Phase-Sensitive Inversion-Recovery MR Imaging in the Detection of Myocardial Infarction[1]

Armin M. Huber, MD
Stefan O. Schoenberg, MD
Carmel Hayes, PhD
Benedikt Spannagl, MD
Markus G. Engelmann, MD
Wolfgang M. Franz, MD
Maximilian F. Reiser, MD

Published online
10.1148/radiol.2373041483
Radiology 2005; 237:854–860

Abbreviations:
CNR = contrast-to-noise ratio
FISP = fast imaging with steady-state precession
FLASH = fast low-angle shot
IR = inversion recovery
TI = inversion time

PURPOSE: To prospectively determine if phase-sensitive inversion-recovery (IR) magnetic resonance (MR) imaging eliminates the need to find the precise inversion time (TI) to null the signal of normal myocardium to achieve high contrast between infarcted and normal myocardium.

MATERIALS AND METHODS: Informed consent was obtained from each patient for this prospective MR imaging research study, which was approved by the institutional review board. Twenty patients (16 men; four women; mean age, 56 years ± 12.3) who experienced Q-wave myocardial infarction 2 weeks earlier were examined with a 1.5-T MR system 10 minutes after administration of 0.1 mmol per kilogram of body weight gadobenate dimeglumine. To determine the optimal TI, a TI scout sequence was used. A segmented two-dimensional IR turbo fast low-angle shot (FLASH) sequence and a segmented two-dimensional IR true fast imaging with steady-state precession (FISP) sequence that produces both phase-sensitive and magnitude-reconstructed images were used at TI values of 200–600 msec (TI values were varied in 100-msec steps) and at optimal TI (mean value, 330 msec). Contrast-to-noise ratios (CNRs) of normal and infarcted myocardium and the area of infarcted myocardium were determined. Magnitude-reconstructed IR turbo FLASH images were compared with magnitude-reconstructed and phase-sensitive IR true FISP images. Two-tailed unpaired sample Student *t* test was used to compare CNRs, and two-tailed paired-sample Student *t* test was used to compare area of infarction.

RESULTS: Mean CNR of images acquired with IR turbo FLASH and IR true FISP (phase-sensitive and magnitude-reconstructed images) at optimal TI (mean value, 330 msec) were 6.6, 6.2, and 6.1, respectively. For a TI of 200 msec, CNR values were −4.3, −4.0, and 7.2, respectively; for TI of 600 msec, CNR values were 3.1, 3.3, and 4.3, respectively. Area of infarcted myocardium was underestimated on magnitude-reconstruction images (P = .002–.03) for short TI values (ie, 200 msec) for both sequences and for a TI of 300 msec for IR true FISP but not on phase-sensitive reconstructed IR true FISP images when compared with IR turbo FLASH images obtained at optimal TI.

CONCLUSION: Phase-sensitive image reconstruction results in reduced need for precise choice of TI and more consistent image quality.

In patients with coronary artery disease and left ventricular dysfunction, the distinction between viable and nonviable myocardium with contrast material–enhanced magnetic resonance (MR) imaging allows the prediction of functional recovery after surgical or interventional revascularization (1). Infarcted myocardium exhibits delayed hyperenhancement after administration of gadolinium-based contrast material and can be imaged by using inversion-recovery (IR) techniques typically 10–30 minutes after administration of contrast material (1–5). Alternative noninvasive methods used in the assessment of myocardial viability include positron emission tomography (PET) and single photon emission computed tomography (4). The clinical utility of these methods has been proved; however, delayed contrast-enhanced MR imaging has superior spatial resolution when

---

[1] From the Institute for Clinical Radiology (A.M.H., S.O.S., B.S., M.F.R.) and Medical Clinic I (M.G.E., W.M.F.), Clinic of Ludwig-Maximilians-University Munich, Grosshadern, Marchioninistr 15, 81377 Munich, Germany; and Cardiovascular MRI, Siemens Medical Systems, Erlangen, Germany (C.H.). Received August 31, 2004; revision requested November 5; revision received January 12, 2005; accepted January 25. **Address correspondence to** A.M.H. (e-mail: *armin.huber@med.uni-muenchen.de*).

See Materials and Methods for pertinent disclosures.

Author contributions:
Guarantors of integrity of entire study, A.M.H., W.M.F., M.F.R.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; literature research, A.M.H., C.H., B.S., M.G.E., W.M.F., M.F.R.; clinical studies, A.M.H., S.O.S., B.S., M.G.E., W.M.F., M.F.R.; experimental studies, A.M.H., M.G.E.; statistical analysis, A.M.H., S.O.S., C.H., B.S., M.F.R.; and manuscript editing, A.M.H., S.O.S., C.H., W.M.F.

compared with these methods, and it can be used to differentiate transmural and nontransmural myocardial infarction. The area of hyperenhancement shows a close correlation with the histopathologically determined area of myocardial infarction in animal experiments (2).

The most widely used pulse sequence in the depiction of late enhancing areas in the myocardium is the IR turbo fast low-angle shot (FLASH) sequence with magnitude reconstruction. This pulse sequence requires an individual adaptation of the inversion time (TI) to achieve optimal signal increase between infarcted and viable myocardium. At the optimal TI, the signal intensity of normal myocardium is nulled. Several breath holds can be necessary to determine the optimal TI value. An error in selection of the optimum null time leads to a reduction in contrast, and it may reduce the visible hyperenhanced area; therefore, it may cause underestimation of the extent of infarction (2–4).

