Computed tomographic coronary angiography: experience at Baylor University Medical Center/Baylor Jack and Jane Hamilton Heart and Vascular Hospital

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Noninvasive cardiac computed tomographic imaging using multislice or electron beam technology has been shown to be highly specific and sensitive in diagnosing coronary heart disease. It is about a fifth of the cost of coronary angiography and is particularly well suited for evaluating patients with a low or low to moderate probability of having obstructive coronary atherosclerosis. In addition, it offers more information than calcium scoring: because of the intravenous contrast used, it temporarily increases the density of the lumen and allows differentiation of soft plaque from calcified plaque. The Baylor Hamilton Heart and Vascular Hospital now uses this modality to define coronary atherosclerosis in patients who would otherwise have needed invasive coronary angiography; several research protocols with the technique are also under way. Baylor has recently upgraded to the 64-slice scanner. It is expected that computed tomographic coronary angiography will replace a significant percentage of invasive cardiac catheterizations.

An estimated 1.46 million diagnostic cardiac catheterizations were performed in 2002. While catheterization is extremely safe, with an in-hospital mortality rate of <1%, there is still a potential risk (1). Overall, 20% to 27% of diagnostic catheterizations result in a diagnosis of "normal" or insignificant coronary disease, a percentage that is acceptable based on expert consensus (2). With an average charge to patients of over $10,000 per admission for cardiac catheterization, several billion dollars are spent yearly on invasive cardiac catheterizations that do not result in the diagnosis of significant coronary disease.

Until recently, there was no way around this issue. Sometimes patients present with symptoms consistent with coronary heart disease (CHD), and invasive catheterization is the test of choice. This situation may occur when stress testing is equivocal or when patients have such a high pretest probability of CHD that noninvasive stress testing is futile. Now, however, a noninvasive imaging modality is available that can fully define the coronary anatomy in a way that has only been available through invasive means.

Computed tomographic coronary angiography (CTCA) has emerged as a new modality to obtain structural information about the coronary arteries as well as the larger cardiac structures. CTCA allows us to fully define the presence of coronary atherosclerosis and may revolutionize the way in which cardiac disease is diagnosed in the future.

COMPUTED TOMOGRAPHY

Computed tomography (CT) has been used clinically since the 1970s. In its most basic form, it consists of a series of x-ray images, taken at various angles around a patient, and then reconstructed using a computer to create high-resolution axial images of the internal structures of the body. It has been one of the most instrumental imaging techniques in modern medicine. However, the constant motion of the heart has made it difficult for traditional CT to produce diagnostic images of the cardiac structures—and especially the coronary arteries, which are only a few millimeters in diameter.

ELECTRON BEAM CT AND MULTISLICE CT

Two technological advances in the last few years have revolutionized cardiac imaging: electron beam CT (EBCT) and multislice CT (MSCT).

EBCT technology, also known as "fast CT," uses an electron gun to create x-rays. Electrons are "bounced" off a tungsten metal ring surrounding the patient. The resulting x-rays are captured by detectors that surround the patient, and images are created. Since the electron gun and detector arrays have few moving parts, this type of technology allows for extremely fast image acquisition and temporal resolution. In order to image the heart, these scanners are triggered so that they image only when the heart is in diastole, the stillest portion of the cardiac cycle.

MSCT is also referred to as multidetector CT, helical CT, or spiral CT. A MSCT scanner consists of a rotating x-ray source, which spins around the patient at an extremely rapid rate. Directly opposite to the x-ray source is an array of x-ray detectors, which rotate at exactly the same rate. As the ring rotates around the patient, x-rays are emitted and images are acquired. The patient moves through the spinning detector on a gantry so that a series of axial slices is acquired in a helical manner. For cardiac CT imaging, the heart is imaged throughout the cardiac cycle, and then the images of the heart obtained in diastole are "stitched" together to form a continuous volume of data.

