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Noninvasive Imaging of the Heart and Coronary Arteries

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OVERVIEW OF NONINVASIVE IMAGING MODALITIES

Noninvasive imaging of the heart and coronary arteries has evolved tremendously since the 1950s when the first rudimentary echocardiogram was performed by Dr. Inge Edler who recorded echoes from the heart of Hellmuth Hertz, a physicist, using a sonar device borrowed from a shipyard.¹ The techniques available today for examination of the heart and coronary arteries include advanced imaging with echocardiography, cardiac magnetic resonance (CMR), nuclear imaging, and computed tomography (CT).

Two-dimensional Transthoracic Echocardiography

Echocardiography allows for a rapid bedside assessment of cardiac including evaluation of myocardial thickness, function, valvular disease, pericardial pathology, and chamber size. An echocardiogram includes information obtained by M-mode imaging, two-dimensional analysis, and Doppler echocardiography. The velocity of blood measured by the Doppler frequency shift can be used to estimate cardiac pressure gradients and valve areas. Obtaining a comprehensive cardiac evaluation by transthoracic echocardiography can be limited with a large patient body habitus or lung hyperinflation as seen with emphysema.

Appropriateness criteria for ordering transthoracic echocardiograms (TTE) were established in 2007, which outline indications for TTE based on several themes: general evaluation of structure and function, evaluation of valvular function, evaluation of patients with hypertension, heart failure, or cardiomyopathy.² In the patient preparing for cardiac surgery, TTE is commonly used for evaluation of the left ventricular (LV) and valvular function to aid in surgical planning. Advances in echocardiography include real time three-dimensional transthoracic echocardiography, the use of myocardial contrast, and strain analysis used for evaluating diastolic dysfunction.

Real time, three-dimensional, transthoracic echocardiography was developed in the 1990s by von Ramm and colleagues,³ providing three-dimensional reconstructions of two-dimensional data. The technology was updated with a new matrix-array transducer in 2002 allowing simultaneous data acquisition and visualization of the beating heart.⁴ Three-dimensional transthoracic echocardiography has several clinical applications: direct three-dimensional visualization of the cardiac chambers structure and volumes, comprehensive valvular views, and enhanced analysis of myocardial abnormalities such as atrial or ventricular septal defects or hypertrophic cardiomyopathy.⁵ In particular, real time three-dimensional echocardiography is helpful in evaluating mitral valve pathology. Imaging the valve opening plane allows measurement of the mitral valve orifice area, which correlates better with the Gorlin formula estimate of mitral valve area than traditional two-dimensional echo valve planimetry.⁶ There is good correlation between the surgically identified location of mitral valve prolapse and the three-dimensional echocardiographic evaluation.⁷ However, there is limited application for transthoracic three-dimensional echocardiography for aortic and tricuspid valve disease. For patients with atrial or ventricular septal defects undergoing repair, real time three-dimensional echocardiography is used to evaluate the location and dimensions of the defect.⁸

Contrast echocardiography is most often used to evaluate for the presence of an intracardiac or intrapulmonary shunt.⁹ The contrast agent used is agitated saline because saline bubbles are too large to cross the pulmonary vascular bed and therefore cannot gain access into the left heart chambers unless there is a shunt present. Other contrast agents have been developed using a gas bubble (perfluoropropane surrounded with either a perflutren lipid microsphere (Definity, Bristol-Myers Squibb Medical Imaging, North Billerica, Massachusetts) or perflutren protein type A microsphere (Optison, GE Healthcare, Princeton, New Jersey)). These injectable contrast agents have durable microbubbles that are small enough to go through the pulmonary circulation and therefore opacify the left ventricle. The main advantage of these agents is enhancement of the endocardial border and they are most often used with stress echocardiography¹⁰ or in TTE with limited windows.¹¹ A Food and Drug Administration (FDA) black box warning was issued for the use of Definity and Optison in October 2007 after reports of serious cardiopulmonary reactions within 30 minutes following administration in high-risk patients.¹² The black box warning was subsequently removed in July 2008 and the current FDA recommendation is that high-risk patients with pulmonary hypertension or unstable cardiopulmonary conditions should be monitored during contrast administration and for 30 minutes afterwards.¹³ A large retrospective review of more than 18,000 patients receiving stress echocardiography with contrast showed that there was no difference in death or myocardial infarction rate at 1 hour and 30 days after the study compared with patients who received stress echocardiography without contrast.¹⁴

