Cardiac imaging techniques: which, when, and why

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SUMMARY Although a variety of cardiac imaging methods are available, their effective use requires knowledge of their underlying principles, clinical applications, potential pitfalls, and expense. This review outlines, for the generalist, the basics of echocardiography, nuclear imaging, and magnetic resonance imaging (MRI) and provides insight into their appropriate use.

KEY POINTS Two-dimensional echocardiography provides a highly detailed image of cardiac structure and function, and is particularly useful in assessing global and regional left ventricular contraction, valvular morphology, and congenital abnormalities.

Doppler echocardiography allows evaluation of the velocity, direction, and turbulence of blood flow. Transesophageal echocardiography provides extremely high-resolution images, particularly of structures around the cardiac base.

Echocardiography during cardiac stress testing can demonstrate regional wall-motion abnormalities that evolve under increasing metabolic demands on the heart. Nuclear imaging techniques are useful in delineating normally perfused tissue from tissue that is either underperfused or nonviable.

Positron-emission tomography can image the heart with very great accuracy. Magnetic resonance imaging provides highly detailed, three-dimensional images.

MORE THAN ANY other field of medicine, cardiovascular medicine demands high-fidelity dynamic imaging. A variety of imaging methods are available, but their effective use requires knowledge of their underlying principles, clinical applications, potential pitfalls, and expense. This review for the generalist outlines the basics of echocardiography, nuclear imaging, and magnetic resonance imaging (MRI) and provides insight into their appropriate use.

Table 1 summarizes the overall utility of various imaging techniques in a variety of cardiac abnormalities. Often, a combination of imaging studies gives much more complete information than any one technique alone.

ECHOCARDIOGRAPHY

In echocardiography, an array of piezoelectric crystals transmits ultrasonic waves (2 to 10 MHz) into the thorax. Within the body, sound propagates at approximately 1540 m/second, and the predictable relationship between depth of a structure from the

TABLE 1
CHARACTERISTICS OF VARIOUS IMAGING TECHNIQUES IN CARDIAC ABNORMALITIES

Condition or consideration	Echo	TEE	Thal	PET	RVG	MRI	Cath
Usefulness							
Global function	++++	++	+	0	+++	++++	+++
Regional function	++++	++	0	0	++	++++	++
Stenosis	++++	++	0	0	0	++	+++
Regurgitation	+++	++++[¶]	0	0	++	+++	+++
Diastolic function	++	+++	0	0	++	+++	+++
Myocardial perfusion	+++[‡]	++	+++	++++	+	++	++
Myocardial viability	+++[§]	++	+++	++++	0	++	0
Coronary anatomy	+	+	0	0	0	+	++++
Endocarditis	+++	++++	0	0	0	+	++
Congenital defects	++++	+++	0	0	+	++++	++++
Aortic disease	++	++++	0	0	+	++++	+++
Pericardial disease	++	+++	0	0	+	++++	+++
Expense	+	++	++	+++	+	+++	++++
Invasiveness	N	++	N	N	N	N	+++
Legend 0 = not useful + = somewhat ++ = moderate +++ = very ++++ = most N = noninvasive							

Echo, echocardiography
TEE, transesophageal echocardiography
Thal, thallium imaging
PET, positron-emission tomography

RVG, radionuclide ventriculography
MRI, magnetic resonance imaging
Cath, cardiac catheterization

[¶]Especially mitral regurgitation
[‡]Stress
[§]Dobutamine

transducer and the time delay before the echo returns to the receiver allows reconstruction of the echocardiographic signal.

Standard echocardiography

M-mode, the simplest form of echocardiography, uses a single beam of ultrasound and displays with high temporal and spatial resolution structures along a single "ice pick" view of the heart. This technique can accurately measure chamber size and thickness, from which one can estimate left ventricular mass. It has also been used to measure the end-systolic dimension of the left ventricle in patients who have regurgitation of the mitral or aortic valve, information that is valuable in their follow-up and in helping decide the optimal time for surgical intervention. Although still used for these purposes, M-mode echocardiography has largely been superseded by two-dimensional echocardiography.