Current MSCT scanners tend to have slightly better spatial resolution than EBCT scanners, allowing for better imaging of smaller structures of the heart (e.g., coronary arteries and coronary plaque). EBCT scanners have typically had the advantage of better temporal resolution, which allows imaging of patients

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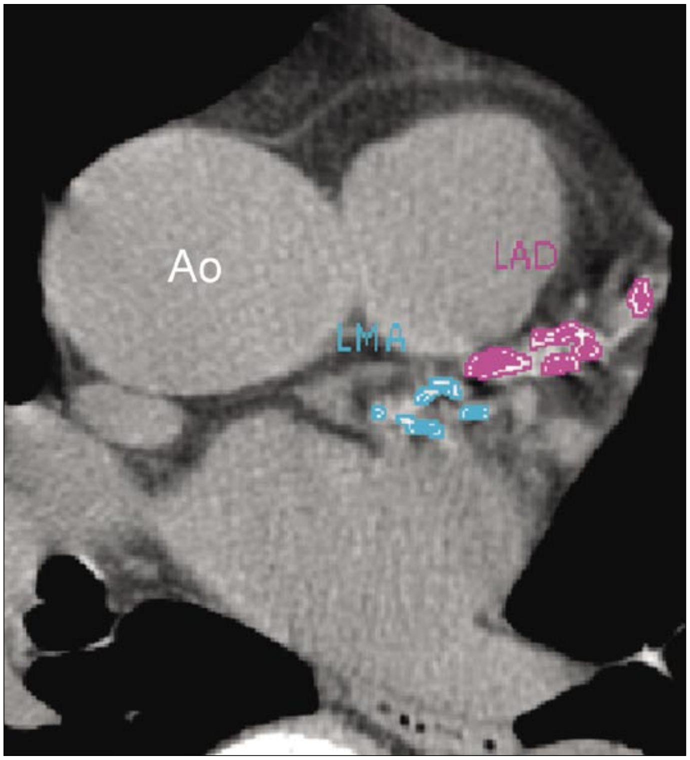

Figure 1. Noncontrast computed tomography (i.e., calcium score) of the left main artery (LMA) and left anterior descending artery (LAD). Areas of dense calcium (HU > 130) are highlighted. The amount of calcium demonstrated would place this patient in the 90th percentile compared with age- and sex-matched controls. Ao indicates aorta.

with faster heart rates. Newer generations of MSCT scanners have improved to the point where the limitations of temporal resolution have nearly been eliminated while the advantage of improved spatial resolution is retained. Furthermore, MSCT scanners are less expensive and are able to function in a wider array of imaging situations.

CALCIUM SCORING VS CT CORONARY ANGIOGRAPHY

There is a great deal of confusion about CTCA and calcium scoring. The basic difference between the two tests is that with CTCA, the patient receives contrast through a peripheral intravenous line.

The original idea behind calcium scoring dates to the 1960s, when an association was noted between coronary calcium on a chest radiograph and coronary syndromes. Calcification of coronary plaque, the so-called "hardening of the arteries," is now known to be the natural progression of all atherosclerosis.

Once CT technology became more widely available, it was found to be exquisitely sensitive for detecting even small amounts of calcium. EBCT technology, with its excellent temporal resolution, was a natural choice to image the moving heart (3). The idea was that if coronary calcium could be quantified, it could be used as both a marker of the presence of coronary atherosclerosis as well as an independent prognostic indicator for cardiovascular events. Calcium scores from thousands of patients were compared, and frequency tables were created for both men and women across many age ranges. The tables allow comparison of an individual with age-matched controls, giving an idea of the relative severity of plaque burden *(Figure 1)*.

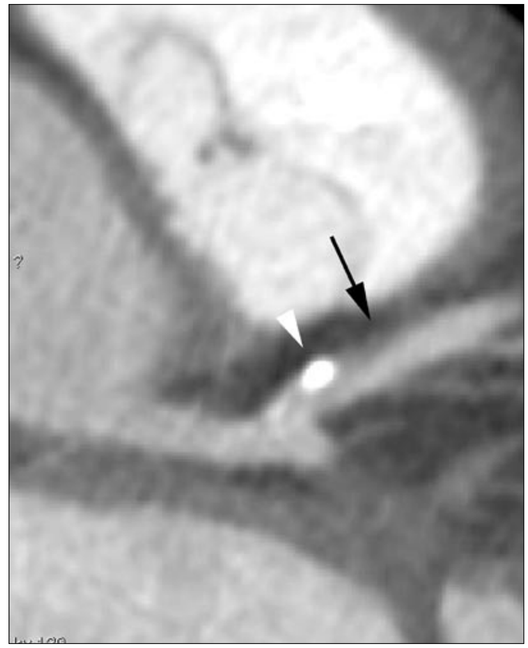

Figure 2. Plaque in the proximal left anterior descending artery: both calcified (white arrowhead) and soft (black arrow).