Echocardiographic evaluation of diastolic dysfunction involves assessment of the LV filling patterns using the pulsed wave Doppler mitral inflow velocities, pulmonary venous flow, and tissue Doppler imaging of mitral annular motion.¹⁵

Transesophageal Echocardiography

Compared with TTE, transesophageal echocardiography (TEE) offers superior views of the posterior cardiac structures due to their proximity with the esophagus. Contra-indications to performing a TEE include esophageal disease including stricture, malignancy or recent ulcer, difficulty swallowing given concern of undiagnosed esophageal pathology, and altered mental status or an uncooperative patient. In 2007, the American Society of Echocardiography outlined indications for TEE as an initial test, including suspected aortic dissection, guidance during percutaneous noncoronary interventions, preoperative evaluation for regurgitant valve repair, diagnosis of endocarditis with a moderate to high pretest probability or persistent fever in the

setting of an intracardiac device, and evaluation for thrombus in the left atrium before ablation or cardioversion.²

The most widely accepted indication for intraoperative TEE is valve surgery. Intraoperative TEE is used before initiating cardiopulmonary bypass to evaluate for any changes occurring in the interval between the decision for surgery and the actual operation, as well as to aid in the decision about feasibility of valve repair versus replacement, particularly with mitral valve pathology.

For mitral valve surgery, the intraoperative pre-bypass TEE changes the operative plan in approximately 6% to 19% of cases.¹⁶ The severity of the mitral regurgitation or stenosis seen at the time of intraoperative echocardiogram may be different from what was found on the outpatient examination due to changes in the patient's hemodynamics due to general anesthesia.¹⁷ The severity of mitral regurgitation is determined based on the size of the jet at its origin (vena contracta), relative area of the regurgitant jet compared with the left atrium, and the proximal isovelocity surface area (PISA) method. The mechanism of the mitral regurgitation can be established by evaluating the jet direction as well as the structure and motion of the mitral valve leaflets.¹⁸ After mitral valve repair, TEE is repeated before the administration of protamine and removal of the cannulas to assess for the degree of mitral regurgitation and any surgical complications such as systolic motion of the anterior leaflet of the mitral valve.¹⁹ Prosthetic heart valves are evaluated post placement with intraoperative TEE to evaluate for appropriate placement and periprosthetic or prosthetic leaks.²⁰

With aortic valve replacement with either a prosthetic valve or pulmonic homograft, intraoperative TEE allows for anatomic assessment of the aortic valve and aorta as well as the degree and mechanism of aortic stenosis (AS) or regurgitation. For instance, feasibility of aortic valve repair can be determined by TEE as it is most often performed in patients with a bicuspid aortic valve and leaflet prolapse, leaflet perforation due to endocarditis, or aortic root dilation causing functional valvular regurgitation.²¹ As with mitral valve surgery, postoperative TEE is used to assess for the adequacy of the aortic valve repair. In addition, regional wall motion abnormalities may arise due to technical difficulties with coronary implantation.

In patients undergoing valve surgery for endocarditis, TEE provides for assessment of whether the valvular regurgitation is transvalvular or paravalvular as well as extension of the infection to involve a ring abscess (Figs. 1 and 2).²² In addition, infectious endocarditis may involve other valves not previously noted on the preoperative evaluation and, as a result, a thorough valvular examination is warranted on the intraoperative TEE.

An additional use of TEE during the intraoperative period is to evaluate for the presence of intracardiac air after routine deairing in patients undergoing cardiac surgery.²³ By identifying persistent intracardiac air with TEE, additional deairing procedures can be taken to prevent air embolism and subsequent central nervous system injury.

Nuclear Imaging

The application of nuclear medicine in cardiac imaging is aimed at identifying myocardial perfusion as part of an ischemia evaluation, evaluating myocardial viability and measuring LV function.

