REVIEW

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CT of the heart: Principles, advances, clinical uses

ABSTRACT

Computed tomography (CT) has become a standard test for many cardiovascular conditions (eg, aortic dissection and pulmonary embolism), and it has great potential in assessing other common diseases, including coronary artery disease. We review the principles of CT and its uses in cardiovascular medicine.

KEY POINTS

Compared with older CT scanners, newer systems have greater spatial and temporal resolution and can reconstruct images in any plane desired, as well as in three dimensions.

To eliminate motion artifact, data acquisition is timed to coincide with the end of diastole.

CT can provide detailed anatomic information about the pericardium, myocardium, cardiac chambers, large vessels, and coronary arteries.

CT can estimate the amount of calcified and noncalcified plaque in coronary arteries; this information may help in predicting coronary events in patients at intermediate risk.

COMPUTED TOMOGRAPHY (CT) is increasingly being used to examine the heart and blood vessels,[1,2] as it has become capable of showing smaller structures in an infinite number of planes and views. It is rapidly becoming the standard for assessing many cardiovascular problems (eg, detecting aortic dissections and pulmonary emboli) and has the potential to help with others, including defining coronary artery disease.

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This article provides basic information about cardiovascular CT, reviews its most common indications, and discusses how it compares with other imaging tests.

PLANAR IMAGING HAS LIMITATIONS

The heart has long been evaluated radiographically,[3,4] but standard planar images (ie, chest radiographs and angiograms) have several limitations.

Standard postero-anterior chest radiographs can reveal the silhouette of the heart, great vessels, and pulmonary vasculature. They cannot, however, show smaller structures or easily resolve superimposed structures (**FIGURE 1**).

Angiography was introduced in the 1960s, and it revolutionized cardiovascular medicine. It remains the standard for assessing the lumen of blood vessels such as the aorta and the coronary arteries.[5] Nevertheless, like a chest radiograph, an angiogram is only a planar image of the silhouette of the contrast-filled vessels.

Planar imaging vs computed tomography

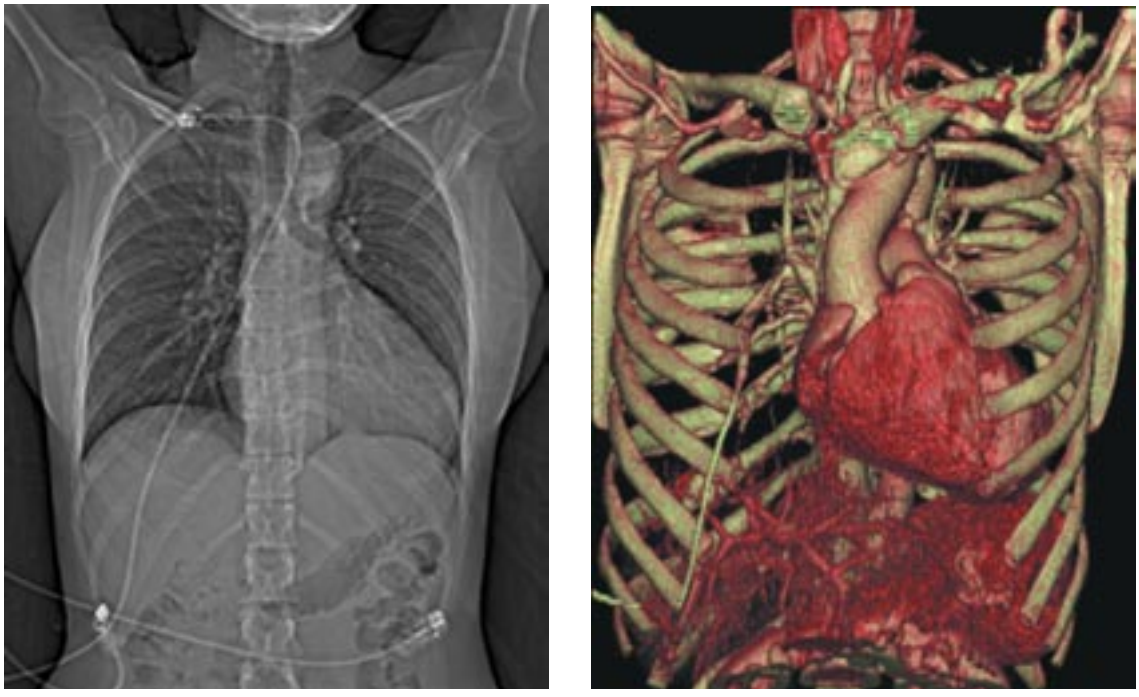

FIGURE 1. Left, the standard chest radiograph is a planar projection. **Right,** the corresponding three-dimensional computed tomographic image can reveal complex anatomy and spatial relationships.