Kellman et al (5) described experimental data and results of phase-sensitive reconstruction that show the potential benefits of both phase-sensitive IR image reconstruction and surface coil intensity normalization in the detection of myocardial infarction.

The purpose of our study was to prospectively determine if phase-sensitive IR MR imaging obviates the need to find the precise TI to null the signal of normal myocardium to achieve high contrast between infarcted and normal myocardium.

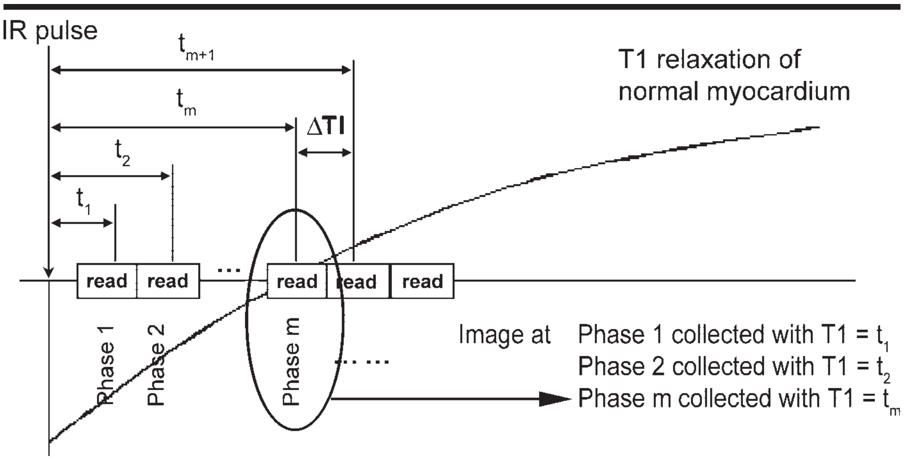

Figure 1. Timing diagram of the cine IR true FISP pulse sequence. The segments acquired with identical TI over all cardiac cycles during one breath hold are used to reconstruct one image. For each delay time *(t_m)* after the inversion pulse, an image with a typical contrast for its phase is reconstructed.

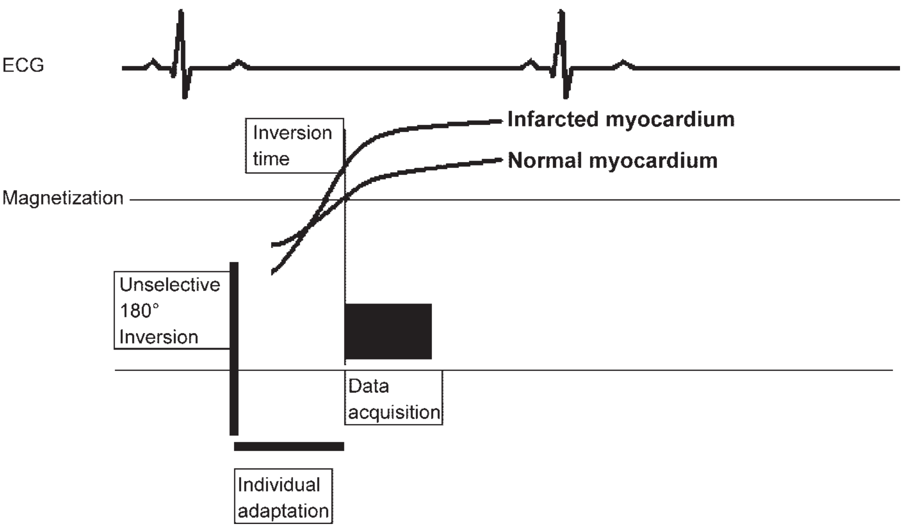

Figure 2. Timing diagram of the segmented IR turbo FLASH sequence. A nonselective 180° inversion pulse is used to improve T1 contrast. The magnetization amplitude for magnitude-reconstructed images is shown schematically for infarcted myocardium and normal myocardium as a function of the delay time to the inversion pulse. The sign of the amplitude is negative for short TIs for normal and infarcted myocardium. At optimal TI, the signal intensity of normal myocardium is near zero.

MATERIALS AND METHODS

The department of cardiovascular MR imaging (Siemens Medical Solutions, Erlangen, Germany) is responsible for the development of the phase-sensitive IR true fast imaging with steady-state precession (FISP) pulse sequence. One author (C.H.) is responsible for implementation and technical support for the use of this technique. Authors who do not work for a company (A.M.H., S.O.S., B.S., M.G.E., W.M.F., M.F.R.) had complete control of data and results.

Patient Population

A total of 20 patients who experienced Q-wave myocardial infarction and who underwent interventional revascularization with delay (ie, between 24 hours and 3 days) were prospectively enrolled in the study. Only patients who met these criteria between June 10, 2002, and May 15, 2003, were included. MR examinations were performed between 10 days and 2 weeks after infarction. The institutional ethics committee approved this study. Informed consent was obtained from each patient for the prospective MR imaging research study and the MR examination. The mean age of the 20 patients (16 men and four women) was 56 years ± 12.3 (age range, 40–76 years). None of the patients had unstable angina, New York Heart Association class III or IV heart failure, or contraindications to MR imaging. Myocardial infarction diagnosis was based on abnormal electrocardiograms and biochemical evidence.

MR Imaging

All MR images were obtained with a 1.5-T unit (Magnetom Sonata; Siemens Medical Solutions, Erlangen, Germany) with eight channels and a dedicated 12-element phased-array body coil. Electrocardiograms and heart rate were monitored with the physiologic monitor of the imager (MR-compatible monitoring system). All patients were examined in the supine position. A 20-gauge cannula was placed in an antecubital vein for injection of contrast material.