ECG-gated single photon emission computed tomography (SPECT) uses a radioactive blood flow marker such as thallium-201 or technetium-99m sestamibi to enter into the cardiac myocytes in proportion with cardiac blood flow. Thallium has similar properties to potassium and accesses the myocardium through a Na-K-ATPase pump, whereas technetium-99m sestamibi is taken up by mitochondria into the cardiac myocytes.²⁴ As the radionuclides decay,

gamma rays are emitted and detected by a gamma camera or multicrystal camera and a computer program then processes the data obtained. The reconstructed images include short-axis, horizontal long-axis, and vertical long-axis views of the heart. With the addition of a 3-lead ECG gating device, regional wall motion can be obtained. The endocardium is identified by computer analysis and cardiac volumes at end-diastole (EDV) and end-systole (ESV) are measured, allowing an accurate assessment of the LV ejection fraction ($EDV - ESV/EDV$) when compared with echocardiography.²⁵ Planar multigated acquisition (MUGA) with radiolabeled red blood cells is used to calculate an accurate and reproducible LV volume and ejection fraction, mostly in patients undergoing chemotherapy with potentially cardiotoxic agents.²⁶

SPECT myocardial perfusion imaging identifies myocardial ischemia as a reversible defect seen on stress images that resolves with rest (Figs. 3 and 4). Myocardial blood flow during stress is reduced in areas supplied by vessels that have fixed stenoses and are hemodynamically significant. Fixed perfusion defects (seen at stress and rest) are indicated prior to myocardial infarction. In the setting of a mild perfusion defect that is fixed, this may be due to a small infarction or artifact due to signal attenuation.²⁷ In addition to obtaining perfusion and LV volume calculations, regional wall motion is assessed by gated-SPECT.

The most common pharmacologic methods for stress myocardial perfusion imaging include adenosine, regadenoson, dipyridamole, or dobutamine. If patients are able to exercise, this is the preferred method of achieving myocardial stress due to the important prognostic information gained from exercise capacity. Of the pharmacologic agents available, adenosine, regadenoson, and dipyridamole all increase myocardial perfusion by affecting adenosine receptors in the coronary vasculature leading to coronary vasodilation. As a result, side effects of these agents include flushing, nausea, chest discomfort, bronchospasm, or transient heart block. Given the potential respiratory side effects, the agents should not be used in patients with active bronchospasm, however, dobutamine remains an option.

CMR

CMR imaging at 1.5 Tesla (T) provides excellent visualization of cardiac structure and function by using steady state free precession (SSFP) cine imaging, first pass contrast-enhanced perfusion, late gadolinium enhancement (LGE) for identification of fibrosis, and magnetic resonance (MR) angiography to visualize vascular anatomy. Most cardiac function and morphology information comes from the cine MRI sequences, which obtain a large number of images throughout the cardiac cycle during a breath hold, that are played in a cine mode. Dobutamine stress can be performed with sequentially higher dobutamine doses with acquisition of SSFP cine images at each stage.²⁸ Using a higher field strength for cardiac imaging such as 3 T allows for improved signal to noise ratios for many cardiovascular applications include perfusion, LGE and angiography. However, assessment of cardiac function with SSFP imaging is challenging at 3 T due to off-resonance artifacts.²⁹

Evaluation of the coronary arteries with CMR is limited by its lower spatial resolution compared with multidetector row computed tomography (MDCT). A review of 28 MR coronary angiography studies involving more than 900 patients, done in 2006 by Schuijf and colleagues,³⁰ found that 83% of segments were analyzable and had a sensitivity of 72% and specificity of 87%.

Myocardial perfusion with pharmacologic stress with CMR at 1.5 T has a high sensitivity to differentiate relevant to nonrelevant coronary stenosis when compared with invasive angiography.³¹ A study done in 2003 with 84 patients referred for coronary angiography who underwent adenosine stress CMR imaging demonstrated that quantitative myocardial perfusion had a sensitivity of 88%, specificity of 90%, and an accuracy of 89% for the detection of