CT is slower than planar imaging, potentially introducing motion artifact

TOMOGRAPHIC IMAGING

In a CT system, an x-ray beam is rotated rapidly around the patient's body, and the raw data are transmitted into a computer. Then, using a mathematical algorithm, the computer assigns each point (voxel) of a cross-sectional image plane a value on a gray scale (Hounsfield unit), indicating the x-ray attenuation of the tissue.

CT images can be enhanced and manipulated in several ways. If iodinated contrast agents are injected intravenously during the scan, small structures such as the lumen of the coronary arteries become visible. Moreover, the computer can reconstruct the data to provide images through different planes of the body or three-dimensional (3-D) images.

Cardiac CT requires synchronization with the beating heart

CT imaging is slower than planar imaging. A planar radiograph is almost instantaneous, with an exposure time of 4 to 10 ms, while one tomographic image slice takes 50 to 250 ms.

The longer exposure time is not a problem with static organs such as the kidney or those that can be kept temporarily still such as the lungs. The continually moving cardiovascular structures, however, pose a challenge.

To reduce motion artifacts, each image slice must be acquired during a period when the heart is moving the least, typically in late diastole. For 3-D reconstructions all slices must be obtained at the same point in the cardiac cycle, but during consecutive heartbeats.

Only recently has CT technology advanced to the point that it has enough spatial resolution (image detail) and temporal resolution (acquisition speed) to show small cardiac structures such as the coronary arteries.

Two types of CT scanners

Electron-beam CT generates a rotating x-ray beam by reflecting a rapidly undulating electron beam onto a stationary tungsten target under the patient table. It was developed specifically for cardiac imaging because it is very fast: 50 to 100 ms per image slice.[6] Each slice is 1.5 to 3 mm thick, and the whole heart

can be imaged during one breath-hold.

Multidetector CT, which was originally developed for body imaging, generates an x-ray beam by mechanically rotating an x-ray tube around the patient.

Early single-detector CT machines took 1 to 2 seconds to acquire each image. The slow speed introduced significant cardiac motion artifacts and ruled out scanning the entire heart in a single breath-hold.

The new multidetector CT scanners rotate faster and can acquire multiple slices per rotation.[7,8] The result is high spatial and temporal resolution of a large volume during a single breath-hold.[9]

Both types of scanners have advantages and limitations, which are beyond the scope of this review; interested readers can see a recent review by Achenbach et al.[10] However, the principles of CT imaging discussed apply to both types of scanners.

THE CT EXAMINATION

A cardiovascular CT examination is performed by a trained CT technologist supervised by a physician experienced in cardiovascular imaging. To obtain clinically meaningful results, this physician must choose a scan protocol designed to address a particular clinical question.

The image data are acquired during one breath-hold, but patient preparation requires a total examination time of about 10 minutes.

Radiation exposure depends on the image protocol. Doses range from less than 1 milli-Sievert (mSv) for calcium scoring to 3.5 to 6.5 mSv for multidetector coronary CT angiography, comparable to the amount received from conventional angiography.[11]

Most protocols require intravenous iodinated contrast agents to enhance cardiovascular structures.

Acquisition mode

The sequential 2-D mode involves taking individual transaxial slices as the patient table is incrementally advanced (the "stop and shoot" mode). Electron-beam CT is performed in this mode.

The spiral mode involves constantly rotating the x-ray tube while the patient table continuously advances through the gantry, creating a 3-D volumetric series. Cardiac multidetector CT is usually performed in this mode.

Slice thickness and volume coverage

Slice thickness is inversely related to volume coverage. A smaller slice thickness allows better resolution in the through-plane (the craniocaudal dimension). However, radiation exposure and scan time increase, and the volume covered during one breath-hold is reduced because more slices are required to image the same volume.

For example, coronary CT angiography is performed with a slice thickness of 1.0 mm but covers only the heart. A scan of the aorta, however, must cover the whole chest and abdomen. To acquire the image in one breath-hold and reduce radiation exposure, the slice thickness is increased to 3 mm, with decreased through-plane resolution. Therefore, an examination optimized for the coronary arteries does not allow the aorta to be adequately assessed, and vice versa.

Influence of heart rate

A slower heart rate allows a longer diastolic window of minimal cardiac motion, improving the CT image quality. This is particularly important when examining small structures such as the coronary arteries. Because electron-beam CT has higher temporal resolution (ie, is faster), it is not as influenced by heart rate as is multidetector CT.

Modern multidetector CT scanners can correct for arrhythmias and a higher heart rate by using special acquisition techniques (segmented acquisition). However, heart-rate control with an intravenous or oral beta-blocker is preferable if the patient has no contraindications to it, such as significant asthma or heart failure.[12]

Beta-blockers are desirable to slow the heart during cardiac CT

REFORMATTING IMAGES AND INTERPRETING CT DATA

After the scan, is done, the supervising physician reviews it, a process that can take 5 to 30 minutes.