Although the amount of coronary calcification does not fully define the severity of coronary stenosis, calcification correlates highly with total plaque burden. In addition, the presence or absence of coronary calcium correlates with a high or low likelihood of future coronary events. Even though this was first described using EBCT technology, it is as useful when determined by MSCT (4, 5).

The problem with coronary calcium scoring is that while it defines the calcified portion of the plaque, it cannot adequately determine the amount of soft plaque in the coronary arteries. Thus, calcium scoring can underestimate the total amount of plaque in younger patients with high risk factors for CHD (e.g., diabetics) (6). In older patients, it becomes less useful in screening for the presence of CHD, since most patients over the age of 70 have coronary calcification regardless of degree of stenosis (7).

With CTCA, intravenous contrast is given. This temporarily increases the relative density of the lumen of the coronary artery and allows differentiation of soft plaque in the wall of the artery from calcified plaque (8, 9) *(Figure 2)*. In this way, the presence or absence of coronary plaque disease can be determined, and an accurate evaluation of the degree of stenosis can be made.

Fundamentally, there is little difference between the image acquisition for calcium scoring and CTCA. However, there are some important differences in their utility. Slice thickness for calcium scoring is rather large (around 2.5 to 3 mm), while the slice thickness is smaller for CTCA (0.5 to 0.75 mm), making the spatial resolution of CTCA much greater. This gives CTCA a greater ability to discriminate between much smaller structures of the heart such as coronary arteries and helps define the composition of atherosclerotic plaque (8–10) *(Table 1)*.

IMAGING A PATIENT

The basics of cardiac imaging are very similar whether EBCT or MSCT technology is used. Images are better acquired in patients who have relatively slow, regular heart rates. Typically, heart

Table 1. Comparison of calcium scoring, CT coronary angiography, and traditional invasive coronary angiography

	Calcium scoring	CT coronary angiography	Invasive coronary angiography
Hospital stay	1 hour (usually including time for paperwork)	1 hour (similar to the amount of time for a calcium score)	Usually at least 4 to 5 hours, including the time before the procedure and bed rest after the procedure
Procedure time	<5 minutes	<5 minutes	Roughly 1 hour including patient preparation time but not including recovery area stay
Level of invasiveness	No intravenous line	Intravenous line in antecubital fossa	Femoral/radial/brachial artery puncture
Cost	Around $500	Around $2000	$10,000 or more
Contrast given	None	Approximately 150 mL	Variable but can be as little as 20 mL
Functional evaluation	No	Yes, ejection fraction can be evaluated	Yes, ejection fraction can be evaluated
Covered by insurance	Rarely	Yes, for certain diagnoses	Yes, for most cardiac diagnoses
Scheduling	Can be requested and performed on the same day. A physician's order is not required.	Can be ordered and performed on the same day in most cases. A physician order is required.	Can be ordered and performed on the same day in most cases
Risk of procedure	Very small: risks are theoretical and related to small amount of radiation exposure	Very small: only risks are related to contrast-related complications	Very small; however, since the test is invasive, there is a chance of death, stroke, bleeding, infection, and contrast-related complications
Exclusionary criteria	• Irregular or fast heart rate • Inability to hold breath for 30 seconds • Inability to hold still or follow instructions	• Irregular or fast heart rate • Inability to hold breath for 30 seconds • Poor intravenous access • Renal insufficiency or contrast reactions	• Inability to give consent
Therapeutic options at the time of procedure	Diagnostic modality only	Diagnostic modality only	Can transition to a therapeutic modality immediately (i.e., angioplasty) if a significant stenosis is discovered
Availability	Available at some hospitals as well as stand-alone clinics	Available at some hospitals; this imaging modality is relatively new	Available at all tertiary care centers and a large percentage of community hospitals
Persons responsible for performing and interpreting the test	Technologists perform and score the test. The test is then reviewed by a staff physician.	Technologists perform the test. Nursing staff is usually necessary if beta-blockade is given. Physicians usually reconstruct and interpret the images.	Physicians perform and interpret the test in the cardiac catheterization lab. Nursing staff and catheter lab technologists are needed for the procedure.

