coronary disease; absence of late enhancement on delayed gadolinium-enhanced sequences on cardiovascular MRI (differentiates TTC from STEMI); T2 hyperintensity (edema) in the hypokinetic myocardium matching wall-motion abnormalities on cine cardiovascular MRI; wall motion abnormalities on echocardiography; and acute phase decreased uptake in the regions of left ventricular wall dysfunction on nuclear imaging including FDG PET and metaiodobenzylguanidine SPECT with significant improvement on follow-up assessment [27].

Acute myocarditis is the inflammation of myocardial tissue, most commonly in response to viral infection, with diverse clinical presentation that can overlap with ACS. Early diagnosis is critical; otherwise, significant myocardial damage, dilated cardiomyopathy, or sudden cardiac death (SCD) can result.

Imaging findings—Cardiovascular MRI, along with established MR parameters for myocardial inflammation called the Lake Louise Criteria, has become the primary tool for noninvasive assessment of patients with suspected myocarditis [28]. The Lake Louise Criteria are regional or global increased

A B C

Fig. 3—Mitral valve prolapse in 47-year-old man presenting in emergency department with acute onset dyspnea and chest pain.
A–C, Axial chest MDCT in lung (**A**) and axial mediastinal (**B**) windows show pulmonary edema, and four-chamber view cardiac MDCT (**C**) depicts bowing of posterior mitral valve leaflet more than 2 mm beyond annular plane (*double arrow*, **C**) into left atrium due to ruptured chordae tendineae consistent with acute mitral valve prolapse.

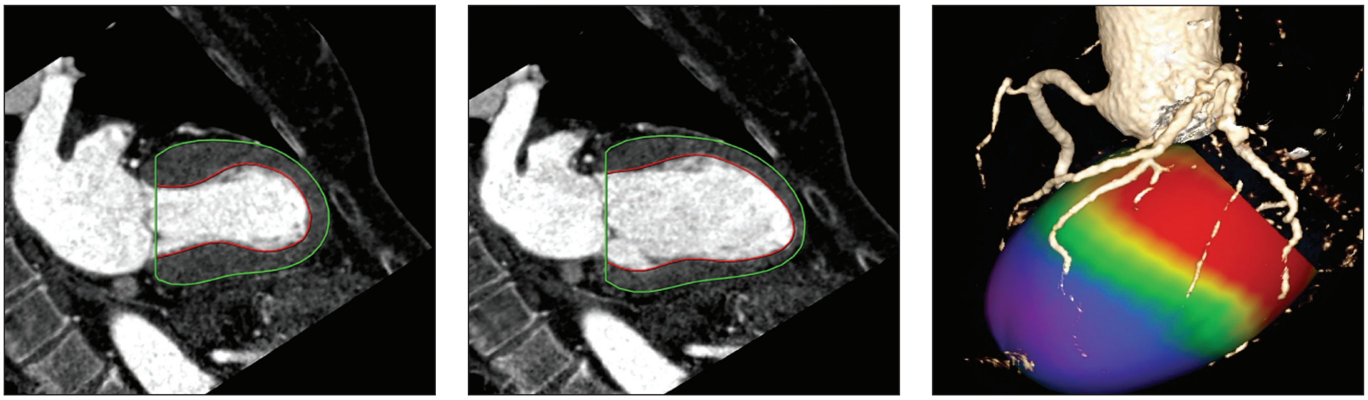


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Fig. 4—Transient left ventricular apical ballooning syndrome (takotsubo cardiomyopathy) in 57-year-old woman presenting with sudden tachycardia and elevated troponin level.
A–C, Two-chamber mid ventricular long-axis view functional cardiac CT image (**A**) shows early systolic phase ballooning of left ventricular apex with basal sparing. Cine images (not shown) showed apical dyskinesia. Red outlines (**A** and **B**) indicate hyperdynamic myocardium. Green outlines (**A** and **B**) indicate akinetic or dyskinetic myocardium.
B, Diastolic phase image for comparison.
C, Hybrid color-coded reformatted image depicts hyperdynamic basal myocardium with akinetic apical myocardium during systole.

