Coronary artery disease affects millions of Americans annually. In evaluating coronary artery disease, it is important to develop diagnostic methodology that can screen patients before the onset of symptoms or cardiac events and, in addition, evaluate the functional aspects of coronary artery disease, including any residual effects on the heart after events have occurred. Electron beam computed tomography allows the identification of coronary calcium, which is a marker for coronary atherosclerotic disease, and also allows the quantification of cardiac function, which may be altered from coronary atherosclerosis or the occurrence of a cardiac event. Thus, electron beam computed tomographic imaging is having a major impact on the diagnosis and follow-up on coronary artery disease.

Coronary artery disease affects 1.2 million Americans annually and accounts for 500,000 deaths. Many of these are sudden and unexpected. Tests that can diagnose coronary artery disease include stress electrocardiogram (stress ECG), stress radionuclide studies (thallium/sestamibi), stress echocardiography, and cardiac catheterization with coronary angiography. In most cases, these tests become positive only after sufficient disease progression to significantly (≥50%) narrow the coronary arterial lumen. Fortunately, there are newer tests that can diagnose coronary artery disease before significant luminal narrowing has occurred. These newer tests are the intravascular ultrasound detection of atherosclerotic plaques and the electron beam computed tomographic (EBCT) detection of coronary artery calcium.

Intravascular ultrasound is invasive and requires the introduction of a catheter into the coronary artery lumen to interrogate the vessel wall by sound waves from a transducer located in the catheter tip. The reflection of these sound waves can demonstrate atherosclerotic plaque within the wall of the artery. The other test is EBCT detection and quantification of coronary artery calcium. The latter is a noninvasive technique that has tremendous importance because it can diagnose coronary atherosclerosis relatively early and often before the onset of significant narrowing and/or a cardiac event. The ability to diagnose the disease early allows the initiation of treatment strategies, which may prevent or minimize luminal narrowing and more importantly cardiac events.

In evaluating atherosclerotic disease, it is not only important to be able to diagnose the disease but also to evaluate disease effects on cardiac structure and function. The ability to define and track cardiac chamber volumes, myocardial wall thickening, wall motion abnormalities, and thrombus formation are important. Valvular regurgitation and pericardial thickening are also important, as is the ability to follow disease progression/regression.

There are four imaging modalities currently being used to obtain quantitative and qualitative functional information about the heart. They are echocardiography, radionuclide ventriculography, magnetic resonance (MR) imaging, and EBCT. Echocardiography provides excellent information regarding cardiac morphology and contractility and does so in real time; however, quantitative measurements have to be based on assumptions of ventricular geometry, and this makes these measurements potentially suspect. Suboptimal acoustic windows, frequent poor endocardial border visualization, and the inability to interrogate the entire heart in a true short-axis orientation also limits its usefulness. The test is highly operator-dependent, and this can affect both accuracy and reproducibility.
Radionuclide ventriculography has poor edge detection, low count-to-noise ratios, and problems caused by overlap of the cardiac chambers. All can compromise the precise quantification of cardiac function.

MR can provide useful and accurate functional information but requires a longer time to acquire the images. The images have a poorer resolution, and the endocardial edge characterization, especially on the cine images, is often poor. Frequent degradation of images by patient motion and arrhythmias also makes MR less attractive. In spite of these drawbacks, MR has the potential of developing into an important imaging modality in evaluating cardiac function.

The EBCT scanner (Cine CT, Fast CT) (Imatron Inc., C-150 model scanner) has made a major impact in functional cardiac imaging. Unlike conventional computed tomography (CT) scanners, EBCT has millisecond image acquisition time; like CT, it has excellent resolution. These factors permit the precise qualitative and quantitative assessment of global and regional cardiac function. A complete assessment of almost all of the functional indicators can readily be obtained from a single imaging sequence.

Because EBCT is playing an ever increasing role in the evaluation of cardiac disease, it is important to be aware of the potential of this imaging modality. Here we review the current applications of EBCT in the diagnosis of coronary artery atherosclerosis and in evaluating cardiac structure and function.