rates in the 60s are required for the best images. Irregularities of the heart rate (e.g., premature atrial or ventricular contractions) during the scan can create artifacts that may render the images nondiagnostic. Therefore, patients who are in atrial fibrillation are not good candidates for this type of examination.

Sixteen-slice CT scanners are the most widely available for imaging of the cardiac and coronary structures. The resolution of these scanners is approximately 0.5 to 0.75 mm, which compares favorably to the 0.2-mm resolution seen with traditional cine angiography. The speed at which images of the heart are acquired depends on the size of the array and the amount of data to be scanned (the size of the heart and the surrounding structures). This amounts to a breath hold of approximately 25 seconds during the scan.

THE PATIENT EXPERIENCE

Typically, a scan takes about an hour, including paperwork and the insertion of an intravenous line (preferably in the antecubital fossa). Patients are prepared in the imaging department, where they disrobe from the waist up and put on a hospital gown, and electrocardiographic electrodes are placed on the chest to allow the scanner to "gate" the image acquisition.

The patient is placed on his or her back on the gantry, with feet through the scanner. This position tends to be more comfortable for patients who are claustrophobic. The patient's heart rate is evaluated, and the patient is asked to practice several breath holds. If the heart rate is too fast, a small dose of intravenous beta-blocker is given (typically metoprolol, in increments of 5 mg).

A scout image is taken of the heart, which allows for the localization of the coronary arteries and creation of a "roadmap" for the following scans. A test bolus of 20 mL of contrast is used to measure the transit time from the arm to the coronary arteries.

Right before the larger bolus of contrast is infused (~120 to 130 mL), the patient may be given a sublingual nitroglycerine tablet. This tends to make the coronary arteries slightly more "plump" during the scan and aids in image interpretation. The remainder of the contrast is then given as the patient holds his or her breath a final time. The entire series of images can be obtained in about 5 minutes.

Radiation exposure

The patient's overall radiation exposure with CTCA is equivalent to that received with a regular chest CT scan. This amounts to approximately 8 mSv, which is slightly more than a patient would expect to receive during a typical diagnostic coronary angiogram. CTCA is considered a low-risk procedure in that the expected lifetime possibility of developing a malignancy is increased minimally (11).

Image reconstruction

Although image acquisition takes only several minutes, a significant amount of time is required afterwards to reconstruct and interpret the data. In contrast, invasive coronary angiograms are interpreted in real time when they are performed.

Once the axial images are obtained, they are sent to the processing workstation, which is a separate computer system. The readers may then evaluate the images using several different modalities.

The simplest evaluation is performed using the raw axial data slices. This data set represents the unprocessed information acquired in the scanner. While these data are important to evaluate, it is sometimes difficult to use them to gain insight into the involvement of the plaque in branch arteries and to evaluate the course and relationship of the coronary arteries to the larger structures of the heart. For a more complete evaluation, standard reconstructions are performed using multiplanar reformat as well as three-dimensional reconstruction techniques *(Figure 3)*.