Cardiac CT: Slice it any way you want

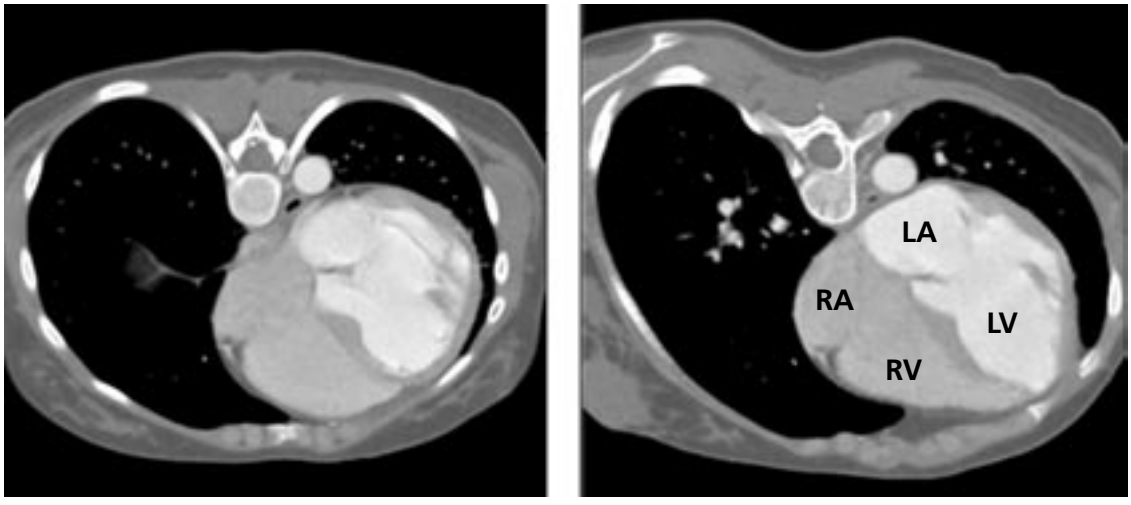

FIGURE 2. Left, transaxial CT images reveal the cardiac anatomy. However, the axes of the heart are oblique to the axial images, which are foreshortened as a result. Therefore, reconstruction of the volumetric data sets in oblique planes is performed, matching planes used in other imaging studies (**right**). LA = left atrium, LV = left ventricle, RA = right atrium, RV = right ventricle.

CT has a wide range of clinical cardiovascular indications

First, he or she looks at the individual transaxial images to assess overall anatomy. But because the axes of the heart and blood vessels are oblique to the axial images, additional data reconfiguration is almost always necessary (FIGURE 2).

Because the CT data are volumetric, the computer can reconstruct images in oblique planes, often matching the views used in echocardiography and angiography. Three-dimensional CT imaging has the advantage that it can be reformatted in an unlimited number of planes not just the planes specified when the data are acquired.

3-D reconstructions

Volume-rendered reconstruction of volumetric data gives semitransparent views of superficial and deep contours of structures, revealing their complex anatomy and spatial relationships. These reconstructions are always possible and do not need to be ordered separately. However, the quality depends on the protocol (see **Slice thickness and volume coverage,** above).

Dynamic or 4-D reconstruction

CT technology is starting to allow data from different phases of the cardiac cycle to be reconstructed into a cine loop to assess dynamic ventricular function and to calculate ejection fraction.

CLINICAL CARDIOVASCULAR INDICATIONS FOR CT

CT can be used for a number of cardiovascular indications, but whether another imaging test would be better in a particular situation should always be considered.

For example, for a patient with hypertension who presents to an emergency department with sharp chest pain radiating to the back, CT is the standard test to detect or exclude aortic dissection. The alternatives are transesophageal echocardiography and magnetic resonance imaging (MRI). Transesophageal echocardiography cannot visualize the abdominal aorta, and MRI does not detect intramural hematomas as well as CT does (see **Aortic disease,** below). Angiography is not a good option in this situation.

On the other hand, for a patient with acute midsternal chest pain and ST-segment elevations, emergency coronary angiography is the best test. CT would probably not provide all the information required and would delay urgent coronary revascularization if needed.