Scout images were obtained to deter-

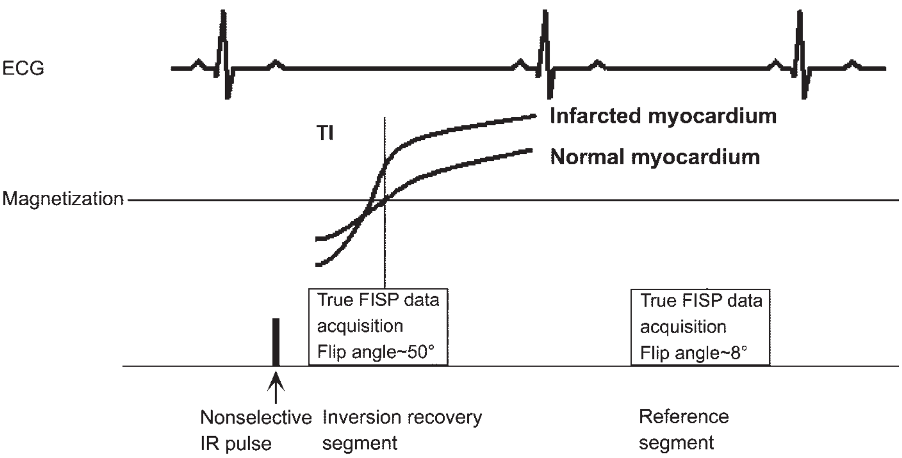

Figure 3. Timing diagram of the segmented, phase-sensitive IR true FISP sequence. Every second heartbeat, a reference segment is acquired with a low flip angle, which is used for reconstruction of phase-sensitive images. The expected magnetization amplitude for magnitude-reconstructed images is shown schematically for normal and infarcted myocardium.

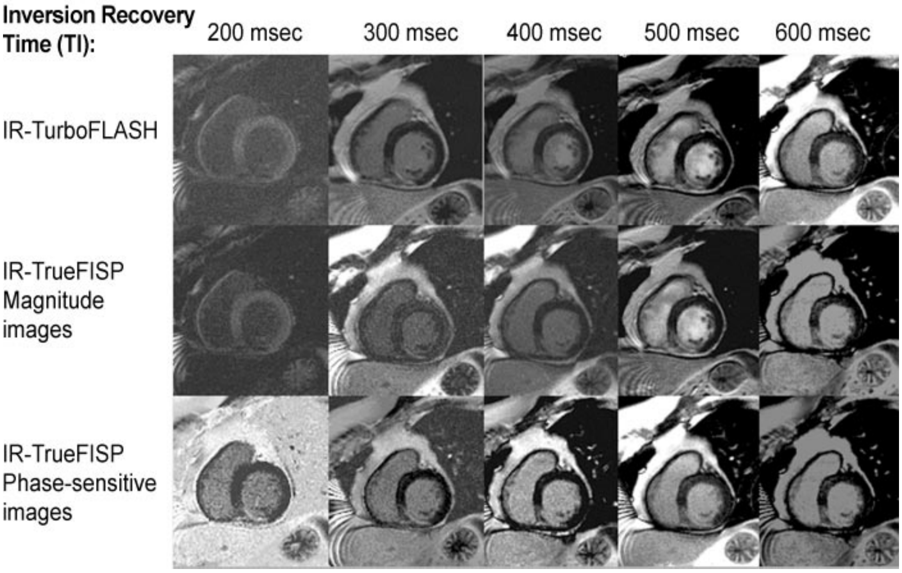

Figure 4. Short-axis MR images obtained in a 55-year-old patient 14 days after myocardial infarction. All 15 images shown were obtained at the same section position. Each row shows images acquired with one sequence type but different TI values in 100-msec steps (eg, 200–600 msec). The first row shows images acquired with the IR turbo FLASH (8.0/4.0; flip angle, 25°) pulse sequence. Images in the second (magnitude-reconstructed images) and third (phase-sensitive reconstructed images) rows were acquired with an IR true FISP (3.0/1.5; flip angles, 50° and 8°) sequence. For a short TI value of 200 msec, the infarct area in the inferior and inferoseptal segment reveals hypointense signal intensity on magnitude-reconstructed images (IR turbo FLASH and IR true FISP) compared with that of normal myocardium. The phase-sensitive images (phase-sensitive IR true FISP), however, show hyperintense signal of the infarction for all TI values (ie, 200–600 msec).

mine the exact position and standard orientations—long-axis, four-chamber, and short-axis views—of the left ventricle. Gadobenate dimeglumine (Multihance; Bracco, Milan, Italy) was injected at a dose of 0.1 mmol per kilogram of body weight and was followed by 20 mL of saline.

