Noninvasive Determination of Coronary Artery Bypass Graft Patency by Cine Magnetic Resonance Imaging

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Cine magnetic resonance imaging (MRI) is a gradient-recalled, retrospectively gated, fast-scan technique that depicts laminar flowing blood as bright signal and has been proposed as a useful method for determination of coronary artery bypass graft (CABG) patency. Therefore, we performed a blinded prospective study to assess the value of cine MRI determination of CABG patency in 20 patients with 45 CABG proximal anastomoses who were undergoing repeat angiography. Ten normal subjects served as controls to define normal intrathoracic vascular patterns. There were 21 left anterior descending (LAD) grafts, of which four were left internal mammary (LIMA), 12 left circumflex (Cx), and 12 right coronary (RCA) grafts. After localizing spin-echo coronal images were obtained, multiple axial multislice interleaved cine MRI acquisitions, each consisting of two to four 5–10-mm-thick slices at eight to 24 frames per cardiac cycle, were obtained from the superior main pulmonary artery to the inferior left ventricle. Each acquisition took 5–8 minutes with a subsequent 5–10 minutes of computer image reconstruction. Total study time per patient was 50–75 minutes. Known to cine MRI interpreters were the original coronary CABG insertions but not the angiographic findings. A graft was called patent if a bright graft flow signal, not corresponding to a normal vessel, was identified on multiple frames at multiple levels abutting the great vessels or epicardial surface of the heart. Angiographically, there were 33 patent grafts, of which 29 were identified as patent by cine MRI (sensitivity, 88%). All false-negatives were encountered in the first seven patients studied, when fewer image plane sections, lower frame rates, and less sophisticated software were used. Patent grafts containing stenoses (n=4) or supplying stenotic distal coronary vessels (n=6) gave flow signal qualitatively similar to that of normal grafts supplying normal distal vessels. The 12 angiographically occluded grafts were correctly classified as totally occluded by cine MRI (specificity, 100%), for an overall accuracy of 91%. There were no differences in results between LAD, RCA, Cx, saphenous vein, and LIMA grafts. Cine MRI requires no radiation or contrast injection and, unlike spin-echo MRI, identifies patent CABGs as a positive flow signal on multiple slices at multiple points in the cardiac cycle. Thus, it minimizes the risk of false-positives. Further, it is possible to derive blood flow velocity and may be possible to directly image graft stenoses with tomographic, angiographic projection, or volume acquisition gradient echo methods in the future. Thus, cine MRI is a potentially valuable method for assessment of CABG patency. (Circulation 1989;80:1595–1602)

Cine magnetic resonance imaging (MRI) is a noninvasive technique that is well suited for imaging normal vascular and intracardiac blood flow as well as flow disturbances associated with cardiac disease. The method can sample the entire thoracic volume, and there is no need for contrast administration. Cine MRI depicts laminar blood flow dynamically as bright signal, while turbulent or high-velocity flow leads to signal voids that are readily distinguishable from laminar flow.1,2


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Studies by us and others have described the potential usefulness of cine MRI in detecting and gauging the severity of mitral and aortic insufficiency, for evaluating left ventricular function, and for detecting coronary bypass graft patency. We report a prospective blinded study of detection of patent coronary artery bypass grafts (CABGs) with cine MRI.

Methods
The study population consisted of 20 patients (age, 49–76 years old) who had undergone CABG surgery and subsequent bypass graft angiography. MRI scanning was performed at a median interval of 25 days after angiography (range, 1–368 days). Three additional patients were recruited but had inadequate studies because of claustrophobia (one patient) and poor image quality (two patients). One additional patient was imaged but had many metallic clips placed in series all along the length of his bypass grafts, producing artefacts that precluded detection of flow signal and was not further analyzed. Ten normal subjects served as known controls to establish normal intrathoracic vascular patterns by cine MRI.

There were a total of 45 bypass grafts: 33 grafts to the left coronary artery, of which 29 were saphenous vein and four were internal mammary artery grafts; and 12 saphenous vein grafts to the right coronary artery. Of the 45 grafts, eight were sequential to two coronary artery branches. However, for the purpose of this study, only proximal anastomoses were counted as grafts. Of the left coronary artery grafts, 21 were primarily to the left anterior descending artery and 12 to the circumflex branches.

MRI Imaging Technique
The imaging protocol, performed on a 1.5 T (General Electric, Signa) MRI system, began with localizing electrocardiographically (ECG) gated coronal spin-echo images of the thorax with a repetition time (TR) equal to the cardiac cycle length and an echo time (TE) of 20 msec. The image acquisition matrix was 128×256 pixels (reconstructed with zero filling for display as 256×256), and the field of view ranged from 32 to 40 cm. Maximal pixel size was, therefore, 1.56×3.12 mm, or 4.9 mm². Cine MRI was performed with a gradient refocused fast-scan technique with retrospective ECG synchronization of a rapid shallow-flip angle pulse sequence. In this study, a 30° flip angle, TR of 22 msec, and TE of 12.5 msec were used. Two or three separate acquisitions, each consisting of two to four axial slices (5 mm to 1 cm thick with interslice distances of 2.5 mm to 2 cm) encompassed the region from the superior aspect of the pulmonary artery to the midleft ventricle. Two or four signal averages were used; the resulting frame rate varied from eight to 24 per cardiac cycle.