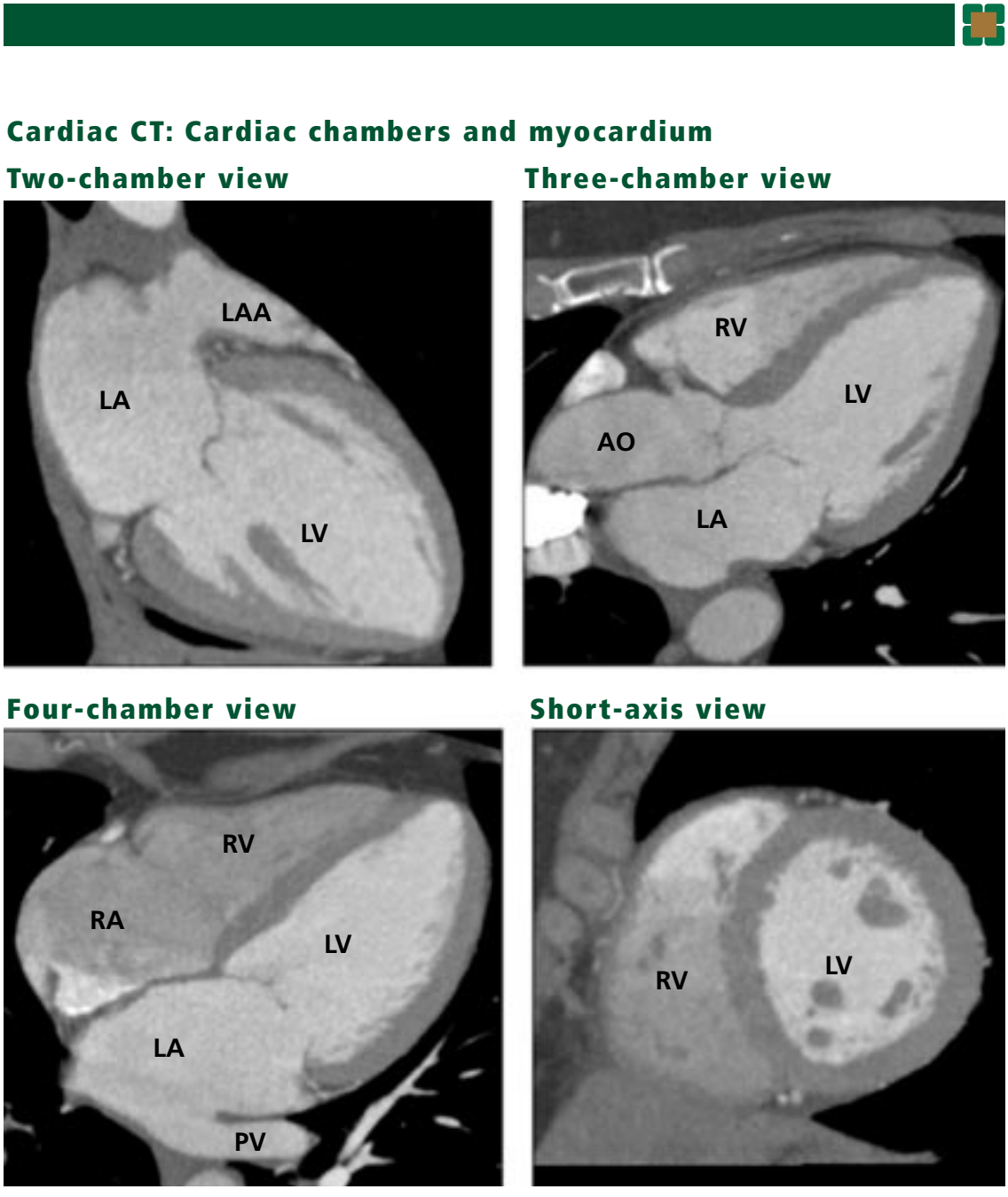

FIGURE 3. Contrast-enhanced CT provides detailed anatomic images of the cardiac chambers and the myocardium. LA = left atrium, LV = left ventricle, RA = right atrium, RV = right ventricle, LAA = left atrial appendage, AO = aorta, PV = pulmonary vein.

Cardiomyopathy: CT, echocardiography, and MRI

Contrast-enhanced CT provides detailed anatomic information about the cardiac chambers and the myocardium (FIGURE 3).[13,14]

In ischemic cardiomyopathy with areas of remote left ventricular myocardial infarction, CT typically shows:

- Focal ventricular wall thinning
- Fibrous or calcified replacement of myocardium (it is very sensitive, but the literature is very sparse as to the quantitative amount of fibrous replacement of muscle it can reliably demonstrate)
- Aneurysm formation with or without intracavitary thrombus.

In nonischemic cardiomyopathy, CT shows either:

- Global dilatation and myocardial thinning (dilated cardiomyopathy) or

CT coronary angiography

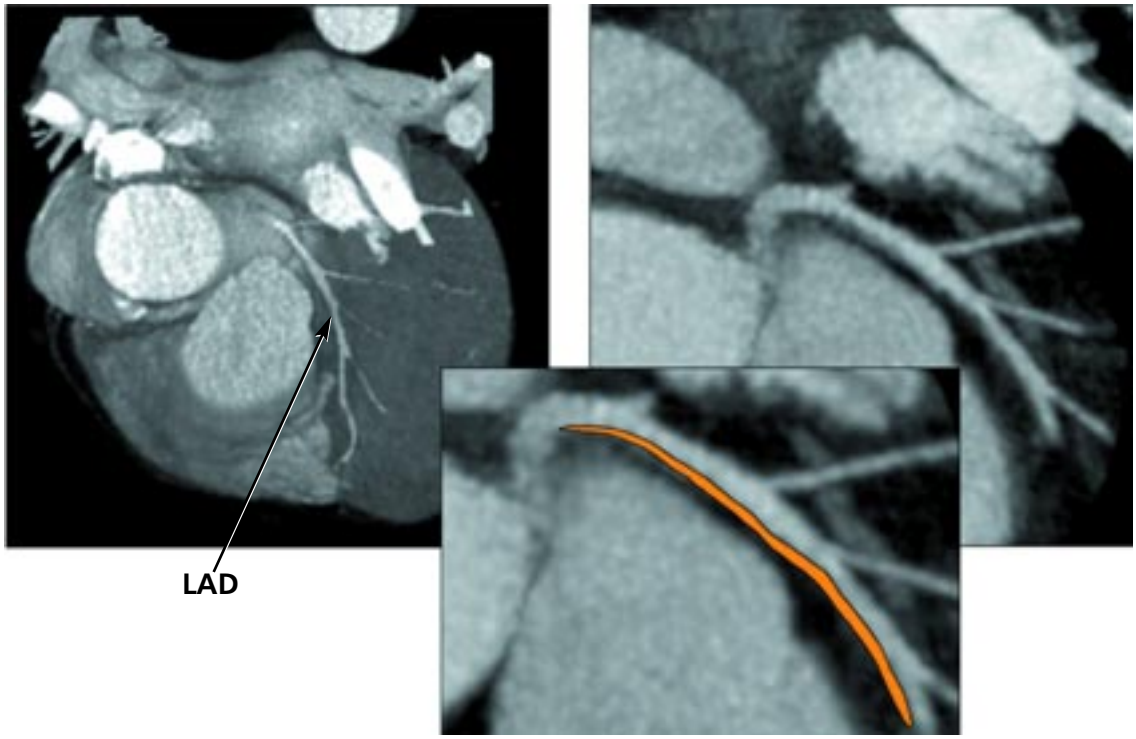

FIGURE 4. Modern CT allows a comprehensive assessment of coronary anatomy. Contrast-enhanced protocols differentiate between the lumen and vessel wall and allow angiographic assessment of both luminal stenosis and noncalcified coronary plaques. **Left,** a volume-rendered image of the heart. The left anterior descending coronary artery (LAD) and diagonal branches are seen. Nonillustrated (**right**) and illustrated (**center insert**) tomographic images of the LAD demonstrate noncalcified plaque in the vessel wall without significant luminal stenosis (orange area).

In suspected acute coronary syndromes, cardiac catheterization remains the test of choice

- Focal myocardial hypertrophy (hypertrophic obstructive cardiomyopathy).

In arrhythmogenic right ventricular dysplasia, CT shows a variable combination of the following:

- Global right ventricular cavity dilatation
- Focal right ventricular wall aneurysm formation
- Focal wall thinning with fibrous or fatty replacement of the right ventricular myocardium and possibly the left ventricular myocardium.

Ventricular function can be assessed with cardiac CT. Results of this technique that are now emerging will need to be validated by echocardiography and MRI.

Coronary artery stenosis: CT and x-ray angiography

CT can now be used to comprehensively evaluate the coronary arteries (FIGURE 4). Scans done without intravenous contrast can measure the calcium score, a measure of calcified plaque burden. Contrast-enhanced scans, which can differentiate between the lumen and vessel wall, allow one to assess luminal stenosis as well as noncalcified coronary plaques.

Coronary CT angiography is challenging, however, because the blood vessels are small, tortuous, and in rapid motion during the cardiac cycle.[9,15–22]

CT still doesn't have enough spatial and temporal resolution to show all the coronary segments clearly in all patients, although state-of-the-art systems that do 16 to 64 slices per rotation are better than earlier systems.[9]

Another limitation is due to plaque calcification. If the coronary arteries are calcified, a "blooming" effect can cause false-positive

results, overestimation of luminal stenosis, and difficulty in assessing adjacent noncalcified plaque structures.[20]

Uses of CT angiography:

- *To rule out severe proximal stenosis.* Consistent with the limitations noted above, CT has a high negative predictive value in excluding severe proximal stenosis, but a lower positive predictive value than x-ray angiography.[15–21] Therefore, CT is suitable for situations in which one must exclude significant disease; for example, in patients scheduled for noncardiac surgery. However, if obstructive coronary disease is likely to be present, conventional angiography remains the best method to detect and evaluate it.
- *To assess anomalous coronary arteries* and to determine their origins and their relationship to other cardiovascular structures.[23] For example, CT can detect an anomalous course between the aorta and the pulmonary artery that may need to be corrected surgically. It can also reveal myocardial bridges and dilated coronary arteries due to aneurysms. In our opinion, it is better than angiography in the late follow-up of Kawasaki disease.
- *To assess patency of surgical bypass grafts after revascularization.*[24,25] CT can also detect and help evaluate the severity of stenosis in venous aortocoronary grafts. However, internal mammary grafts, which are smaller, often are partially obscured by artifacts from metallic surgical clips. Whether CT is sufficient for screening for graft patency is currently a topic of research.