**EBCT Scanner**

The EBCT scanner, unlike the slower conventional CT scanners with rotating x-ray sources and stationary detectors, utilizes electromagnetically focused electrons to sweep tungsten target rings (2) (Fig. 1). The x-rays generated from the sweeps of the target rings pass through the patient to activate a series of detectors located in the gantry above the patient. Each sweep of the target ring requires 50 ms and produces two contiguous images 8 mm in thickness. There is a 8-ms delay to reset the beam, and thus an image can be acquired every 17 ms; 100-ms images are also possible. In the volume mode configuration, the scanner can obtain images at 1.5-, 3-, 6-, and 10-mm slice thicknesses. If operated in the cine or flow mode configurations, the images are 8 mm thick.

In the volume mode sequence, a 100-ms axial image is obtained as the scanner couch moves through the gantry of the scanner. This sequence is similar to conventional CT although much faster.

The flow and cine mode sequences differ from the volume mode sequences. The flow mode sequence is triggered from the R wave of the ECG and directs the scanner to sweep one or more of the target rings to produce two 8-mm contiguous images from each target ring. There is a 4-mm gap between images from adjacent target rings. Thus the flow mode sequence can interrogate a 8-cm area of the heart or aorta in 240 ms. Repeated sweeps of the same area can be triggered from the ECG up to a total of 160 images. In the cine mode, images from the same target ring can be collected every 58 ms (17 images/s) until the desired number of images are obtained. The beam then moves to the next target ring, and the sequence is repeated. This sequence allows imaging of the contraction pattern of the myocardium. Thus the scanner can produce both static and functional images (3, 4).

**Coronary Artery Calcification Screening**

The presence of atheromata within the intima of coronary arteries and the existence of calcium as a marker of the atherosclerotic process are now universally accepted (5–9). Of the many papers documenting this association is the classic one by Blankenhorn and Stern (10), who examined 3500 coronary arterial segments from 89 patients and found that in each instance coronary calcification was associated with intimal atheroma.

The earliest detectable atherosclerotic lesion is the fatty streak. These fatty streaks often occur in the first decade of life (11) and are increasingly found by the second decade (12, 13). The fatty streaks are later seen as crescent-shaped masses of lipid separated from the vessel lumen by a
fibrous cap. These plaques tend to be relatively soft and have high concentrations of cholesterol and cholesterol esters, and as the disease progresses, the fibrous caps may thin and rupture with the most common site of rupture being at the junction of the fibrous cap with the healthy vessel wall. Plaques in which the lipid pool is eccentric and plaques located at sites of increased shear forces are also more prone to rupture (14).

Once a plaque ruptures, it exposes the blood to collagen, lipids, and smooth muscle cells within the vessel wall; this leads to deposition of platelets and activation of the coagulation cascade system. The resulting thrombus can acutely narrow the vessel, causing infarction, or can be incorporated into the vessel wall to cause a more gradual narrowing (15). In many instances, because of remodeling, the plaques may not produce stenosis or thrombotic occlusion and instead only minimally or moderately narrow the coronary artery lumen (16–18). In fact, up to two-thirds of patients who have acute myocardial infarction or unstable angina may have only minimal narrowing at the site of the occlusion; hence, exercise ECG and echo and nuclear medicine studies, which detect abnormalities in blood flow through stenotic arteries, often show no abnormalities (15). However, once formed, the occluding thrombus continues to be exposed to circulating blood, and this can produce repeated episodes of re-thrombosis and re-occlusion (14–16). If infarction occurs, its extent is determined by the size of the vessel, the location and duration of the occlusion, and the extent of collateralization that may be present.

A number of histologic studies have supported the association of CT tissue densities of 130 Hounsfield Units with calcified plaque (Fig. 2). Mautner et al. (19) examined 1298 segments from 50 heart specimens and observed that 93% of coronary arteries with stenosis ≥75% had calcification vs 20% of those with <50% and only 4% of those with <25% (20). These investigators also found that EBCT calcium was present in 41% of the 1426 segments from coronary arteries of patients with symptomatic coronary artery disease vs 24% in 1535 segments from asymptomatic patients and 4% in 1337 segments from healthy controls.

Because coronary calcification increases with age, it has been argued that this is merely a sign of aging; however, quantitative studies (6–8) have consistently shown a direct relationship between the extent of coronary calcification and the severity of coronary atherosclerosis independent of age.