Two-dimensional echocardiography (also called sector scanning) displays a moving-picture cross-section of the heart at approximately 30 frames per second. This technique provides a highly detailed image of cardiac structure and function, and is particularly useful in assessing global and regional left ventricular contraction, valvular morphology, and congenital abnormalities.[1] Placing the transducer in different positions (generally at the left sternal border, at the apex, below the ribs, and at the left sternal notch) allows one to view the heart in multiple planes. If air in lung tissue interposes between the transducer and the heart (a condition more common in patients with chronic obstructive pulmonary disease), the images are less clear.

Doppler echocardiography

Integral to any complete echocardiographic examination is an evaluation of the velocity and direction of blood flow, using Doppler echocardiography. This technique exploits the predictable change in frequency of a sound wave when it is reflected by a moving object—or a group of objects, such as blood cells. In general, the shift in frequency varies directly with both the velocity of blood and the frequency of the transducer. The three principal Doppler methods are continuous-wave, pulsed-wave, and color-flow mapping.[2,3]

Continuous-wave Doppler echocardiography uses a continuous signal, with or without visual guidance from two-dimensional sector scanning, to examine regions of high-velocity flow such as steno-

tic or regurgitant valves. Because the signal is continuously emitted and analyzed, this technique can measure any velocity of blood. However, it does not tell the location along the scan line where a particular velocity has arisen. This limitation is generally not serious, since this method is usually reserved for high-velocity structures, which occur in only a few areas of the heart.

Knowing the velocity (v) of blood through a stenotic orifice, one can calculate the decrease in pressure across the stenosis (ΔP) by using the Bernoulli equation: $\Delta P = 4v^2$. For example, a 5-m/second jet in aortic stenosis would predict a 100-mm Hg transvalvular gradient.[4,5] Besides accurately measuring valvular stenosis, other uses are to detect high-velocity flow through ventricular septal defects and to measure the rate of rise in isovolumic pressure (dP/dt) in the left ventricle by analyzing the increase in mitral regurgitant velocity during systole.

Pulsed-wave Doppler echocardiography, unlike continuous-wave Doppler, examines only a single region of the heart at a time. The transducer emits a pulse of ultrasound along a single scan line, waits until echoes from the chosen depth have returned, and only then emits a second pulse. This technique allows one to measure blood flow at specific points within the heart, but has the limitation of being able to send and receive only a limited number of pulses, typically 5000 to 10 000 per second. This relatively low number of pulses limits the maximal velocity that this method can measure to around 100 cm/second, adequate for most normal flow in the heart, but not for the high-velocity stenotic flow for which continuous-wave Doppler is best suited.

Pulsed-wave Doppler echocardiography can also be used to calculate cardiac output. If blood velocity can be measured through a circular structure of known cross-sectional area (such as the left ventricular outflow tract), then multiplying velocity times area yields the instantaneous volume flow rate, and integrating this over a cardiac cycle yields stroke volume, from which cardiac output may be obtained by multiplying by heart rate. Further, knowing the stroke volumes through the aortic and mitral valves, one can calculate the amount of mitral or aortic regurgitation.[6,7] Similarly, information about the right- and left-sided flows can be used to assess the severity of an atrial septal defect, ventricular septal defect, or patent ductus arteriosus.

Pulsed-wave Doppler echocardiography is also very helpful in evaluating left ventricular diastolic filling. Measuring blood flow through the tips of the mitral leaflets distinguishes separate waves that represent early relaxation and atrial contraction. Typical patterns of delayed relaxation and restrictive cardiomyopathy have been described with this method.[8–12] This method can be further enhanced by combining it with filling patterns from the pulmonary veins.