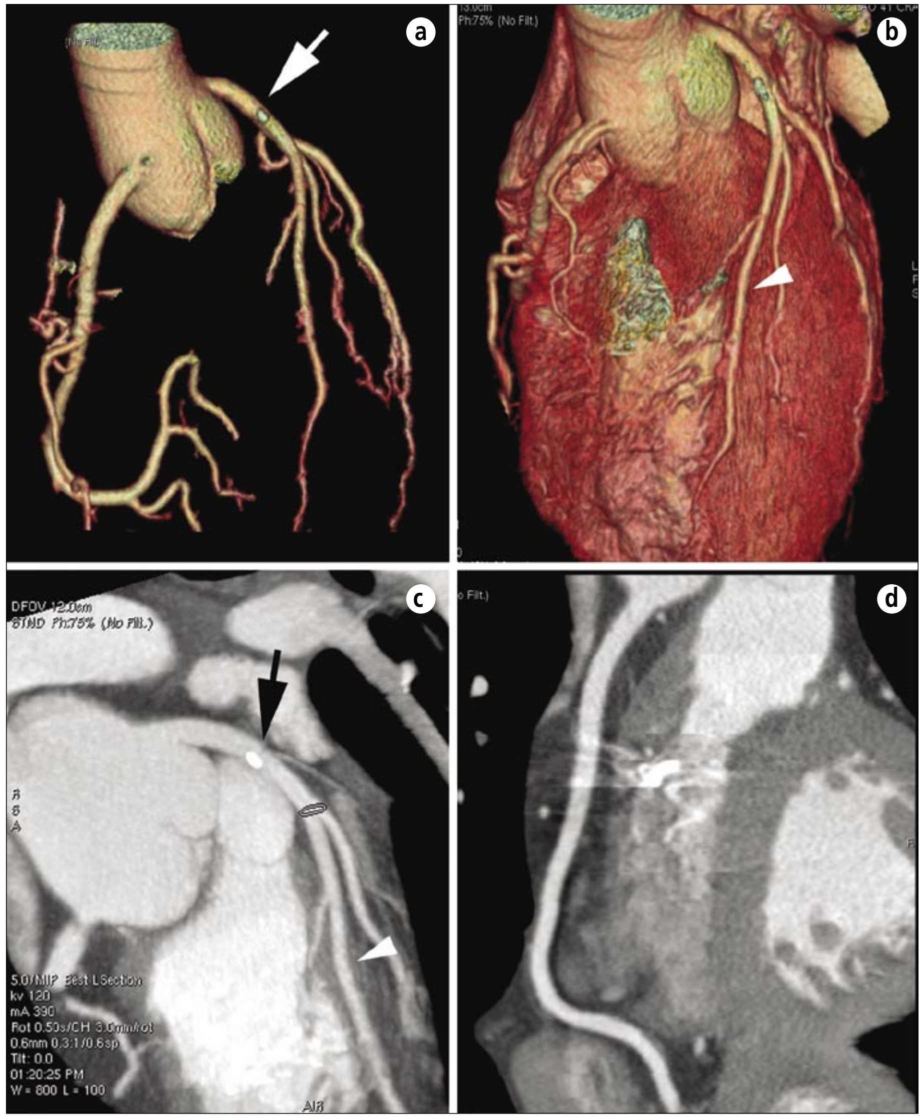

Figure 3. Multiple reconstructions of the same data set to visualize the coronary arteries. Three-dimensional reconstruction of the **(a)** coronary tree and **(b)** larger cardiac structures demonstrates the spatial relationships of the arteries as well as their relationship to the larger cardiac structures. Multiplanar reformat views of the **(c)** left anterior descending artery and **(d)** right coronary artery allow for more detailed evaluation of the coronary lumen. A small amount of calcific plaque (arrow) is seen, as well as a mild amount of soft plaque (arrowhead).

CURRENT DATA FOR CT CORONARY ANGIOGRAPHY

A growing body of literature supports the use of CTCA in a wide spectrum of patients and clinical situations. Typically, CTCA is helpful in evaluating patients with low and low to moderate probability for having obstructive coronary atherosclerosis.

CTCA is highly sensitive in identifying the presence of disease and in labeling plaque as stenotic. Even more importantly, this technology is highly specific; cardiac evaluations can be stopped when significant obstructive coronary disease is ruled out (10, 12–15).

CTCA is applicable to bypass graft disease as well as native coronary disease *(Figure 4)*. In many studies, the sensitivity and specificity are even higher in the evaluation of vein grafts as compared with evaluation of native disease (16–20). CTCA has even been used successfully in the evaluation of stents after coronary intervention (21). In our experience, it has served as a bridge between functional stress testing and invasive cardiac catheterization.

In patients with a very low probability of having obstructive coronary atherosclerosis (e.g., asymptomatic patients) but in whom there is significant reason for concern about premature coronary disease (e.g., severe family history of CHD), CTCA is the only noninvasive tool that can accurately determine the presence of both calcified and soft plaque. Although not universally accepted, it is a promising screening tool for the presence of CHD.