Because coronary stents are made of high-density metallic mesh, causing image artifact, coronary CT angiography cannot be confidently used to detect and grade in-stent restenosis. However, it is often possible to determine whether a stent is patent or occluded and to evaluate stenosis at the leading or trailing ends.[26]

Coronary plaque imaging: CT and intravascular ultrasonography

Atherosclerotic plaque accumulates in the vessel wall long before it can be detected by angiography.[27,28] Physicians can now use CT to evaluate overall plaque burden and plaque characteristics to help predict future cardiovascular risk.[29]

Measuring calcified plaque. Calcification in the coronary arteries is a reliable sign of chronic atherosclerotic changes. Many advanced stenotic lesions that cause chronic, stable angina are densely calcified. However, no predictive data are yet available comparing calcified vs noncalcified plaque as measured by CT.

CT without contrast is sensitive for detecting and quantifying coronary arterial calcification, a test known as calcium scoring.[6,30,31] It is usually done with electron-beam CT, but multidetector CT has recently emerged as an alternative.[32,33] Several calcium scoring algorithms are available, including Agatston scoring,[30] volume scoring,[34] and mass scoring.[35]

Coronary calcium scores correlate with the total atherosclerotic plaque burden (calcified and noncalcified plaque as assessed by histologic study), although they significantly underestimate it.[36,37] Overall Agatston scores also correlate with the risk of future coronary events,[38] although the events do not always occur at calcified sites. Serial CT studies over 1 to 2 years show that the calcium volume score declines after lipid-lowering therapy.[39,40]

As to whether calcium scoring adds useful information to what can be obtained by traditional multivariate risk assessment, the 2000 American College of Cardiology and American Heart Association consensus statement concluded that it may be justified for certain patients at intermediate risk.[41] This conclusion has been confirmed in recent studies.[42,43]

Coronary CT can exclude significant obstructive disease and assess atherosclerotic plaque

Detecting noncalcified, vulnerable plaque. Most acute coronary events begin when a mildly stenotic but vulnerable lesion ruptures or erodes.[44] These high-risk lesions are frequently noncalcified.[45,46] Often, angiographically normal segments are found to contain a surprisingly large amount of plaque when examined by intravascular ultrasonography or CT angiography.[47–49] Calcified plaque is always associated with additional noncalcified plaque. While the calcified plaque is a marker of risk, it may not show the site of future acute events. Plaque accumulation is associated with "outward remodeling": the vessel wall expands outward, but the lumen maintains its diameter.[50–53]