Color flow mapping is similar to the pulsed Doppler method, except that it superimposes color-coded information about blood velocity on the two-dimensional sector scan. Typically, blood moving towards the transducer is coded in red, blood moving away from the transducer is blue, and areas of high turbulence are green. Color Doppler is particularly useful for visualizing the spatial extent of regurgitant jets. In this way, it provides a very rapid, semiquantitative assessment of the severity of valvular regurgitation.[13–15] The direction and shape of the regurgitant jet are also important clues to the cause of the regurgitation. Color flow imaging is also highly useful for detecting intracardiac shunts, such as atrial or ventricular septal defects.

Transesophageal echocardiography

Transesophageal echocardiography, a relatively new imaging technology, provides extremely high-resolution images, particularly of structures around the cardiac base.[16] With this method, the patient first receives topical pharyngeal anesthesia and light systemic sedation; then a probe, typically the size of a gastroscope, is introduced into the esophagus. The full range of echocardiographic and Doppler methods are available, using a variety of imaging planes. This test is particularly useful for assessing bacterial endocarditis and deep tissue infections of the heart,[17] in searching for the source of an embolus (particularly to rule out thrombi within the left atrial appendage, a small patent foramen ovale, or atrial septal aneurysms), in evaluating prosthetic valve dysfunction (particularly to locate perivalvular leaks around the mitral valve), in assessing aortic aneurysms and dissections (*Figure 1*),[18] and for determining the precise etiology of native valvular regurgitation.

Transesophageal echocardiography is also very helpful in critically ill patients in whom transthoracic echocardiography fails to yield diagnostic images, such as patients with lung disease or connected to ventilators. It is being used more often during cardiac surgery, especially mitral valve repair.[19]
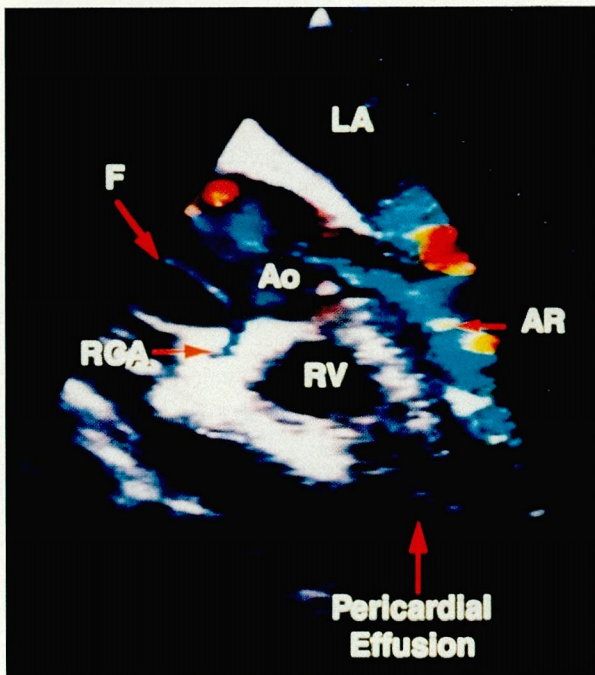
FIGURE 1. Transesophageal echocardiogram of the left ventricle and aorta (Ao) of a patient with type 1 aortic dissection. A dissection flap (F) arises just distal to the right coronary artery (RCA), which is patent. Significant aortic regurgitation (AR) is present, as is a pericardial effusion.

Stress echocardiography

Echocardiography during cardiac stress from either exercise or infusions of dobutamine, arbutamine, dipyridamole, or adenosine can demonstrate regional wall-motion abnormalities that evolve under increasing metabolic demands on the heart. These techniques have shown sensitivity and specificity in detecting coronary artery disease similar to that of thallium 201 imaging.[20] They also give important information about changes in valvular regurgitation and intracardiac pressure gradients. Dobutamine echocardiography appears useful as a screening test for ruling out significant coronary disease in high-risk candidates for noncardiac surgery such as vascular reconstruction or renal transplantation.

