Rapid Detection of Myocardial Infarction by Subsecond, Free-Breathing Delayed Contrast-Enhancement Cardiovascular Magnetic Resonance

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Background—An ultrafast, delayed contrast-enhancement cardiovascular magnetic resonance technique that can acquire subsecond, “snapshot” images during free breathing (subsecond) is becoming widely available. This technique provides myocardial infarction (MI) imaging with complete left ventricular coverage in <30 seconds. However, the accuracy of this technique is unknown.

Methods and Results—We prospectively compared subsecond imaging with routine breath-hold delayed contrast-enhancement cardiovascular magnetic resonance (standard) in consecutive patients. Two cohorts with unambiguous standards of truth were prespecified: (1) patients with documented prior MI (n=135) and (2) patients without MI and with low likelihood of coronary disease (lowest Framingham risk category; n=103). Scans were scored masked to identity and clinical information. Sensitivity, specificity, and accuracy of subsecond imaging for MI diagnosis were 87%, 96%, and 91%, respectively. Compared with the standard technique (98%, 100%, 99%), the subsecond technique had modestly reduced sensitivity (P=0.0001), but specificity was excellent. Missed infarcts were generally small or subendocardial (87%). Overall, regional transmural extent of infarction scores were highly concordant (2083/2294; 91%); however, 51 of 337 regions (15%) considered predominantly infarcted (>50% transmural extent of infarction) by the standard technique were considered viable (≤25% transmural extent of infarction) by the subsecond technique. Quantitative analysis demonstrated moderately reduced contrast-to-noise ratios for subsecond imaging between infarct and remote myocardium (12.0±7.2 versus 20.1±6.6; P<0.0001) and infarct and left ventricular cavity (2.5±2.7 versus 3.6±3.7; P<0.0001).

Conclusions—MI can be rapidly detected by subsecond delayed contrast-enhancement cardiovascular magnetic resonance during free breathing with high accuracy. This technique could be considered the preferred approach in patients who are more acutely ill or unable to hold their breath. However, compared with standard imaging, sensitivity is mildly reduced, and the transmural extent of infarction may be underestimated. (Circulation. 2007;115:236-244.)

Key Words: imaging ■ magnetic resonance imaging ■ myocardial infarction

Myocardial infarction (MI) occurs in almost a million people in the United States each year, and coronary heart disease is the leading cause of hospital admissions.1 According to the joint American College of Cardiology and European Society of Cardiology consensus document concerning the redefinition of MI, the diagnosis of MI is substantially based on cardiac biomarkers and ECG changes.2 However, biomarkers are only elevated for 4 to 10 days after an acute event; thus, biomarkers are not useful for the diagnosis of subacute or chronic MI. The ECG also has limitations: Q waves that form the fundamental basis of the diagnosis of chronic MI may be absent or, if initially present, may disappear at a later time point.3

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Delayed enhancement cardiovascular magnetic resonance (DE-CMR) may overcome some of these limitations. Studies in animal models suggest a nearly perfect match of infarcted regions by DE-CMR to histology.4 In patients, DE-CMR can provide accurate and reproducible diagnosis of both acute and chronic MI.5,6 Furthermore, even small subendocardial infarcts can be detected reliably in the absence of Q waves.6–8 CMR is a rapidly progressing field, and new DE-CMR techniques are becoming widely available. One of these new techniques, which is highly promising, uses a single-shot
acquisition that can acquire subsecond ("snapshot") images during free breathing rather than acquiring data for 1 image over several heartbeats during a prolonged breath-hold as required by the standard technique. This rapid technique can potentially speed up imaging 10- to 20-fold and enable image acquisition of the entire heart during free breathing in <30 seconds. This advantage has the potential to fundamentally change current CMR practice. Either clinical throughput could be increased multifold, with several scans completed per hour, or the improved efficiency could be utilized for a comprehensive examination: Cardiac morphology, function, viability, stress-rest perfusion, and coronary imaging could be performed in under an hour. Therefore, not surprisingly, many centers are considering switching or have already switched to this new subsecond method as the preferred delayed-enhancement technique.