A number of papers have documented the relationship of calcification to vessel narrowing. Margolis et al. (21) evaluated calcification of coronary arteries in 800 consecutive patients by cine cardiac fluoroscopy and selective coronary angiography performed within 5 days of each other. They found calcification in 236 of 250 (94%) of those with stenoses of >75% in one or more major coronary arteries. The study also showed the survival rate at 6 months to 5 years was poorer in patients with calcification than in those without (5-year survival rate, 58% with vs 87% without). The predictive value of calcium for future coronary events was independent of age, sex, number of diseased vessels, results of exercise tests, and left ventricular (LV) function.

Agatston et al. (22) in 1990 reported the first large series where EBCT was used to detect calcification of the coronary arteries. These investigators studied 584 consecutive patients, 50 of whom also had fluoroscopy. In this group, 109 patients had a history of coronary artery disease, and 475 did not. [Coronary artery disease was established by a history of myocardial infarction (22 patients) or angiographic evidence of >50% diameter narrowing of coronary arteries (87 patients)]. The mean age was 48 years. A
significant difference ($P \leq 0.0001$) was found in the group with coronary artery disease vs the group without coronary artery disease. The sensitivities of calcium detecting major occlusion were 71–74%, and the specificities were 70–91%. The negative predictive value of a zero calcification score was 94–100%. EBCT showed calcium in 90%, whereas fluoroscopy showed calcification in only 52%. Thus the authors concluded that EBCT appears to be an excellent technique for detecting and quantifying calcification in coronary arteries.

Breen et al. (23) studied 100 patients 23–59 years old who had coronary arteries studied with EBCT and angiography; significant obstruction was defined as >50% narrowing of the vessel diameter on the angiogram. The sensitivity of detecting any calcium (i.e., calcium score >0) in individuals with significant angiographic obstruction was 100% and the specificity was 47%. In patients in whom angiography showed stenosis of >10%, the sensitivity for detecting any calcium by EBCT was 94%, and the specificity was 72%. In this series, eight patients with calcification had no angiographic evidence of coronary artery disease, and 28 patients with calcification had mild or moderate coronary artery disease.

A larger multicenter study that examined coronary calcification as an indicator of significant stenosis involved 710 patients presenting with symptoms of coronary artery disease (24). There were 456 men and 254 women (mean age, 56 years). In this group, the sensitivity of EBCT in detecting calcification as an indicator of significant stenosis (50% narrowing) was 95%, and the specificity was 44%. The positive predictive value was 72%, and the negative predictive value was 84%. When these CT images were reinterpreted in a blinded and standardized fashion using a calcium threshold of 100 Hounsfield Units, the sensitivity was 70%, and the specificity was 71% (25).

Although the amount of stenosis varies with the calcium score, a recent report by Rumberger et al. (26) found that a calcium score of 80 had a high sensitivity (84%) and specificity (84%) in predicting stenosis somewhere within the coronary system. These investigators also found "cut points" in the calcium scores that would provide 90–95% sensitivity and specificity in detecting angiographic coronary artery stenosis (27). Thus calcium appears to be a valid predictor of significant stenosis within the coronary system.

Although the calcium score could not be used to predict significant site-specific stenosis, Stanford et al. (28) determined that absence of calcium on EBCT scans appeared to be an important indicator of the absence of coronary artery disease. In a group of 150 patients from two institutions, only one patient had significant stenosis in the absence of calcification. The angiographic and EBCT studies were done within 18 days (mean, 1.7 days) of each other.

EBCT can also be used to follow the progression of coronary artery disease. Janowitz et al. (29) evaluated coronary calcification in 25 subjects who had two EBCT scans, 406 days apart. Twenty individuals who had calcium in the first study had statistically significant increases in calcium in the second study. Subjects with angiographic coronary artery disease showed a 48% increase in calcified plaque volume; asymptomatic subjects had a 22% increase, with 98% of the deposits seen in the first study being accounted for in the second study. Also, patients with obstructive coronary artery disease had significantly more new calcific deposits than did the asymptomatic group (55 vs 18). From these data, the authors concluded that EBCT was useful in studying the natural history of coronary artery disease as well as the changes that occur after modification of risk factors.