Optimization of TI

At 10 minutes after contrast material administration, a segmented IR cine true FISP pulse sequence was performed at a midventricular short-axis location. This sequence was used to determine the TI at which the signal of normal myocardium is null for the subsequent delayed enhancement acquisition (6). The sequence technique (7), which is based on an approach proposed by Scheffler and Henning (8), is shown schematically in Figure 1. Thus, after a nonselective hyperbolic secant pulse applied after the R-wave trigger, multiple cardiac phases were acquired by using a segmented true FISP readout. The resulting 23 cine images show the recovery of the longitudinal magnetization at multiple time intervals, in increments given by the temporal resolution, after inversion. In our implementation, seven k-space lines were acquired per segment per cardiac phase, thus resulting in a temporal resolution of 15.0 msec (repetition time msec/echo time msec, 2.2/1.1; flip angle, 50°), and breath-hold duration of 14 cardiac cycles. The spatial resolution was typically 2.6 × 1.8 × 10.0 mm, the field of view was 340 × 265 cm, and the matrix was 192 × 102. From the images obtained with TI values of 185–515 msec, the optimum TI value was determined with visual assessment performed by two operators working in agreement (A.M.H., S.O.S.). The optimum TI was that which was used to obtain the image in which the signal intensity of normal myocardium was near null, and the signal intensity of the left ventricular cavity was lower than that of the infarcted region.

Imaging of Delayed Contrast Enhancement

A segmented IR turbo FLASH sequence (Fig 2), with TI adjusted as described previously, was used to cover the entire left ventricle in the short-axis view, with a 1-cm section distance (3). This pulse sequence is well established, and it served as the reference standard. Pulse sequence parameters were as follows: 8.0/4.0; flip angle, 25°; and bandwidth, 140 Hz per pixel. A total of 20 k-space lines were acquired in 160 msec in mid-diastole during a time window of minimal cardiac motion. With data acquisition every second heartbeat, imaging of one section was possible during nine cardiac cycles. These pulse sequence parameters are similar to those used by Simonetti et al (3). At one representative section location chosen by two investigators in agreement (A.M.H. and S.O.S., each with 6 years of experience in cardiac MR imaging), images were acquired at different TI values by using the segmented IR turbo FLASH sequence described previously and a segmented IR true FISP sequence that uses both magnitude and phase-sensitive reconstruction (sequence will be described later). The TI values were consecutively increased from 200 to 600 msec in 100-msec

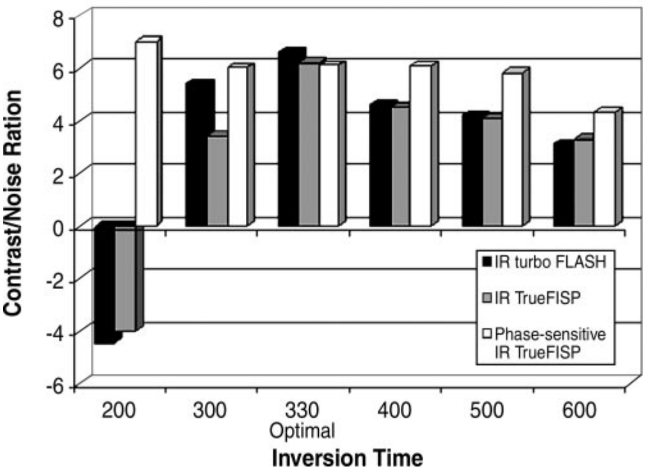

Figure 5. Bar graph compares the CNR of infarcted and normal myocardium as a function of TI for magnitude-reconstructed IR turbo FLASH, IR true FISP, and phase-sensitive reconstructed IR true FISP image acquisitions.

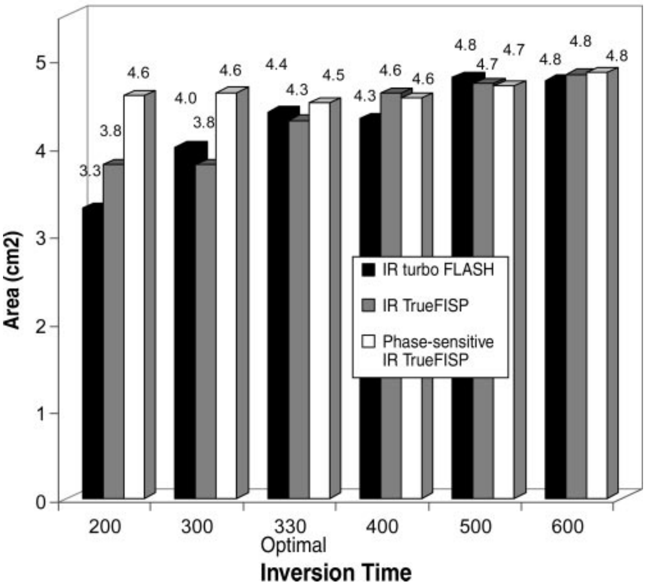

Figure 6. Bar graph compares the myocardial infarcted area as a function of the TI for magnitude-reconstructed IR turbo FLASH, IR true FISP, and phase-sensitive reconstructed IR true FISP image acquisitions. Mean values for the area of infarction determined for each image type and TI are shown; the values are written as numbers on the top.

steps. Images at the selected section location were acquired in alternating sequence order. The alternating order was chosen to eliminate a systematic error due to the change in the optimal TI over the time of the examination owing to washout of contrast material (6,9). For comparison purposes, the field of view (330 × 330 cm) and spatial resolution (1.8 × 1.3 × 8 mm) were the same for both pulse sequences.

The details of the IR true FISP pulse sequence are shown in Figure 3. After a trigger delay to allow data acquisition in mid-diastole during 180 msec, a nonselective adiabatic inversion pulse is applied every second heartbeat. After a time delay, 60 k-space lines are acquired with a true FISP readout and a flip angle of 50°. This is followed by the acquisition of a reference data set in the next heartbeat and in mid- to late diastole by using a true FISP readout; however, a flip angle of 8° is used. In our implementation, for a matrix size of 256 × 180, a repetition time of 3 msec, an echo time of 1.5 msec, and a bandwidth of 760 Hz/pixel, six cardiac cycles were required to complete the entire acquisition of one section. Two images, a magnitude-reconstructed image and a real image, are reconstructed. The real image is obtained by using phase-sensitive reconstruction, whereas the reference data, which are acquired every second heartbeat, are used to perform background phase correction and surface coil normalization. The phase-sensitive reconstruction method is described in detail by Kellman et al (5).