Total time per cine acquisition consisted of 2–3 minutes for prescan, 3–5 minutes for imaging, and 5–10 minutes for image reconstruction. Total time per study was typically 50–75 minutes.

Angiography
Bypass graft angiography was performed in all patients by the Judkins or Sones technique. Information about the number, location, and type of bypass graft (e.g., saphenous, mammary, sequential) was obtained from the operative report in all patients and all proximal anastomoses were visualized.

Image Interpretation
Angiographic images were interpreted by the staff of the Cardiac Catheterization Laboratory, who were blinded to cine MRI findings. Data obtained from the angiographic analyses included whether grafts were patent or totally occluded; if patent, the presence and percent narrowing at any graft stenoses; and if patent, whether stenosis or occlusion was present in the distal native coronary artery supplied by the graft.

Cine images were interpreted from hard copy by two observers. They were aware of the original graft anatomy as described in the operative note but not the results of bypass graft angiography. A graft was defined as patent if a bright blood flow signal, indicating laminar flow, was identified at multiple points in the cardiac cycle on images at multiple slice levels abutting the epicardial surface of the left or right heart, ascending aorta, or pulmonary artery and did not correspond in size or location to a normal vessel. Cine loop review of multiple images on the Signa display was performed to supplement still-frame interpretation. If not identified by its blood-flow signal, a graft was classified as totally occluded. No attempt was made to determine whether graft stenoses or stenosis or occlusion of native coronary artery branches was present from the cine MRI images because the slice orientation, pixel size, and slice thickness available were judged unsuitable for such purposes.

Results
Figure 1 shows the typical locations of saphenous vein bypass grafts in patients. Right coronary grafts have the most caudal proximal anastomoses and run relatively vertically over the right atrium and atrioventricular groove and around the acute margin of the heart. Left anterior descending vein grafts insert above right grafts and extend caudally and gradually leftward, draping over the right ventricular outflow tract or proximal main pulmonary artery before reaching the anteroseptal territory. Left circumflex saphenous vein grafts have the most cephalad aortic anastomoses and course leftward and posteriorly to circumflex marginal branches. In contrast, left internal mammary artery grafts extend caudally and posteriorly from the chest wall toward the left anterior descending territory.

Figure 2, Panels A–D are representative images from the study of a patient with a patent saphenous
saphenous vein graft en route to a left circumflex marginal branch passing to the left of the left atrium. Figure 5 depicts an internal mammary artery graft to the left anterior descending coronary artery. The right internal mammary artery is in its normal anatomic location, but the flow signal is obscured by artefact from the sternal sutures.

Table 1 compares results of contrast angiography and cine MRI scanning. Overall, 33 of 45 grafts were patent by angiography. Among the 33 patent grafts, there were three stenotic saphenous vein grafts (two to the right and one to the left coronary artery) and one left internal mammary graft supplied by a stenotic left subclavian artery. Graft stenosis severity ranged from less than 50% to more than 90%. There were also six grafts supplying stenotic distal vessels, with distal vessel stenosis severity ranging from 50% to 90%. Among the 12 occluded grafts, there were 10 left saphenous vein grafts, two left anterior descending and eight circumflex, and two right saphenous vein grafts.

Cine MRI visualized 29 of 33 patent grafts, including 16 of 19 left anterior descending, four of four circumflex, and nine of 10 right coronary grafts. Thus, the overall sensitivity of the technique was 88%. All four patent grafts with stenoses in or proximal to the graft, and all six patent grafts supplying stenotic distal vessels were identified as patent. Patent grafts that were not visualized were all encountered in the first seven patients, who were studied with fewer image plane sections at lower frame rates. Thereafter, no patent grafts were missed. While sternal wire sutures and metallic graft clips often produced local artefacts on a given slice, patent grafts were identifiable by evaluation of multiple slices, with the exception of one patient excluded from analysis (see "Methods") in whom clips had been applied throughout the length of the grafts. The 12 grafts found to be occluded by angiography had no demonstrable flow signal by cine MRI. Thus, there were no false-positives.

In the course of the study, we sought to define an optimal protocol for detecting patent CABGs. We concluded that the optimal imaging protocol consisted of three interleaved acquisitions, each consisting of three 1-cm-thick slices with 2-cm separations, resulting in a 9-cm-thick contiguous axial volume imaged. The highest slice was placed at the superior margin of the main pulmonary artery and typically demonstrated graft clips and graft anastomoses to the ascending aorta. The lowest slice typically included the inferior portion of the left ventricular cavity.