T2 signal intensity (myocardial edema); increased early gadolinium enhancement ratio between skeletal muscle and myocardium on T1-weighted gadolinium-enhanced sequences (hyperemia or capillary leakage); and focal lesions on late gadolinium-enhanced T1 sequences with nonischemic distribution (irreversible cell injury) (Fig. 5). At least two of the three criteria must be present to indicate myocarditis.

Studies have reported sensitivity and specificity of 67% and 91%, respectively, with a diagnostic accuracy of 78% for cardiovascular MRI [29, 30]. The evidence for CT has been limited and proposes a CT criteria for differentiating acute myocarditis from MI with similar diagnostic accuracy to cardiovascular MRI [31, 32].

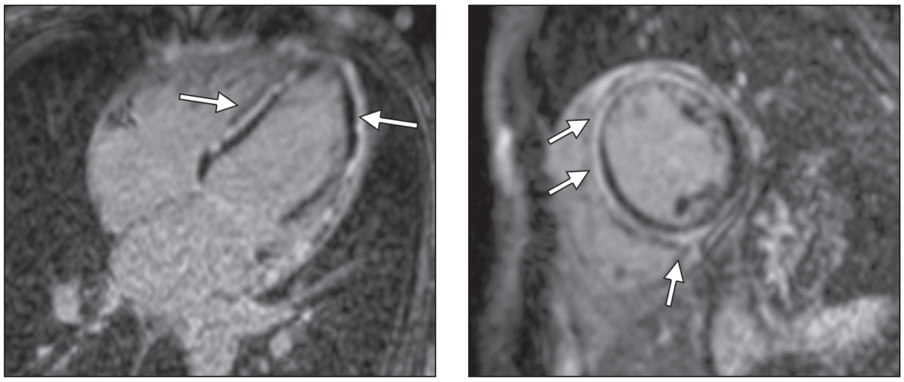

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Fig. 5—44-year-old woman with acute myocarditis with prior upper airway infection presenting with chest pain in emergency department. Patient had ST elevation on ECG with increased serum troponin and creatine phosphokinase levels and normal echocardiography.
A and **B,** Four-chamber (**A**) and mid ventricle short-axis (**B**) gadolinium-enhanced cardiac MR images depict typical mid myocardial late enhancement (*arrows*), indicating certain degree of myocardial necrosis.

Traumatic Emergencies

Prompt and early diagnosis is vital for timely treatment of traumatic cardiac emergencies. Myocardial rupture is a rare cause of immediate death after blunt cardiac trauma, with only 0.3–1.1% of patients with trauma reaching the ED [33]. Pericardial tears caused by deceleration forces or rib cage fractures are uncommon after blunt chest trauma, with a frequency of 0.3–0.5%. Rarely, valvular dysfunction can be seen due to an abrupt raised intracardiac pressure against a closed valve resulting from sudden rise in intraabdominal pressure translating into the heart causing valve cusp avulsion or tear [34]. Penetrating trauma can result in pericardial injuries further complicated by life-threatening conditions including partial or complete transdefect cardiac herniation or luxation with a mortality rate as high as 67%.

Plain radiographs will show pneumopericardium, hydrothorax or hemothorax, and mediastinal hematoma. Echocardiography will show abnormal valve function; wall motion abnormalities with decreased left ventricular ejection fraction; and pericardial effusion, signs of cardiac tamponade, or both. CT will show pneumopericardium, pericardial effusion, pericardial or myocardial laceration or rupture, cardiac herniation or luxation with associated SVC obstruction or right heart strain, valvular cusp avulsion or tears, coronary artery dissection or rupture, and associated rib cage fractures, retained foreign bodies, bullet fragments, and wound tracks [35] (Fig. 6).

Imaging Pearls and Pitfalls in Cardiac Trauma

Any pericardial effusion detected in the acute trauma setting is presumed to be hemopericardium until proven otherwise. CT provides valuable information about the possible nature of pericardial effusions on the basis of the attenuation measurements of the collection. Coronary artery injuries are rare (in less than 2%

of chest trauma cases), with left anterior descending artery being most commonly injured [36]. Penetrating cardiac trauma can result in pericardial injuries, which can result in partial or complete transdefect cardiac herniation or luxation with mortality up to 70% [37]. Portable supine studies in ED are suboptimal with overlying artifacts, which limits evaluation. TEE is invasive and difficult to perform in patients with acute craniocervical injuries. Cardiac MRI in trauma is primarily useful as a problem-solving tool after patients are admitted, especially to delineate the extent of myocardial contusion, regional infarction, wall motion abnormality, and valvular dysfunction.