significant coronary artery disease (CAD).³² A systematic review by Nandalur and colleagues³³ of all stress CMR studies with angiographic correlation that were done between 1990 and 2007 evaluated the diagnostic performance of CMR perfusion imaging and stress-induced wall motion abnormalities for diagnosis of CAD. There was a high prevalence of CAD in the included studies; the CMR perfusion studies had a prevalence of 57.4% compared with 70.5% in the stress-induced wall motion abnormality group. The CMR perfusion imaging had a sensitivity of 0.91 (95% CI 0.88–0.94), and specificity of 0.81 (95% CI 0.77–0.85) compared with angiography. The stress-induced wall motion abnormalities imaging had a sensitivity of 0.83 (95% CI 0.79–0.88) and specificity of 0.86 (95% CI 0.81–0.91) for detecting CAD in patients. A multicenter trial was published in 2008, which evaluated the diagnostic performance for perfusion-CMR compared with radiograph coronary angiography and SPECT myocardial perfusion imaging; more than 200 patients with known or suspected CAD were evaluated by all three modalities.³⁴ The difference between perfusion-CMR and gated-SPECT did not reach statistical significance, however, comparing perfusion-CMR with all SPECT studies, the area under the receiver operating characteristic curve for CMR is larger than for SPECT (0.86 + 0.06 vs 0.67 + 0.5, $P < .013$).

LGE uses gadolinium chelates to identify areas of myocardial fibrosis and necrosis. There is delayed washout of gadolinium from myocardium, which also has an increased volume of distribution in interstitial space due to loss of intact myocytes.³⁵ LGE allows for the accurate assessment of areas of myocardial infarction and nonviable myocardium (Fig. 5). Determining areas of myocardial viability is critical when deciding which patients are likely to benefit from revascularization procedures, particularly in the setting of reduced LV function. In the study by Kim and colleagues³⁶ evaluating 50 patients with LV dysfunction before revascularization, the likelihood of functional improvement in regions without LGE was 86% for segments with at least severe hypokinesia and 100% for segments with akinesia or dyskinesia. In addition, the transmural extent of myocardial infarction is inversely related to recovery of regional LV function after revascularization. Adding low-dose dobutamine cine CMR to LGE may increase the predictive value for regional functional recovery, particularly in cases of preserved end-diastolic wall thickness.³⁷ In a group of patients with chronic ischemic heart disease and LV systolic dysfunction evaluated with dobutamine CMR before and after revascularization with coronary artery bypass graft (CABG), improved function in myocardial segments with less than 50% transmural infarcts was predicted by the response to dobutamine.³⁸

Compared with thallium-201 SPECT myocardial perfusion imaging, CMR using LGE has similar specificity for detecting transmural myocardial infarctions (MI; 98% compared with 97%); however, LGE has higher diagnostic power to identify subendocardial MI not appreciated by SPECT in 47% of myocardial segments and 13% of patients.³⁹ LGE aids in differentiating ischemic and nonischemic cardiomyopathies based on the presence of myocardial scar in an ischemic pattern seen by LGE in patients with reduced LV function due to CAD. There are distinct patterns of LGE that aid in the identification of the cause of certain cardiomyopathies such as myocarditis (acute and chronic), cardiac sarcoidosis, amyloidosis, and endomyocardial fibrosis.⁴⁰

CMR provides excellent characterization of right ventricular function and allows for the diagnosis of arrhythmogenic right ventricular cardiomyopathy based on ventricular size, wall motion abnormalities as well as the presence of LGE consistent with fibro-fatty replacement of the myocardium.⁴¹ Accurate assessment of right ventricular function and the motion of the interventricular septum during real time free breathing imaging provides a framework for evaluating pericardial constriction with CMR in addition to imaging of pericardial thickness.

Valvular heart disease is most frequently evaluated by echocardiography, including Doppler techniques. The essential information needed for the diagnosis and management of patients

with valvular heart disease includes data on valve morphology, valve function, ventricular function, and the presence of coexisting cardiac disease.⁴² SSFP or gradient echo sequences by CMR provide visualization of the valve structure and dysfunction. Velocity-encoded cine allows for quantification of flow across valves and therefore blood flow velocities and volumes to be measured.⁴³ In particular, stroke volume, cardiac output, regurgitant flow through incompetent valves or high velocity jets through stenotic valves can be readily calculated. The limits for regurgitation fraction for mitral regurgitation have been established using CMR and are derived by subtracting the forward flow of the aorta from the ventricular stroke volume.⁴⁴