Gender differences also appear to play a role in the development of coronary calcification. In a study evaluating the prevalence of coronary calcification at intervals of 5–10 years in 1396 male and 502 female asymptomatic subjects (age range, 14–88 years) Janowitz et al. (30) found that the prevalence of coronary calcium in women was one-half that of men until age 60 years, when the difference diminished. The calcium distributions in men 40–69 years of age was virtually identical to those in women 50–79 years of age. These findings were confirmed by Devries et al. (31). However, there appeared to be no differences between men and women in the value of the EBCT calcium score in predicting angiographic stenosis (32).

**Coronary Artery Calcification as a Predictor of Cardiac Events**

Detrano et al. (33) followed 1461 asymptomatic high-risk subjects with a >10% risk of having a coronary event within 8 years. All had coronary artery calcification detected on fluoroscopy. At 1 year, events occurred in 5.4% of 691 subjects with coronary calcification vs 2.1% of the 768 subjects without fluoroscopic calcium ($P < 0.001$). (A coronary event was defined as angina, documented myocardial infarction, myocardial revascularization, or death from coronary heart disease.) One-vessel calcification incurred an event risk of 5.4%; two-vessel calcification incurred 5.6%; and three-vessel calcification incurred 6.2%. These investigators found that radiographically detectable calcium was associated with a risk 2.7 times greater for an event when compared with the group with no calcification. They also found that the presence of calcification was an independent predictor of at least one coronary event when controlled for age, gender, and other risk factors.

Another EBCT calcium multicenter study looked at event data in 501 symptomatic patients who had both a coronary calcium study and coronary angiography (34). In this group, 1.8% died and 1.2% had nonfatal myocardial infarctions during a mean follow-up period of 31 months. A threshold of $\geq 100$ in the calcium score was shown to be highly predictive in separating patients with cardiac events at follow-up from those without events. In
this study, a logistic regression that included calcium score, age, sex, and coronary angiographic findings as independent variables showed that only log calcium score predicted events.

The same was true for asymptomatic patients. Arad et al. (35) followed 1173 asymptomatic patients an average of 19 months. Nineteen patients had 27 cardiovascular events. These included one death, seven myocardial infarctions, and one nonhemorrhagic stroke. In addition, there were 18 patients who developed symptoms requiring coronary bypass surgery (8) or percutaneous coronary angioplasty (10). For coronary artery calcium score thresholds of 100, 160, and 680, the EBCT sensitivities for cardiac events were 89%, 89%, and 50%; the specificities were 77%, 82%, and 95%, respectively. The odds ratios ranged from 20.0 to 35.4 (P <0.00001) for these thresholds. Other risk factors, such as presence of hypercholesterolemia, low HDL-cholesterol, hypertension, diabetes, and family history, failed to predict subsequent events.

Therefore, it appears that the detection of coronary artery calcium is useful in identifying those at risk for acute coronary events; thus the early detection of individuals with mild coronary atherosclerosis is of value, particularly if the process can be retarded, arrested, or reversed by diet or drug therapy. Recently, there have been data to indicate that lowering serum cholesterol in patients with known coronary artery disease (secondary prevention) reduces the incidence of nonfatal infarction, fatal infarction, cardiovascular mortality, and all cause mortality (20), and that risk reduction and lipid lowering in patients with increased cholesterol without clinical disease (i.e., high-risk, asymptomatic individuals) is efficacious (36–38).

Cardiac Structure and Function
Cardiac function studies should routinely include, in addition to the qualitative studies of cardiac morphology and contractility, an ability to quantify LV and right ventricular (RV) end-diastolic and end-systolic volumes (EDV and ESV), stroke volume (SV), ejection fraction (EF), and myocardial mass.