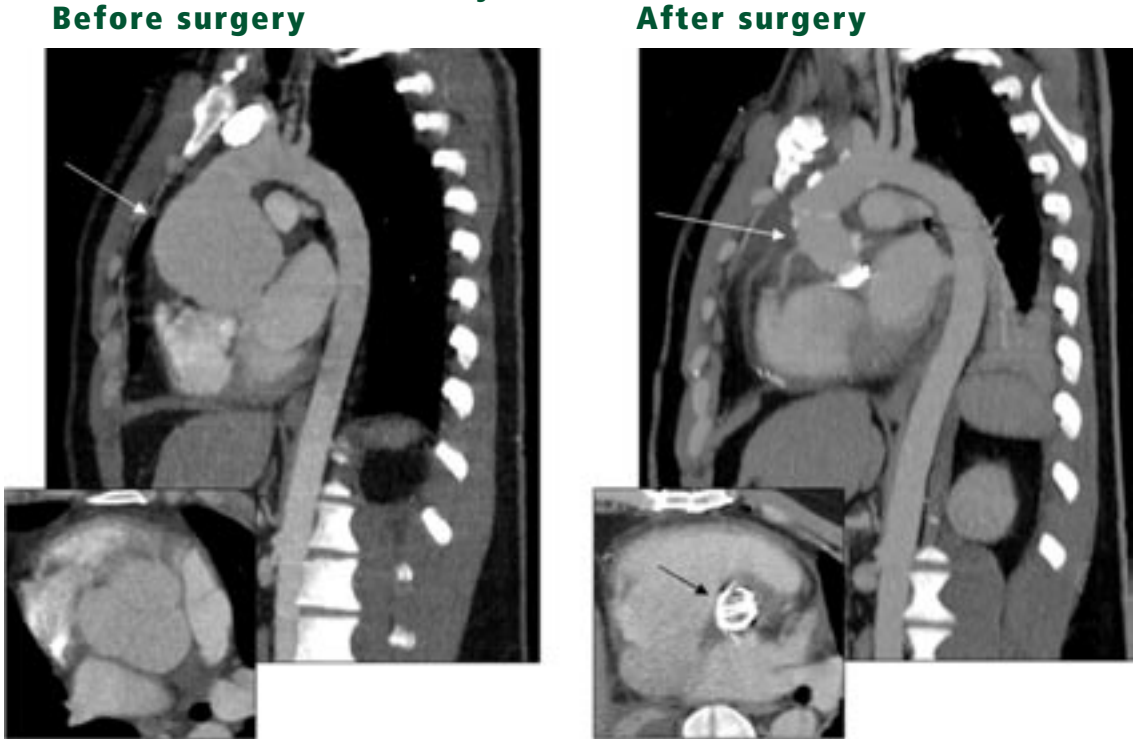

FIGURE 5. **Left,** preoperative images of a patient with Marfan syndrome and aneurysmal dilatation of the ascending aorta (arrow). **Right,** postoperative images show the surgical graft of the ascending aorta (white arrow) and the mechanical aortic valve prosthesis (black arrow). The smaller inset images are transaxial views at the level of the aortic valve.

In nongated studies, motion artifact can be mistaken for aortic root dissection

In recent CT studies,[47] noncalcified plaque has been further characterized by its Hounsfield number and compared with plaque characteristics described by intravascular ultrasonography. In theory, coronary risk might be better predicted by identifying vulnerable atherosclerotic lesions and the overall plaque burden than by measuring luminal stenosis.[54–56]

Pericardial disease: CT, echocardiography, and MRI

Contrast-enhanced CT provides detailed anatomic information about the pericardium.[57] Normal layers of fat on the epicardial surface of the heart and the outer surface of the pericardial sac provide natural contrast and permit the examiner to reliably identify the pericardium. CT is sensitive in identifying pericardial effusion over the left and right ventricle.

Inflammation of the pericardium in patients with pericarditis can be detected with contrast-enhanced CT, although the cause cannot be reliably differentiated.

Tamponade can be identified with CT by right atrial or ventricular collapse or by indirect signs such as enlarged hepatic veins.

Constrictive pericarditis is characterized on CT by a thickened pericardium with conical or tubular compression of the left and right ventricles. However, while a thickened and calcified pericardium is a reliable sign of pericardial disease, it does not prove that constrictive physiology is present. This is best assessed with echocardiography or MRI.

Cardiac masses: CT and MRI

Cardiac masses can be described on CT according to their size, density, and spatial relationship to adjacent structures. CT can also detect tumor neovascularity. However, tumors vary widely in their morphology, and their qualitative assessment with CT is limited. MRI may be needed as a complementary examination,[58] and a definitive diagnosis requires histologic confirmation after biopsy or surgical removal.

Valve stenosis and regurgitation: Echocardiography is best

Valvular function is best assessed by echocardiography. Although CT images can be reconstructed into a cine loop from different phases of the cardiac cycle, echocardiography offers real-time imaging of up to 30 phases of the same heartbeat, and assessment of functional significance by flow and Doppler gradients.

Aortic disease: CT, MRI, angiography, and Doppler ultrasonography

Many of the limitations of CT coronary imaging do not apply to the aorta, because it is large and (except for the aortic root and the proximal ascending aorta) moves only minimally.[59]

State-of-the-art CT scanners can take gated scans of the entire thoracic and abdominal aorta in one breath-hold. Contrast enhancement is needed for most indications, except to assess aortic calcification before bypass surgery. Gated scans are preferred for aortic imaging and are particularly important for imaging of the aortic root and ascending aorta. Motion artifact at the aortic root in nongated studies can be mistaken as a dissection.

The superior detail of modern CT images allows the physician to reliably diagnose intramural hematomas and communicating dissections when assessing a patient for suspected acute or chronic aortic disease.[60] It is the first test that should be ordered in a patient with suspected or proven aortic dissection, if no contraindication is present.

CT is often performed before and after cardiothoracic surgery (FIGURE 5). It provides important advantages to the examiner, who can simultaneously assess associated findings such as:

- Mediastinal hematoma or infection
- Pericardial and pleural effusion or hemorrhage
- Pulmonary embolus
- Pneumothorax.

3-D reconstructions of diseased aortic segments are used for precise quantitative assessment in clinical studies and special applications, including planning of endovascular repair with custom-made stent grafts.

A disadvantage of CT is its lack of functional data, making it impossible to assess aortic insufficiency complicating ascending aortic disease. In this situation, echocardiography or MRI should be considered. Transesophageal echocardiography is best for an unstable patient in the intensive care unit or operating room.

Pulmonary embolism: CT, V/Q scanning, and pulmonary angiography

CT with contrast is sensitive and specific for diagnosing a proximal pulmonary embolus.[61–64] It allows an examiner to directly visualize a thrombus and simultaneously assess lung parenchyma and cardiac chamber size (eg, to detect right ventricular enlargement). The scan can be extended through the abdomen and pelvis to identify the source of an embolus.[65]

However, CT does not allow one to assess lung ventilation or perfusion, as does nuclear scanning, or right ventricular function, as do echocardiography and MRI.[66] Nuclear scanning is also better for assessing chronic microemboli in the peripheral pulmonary arteries.