NUCLEAR IMAGING

In nuclear imaging, a radioactive substance is delivered to a specific body structure such as the myocardium, blood pool, or thyroid. As the substance undergoes radioactive decay it emits gamma rays, which external cameras detect to provide structural and functional information about the organ under investigation. Because of scattering, attenuation, and the random direction in which gamma rays are emitted, nuclear imaging provides lower-resolution images than does conventional radiography, with important trade-offs between spatial resolution and detector sensitivity. Nuclear medicine can improve resolution by using only those photons that have passed through a pinhole. Because most photons are excluded, it takes longer to get an image, decreasing sensitivity.

Thallium imaging

Assessment of myocardial perfusion with thallium 201 is the most commonly used cardiac nuclear imaging technique.[21] Adequately perfused myocardial tissue avidly takes up thallium, an analog of potassium. Injected into the bloodstream during maximal exercise, thallium delineates normally perfused tissue from tissue that is either underperfused or nonviable. When repeat imaging is performed several hours later, underperfused but viable tissue will have taken up the thallium, demonstrating a reversible defect, whereas truly infarcted tissue will remain unmarked by the thallium. Thus, by taking two images several hours apart, one can delineate the location, extent, and severity of myocardial ischemia and identify regions of the heart that are completely infarcted. Occasionally, delayed scanning or reinjection of thallium can demonstrate areas of reversible ischemia that appeared to be scar on the reperfusion images obtained several hours after exercise.[22]

Patients unable to exercise, such as those with peripheral vascular disease, can undergo pharmacological stress testing with either dipyridamole or adenosine.[23,24] Dipyridamole-thallium testing is used to screen patients before vascular surgery, as positive test results indicate an increased risk of perioperative cardiac events. In this setting the test appears most useful in patients found to be at intermediate risk on clinical grounds.[25]

Because of its expense thallium imaging should be reserved for patients with specific indications, generally patients at intermediate risk for coronary artery disease (*Table 2*).

SPECT imaging

Higher-resolution images of the myocardium can be obtained with single-photon emission computed

tomography (SPECT), which uses the filtered back-projection technique of computed tomography to generate images of specific slices of the heart in a variety of orientations. Quantitative computer-assisted analysis also helps reduce interobserver and intraobserver variability in interpreting thallium images.

TABLE 2
SPECIFIC INDICATIONS FOR STRESS THALLIUM IMAGING

Typical anginal history, but electrocardiographic abnormalities that would render exercise electrocardiography nondiagnostic (left ventricular hypertrophy, left bundle branch block, digoxin therapy)

Atypical or nonanginal chest pain, but a positive exercise test (more common in women)

Highly typical anginal history, but a negative exercise electrocardiogram

After myocardial revascularization, or with known multivessel disease if specific localization of the ischemic territory is necessary to plan appropriate therapy

Before vascular surgery

New perfusion agents

Thallium 201 emits a relatively low-energy photon, making high-resolution imaging difficult. Two new perfusion agents have recently become available that use technetium 99m, which emits a much higher-energy photon than does thallium. This allows a signal-to-noise ratio up to 10 times higher than with thallium at a comparable dose.

Technetium 99m sestamibi is taken up by normally perfused myocardium, but does not redistribute over time. That is, its distribution is determined by blood flow at initial injection and does not change despite subsequent alteration in blood flow. One disadvantage of this agent is that two separate injections are therefore required to obtain exercise and resting images. An important advantage, however, is that one can inject it during chest pain or threatened myocardial infarction, start emergency thrombolysis or perform percutaneous transluminal coronary angioplasty, and then, later, obtain the images, which will still outline the ischemic territory.[26] Technetium 99m teboroxime, in contrast, redistributes very rapidly and can distinguish between ischemic and infarcted tissue with a single injection.