THE BAYLOR EXPERIENCE

When the MSCT scanner was first installed at Baylor Heart and Vascular Hospital, no one had any experience reading CT coronary angiograms. Although the cardiologists had a great deal of experience reading invasive angiograms, none had any significant experience reading CT scans. Likewise, radiologists who were expert in interpreting CT imaging had little practical experience with coronary anatomy. In order to overcome this

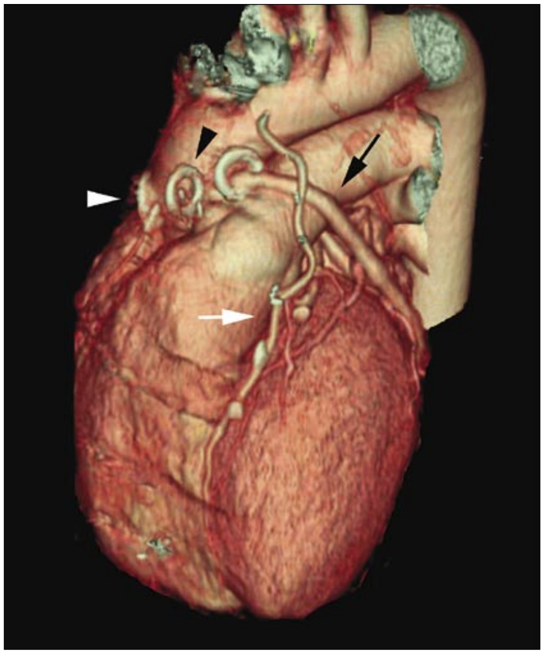

Figure 4. This patient presented with minimal symptoms of angina approximately 10 years after four-vessel coronary bypass. Three-dimensional reconstruction of the heart clearly demonstrates patent left internal mammary artery graft to left anterior descending coronary artery (white arrow), patent saphenous vein graft to circumflex system (black arrow), and occluded saphenous vein graft to diagonal artery (black arrowhead). The saphenous vein graft to the right coronary artery is also occluded (white arrowhead).

deficit, we brought together people from both disciplines and, over approximately 10 months' time, taught ourselves to read these examinations.

Our initial experience involved enrolling patients who were having invasive cardiac catheterizations in a research protocol. This research protocol involved CTCA as part of the precatheterization evaluation. The group of interested physician readers spent many hours learning the nuances of acquisition techniques, the workstation software, and the techniques of imaging. Then the interpretations of the noninvasive scans were compared with those of the invasive catheterizations. In this manner, we acquired practical experience in interpreting these scans, with good examples of both normal and diseased arteries.

Currently, all calcium scores as well as CT coronary angiograms are read by a small group of credentialed cardiologists and radiologists. It is important to realize that a large volume of information obtained at the time of the scan does not pertain to the heart or the coronary arteries. This information is reviewed by credentialed radiologists.

Although it is rare, we have identified malignancy or another noncardiac process in several patients at the time of cardiac evaluation.

Current clinical use at Baylor

Cardiac imaging using MSCT at Baylor Heart and Vascular Hospital includes the modalities discussed above. An active screening program uses calcium scoring and CTCA to define coronary atherosclerosis in patients who otherwise would have needed invasive coronary angiography *(Table 2)*. Patients who are found to have little or no coronary atherosclerosis do not need to have invasive coronary angiography and can simply concentrate on risk factor modifications. When significant plaque is found, patients are scheduled for invasive tests.

Table 2. Situations in which computed tomographic coronary angiography may be beneficial

- Early detection of coronary atherosclerosis in patients who are asymptomatic but who have strong risk factors for coronary heart disease.
- Patients with atypical chest pain and strong risk factors for coronary heart disease in whom negative stress test results would not be satisfactory.
- Patients with low or moderate probability of coronary heart disease whose functional stress test results were equivocal.
- Patients who have indications for invasive angiography but who are reluctant to have the procedure performed unless absolutely necessary.