The imaging sequence used for functional analysis is generally a short-axis movie sequence. As mentioned, the movie acquisition sequence consists of a series of same level, 8-mm thick, tomographic images acquired every 58 ms. To orient the slices perpendicular to the long axis of the heart, the scanner couch is slewed 25° to the subject’s right and placed in 15° reverse Trendelenberg. This brings the short axis of the heart approximately perpendicular to the scanner gantry (39). This orientation approximates the parasternal short-axis orientation of two-dimensional echocardiography (Fig. 3). In this position, all wall segments except the cardiac apex are well visualized. To best evaluate the cardiac apex, the patient table is slewed 25° degrees to the subject’s left and remains horizontal. This produces a long-axis image similar to the four-chamber view of echocardiography. Because there is essentially no overlap of slices, problems with volume averaging are minimized.

In the most commonly used cine sequences, 10 images are acquired per level. The initial image is triggered from the R wave of the ECG, and subsequent images are obtained every 58 ms. With this sequence, the image acquisitions are sufficient to encompass an entire ventricular contraction from diastole through systole. By displaying the images temporally, the contracting heart can be viewed level-by-level in near real time. Images are generally viewed on a 256 × 256 display matrix, using a 30-cm reconstruction circle. This yields a pixel size of 1.17 mm. With a slice thickness of 8 mm, it usually requires two complete short-axis acquisitions (16 levels) to encompass the entire heart; the long-axis study typically requires only one acquisition.

Contrast Administration
Quantification of cardiac function requires visualization of the endocardial and epicardial borders, and this necessitates the use of contrast material. To ensure peak chamber enhancement, the circulation time is usually determined using a 10-mL bolus of a solution of 5 g/L magnesium sulfate injected intravenously. The interval between the intravenous injection and the time the subject experiences a warm, salty taste in the mouth is the circulation time. Alternatively, the circulation time can be determined by recording either the transit time required for a bolus of cardiogreen dye to arrive at an ear densitometer or by calculating the elapsed time that it takes for a small test bolus of contrast material to arrive in the heart (4).

To ensure maximal opacification, scanning is delayed for a period equal to the patient’s circulation time plus 10 s, with optimal enhancement occurring when approximately two-thirds of the total contrast dose has been injected. For each sequence, the contrast dose is usually 60–90 mL; however, the maximum contrast dose should not exceed 3 mL/kg patient weight. In the movie sequence, contrast material is usually administered at a rate of 1.5–2.0 mL/s. However, to ensure optimal chamber opacification in patients with cardiac enlargement, poor cardiac contractility, or long circulation times, the admin-
istration rate may be increased to 2.2 mL/s. Because it often requires additional sequences to image an enlarged heart, care must be taken not to exceed the above-mentioned contrast limitation. To minimize respiratory motion and to further improve image resolution, the study is usually performed during breath-holding (4).

Nonionic contrast material needs to be used for all ventricular function studies because it prevents the undesirable cardiac and hemodynamic perturbations that can occur with ionic contrast administration. These perturbations may affect functional measurements by altering heart rate and blood pressure (4, 39). An additional advantage of nonionic contrast material is that patients experience less discomfort, and this improves acceptance of the study.

**Cardiac Chamber Volume**

To determine cardiac chamber volume, track ball-assisted cursor planimetry of the endocardial borders is done; from this, the intrinsic software within the scanner calculates chamber volumes for each level. Global chamber volumes are determined by applying a modified Simpson’s rule to these data and summing the data.

Numerous validation studies have shown a high accuracy for EBCT in the determination of cardiac volumes (40). Using casts with various volumes, Pietras et al. (41) found both an excellent correlation with volumes calculated by EBCT as well as an excellent correlation between EBCT results and biplane cineangiography \( r = 0.99, S_{y|x} = 4.36 \). Similar results have been shown in the quantification of atrial (42, 43) and ventricular (44–48) volumes and in radiopaque casts of postmortem hearts (45) \( r = 0.99, S_{y|x} = 2 \) mL.

**Myocardial Contractility**

Functional cardiac imaging is frequently performed to evaluate regional wall motion abnormalities. This cine display of the heart in near real time allows the observer to identify areas of hypokinesia, akinesis, and dyskinesia. Myocardial thinning may occur in conjunction with a wall motion abnormality, and its presence provides additional documentation of previous myocardial infarction with or without aneurysm formation (Fig. 4) (4).