Positron-emission tomography

One of the most exciting areas in nuclear imaging is positron-emission tomography (PET scanning). This technique uses radionuclides that emit a positron (a positively charged electron) when they decay. Because a positron is an antimatter particle, when it collides with an adjacent electron, the two completely annihilate each other, producing two 511-keV photons directed in opposite directions from each other. The combination of extremely high-energy photons and the occurrence of two simultaneous photon events exactly opposite each other allows PET scanning to image the heart with extreme accuracy—a spatial resolution of about 5 mm.

Rubidium 82 functions similarly to thallium and provides a high-resolution image of myocardial perfusion. A number of agents are available for assessing myocardial metabolism and have proven useful in distinguishing infarcted from hibernating myocardial tissue.[27,28] Fluorine 18 deoxyglucose (FDG), an analog of glucose, is avidly taken up in regions of the myocardium that are ischemic but maintaining viability by using the anaerobic glucose pathway. In a region of the heart with poor mechanical function, evidence of hypoperfusion by rubidium scanning combined with positive uptake of FDG is strong evidence that the myocardium is hibernating and may benefit from a revascularization procedure (*Figure 2*). Images can also be obtained with radioactive carbon-labeled free fatty acids, which identify regions of the heart with normal aerobic metabolism.

The extremely short half-life of a number of these positron-emitting agents (seconds to a few minutes) usually limits their use to medical centers that have cyclotrons on site. Rubidium 82, however, can be obtained continuously from a generator source and thus is most suited for general PET imaging.

Radionuclide ventriculography

Global and regional ventricular function can be assessed with radionuclide ventriculography. With this technique a blood sample is withdrawn, labeled with technetium 99m, and then reinjected.[29] This label stays within the blood pool and outlines the cardiac chambers. Radionuclide ventriculography can measure the ejection fraction and, to some extent, valvular regurgitation and shunts. As a technique to assess ventricular function, radionuclide ventriculography has largely been superseded by echocardiography, which provides more detailed
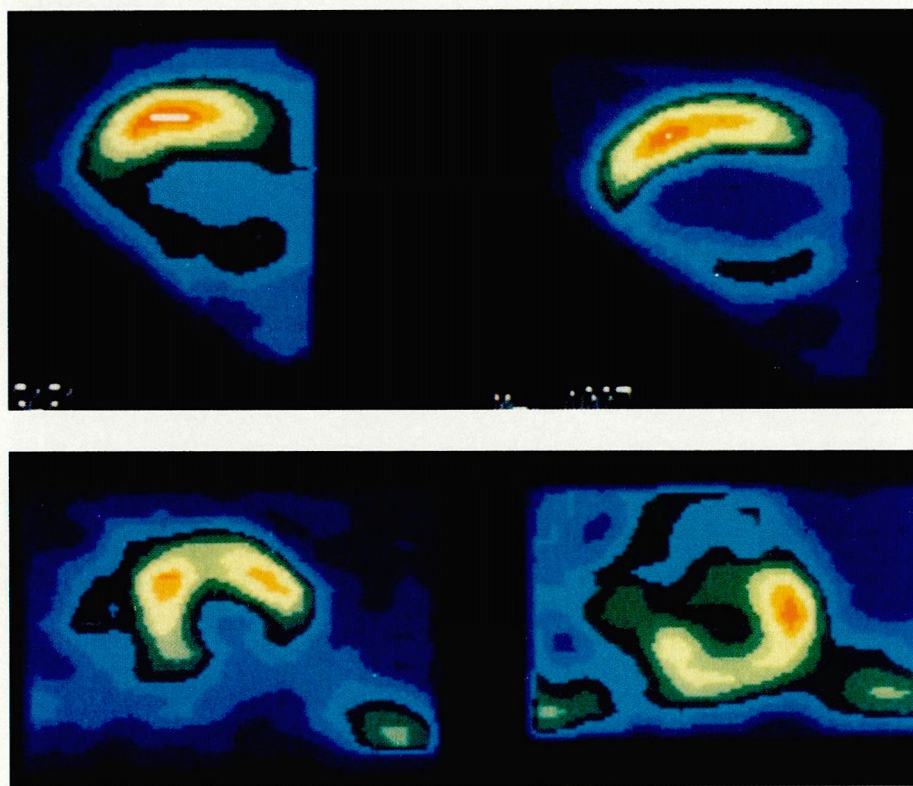
FIGURE 2. Top, rubidium and fluorine 18 deoxyglucose (FDG) positron-emission tomographic images (left and right, respectively) of a patient with scar in the inferior wall without evidence of hibernation. There is poor tracer uptake by both techniques inferiorly. Bottom, hibernating myocardium inferiorly. There is no uptake of tracer in the inferior wall on the rubidium image (left) but avid uptake of tracer in this area on the FDG image (right).