Cardiac Computed Tomography

Initial cardiac CT technology with electrocardiographic gating for imaging of the heart used electron beam CT (EBCT) and had limitations with spatial resolution. EBCT was mainly used for calculating a CT-based calcium score of the coronary arteries to aid in stratifying the patient's risk of coronary atherosclerosis. The temporal and spatial resolution of CT improved significantly with the development of MDCT. Since its advent in 1999, the use of MDCT with retrospective cardiac gating has steadily increased for cardiac imaging. The number of detectors used for acquiring raw data has increased geometrically. The advent of 64 detector scanners allowed for enhanced temporal and spatial resolution with short scan times. Scanners are now becoming available with as many as 256 or 320 detectors and data can be acquired during a single breath hold in as little as one heartbeat. A typical amount of intravenous iodinated contrast used for coronary CT angiography is between 60 and 100 mL depending on patient size and heart rate. The average dose of ionizing radiation from a 64-slice cardiac MDCT examination using ECG gating and dose modulation is 7 to 11 mSv,⁴⁵ but these doses can be reduced further with prospective gating as well as 256 or 320 detector scanners. The radiation dose is similar to that from an abdomen and pelvis CT (8–11 mSv) but higher than x-ray coronary angiography (3–6 mSv).⁴⁶

As part of a CT coronary angiographic study, a coronary calcium score is usually obtained first. If patients have a high calcium score (greater than 400 Agaston units), there is a greater likelihood of coronary artery calcifications, which can cause a blooming artifact, obscuring the ability to analyze plaque within the vessel.⁴⁷ Excess artifact is also caused by irregular heartbeats, difficulty with breath holding, and pacing wires.

A review in the European Heart Journal from 2008 pooled the data of more than 800 patients who had CT coronary angiography using 64 detector MDCT in patients with suspected CAD.⁴⁸ The sensitivity was 89% (95% CI 87–90) with a specificity of 96% (95% CI 96–97) and a positive and negative predictive value (NPV) of 78% (95% CI 76–80) and 98% (95% CI 98–99), respectively. Another recent study of CT coronary angiography using a 64-slice multidetector scanner in patients with chest pain and low to intermediate risk of underlying CAD, showed a high NPV (99%) for detecting stenosis greater than 70%.⁴⁹ However, the positive predictive value (PPV) was low at 48%.

Given the high NPV of CT coronary angiography, the main clinical application at the present time is evaluating chest pain in patients with low to intermediate risk of CAD, especially in emergency department patients. Other clinical indications include detection of CAD with prior equivocal stress test results, suspected coronary anomalies, and evaluation of pericardial disease. In addition, cardiac CT is used before interventional and surgical procedures, including evaluation of pulmonary vein anatomy before atrial fibrillation ablation and noninvasive coronary imaging before ventricular tachycardia ablation. CT coronary angiography is not routinely used for assessing coronary stent patency as the overall accuracy is inadequate for diagnostic purposes especially in smaller stents.

Identification of occluded or stenosed bypass grafts is straightforward on cardiac CT angiography given their large diameter; however, accurate visualization can be limited by the presence of surgical metal clips. Evaluation of native coronary arteries after bypass surgery with CT angiography is limited due to coronary calcifications and advanced atherosclerosis. The European Society of Cardiology published a report in 2008 on cardiac CT, which pooled the available literature on the diagnostic accuracy of 16- and 64-slice MDCT for evaluation of patients after coronary artery bypass surgery (Table 1).⁴⁸

Evaluation of the coronary vessels is usually done with images reconstructed from mid- to end-diastole (Fig. 6). However, LV function, volume, and wall thickness can be obtained from reconstruction of the raw data throughout the cardiac cycle.⁵⁰ When compared with cardiac MR measurements the LV ejection fraction correlates well, as do EDVs and ESVs, but there is a tendency to systematic overestimation of volumes compared with cardiac MR due to lower temporal resolution.