**Discussion**

This study confirms the feasibility of imaging patent coronary artery bypass grafts with cine MRI, as described in preliminary reports from our own laboratory and from White and coworkers. Bypass graft size (generally accepted as 0.4–1 cm in diameter) permits successful cross-sectional imaging despite par-
FIGURE 2. Top left panel: Saphenous vein graft to left anterior descending (LAD) branch of the left coronary artery (CABG) is shown draped over the right ventricular outflow tract (RVOT) in an axial diastolic cine magnetic resonance image. The ascending and descending aorta (AO), superior vena cava (SVC) and left atrium (LA) are seen, and all show bright signal derived from protons in laminar flowing blood, as does the CABG. Top right panel: Two centimeters lower, the LAD CABG is displayed over the RVOT. The more proximal ascending aorta, descending aorta, left atrium, and superior vena cava are also seen. Bottom left panel: Two centimeters caudal to top right, the LAD CABG overlies the proximal RVOT. The aortic valve, caudal left atrium and right interior pulmonary vein, descending aorta, and superior vena cava are also seen. Bottom right panel: Further caudally, the LAD CABG and the native LAD (right lower aspect of flow signal) are in contact in the anteroseptal region.

Partial volume effects because the cross-sectional area of the graft is fourfold to 10-fold larger than the pixel size used (see “Methods”). Patent bypass grafts demonstrate a positive flow signal, as would be predicted from the in vitro work of Fram et al., who investigated the relation between cine MRI signal properties and flow velocity in vitro at various repetition times. At short repetition times and small flip angles, positive signal was observed by Fram et al with flow velocities as low as 10–20 cm/sec and as high as 80–90 cm/sec. Our own comparisons of cine MRI signal to Doppler ultrasound velocimetry have confirmed these findings in vivo in humans. It is likely that the sensitivity of cine MRI to flow over such a wide velocity range accounts for the ability to detect patency of stenotic grafts and grafts supplying stenotic distal vessels.
Recent work has demonstrated the ability of both cine computed tomography and spin-echo MRI to noninvasively assess the patency of CABGs. However, cine MRI appears to have several inherent advantages over other tomographic imaging methods for determining bypass graft patency. Unlike cine computed tomography, neither contrast injection nor radiographic exposure is required. Furthermore, with recent software advances, good-quality coronal, sagittal and oblique imaging can be performed readily without patient repositioning.

With respect to spin-echo MRI, the sensitivity of cine MRI for detecting patent CABGs in this series was 88%, comparable to spin-echo MRI results obtained by White and coworkers, Gomes et al, Rubenstein et al, and Frija et al. A recent study by White and coworkers using cine MRI in 10 patients also detected 93% of patent grafts. While spin echo has been reported to have low specificity for graft potency, we encountered no false-positives in 12 occluded grafts, whereas White et al had two of 14 false-positives with cine MRI (specificity, 88%). Spin-echo imaging of bypass grafts is typically done at a single point in the cardiac cycle and depends on the fact that flow can lead to signal voids within vascular structures, but such signal voids may also be produced by artefact or air-filled tissue. Moreover, using spin-echo MRI, slow flow in a vessel can result in intraluminal signal that could be hard to distinguish from soft-tissue signal unless multiecho acquisitions are used. In contrast, cine MRI detected flow signal in stenotic grafts, a
FIGURE 4. The midportion of a saphenous vein CABG to a circumflex marginal branch of the left coronary artery (CX CABG) is seen lateral to the left atrium at a slice level that also shows the ascending aorta, superior vena cava, and distal right ventricular outflow tract.

graft supplied by a stenotic subclavian artery, and grafts supplying stenotic distal coronary arteries in the present study. Thus, there are three principal theoretic advantages to the use of cine MRI in evaluating bypass graft patency: 1) flow, and therefore patency, is denoted by a positive signal, 2) flow signal is qualitatively present over the entire range of flow velocities that might be encountered in

FIGURE 5. A left internal mammary artery bypass graft (LIMA) to the left anterior descending branch of the left coronary artery is seen just below the anterior chest wall on a systolic frame at the level of the aortic valve, right ventricular outflow tract, superior vena cava, and left atrium. On lower slices, the graft could be followed toward the left anterior descending branch.
patent grafts, and 3) images are obtained throughout the cardiac cycle and can be viewed in cine loop format to display pulsatile flow. A complete study generates up to 148 static images. In contrast, a typical multiplane single-phase spin-echo study encompassing the entire heart produces 10–16 images, each at a different time and in a different slice through the heart.