Several studies have validated the applicability of EBCT in evaluating wall motion abnormalities (49). MacMillan et al. (50) compared EBCT and biplane contrast ventriculography in the evaluation of LV wall motion abnormalities in patients with ischemic heart disease. These investigators evaluated 84 ventricular segments and found agreement between EBCT and ventriculography in 90% (76 of 84) segments. In patients with unaffected contractility, EBCT agreed with ventriculography 92% of the time, and no wall segment classified as normal by ventriculography was found to be abnormal on EBCT. Similarly, no regional wall segment that demonstrated abnormal contractility on ventriculography was interpreted as having unaffected motion on EBCT. Similar findings were found by Bateman et al. (51). These authors found a 94% agreement between EBCT and catheterization in characterizing wall motion abnormalities.

Feiring et al. (52) studied regional wall motion in healthy volunteers and found considerable regional variations in ventricular contractility. These investigators showed a frequent nonuniform pattern of segmental LV contraction in healthy subjects. This heterogeneity varied from segment to segment and also between the cardiac apex and base. Specifically, regional contractility was found to be greatest near the apex and decreased in a fairly predictable manner toward the base (40, 52).

Chamber size and loading conditions can change contractility, and recent studies have shown that heterogeneity in segmental contractility can be modified by changing preload and afterload conditions (40, 53–55). For example, during periods of inotropic stress, there is a decrease in the segmental heterogeneity, and this is accompanied by augmented performance in each wall segment (40, 52). Thus, EBCT can provide an accurate assessment of ventricular contractility, and in patients with suspected cardiac dysfunction, these techniques represent an excellent way to monitor disease progression/regression.

A different EBCT technique has used radii to look at myocardial contraction. The ventricle at each level can be interrogated by radii, thereby generating data relating to regional segmental performance (contractility) and EF. By using either an endocardial or epicardial centroid, regional contractility can be displayed graphically and numerically calculated (40, 52). Quantitatively, this form of analysis provides a more specific assessment of ven-
tricular contractility and may be useful in monitoring patients with regional myocardial contraction abnormalities.

**Stroke Volume**

Reiter et al. (46) compared the EBCT quantification of left (LVSV) and right (RVSV) ventricular SVs, using thermodilution techniques and electromagnetic flow probe (EFP) measurements in instrumented dogs. Using these techniques, the EBCT and thermodilution/EFP LVSV determinations showed a very good correlation ($r = 0.99, S_{y|x} = 1.47 \text{ mL}$; Fig. 5).

The quantification of RV volumes has been more difficult, primarily because there were no geometric models that satisfactorily approximate the shape of this ventricle. As a result, accurate RV volumetric measurements using two-dimensional echocardiography and angiography have been difficult to achieve (56). With EBCT, RV volumetric determinations are readily obtainable, and cross-sectional EBCT imaging permits the reproducible and accurate measurement of RV EDV, and systolic (ESV) volumes, and also SV as reported in experiments by Ringertz et al. (45) and Mahoney et al. (47). For RVSV, similar agreement was found between EBCT and EFP ($r = 0.98, S_{y|x} = 1.73 \text{ mL}$) (46).

**Diastolic Function**

The assessment of cardiac function is not limited solely to systolic performance; regionalized ventricular diastolic functional information can also be obtained. As with contractility, regional ventricular compliance can vary substantially not only between ventricles but also within each ventricle (53, 57).

In measuring diastolic filling, additional sequences are required, and the movie study is modified slightly so that more images are obtained early in diastole. A typical acquisition would consist of a six-level, 13-image run. This is in contrast to the standard eight-level, 10-image sequence used in LV functional imaging. Because ventricular compliance is measured by the rate of diastolic filling, which typically occurs within the first 300–450 ms of diastole, more frequent images during this time period are required to quantitate effective RV compliance. With slower heart rates (<60 beats/ min), the acquisition rate may need to be further modified to include a four-level, 20-image acquisition sequence. For heart rates higher than 90 beats/min, the maximum EBCT framing rate of 17 images per second may not be fast enough to generate reliable diastolic filling curves (57).

The diastolic filling curve is generated by cursor-assisted planimetry of the RV chamber at each time sequence. Three determinants are obtained from these data: time to peak filling, filling fraction, and time to peak filling rate. These calculations are then compared with health-related reference values (54, 57–59). Normalization of peak filling rate needs to be done to account for differences in ventricular size and SV (54, 57, 59). Diastolic filling measurements quantitated either globally or at each individual level correlate very well with radionuclide angiographic measurements (60).