Limitations of MDCT

First, CT involves use of ionizing radiation which increase the radiation exposure in the population. Second, the quality of MDCT images suffers with fast heart rate and high calcium burden. Finally, the patients with arrhythmias, ectopy or misregistration ECG artifacts degrade the image quality and limit evaluation. Optimizing techniques should be incorporated to counter these limiting factors.

Reduction of Radiation Dose

Radiation dose can be reduced with a prospective ECG-gated technique with narrow window acquisition, ECG tube current modulation, and limited pulse windows; tube voltage reduction based on body mass index; automated tube voltage reduction based on topogram attenuation profile; adaptive collimation limiting helical over spiral scanning; and iterative reconstructive techniques to reduce noise and ultimately reduce dose.

Optimizing Quality of Cardiac CT

Several steps can be taken to optimize the quality of cardiac CT studies. A heart rate of less than 65 beats/min can be achieved by administering 5–20 mg of β-blocker (metoprolol) IV or 50–100 mg by mouth 1 hour before the CT. Lowering the heart rate widens diastole and decreases beat-to-beat variability. Coronary arterial dilatation for optimal visualization can be achieved by administering 0.4–0.8 mg of nitroglycerin sublingually 5 minutes before contrast injection. Reconstruction algorithms can be used to reduce beam-hardening artifacts from iodine that mimic ischemia (Fig. 7). Edge-enhancing reconstruction algorithms can be used to reduce noise caused by extensive coronary calcifications or coronary stents.

Emerging Applications and Outlook

Coronary Atherosclerotic Plaque Characterization

The rationale behind growing efforts to accurately characterize a vulnerable, predominantly lipid-rich, plaque is its grave association with ACS and SCD. Novel attenuation-based application of dual-energy CT (DECT) has shown promising results when correlated with histologic findings. Spectral attenuation curves for material characterization are generated using attenuation values of a specific material for each and every monochromatic energy ranging from 40 to 140 keV [38]. Lipid-rich atherosclerotic plaques share the known attenuation curve of fat, in which attenuation decreases with lower monochromatic energy, thus differentiating lipid-rich plaques from fibrous plaques [39].

CT-Derived Fractional Flow Reserve

Coronary blood-flow volume effectively provides an estimation of lesion-specific ischemia. Recent vigorous advancements in digital analysis of fluid dynamics allow noninvasive assessment of coronary flow on the basis of mathematic models. CT-derived fractional flow reserve (FFR) calculates lesion-specific FFR using static coronary CT data without additional radiation or modification in image acquisition

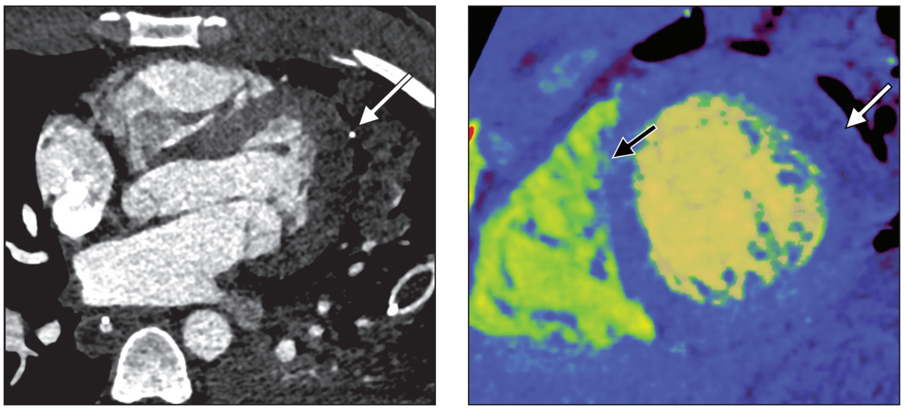

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Fig. 6—29-year-old man with gunshot wound.
A, Axial four-chamber cardiac CT image shows bullet fragment (*arrow*) abutting left ventricular side wall at mid cardiac level without myocardial penetration.
B, Mid ventricle short-axis color-coded functional cardiac CT image depicts reduced perfusion (*white arrow*) consistent with myocardial contusion. Black arrow indicates bullet fragment.