Technically adequate studies in this initial series were obtained in 20 out of 24 patients, an experience similar to that of investigators using spin-echo methods. Study duration was relatively long. However, software enhancements and protocol modifications have since made it possible to reduce the amount of time spent by the patient in the scanner. Currently, a coronal localizing series and three consecutive acquisitions of three 1-cm-thick slices with interslice distances of 2 cm interleaved to image 9 contiguous cm of thoracic volume can be accomplished in less than 35 minutes. Computer reconstruction for the cine MRI study, performed after removal of the patient from the scanner, takes 10 minutes.

In our experience, bypass graft signal appears to be more readily detected with 1-cm rather than 5-mm slice thickness and with 2-cm interslice separation on each acquisition. The thicker slice thickness improves the signal-to-noise ratio of the images, and the interslice separation helps ensure relatively strong signal from blood flowing into the slices being imaged. Though there is the potential for increased partial volume averaging with greater slice thickness,17 this did not appear to present difficulties for the assessment of qualitative graft patency. The signal voids produced by sternal wire sutures and graft clips have not precluded successful imaging, with the exception of one patient with a multitude of graft clips along the full length of the grafts, because the grafts are tracked through multiple slices. Confusion of bypass grafts with native coronaries (particularly the right coronary) at the ventricular level has been commented on by Rubinstein et al.17 This was not a problem in the present study because patent grafts were tracked from levels cephalad to the left ventricle.

The methods used in the present study have many important limitations, which are potentially soluble with further technologic development. Thus, we were able to distinguish reliably between totally occluded and patent grafts, but stenotic and normal grafts as well as grafts supplying unobstructed and stenotic coronary arteries all gave qualitatively similar results. Given the relatively large pixel sizes and thick slice thicknesses used, we did not attempt to identify graft stenoses visually. Several alternative approaches might be taken to permit identification of stenoses in grafts or distal coronary arteries supplied by grafts. Given the rapid rate of technologic advancement in the field, it is likely that one or more will come to fruition in the near future.

First, Longmore and colleagues18 have demonstrated that velocity of flow in vessels as small as native coronary arteries can be determined from phase information inherent in the flow signal obtained using gradient refocused methods like cine MRI, and that velocity changes produced by a coronary stenosis can be detected. Thus, it should be possible to detect the functional effects of graft or distal vessel stenosis without relying on morphologic imaging of stenoses. Such an approach could be used in conjunction with administration of agents such as dipyridamole to stress coronary functional reserve.

Second, it may be possible in the future to directly image bypass grafts and even native coronary stenoses with conventional tomographic cine MRI. Compound oblique imaging planes, which have become available, would be required rather than the axial sections used in the present study to permit short-axis imaging of vessels. In addition, slice thickness would need to be reduced to minimize partial volume effects. At present, slice thickness can be reduced to 3 mm. Thinner slices could be obtained, but adequate flow signal with thinner slices requires more signal averaging. The combination of more signal averaging and more thin slices imaged would greatly prolong image acquisition time with current methods. However, so-called echo-planar MRI, a technique providing image acquisitions in 60 msec or less, can be used for gradient echo imaging and could greatly shorten acquisition time for such an approach.20 Pixel size would also have to be reduced substantially. Even for saphenous vein grafts, pixel size of less than 1 mm² would be required rather than the 4.9 mm² used in the present study to permit accurate assessment of graft stenoses. This could be accomplished with more powerful gradient amplifiers and smaller field of view if phase-wrap artefacts are suppressed. Finally, marked reduction of artefact on cine MRI images, using improved velocity and acceleration compensation methods, would be required for successful imaging of stenoses.

Two other approaches to direct imaging of bypass graft stenoses and, potentially, coronary artery stenoses also show promise. First, volume acquisition with subsequent generation of slice images in any plane of interest is feasible.21 A major obstacle at present is the long duration of image acquisition and reconstruction if appropriate voxel sizes and ECG gating are used. Second, MRI angiography, using gradient refocused acquisitions and projection

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Sensitivity, 88%; specificity, 100%.
rather than tomographic techniques is already applicable to extrathoracic vascular beds, with very short acquisition times. Application of similar techniques in the thorax will require improved strategies for dealing with respiratory motion.

The clinical role of cine MRI determination of bypass graft patency remains to be clarified. Studies with ultrafast computed tomography have defined bypass graft patency status with high sensitivity and specificity. Furthermore, ultrafast computed tomography can potentially measure graft flow and myocardial perfusion. Cine MRI is at an earlier stage of development, and additional large clinical series are needed to clarify its role, even in detection of graft occlusion. Further technical developments will be required to permit extraction of velocity information or permit direct imaging of graft stenoses or diseased native coronary arteries. However, technologic progress is being made at a rapid rate. Given the fact that cine MRI requires neither radiation nor intravenous contrast injection, further development appears warranted.

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KEY WORDS • magnetic resonance imaging • surgery, coronary artery bypass
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