SPECIFIC APPLICATIONS OF CARDIAC IMAGING

Evaluation for Ischemia

Exercise ECG stress testing has a lower sensitivity than stress imaging, however, it remains useful in patients who have a normal baseline ECG and can exercise to a high level. The 2007 update to the American College of Cardiology (ACC)/American Heart Association (AHA) task force on chronic stable angina reinforced that among patients who are able to exercise and have an intermediate pretest probability of disease with resting ECG abnormalities, either exercise echocardiography or exercise radionuclide myocardial perfusion imaging is acceptable.⁵¹

If patients are unable to exercise, dobutamine stress echocardiography is an option. The inotropic and chronotropic effects of dobutamine elicit ischemia from regions of myocardium with impaired blood flow. Echo images are obtained throughout the dobutamine infusion and during peak stress. Exercise echo and myocardial perfusion imaging have similar NPVs for MI or cardiac death over a 3-year period: 98.4% and 98.9%, respectively.⁵² In terms of ability to detect CAD, a meta-analysis demonstrated exercise echo and exercise MPI stress tests have similar sensitivities (85% and 87%, respectively), however, exercise echo has a higher specificity (77% vs 64%).⁵³ In terms of pharmacologic stress testing, another meta-analysis compared patients who underwent echo or SPECT stress testing with adenosine, dipyridamole, or dobutamine for diagnosis of CAD. The study found that SPECT imaging with vasodilators has the highest sensitivity, whereas the maximum combination of sensitivity and specificity is found with dobutamine echocardiography.⁵⁴

Pharmacologic stress CMR testing uses either vasodilator therapy for perfusion imaging or dobutamine for stress functional imaging. The former has higher sensitivity but the latter has higher specificity.³³ Both have excellent NPVs over 2 to 3 years.⁵⁵

Viability Testing

Studies suggest approximately 25% to 40% of patients with ischemic cardiomyopathy will demonstrate improved LV function with revascularization.⁵⁶ In patients with CAD and abnormal LV function, myocardial viability seen on noninvasive imaging is strongly associated with improved survival after revascularization.⁵⁷

Given the prognostic importance of identifying viable myocardium, accurate assessment of patients likely to benefit from revascularization is a key component of the preprocedure evaluation. A pooled literature review performed by Bax and colleagues⁵⁸ in 2001 compared the sensitivity, specificity, PPV and NPV for improved LV function with revascularization of the most often used viability techniques at that time: dobutamine stress echo, SPECT with

thallium- or technetium-labeled sestamibi, and positron emission tomography (PET) with [^{18}F]fluorodeoxyglucose (FDG). For dobutamine stress echo, the mean sensitivity was 81% and the specificity was 80%, with a PPV and NPV of 77% and 85%, respectively. Dobutamine stress echo tests for contractile reserve and identifies viable myocardium based on the myocardium's response to dobutamine with either an initial improvement in LV contractility followed by worsened wall motion or an immediate decrease in LV contractility. In comparison, for technetium-labeled sestamibi SPECT viability studies, most were 1-day resting studies without the use of nitroglycerin and had a mean sensitivity of 81% and specificity of 66%, with a PPV and NPV of 71% and 77%, respectively.

CMR has been validated as an accurate method of determining viability with either LGE or low-dose dobutamine contractile reserve as discussed above. It is being increasingly used to evaluate patients before planned coronary artery bypass surgery and is especially useful to evaluate the LV apex when considering ventricular restoration surgery.

There are limited clinical data to date on the use of cardiac CT for assessment of myocardial perfusion and viability. Sixty four-slice MDCT was performed in 34 patients with acute myocardial infarction and the perfusion defects on MDCT had a moderate correlation with SPECT ($r = 0.48$, $-7\% \pm 9\%$).⁵⁹ MDCT has been shown to detect myocardial scar as late hyperenhancement compared with CMR. In a study of 28 patients with reperfused infarction by Mahnken and colleagues,⁶⁰ late myocardial enhancement seen on MDCT and CMR had good agreement.