Image Evaluation

Images were analyzed by definition of regions of interest: Signal intensity, standard deviation of signal intensity, and contrast-to-noise ratio (CNR) were determined by measuring signal intensities in regions of interest that were placed by one reader (B.S.) in the remote myocardium (no hyperenhancement), the left ventricular cavity (fixed size of region of interest, 2 cm^2), the infarct area (hyperenhancement), and the background ventral and lateral to the patient. Infarct size was measured with agreement of two readers (B.S., 3 years of cardiac MR experience; A.M.H.) by means of manual tracing of the borders of the entire myocardium and the hyperintense myocardium on each section at all TI values by using Argus software at a Leonardo workstation (Siemens Medical Solutions). An evaluation was performed in a manner similar to that described by Flacke et al (10).

Signal intensity and CNR (the difference of infarction signal intensity minus normal myocardium signal intensity divided by the standard deviation of signal intensity of background) values were determined for both sequence types at each TI value for enhanced myocardium and normal myocardium.

The area of hyperenhanced myocardium was determined first for each short-axis section on IR turbo FLASH images. The values of the area of hyperenhanced myocardium of single sections were added to determine the entire infarct volume. The hyperenhanced area was then determined on the selected section for comparison of the different image types and TI values. The two image sets obtained with the IR true FISP sequence and the image set obtained with the IR turbo FLASH sequence performed with different TI values were compared with the images obtained with the IR turbo FLASH sequence performed with optimal TI (reference standard).

Statistical Analysis

Two-tailed unpaired Student *t* test was used to compare CNR in the hyperenhanced regions and the normal myocardium for the three image types with CNR obtained with IR turbo FLASH at optimized TI. A *P* value greater than .05 indicates there is no statistically significant difference between the mean values of CNR of the different image types (95% confidence interval: 0.05, 0.95). Two-tailed paired Student *t* test was used to compare the values of the area of the infarcted regions for the three image types with the values obtained with IR turbo FLASH at optimized TI. A *P* value of more than .05 indicates there is no statistically significant difference between the mean values of the areas of myocardial infarction of the different image types (95% confidence interval: 0.05, 0.95).

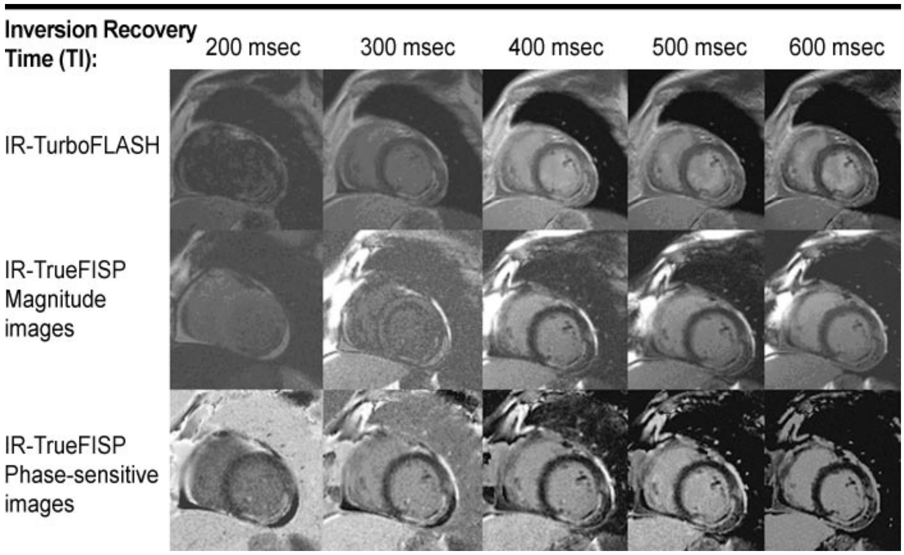

Figure 7. Short-axis MR images obtained in a 53-year-old patient 12 days after inferior myocardial infarction. All 15 images shown were obtained at the same section position. Each row shows images acquired with one sequence type but with different TI values in 100-msec steps (eg, 200–600 msec). The first row shows magnitude-reconstructed images acquired with the IR turbo FLASH pulse sequence (8.0/4.0; flip angle, 25°). The second and third rows show magnitude-reconstructed images and phase-sensitive reconstructed images, respectively, that were acquired with an IR true FISP sequence (3.0/1.5; flip angles, 50° and 8°). The images illustrate the TI dependence of the contrast and the apparent area of infarction in the case of magnitude-reconstructed images. The apparent infarct area is smaller on the IR turbo FLASH image acquired with a 200-msec TI compared with those acquired with longer TI values and with the phase-sensitive image also acquired with a 200-msec TI. The magnitude-reconstructed IR true FISP images also show negative contrast for a 200-msec TI, positive contrast but reduced area for a 300-msec TI, and stable positive contrast and area for 400–600-msec TIs.