Imaging the pulmonary veins: CT, MRI, and angiography

Historically, the pulmonary veins were mostly imaged to assess abnormal venous return in patients with congenital syndromes.

Now, in specialized clinical centers, they are commonly imaged before and after percutaneous ablation procedures at the pulmonary vein ostia for treating chronic atrial fibrillation.[67] A preprocedure study is for anatomic guidance; postprocedure studies are performed to detect pulmonary vein stenosis (FIGURE 6). CT has the advantage that it can reveal inflammatory changes associated with the development of vein stenosis, including wall thickening at the vein ostia and mediastinal lymph node enlargement.

CT should be the first test ordered if aortic dissection is suspected

Peripheral artery disease: CT, ultrasonography, and MRI

CT can reliably identify and quantify luminal stenosis in peripheral arteries, which are large, less mobile, and often run a straight course.[68]

Multidetector CT protocols use a spiral examination mode with thin, overlapping images. It is important to carefully time the rapid contrast bolus injection for arterial enhancement.

CT of the pulmonary veins after percutaneous ablation for atrial fibrillation

Axial image **Two-chamber view** **Coronal image**

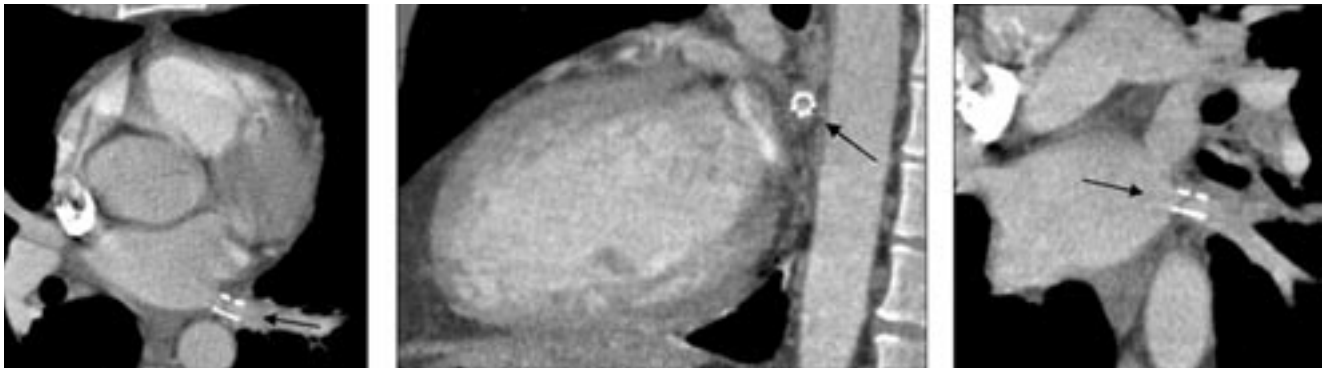

FIGURE 6. CT imaging of the pulmonary veins is now commonly performed before percutaneous ablation procedures at the pulmonary vein ostia to treat atrial fibrillation and after the procedure for diagnosis and surveillance of pulmonary vein stenosis. This figure shows images of a patient who developed severe pulmonary vein stenosis. A stent has been placed in the ostium of the left inferior pulmonary vein to treat the stenosis (arrow).

Neuroradiologists now use CT to simultaneously assess the carotid arteries, intracranial vessels, brain morphology, and brain perfusion.[69] CT is also increasingly being used to assess renal artery disease and atherosclerotic disease of the lower extremity arteries, often as a "roadmap" for subsequent angioplasty.[70–73]

A disadvantage of CT compared with ultrasonography and MRI, however, is the lack of flow information.

Congenital heart disease: CT, echocardiography, MRI, and angiography

Cardiac CT is emerging as a tool for assessing congenital heart disease. Echocardiography and standard angiography have well-recognized limitations in adults, including detecting sinus venosus atrial septal defect, anomalous pulmonary venous return, and patent ductus arteriosus.

Echocardiography remains best for initially examining children. However, if findings are unclear or need confirmation, CT is useful and can often be performed with only mild sedation because of the short acquisition time. Three-dimensional reconstructions often allow a comprehensive understanding of highly complex anatomy.[74]

MORE CLINICAL COMPARISONS NEEDED

Cardiac CT needs to be further compared with other imaging tests, including echocardiography, nuclear imaging, conventional angiography, and MRI.

The decision to use a particular imaging test should be based on evidence from clinical studies. This requires that cardiovascular imaging be integrated at clinical and academic levels, a trend already observed in leading medical centers in the United States and Europe.

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