quency encodings in two and three dimensions allow complete reconstruction of the heart.[30,31]

MRI is useful in displaying the three-dimensional spatial orientation of complex cardiac structures, such as congenital malformations and aortic dissections.[32] In addition, dynamic structural imaging (eg, cine MRI) permits physiological evaluation of segmental or global ventricular function or valvular function and allows volumetric analysis to be performed without relying on geometric assumptions. For example, left ventricular volume can be determined without assuming whether the ventricle is spherical or elliptical. The technique of dynamic phase mapping allows one to measure the velocity of blood within the heart and vessels, providing another method of measuring cardiac or valvular function. Highly detailed displays of regional myocardial mechanics can also be obtained by labeling regions of the myocardial wall with magnetic saturation bands in a grid pattern and following the evolution of this grid throughout the cardiac cycle.

Because of the time required and the expense of these studies, cardiac MRI is usually reserved for cases that require three-dimensional spatial orientation of structures or in which other imaging techniques have failed to provide a diagnosis. For instance, MRI is useful in planning pericardiectomies in patients with constrictive pericarditis and in planning septal myectomies in patients with hypertrophic cardiomyopathy (*Figure 3*). Its clear utility in acute aortic dissection has been partly superseded by that of transesophageal echocardiography, as these patients are often too unstable to undergo MRI, in which the strong magnetic field and narrow confines of the device limit monitoring of the patient.

anatomic and functional information about specific ventricular walls and all the valves.

MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI) provides highly detailed, three-dimensional reconstructions of the heart and great vessels. It exploits the magnetic properties of atomic nuclei, most commonly the proton of hydrogen. When these protons are lined up in a strong magnetic field and then perturbed by a radio-frequency energy pulse, they precess or "ring" at specific frequencies reflecting their environment, usually at millions of cycles per second. Varying the strength of the magnetic field across the patient's body causes protons in different regions to ring at different frequencies, allowing localization of structures, much the way one can locate where on a piano keyboard a certain note is struck by listening to the frequency of the note. Similar fre-

CARDIAC CATHETERIZATION

Cardiac catheterization is mainly reserved for precisely delineating the coronary anatomy, and, increasingly, for performing interventions such as angioplasty, atherectomy, and stent placement.[33,34] With improvements in Doppler echocardiography, there is rarely a need to perform cardiac catheterization solely to diagnose or measure valvular stenosis or regurgitation. Cardiac catheterization to define coronary artery disease should be reserved for specific high-risk patient subgroups, including patients with angina following myocardial infarction, patients with unstable angina, patients with low-threshold angina or extensive ischemic zones on thallium imaging, and patients with unacceptable symptoms despite medical therapy.