RESULTS

Characterization of Myocardial Infarction

Eleven infarctions were located in the anteroseptal segments, five were located in the inferoseptal segments, and four were located in the inferolateral segments. The IR turbo FLASH images, which were acquired with optimal TI (mean, 330 msec ± 55), showed eight infarctions with a complete transmural extent, five with a 50%–75% extent, five with a 25%–50% extent, and two with a 25% maximum extent of the thickness of the myocardium. The mean volume of injured myocardium was 32.5 mL ± 13 (standard deviation). The mean percentage of infarcted myocardium in relation to the entire left ventricular myocardium was 22%.

Contrast of Infarction

In the case of images acquired with the IR turbo FLASH pulse sequence and a TI value of 200 msec, the infarcted myocardium can show hypointense signal intensity (Fig 4) or hyperintense signal intensity, with weak contrast (Figs 4, 5) compared with that of the normal myocardium. For longer TI values, however, the infarcted region is hyperintense when compared with normal myocardium (Figs 4, 5). Similar trends are observed in the case of the magnitude-reconstructed IR true FISP images. The myocardial infarct is hyperintense for all TI values in the case of the phase-sensitive reconstructed IR true FISP images (Figs 4, 5).

The highest loss of CNR between normal and infarcted myocardium for all three image types was found for the shortest TI value (200 msec) in the case of the magnitude-reconstructed images. Phase-sensitive reconstructed images, however, show no loss of CNR for short TI values. In contrast to magnitude-reconstructed images, the highest CNR mean value for phase-sensitive images was found for a TI of 200 msec.

For optimal TI, the three image types show very similar CNR values: 6.6 for IR turbo FLASH images and 6.2 and 6.1 for magnitude-reconstructed and phase-sensitive images of the IR true FISP sequence, respectively. The mean CNR values of all images acquired with different TI values were compared with those of magnitude-reconstructed IR turbo FLASH images, which were acquired with optimal TI: There was no significant difference for all image types acquired with the optimal TI and for all phase-sensitive reconstructed images, except for those acquired with a TI value of 600 msec (Table 1, Fig 5). A significant difference was found for magnitude-reconstructed images (IR turbo FLASH and IR true FISP) when they were acquired with a TI value that was shorter or longer than the optimal TI value (Table 1). CNR loss for the magnitude-reconstructed image is lower for longer TI values (≥330 msec) compared with CNR loss for the shortest TI value (200 msec) (Fig 5).

Area of Infarction

The area of hyperenhanced myocardium is in close agreement for the three image types with longer TI values (400–600 msec). Comparison of the mean areas determined from the different image types with the Student *t* test (Table 2) shows no significant difference between the area of infarcted myocardium on the magnitude-reconstructed IR turbo FLASH images and both magnitude-reconstructed and phase-sensitive IR true FISP images acquired with TI values of 400–600 msec compared with the reference images (IR turbo FLASH with optimized TI). At 200 msec, the infarct area is significantly underestimated on the magnitude-reconstructed images acquired with both the IR turbo FLASH and the IR true FISP sequences compared with that on images obtained with optimal TI (Table 2, Figs 6, 7).

DISCUSSION

Kim et al (2) investigated acute and chronic infarction in dogs. MR images acquired 30 minutes after administration of contrast material showed hyperenhancement of myocardial tissue, with excellent spatial correlation between the hyperenhancing areas and the necrotic areas identified at histopathologic examination after staining of the entire left ventricle with triphenyltetrazolium chloride. The same study also showed that transient ischemia with reperfusion caused no hyperenhancement.

In contrast to fluorine 18 fluorodeoxyglucose PET, contrast-enhanced MR imaging is able to image the myocardium with superior spatial resolution (2). Thus, complete transmural infarctions can be distinguished from nontransmural infarctions by steps smaller than 25% of the thickness of the left ventricular myocardium. The contractility of dysfunctional but viable myocardium (ie, no hyperenhancement) can potentially improve after revascularization, even if the transmural extent of hyperenhancement is 50%. Complete transmural infarctions have a low probability of improved contractility (1). Thus, knowledge of the transmural extent of viability is important in the prediction of an improvement of regional wall motion after surgical revascularization, especially in patients with reduced left ventricular ejection fraction (1).

It is known that regions of myocardial infarction exhibit higher signal intensity than do regions of normal myocardium on unenhanced T2-weighted MR images (11,12) and contrast-enhanced T1-weighted MR images (13–16). Since the initial investigations, many studies have been performed with a variety of pulse sequences to differentiate between infarcted and normal myocardium and to distinguish between reversible and irreversible ischemic injury. Kim et al (2) and Simonetti et al (3) implemented a breath-hold IR segmented turbo FLASH MR sequence for T1-weighted contrast-enhanced imaging of infarction that produces strongly T1-weighted images. Some features of the sequence are similar to those of the segmented turbo FLASH technique for breath-hold MR imaging of the abdomen, as described by Edelman et al (17). Simonetti et al (3) compared 10 different pulse sequences acquired with unenhanced and contrast-enhanced administration and found the greatest differences in regional myocardial signal intensity for the breath-hold segmented IR turbo FLASH sequence. In the literature, this is the pulse sequence that is the most investigated and established (2,3,13,14,18); therefore, we chose this sequence as the reference standard in the present study.