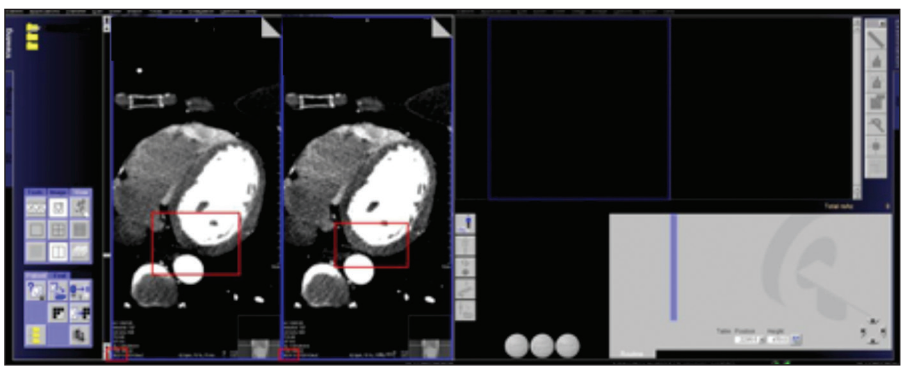

Fig. 7—CT images show beam-hardening correction (*left*) and utility of B23 kernel (*right*) as it reduces beam-hardening artifact from iodine in left ventricle and thoracic aorta, affecting posterior inferior aspect of left ventricle wall mimicking infarct.

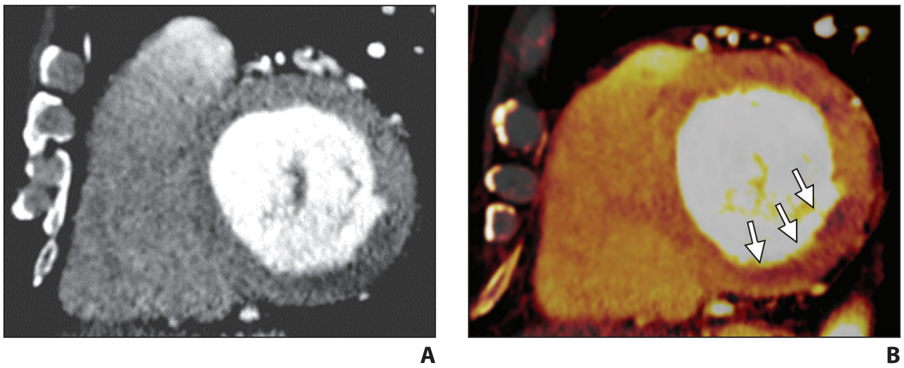

Fig. 8—Myocardial ischemia in 51-year-old man.
A and **B,** Mid ventricle short-axis cardiac CT image (**A**) and iodine perfusion map (**B**) show decreased subendocardial iodine uptake (*arrows*) in inferior basal ventricle, suggesting perfusion defect consistent with myocardial ischemia.

protocols. Studies have found that CT FFR shows 90% sensitivity and nearly 83% specificity for lesions with moderate stenosis causing ischemia [38]. A multicenter prospective trial showed 73% specificity and 90% sensitivity for CT FFR in diagnosing obstructive CAD compared with conventional angiographic FFR [40].

CT Myocardial Perfusion and Viability

Myocardial perfusion is one of the most important prognostic indicators for patient outcome and management of CAD. CT myocardial blood pool analysis using myocardial iodine content is a promising dynamic technology. DECT color-coded iodine maps permit sensitive detection of myocardial perfusion by depicting myocardial blood pooling [41]. The perfused myocardium takes up iodine, but no iodine uptake is seen in the infarcted myocardium (Fig. 8). Assessment of myocardial viability predicts successful revascularization therapy.

Conclusion

MDCT is a viable, reliable, and potentially effective imaging modality in evaluation of coronary and noncoronary cardiac emergencies. Cardiac CT efficiently rules out CAD in patients with low to intermediate risk who present with acute chest pain in the ED and accurately predicts midterm adverse outcome. With integration of innovative applications like morphologic plaque characterization, coronary FFR and myocardial perfusion, cardiac CT will be able to offer unprecedented benefits, ranging from triage to treatment decisions in the ED.

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