Intracoronary ultrasonography

A very exciting area under development is imaging of the coronary arteries from within, with high-frequency (20 to 40 MHZ) ultrasound. Though largely confined to research studies at present, this technique shows promise for guiding the selection of interventional devices, assessing the results of such procedures, detecting plaques at high risk of rupturing and producing unstable angina (even if they are angiographically unimpressive), and assessing the natural history of coronary artery disease.[35] *Figure 4* illustrates a concentric atheroma in a patient with angiographically normal coronary arteries.
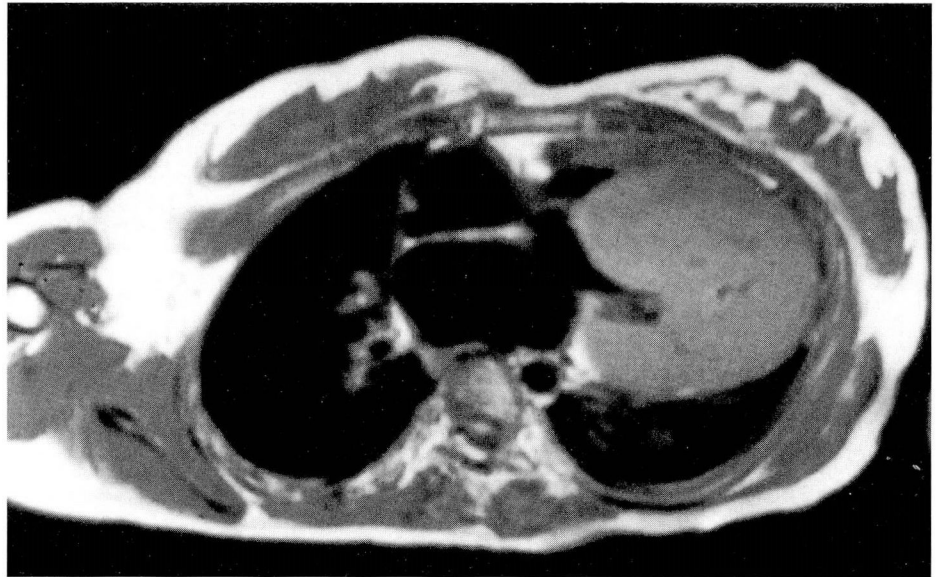

FIGURE 3. Magnetic resonance image of a patient with hypertrophic cardiomyopathy, illustrating the severe left ventricular hypertrophy and the small left ventricular cavity typically seen in this condition.
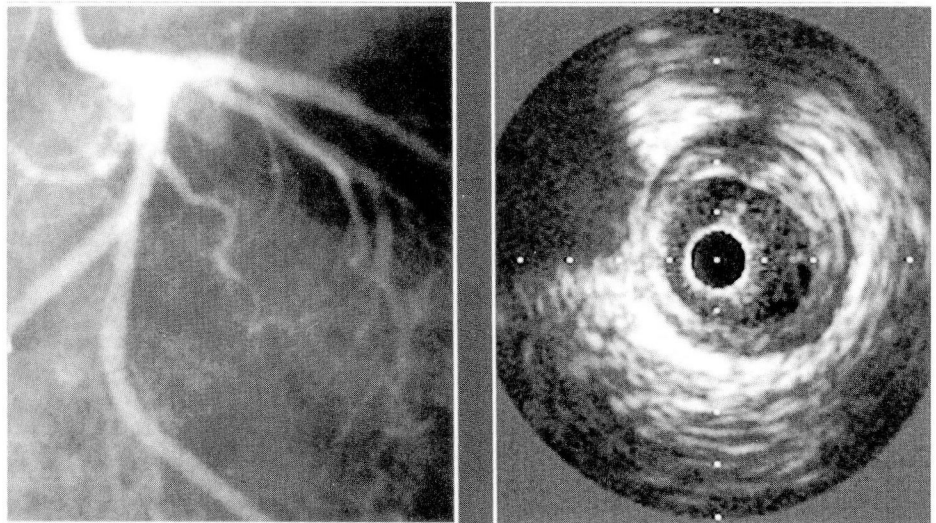

FIGURE 4. Intravascular ultrasonogram of a patient with angiographically normal (left) coronary blood vessels. A concentric atheroma is seen on the ultrasound image (right). The black area in the center of the ultrasound image is signal void due to the catheter. *Courtesy of E. Murat Tuzcu, MD and Steven E. Nissen, MD.*

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