Aortic Valve Disease

AS severity is established noninvasively by echocardiography using the continuity equation and Doppler analysis.⁶¹ The aortic jet velocity, mean pressure gradient, and valve area stratify patients into mild, moderate, and severe AS. Indications for surgery in patients with severe AS include the presence of symptoms, LV systolic dysfunction, or planned cardiac surgery for another indication. If it is unclear whether a patient is symptomatic, exercise testing can be performed to assess for development of symptoms, degree of functional ability, decrease in blood pressure, or the presence of ventricular arrhythmia.⁶²

Echocardiography provides excellent imaging of the aortic valve, particularly with TEE. Calculation of the aortic valve area (AVA) using direct planimetry with CMR has been validated in patients with severe AS against the AVA measured invasively using the Gorlin equation, the AVA from TEE with planimetry, and the AVA generated from TTE using the continuity equation.⁶³ The AVA measured by the continuity equation with CMR correlates well with the continuity equation measured by TTE ($r = 0.98$). In TEE and CMR, the AVA measured by planimetry is larger than that calculated by the continuity equation. CMR studies of patients with AS show the peak jet velocity measured by phase-shift velocity mapping has good agreement with measurements made by conventional Doppler ultrasound.⁶⁴

A study by Pouleur and colleagues⁶⁵ in 2007 compared the accuracy of MDCT, TEE, and CMR measurements of the AVA in patients with severe AS preparing for valve surgery, using TTE as the reference standard. The AVA by planimetry from MDCT correlated closely with CMR ($r = 0.98$), TEE ($r = 0.98$), and TTE ($r = 0.96$). The planimetry determinations of AVA were all significantly higher than the AVA generated by the continuity equation with TTE. Echocardiography, however, remains the mainstay of aortic valve evaluation.

Mitral Valve Disease

Mitral valve regurgitation is easily assessed with TTE and information about the cause of the valve dysfunction can be obtained. Primary mitral regurgitation stems from anatomic

disruption of the mitral valve apparatus and secondary mitral regurgitation occurs in the setting of LV dysfunction due to prior infarction or cardiomyopathy. The severity of mitral regurgitation can be estimated by regurgitant fraction and regurgitant orifice area. With increasing severity and duration of the valvular regurgitation, patients develop depressed LV ejection fraction and enlarged LV systolic dimensions, which are predictors of poor outcome.⁶⁶ Surgery for primary mitral valve disease is usually recommended before LV dilatation and dysfunction develops.

The gold standard for evaluation of mitral valve disease is echocardiography. However if patient body habitus or presence of lung disease precludes an adequate examination and sedation for a transesophageal study is not desired, then a viable alternative is CMR. An advantage in using CMR to characterize mitral regurgitation is obtaining accurate information about LV volume and function as well as viability and regional wall motion in patients with ischemic mitral regurgitation.⁶⁷ In addition, the location of leaflet prolapse or restriction is identified.

Pericardial Disease

The pericardium is visualized easily by echocardiography, CMR, and cardiac CT. The best diagnostic test depends on the clinical question at hand. Echocardiography is the gold standard for assessing pericardial effusions and evaluating for tamponade. CMR is an excellent modality for diagnosing constriction based on the appearance of the pericardium and ventricular interdependence demonstrated on real time cine imaging. Using CMR, normal pericardium appears as a thin, less than 3 mm, low signal rim around the heart surrounded by higher signal fat. Thickened pericardium suggests fibrinous pericarditis and CMR can also identify the presence of pericardial fluid and constriction (Fig. 7).⁶⁸ Cardiac CT readily demonstrates pericardial calcification, pericardial thickening, and the presence of effusion.⁶⁹

Cardiac tamponade occurring after cardiac surgery occurs in 0.5% to 5.8% of patients and can present either early or late in the postoperative course.⁷⁰ Late tamponade has been defined in the literature as occurring 5 to 7 days postoperatively, but has been reported up to 6 months after surgery.⁷¹ A retrospective review of 510 consecutive cardiac surgery patients was performed to identify the frequency and clinical features of postoperative cardiac tamponade, which found 10 diagnosed cases, with five or six patients having late tamponade.⁷² The two-dimensional echocardiography found loculated pericardial effusions and selective chamber compression in most patients. The presence of loculated pericardial effusions or selective chamber compression due to clot can result in atypical presentations of tamponade. In addition, TTE can be technically challenging in surgical patients due to limited acoustic windows secondary to mechanical ventilation, patient position or incisional pain. In cases of suspected tamponade with nondiagnostic transthoracic images, TEE is indicated.⁷³