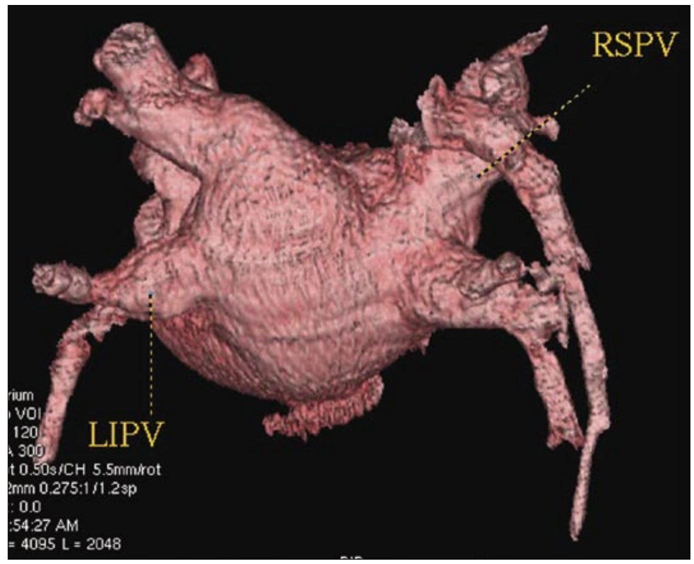

Figure 5. Three-dimensional reconstruction of the left atrium and pulmonary veins. There are four normal pulmonary veins, two superior and two inferior veins, with normal branch distribution and separate ostiae. RSPV indicates right superior pulmonary vein; LIPV, left inferior pulmonary vein.

Besides coronary imaging, MSCT imaging of the heart has other uses. In many patients undergoing atrial fibrillation ablations, the size and relative location of the pulmonary veins must be evaluated. It is also important to evaluate patients for the presence of anomalous pulmonary venous return. CT cardiac imaging can provide this type of evaluation before atrial fibrillation ablation procedures *(Figure 5)*.

Research protocols using MSCT

Currently, several active research protocols involve MSCT cardiac imaging.

The physicians' CTCA study is currently enrolling healthy physicians with risk factors for coronary atherosclerosis but no known CHD. Participants receive a CT coronary angiogram and blood work to assess the presence of coronary plaque and the overall risk of cardiovascular events. Participants are then followed clinically over several years. If significant plaque is seen on the original scan, a second scan is offered 18 months later to follow the progression of the disease.

Patients who are diagnosed with atrial septal defects, and in whom closure is planned, are receiving cardiac CT scans to evaluate their right ventricular volumes. It is well known that right ventricular volumes, expanded due to increased blood flow, reduce quickly once the shunt is corrected. This reduction has been demonstrated by echocardiography, and CT cardiac imaging may be an even more exact technique for evaluation and follow-up.

Enrollment is to start in a small pilot project to compare invasive cardiac catheterization with CTCA. Cardiac catheterization, the "gold standard" for evaluation of coronary arteries, can sometimes miss small plaque. Intravascular ultrasound has demonstrated the limitations of invasive angiography, and CTCA may also improve on this modality.

FUTURE DIRECTION FOR CARDIAC CT

In the next several months, the 64-slice scanners will begin to be used on a much larger clinical scale. These scanners, which have much larger arrays of x-ray detectors, will be able to image the heart more quickly. Baylor upgraded to the 64-slice scanner in spring 2005.

Although these newer scanners will have the same spatial resolution as our current technology, they will capture a complete scan of the heart in approximately 5 seconds. Thus, a much larger percentage of scans will be free of artifact due to patient movement, heart rate variability, and inability to maintain breath hold.

With these faster scanners, the so-called "triple rule out" for chest pain (e.g., myocardial infarction, pulmonary embolus, and aortic dissection) may become a reality for emergency departments.

CONCLUSION

Cardiac CT imaging using multislice technology has quickly become a valuable tool to diagnose cardiac disease. CTCA may replace a significant percentage of invasive cardiac catheterizations. As a result, the health care system would reap significant cost reductions. CTCA would increase the safety and satisfaction of a large number of patients, who would not have to have an invasive procedure. Finally, it would give physicians more flexibility in discerning the presence of cardiac disease and allow them to make better decisions for their patients.

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