In contrast-enhanced IR imaging, TI is adapted individually for each examination to null the signal of the normal myocardium, thus ensuring optimal contrast between infarcted and viable myocardium. In the case of magnitude image reconstruction, the performance of IR delayed hyperenhancement is highly sensitive to the choice of TI. A suboptimal TI can result in a reduction in contrast or even nullify the contrast between infarcted and normal myocardium completely (12). There are different methods available to optimize the TI value. Images can be acquired with different TI values, and the best TI value can be chosen by trial and error. This can be time consuming. An alternative approach is to use a TI optimizing sequence, such as that described previously, that acquires images with different TI values and reduced spatial resolution (6–8). To avoid this optimization procedure, Kellman et al (5) proposed the use of phase-sensitive IR with surface coil normalization and presented experimental results demonstrating the advantages of the technique for visualization of myocardial infarction. A fast gradient-recalled echo pulse sequence with interleaved phase-encode ordering and phase-sensitive reconstruction was used by Kellman et al (5), with the acquisition of an IR image (flip angle, 20°) and a reference image (flip angle, 5°) during a single breath hold. The sequence used in the present study, unlike that used by Kellman et al (5), combines phase-sensitive reconstruction and surface coil normalization with a true FISP imaging technique. Otherwise, the acquisition and image reconstruction methods are similar. In contrast to the findings of Kellman et al (5), the TI values used in our study were 200 msec and longer, as our clinical experience and the experience of other researchers have shown that an optimal TI of 200–350 msec is typical for images acquired 10 minutes after contrast material administration (11,13,14). In the present study, the optimal TI was, on average, 330 msec.

TABLE 1
***P* Values for Comparison of Mean Values of CNR for Different Imaging Sequences and TIs**

Imaging Sequence	TI (msec) 200	300	330*	400	500	600
IR turbo FLASH with magnitude reconstruction	.01	.04	NS	.04	.03	.01
IR true FISP						
Magnitude reconstruction	.001	.01	NS	.04	.03	.03
Phase-sensitive reconstruction	NS	NS	NS	NS	NS	.03

Note.—NS = not significant.
* Optimal inversion time.

TABLE 2
***P* Values for Comparison of Mean Values of Infarct Area for Different Imaging Sequences and TIs**

Imaging Sequence	TI (msec) 200	300	330*	400	500	600
IR turbo FLASH with magnitude reconstruction	.002	NS	NS	NS	NS	NS
Phase-sensitive IR true FISP						
Magnitude reconstruction	.003	.03	.04	NS	NS	NS
Phase-sensitive reconstruction	NS	NS	NS	NS	NS	NS

Note.—NS = not significant.
* Optimal inversion time.

The results of the present study show that the CNR values of the phase-sensitive reconstructed IR true FISP images are superior for short (ie, 200–300 msec) and long (ie, 400–600 msec) TI values compared with the CNR values of magnitude-reconstructed images of the IR turbo FLASH pulse sequence. On average, the CNR of the phase-sensitive reconstructed IR true FISP images was lower than that of the magnitude-reconstructed IR turbo FLASH images only at TI values determined as optimal for the latter; however, this difference was not significant. The clear advantage of phase-sensitive reconstruction compared with magnitude reconstruction is that the difference in CNR between normal and infarcted myocardium is consistently positive, and the infarct area remains relatively constant over a wide range of TIs. The average estimated infarct area decreased significantly at a TI of 200 msec for both IR turbo FLASH and IR true FISP magnitude-reconstructed images compared with that for the magnitude-reconstructed IR turbo FLASH image acquired at optimal TI. This is likely caused by the reduction in contrast between normal and infarcted myocardium; this reduction is due to the loss of signal polarity when short TI values are used.

It should be pointed out, however, that phase-sensitive reconstruction combined with surface coil normalization could result in a loss in CNR and signal-to-noise ratio. Given that surface coil normalization was not performed for the magnitude-reconstructed images, the CNR comparison in the present study is not entirely justified. As the results demonstrate, however, the CNR gain due to the preservation of signal polarity with phase-sensitive detection outweighs any loss due to surface coil intensity correction.

Especially in the early phase after infarction, injured myocardium shows edema and, therefore, hyperintense signal intensity on images obtained with T2-weighted pulse sequences (13,14,19). It has been previously reported that the area of edema can be larger than the hyperenhanced region on delayed enhanced images (20). One could argue that true FISP–based sequences are likely to have a reduced T1 contrast (3), which will result in reduced differentiation between edema and hyperenhanced infarct. However, Scheffler and Henning (8) and Li et al (21) have shown that IR-prepared true FISP results in images with strong T1 weighting, comparable with that of IR snapshot FLASH. Furthermore, in the present study, no overestimation of the area of infarction for the phase-sensitive reconstructed true FISP images compared with the magnitude-reconstructed IR turbo FLASH images acquired at optimal TI was found. In fact, the lesion area remained constant over the entire range of TI values (200–600 msec) in the phase-sensitive reconstructed images. While comparison of the magnitude-reconstructed images was not the aim of the present study, it is interesting to note that the CNR of the magnitude-reconstructed IR true FISP images was comparable with that of IR turbo FLASH images for all TI values except 200 msec. This exception may be attributed to slight differences in T1 weighting with the two techniques, which would be expected to be more prominent for shorter TIs.

The results of the current study provide evidence to support the use of phase-sensitive reconstruction (22) at a nominal standard TI, as suggested by Kellman et al (5) on the basis of a study that used a similar phase-sensitive reconstruction technique with IR turbo FLASH. Phase-sensitive reconstruction is likely to reduce the number of breath holds necessary to ensure optimal image quality (eg, small endocardial infarcts or myocardial enhancement in hypertrophic cardiomyopathy, where meticulous attention to the choice of TI in magnitude reconstruction techniques is essential). Our results suggest that the phase-sensitive IR true FISP pulse sequence could be used with a nominal standard TI between 200 and 300 msec, without loss in image contrast and diagnostic information.