**Ejection Fraction**

EF is the most universally used measure of cardiac performance. The quantification of EF using EBCT requires planimetry of ventricular EDV and ESV at each level. In the hands of an experienced operator, this requires ~30 min. Once the planimetry is accomplished, the EF is computed for each level, using software inherent within the scanner. This software calculates the volume differences between EDV and ESV at each level. The global EF is readily determined by applying a modified Simpson’s rule. Because EBCT volumetric measurements have been extremely accurate, it is no surprise that EBCT EF calculations are similarly accurate and highly reproducible, and they correlate well with ventriculography (46, 58, 61, 62) and radionuclide angiographic determinations ($r = 0.92$). From these studies, reference values for EDV, ESV, and EF have been determined (40, 58).

**Regurgitant Volumes**

The calculation of regurgitant volume requires measurements of RV and LV ESV and EDV. From these data, it is possible to calculate EF and SV (EDV - ESV = SV). In healthy individuals, the SV for the RV and LV should be nearly identical; therefore, any differences between the two should be the result of valvular insufficiency. Experimentally, close correlations were found between EBCT and EFP measurements of regurgitant volumes and regurgitant fractions (63). In addition, thickened or calcified valve leaflets are readily seen and can be qualitatively evaluated. In patients with more than one insufficient
Cardiac Output
Cardiac output (CO) is another excellent measurement of overall cardiac performance. Before the development of EBCT, the noninvasive measurement of CO was by indicator dilution techniques. A comparison of indicator dilution techniques and flow mode imaging sequences has shown EBCT to be a highly accurate in measuring CO (64, 65). Because of a linear relationship between blood pool indicator (contrast) concentration and CT density, CO can be determined using time-density analyses. By placing selected regions of interest within the blood pool (LV cavity), the concentration (density in Hounsfield Units) of contrast material can be measured as a function of time. This time-density relationship can then be plotted, and curves can be fitted to a least-squares gamma variate analysis. Using nonionic contrast material and standard thermodi- luton techniques, Garrett et al. (64) showed good correlation between EBCT and thermolituation measurements of CO over a wide range of COs (r = 0.92).

Myocardial Perfusion
Tissue perfusion is often affected by atherosclerotic disease states, and thus the ability to measure myocardial perfusion is of clinical importance (66). EBCT myocardial perfusion can be assessed from short-axis images showing contrast arrival, peak enhancement and washout in the myocardium compared with the LV blood pool (66, 67).

Myocardial Mass Quantification
Ventricular mass is an important measurement that can assess disease processes that produce myocardial hypertrophy. In fact, increased muscle mass has been reported to be an important predictor of cardiac mortality (68). Modalities such as radionuclide ventriculography, thallium imaging, and biplane ventriculography are unable to quantify ventricular mass. With EBCT, this determination is straightforward and requires only planimetry of the endocardial and epicardial borders. The computer software then multiplies this differential by 1.05 (the specific gravity of myocardium) and automatically calculates myocardial mass at each level.

The EBCT determination of myocardial mass was initially validated by Feiring et al. (69). These investigators showed an excellent correlation between EBCT and myocardial mass in autopsied dogs (r = 0.99, Syx = 4.1 g). Furthermore, measurement reproducibility was excellent, and there was little intraobserver (r = 0.99) or interobserver (r = 0.99) variability. The accuracy of EBCT as compared with that of two-dimensional echocardiography in the estimation of LV mass has also been good (r = 0.89, P < 0.002) (70).

In addition, one group of investigators has measured RV mass using volume imaging. In this study, Hajduczok et al. (68) showed that RV mass measurements using 3-mm thick, short-axis EBCT diastolic images acquired in a volume mode were reliable and correlated well with autopsy measurements.

Measurement Reproducibility
Reproducibility is extremely important in any imaging modality, especially when serial examinations are performed to monitor progression/regression and to follow responses to treatment. Unlike other imaging modalities, such as echocardiography, where results can be influenced by operator performance, EBCT has been repeatedly shown to have little interstudy variability in either mass or ventricular volume calculations (40, 46, 51, 71). Furthermore, multiple studies over time have shown minimal inter- and intraobserver variability (46, 47, 68, 69, 71).