Cardiac Masses/Thrombus

Echocardiography and CMR play a complementary role in evaluating patients suspected of cardiac masses or thrombus. Most initial evaluation of cardiac masses is done by TTE, however, it has limited acoustic windows. The clinical application of three-dimensional echocardiography for evaluation of cardiac masses or thrombi is still evolving. Intracardiac masses visualized with three-dimensional echocardiography may become a standard preoperative evaluation, complementing the traditional two-dimensional TTE and TEE.⁷⁴

Further characterization of a cardiac mass can be done with TEE or CMR. CMR offers a complete morphologic and functional evaluation, particularly with respect to associated pericardial or extracardiac involvement.⁷⁵ Bright blood cine CMR details the morphology of a cardiac mass including the origin and involvement of surrounding structures. Additional

sequences answer the questions about the presence of hemorrhage, vascularity, and calcification.⁷⁶ Cardiac CT can provide information about the involvement of the surrounding pericardium, mediastinum, and lungs; however, the widespread use of CT in evaluating cardiac masses is limited due to the superior tissue characterization by CMR and the radiation exposure of CT.

Congenital Heart Disease

Echocardiography is the primary tool used to diagnose and follow patients with congenital heart disease. CMR is used to diagnose more complex congenital heart disease as well as follow patients after surgical therapy. Transposition of the great vessels, tetralogy of Fallot, pulmonary artery stenosis, double outlet RV, truncus arteriosus, and total anomalous pulmonary venous return are just some of the conditions with excellent characterization using CMR and MR angiography.⁷⁷ Cardiac CT can diagnose anomalous coronary arteries, total anomalous pulmonary venous return, bicuspid aortic valve, and pulmonary artery anomalies but has limited experience with more complex congenital heart disease⁷⁸ and should be avoided in pediatric patients who are at higher risk from radiation exposure.

SUMMARY

The growth and development in noninvasive imaging of the heart and coronary arteries provides for an environment whereby a true multimodality approach can be taken when evaluating patients with known or suspected heart disease. The application of each imaging modality is best interpreted in the context of the specific diagnostic question and the underlying patient characteristics.

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Fig. 1.
TEE demonstrating the three-chamber view with a mass on the aortic valve, which is consistent with a vegetation.

Fig. 2. The addition of color Doppler to the TEE in the same view as Fig.1 demonstrates the presence of moderate to severe aortic regurgitation as well as an aortic abscess.

Fig. 3.

There is a large region with severe reduction in uptake in the anterior, anteroseptal, and inferoseptal segments that is predominantly reversible. The defect is consistent with ischemia.

Fig. 4. Cardiac catheterization following the myocardial perfusion imaging in Fig. 3 that demonstrates a significant proximal left anterior descending (LAD) stenosis.

Fig. 5.

Example of a patient with an ST elevation myocardial infarction imaged with CMR. The image shows a short-axis view of the left ventricle with delayed contrast enhancement to demonstrate the area of anteroseptal transmural myocardial infarction (*light gray*), and endocardial microvascular obstruction (*black*).

Fig. 6. Coronary CT angiogram in the two-chamber view demonstrating the CAD artery with a small amount of proximal calcium.

Fig. 7. Example of thickened pericardium seen on a four-chamber axial CMR image for evaluation of constrictive pericarditis. The normal thickness of pericardium is less than 0.3 cm and this patient has a pericardial thickness of 0.63 cm.

Table 1

Diagnostic accuracy of MDCT for evaluation of patients after coronary artery bypass surgery

Vessel	Not Evaluable (%)	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Graft occlusion	0.7 (3/418) (95% CI 0.15–0.21)	100 (130/130) (95% CI 97–100)	100 (494/495) (95% CI 99–100)	99 (13/131) (95% CI 96–100)	100 (494/494) (95% CI 99–100)
Graft stenosis	6.4 (39/611) (95% CI 4.6–8.6)	97 (184/1889) (95% CI 94–99)	95 (337/354) (95% CI 92–97)	92 (184/201) (95% CI 87–95)	99 (337/342) (95% CI 97–100)
Native arteries	19.6 (333/1697) (95% CI 18–22)	95 (524/545) (95% CI 93–97)	75 (608/813) (95% CI 72–78)	67 (424/629) (95% CI 64–71)	97 (608/629) (95% CI 95–98)

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