Our study has limitations. Instead of the entire infarction, one representative section was compared for two different pulse sequences and two reconstruction methods. When the entire short axis is acquired with two different pulse sequences and seven different TI values, however, the acquisition time is too long to avoid contrast material washout and relevant change of optimal TI during the acquisition time that is necessary to image the infarction completely.

In conclusion, phase-sensitive image reconstruction results in reduced need for precise choice of TI and more consistent image quality. In the future, it is expected that magnitude image reconstruction may be replaced by phase-sensitive reconstruction techniques, with a default TI for a given contrast material dose and delay after injection.

References

1. Kim RJ, Wu E, Rafael A, et al. The use of contrast-enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. N Engl J Med 2000;343:1445–1453.
2. Kim RJ, Fieno DS, Parrish TB, et al. Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. Circulation 1999;100:1992–2002.
3. Simonetti OP, Kim RJ, Fieno DS, et al. An improved MR imaging technique for the visualization of myocardial infarction. Radiology 2001;218:215–223.
4. Kuhl HP, Beek AM, van der Weerdt AP, et al. Myocardial viability in chronic ischemic heart disease: comparison of contrast-enhanced magnetic resonance imaging with (18)F-fluorodeoxyglucose positron emission tomography. J Am Coll Cardiol 2003;41:1341–1348.
5. Kellman P, Arai AE, McVeigh ER, Aletras AH. Phase-sensitive inversion recovery for detecting myocardial infarction using gadolinium-delayed hyperenhancement. Magn Reson Med 2002;47:372–383.
6. Spuentrup E, Buecker A, Karassimos E, Gunther RW, Stuber M. Navigator-gated and real-time motion corrected free-breathing MR imaging of myocardial late enhancement [in German]. Rofo 2002;174:562–567.
7. Chung YC, Lee VS, Laub G, Simonetti OP. Inversion recovery cine TrueFISP (abstr). In: Proceedings of the 10th Meeting of the International Society for Magnetic Resonance in Medicine. Berkeley, Calif: International Society for Magnetic Resonance in Medicine, 2002; 219.
8. Scheffler K, Henning JT. Quantification with inversion recovery TrueFISP. Magn Reson Med 2001;45:720–723.
9. Moran GR, Thornhill RE, Sykes J, Prato FS. Myocardial viability imaging using Gd-DTPA: physiological modeling of infarcted myocardium, and impact on injection strategy and imaging time. Magn Reson Med 2002;48:791–800.
10. Flacke S, Allen JS, Chia JM, et al. Characterization of viable and nonviable myocardium at MR imaging: comparison of gadolinium-based extracellular and blood pool contrast materials versus manganese-based contrast materials in a rat myocardial infarction model. Radiology 2003;226:731–738.
11. Higgins CB, Herfkens R, Lipton MJ, et al. Nuclear magnetic resonance imaging of acute myocardial infarction in dogs: alterations in magnetic relaxation times. Am J Cardiol 1983; 52:184–188.
12. Johnston DL, Brady TJ, Ratner AV, et al. Assessment of myocardial ischemia with proton magnetic resonance: effects of a three hour coronary occlusion with and without reperfusion. Circulation 1985;71:595–601.
13. Oshinski JN, Yang Z, Jones JR, Mata JF, French BA. Imaging time after Gd-DTPA injection is critical in using delayed enhancement to determine infarct size accurately with magnetic resonance imaging. Circulation 2001;104:2838–2842.
14. Klein C, Nekolla SG, Bengel FM, et al. Assessment of myocardial viability with contrast-enhanced magnetic resonance imaging: comparison with positron emission tomography. Circulation 2002;105:162–167.
15. Rehr RB, Peshock RM, Malloy CR, et al. Improved in vivo magnetic resonance imaging of acute myocardial infarction after intravenous paramagnetic contrast agent administration. Am J Cardiol 1986;57:864–868.
16. Tscholakoff D, Higgins CB, Sechtem U, McNamara MT. Occlusive and reperfused myocardial infarcts: effect of Gd-DTPA on ECG-gated MR imaging. Radiology 1986;160:515–519.
17. Edelman RR, Wallner B, Singer A, Atkinson DJ, Saini S. Segmented turboFLASH: method for breath-hold MR imaging of the liver with flexible contrast. Radiology 1990;177:515–521.
18. Noll DC, Nishimura DG, Macovski A. Homodyne detection in magnetic resonance imaging. IEEE Trans Med Imaging 1991;1:154–163.
19. Nilsson JC, Nielsen G, Groenning BA, et al. Sustained postinfarction myocardial oedema in humans visualised by magnetic resonance imaging. Heart 2001;85:639–642.
20. Schulz-Menger J, Gross M, Messroghli D, Uhlich F, Dietz R, Friedrich M. Cardiovascular magnetic resonance of acute myocardial infarction at a very early stage. J Am Coll Cardiol 2003;42:513–518.
21. Li W, Li BS, Polzin JA, Mai VM, Prasad PV, Edelman RR. Myocardial delayed enhancement imaging using inversion recovery single-shot steady-state free precession: initial experience. J Magn Reson Imaging 2004;20: 327–330.
22. Bernstein MA, Thomasson DM, Perman WH. Improved detectability in low signal-to-noise ratio magnetic resonance images by means of a phase-corrected real reconstruction. Med Phys 1989;16:813–817.