Constrictive Pericarditis
The diagnosis of constrictive pericarditis can be problematic. The disease syndrome results from limitation of cardiac filling by chronically inflamed or scarred pericardium. The clinical presentation is characterized by overt systemic venous congestion and inability to raise CO during stress. Conventional imaging techniques do not reliably image pericardium—particularly in the absence of dense calcification (72). Invasive hemodynamic studies can reveal characteristic findings, but even these may be misleading. EBCT, by virtue of imaging with superior spatial and temporal resolution, is a very useful diagnostic tool in this setting, as shown by Grover-McKay et al. (73), who demonstrated a very high accuracy in pericardial thickness measurements using an animal model of pericarditis. Oren et al. (74) studied a series of 12 patients who had suspected constrictive pericarditis on the basis of complete clinical evaluation, including invasive hemodynamic studies. Each patient had histopathologic confirmation of the status of the pericardium at surgery or autopsy. EBCT assessments were able to definitively demonstrate both the abnormal anatomy (thickened pericardium) and physiology (abnormally rapid early RV diastolic filling) in patients with constriction and clearly distinguish them from the patients who were ultimately found to have histopathologically normal pericardium. In these patients, it is critically important for the clinician to ascertain both the abnormal anatomy and physiology in this setting, because some patients can present with grossly thickened pericardium in the absence of functional sequelae (75).

Intracardiac Thrombus
The principal advantage of imaging cardiac thrombi with EBCT is the ability to obtain high quality tomograms without overlapping of tissues. This advantage is not universally shared by other imaging modalities (Fig. 6). For example, a study by Love et al. (76) evaluated the utility of EBCT and transthoracic echocardiography to diagnose cardiac mural thrombus in patients presenting with stroke. These investigators found that conventional
two-dimensional echocardiographic images were technically inadequate to make this determination in roughly one-third of cases, whereas EBCT provided adequate images 97% of the time. Vigneswaran et al. (44) found a similar degree of difficulty in obtaining adequate visualization of the right ventricle, using echocardiography in a series of patients undergoing cardiac evaluation before lung transplantation, whereas EBCT provided high-quality images in all cases.

Disadvantages of EBCT

The advantages of EBCT in the quantitation of cardiac function have been discussed in detail. Nevertheless, there are disadvantages that temper the role of EBCT in functional imaging. Although it may be reasonable to consider EBCT as a noninvasive test, cardiac examinations do require contrast enhancement, and this necessitates the placement of an intravenous catheter. This may pose a problem for patients with borderline renal function or known allergies to contrast material.

Additionally, the EBCT scanner is not readily available in many medical centers, and the relatively high price of the scanner limits its availability. Also, the perceived radiation danger and lack of portability may support a clinician’s preference for echocardiography. Lastly, the ability to perform a noninvasive bedside examination is a considerable advantage for echocardiography.

Technical problems seen in EBCT imaging primarily relate to image acquisition. Functional quantification cannot be performed unless scanning is properly triggered from the R wave of the ECG tracing. If mistriggering occurs, the images may not be acquired throughout the entire cardiac cycle. Cardiac arrhythmia, particularly atrial fibrillation, is relatively common, and often leads to improper triggering, thus precluding quantitative analysis; qualitative assessment, however, is still possible. If improper triggering occurs and contrast dose limits have not yet been reached, then the short-axis sequence may be repeated. For these reasons, it is preferable that the short-axis movie study be obtained initially.

Conclusion

Electron beam technology has proven to be extremely useful in the qualitative and quantitative analysis of cardiac function. The millisecond image acquisition time, superior spatial resolution, and the ability to obtain several studies in one setting make EBCT an attractive imaging modality for the determination of cardiac function. High-performance dynamic imaging coupled with proven measurement accuracy and reliability characterizes the superiority of EBCT in performing functional cardiac analysis. In some institutions, EBCT has been used as a clinical “gold standard” for the validation of other methods. EBCT also allows the identification of coronary calcium, which is a marker for coronary atherosclerotic disease.

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