However, there are limited data regarding the utility of subsecond imaging in clinical practice.9 The purpose of the present study was to systematically evaluate the accuracy of subsecond imaging compared with standard segmented inversion-recovery DE-CMR for the diagnosis of MI and the determination of infarct size.

Methods

Patients

Consecutive patients scheduled to undergo standard DE-CMR at the Duke Cardiovascular Magnetic Resonance Center starting February 2003 and ending October 2004 were prospectively evaluated. Only 2 cohorts with prespecified unambiguous standards of truth for either the presence or absence of MI were considered for enrollment. Patients with nonischemic cardiac disorders such as idiopathic dilated cardiomyopathy, hypertrophic cardiomyopathy, and myocarditis were excluded.

The infarct group (n=135) consisted of patients with documented MI in their medical history according to the recent joint European Society of Cardiology/American College of Cardiology consensus document for the redefinition of MI.2 Thus, patients had typical rise and fall of cardiac biomarkers with either appropriate ECG changes, ischemic symptoms, or both at the time of the acute event. The no-infarct group (n=103) consisted of subjects without known coronary heart disease and with a very low probability of developing coronary disease over the next 10 years10 (lowest Framingham risk score category: 1% for women, 2% for men). The study was approved by the Duke University institutional review board; all patients gave informed written consent.

Data Acquisition

All available cardiac enzyme data were collected. Patients with peak enzyme levels occurring <14 days before CMR were considered acute MI patients. All ECGs performed within a short time period of CMR (2 days for acute MI patients and 10 weeks for chronic MI or no-infarct patients) were collected. Patients were imaged in a 1.5-T scanner (Siemens, Sonata) with the use of an 8-element phased-array system. Multiple short-axis views that covered the left ventricle (LV) from base to apex (every 1 cm) were obtained by cine imaging and both delayed enhancement techniques. All images were ECG gated.

Segmented inversion-recovery gradient-echo imaging was performed in the standard fashion.11,12 Briefly, data for 1 image were acquired over multiple heartbeats; thus, images were obtained during repetitive 6- to 10-second breath-holds. Inversion times were typically 280 to 380 ms to null normal myocardium.13 Specific sequence parameters are displayed in Table 1. Importantly, images were acquired between 10 and 30 minutes after intravenous contrast administration (gadoversetamide, 0.15 mmol/kg). This time-window/dose combination for infarct imaging was chosen on the basis of previous results that have demonstrated accurate and reproducible infarct size measurements.5,13

Subsecond DE-CMR

Rapid imaging was performed with a single-shot, inversion-recovery, steady state free-precession sequence. Similar to standard imaging, an inversion recovery prepulse was used to accentuate the conspicuity of infarcted regions, and the inversion time was set to null normal myocardium (typically 20 to 50 ms longer than for the standard method). Dissimilar to standard imaging, parallel image acquisition14 was used to speed up imaging; however, this was at the cost of the signal-to-noise ratio. Importantly, the entire data set for 1 image was acquired in a single contiguous stream (single-shot) rather than in a segmented manner over several heartbeats. The patient was instructed to take slow and shallow breaths through the 25 to 30 seconds of image acquisition. A potential limitation is that translational motion of the heart during free breathing may result in asymmetrical coverage of the LV during image acquisition. To test the significance of this limitation, we performed subsecond imaging twice, immediately before and after standard imaging, in a subgroup of MI patients.

Parameter Matching

Even with parallel image acquisition, it is not possible for subsecond imaging to match both the high temporal and high spatial resolution of standard imaging. We chose to match the temporal resolution at the cost of a lower spatial resolution (Table 1); therefore, both standard and subsecond data acquisition occurs during a 207-ms time window during mid-diastole, to take advantage of the fact that the heart is relatively motionless during this time. We did not match the spatial resolution or pursue an intermediate compromise because any increase in data readout period would result in increased image blurring and partial volume effects due to substantial cardiac motion outside the diastolic standstill period, thus negating any potential improvement in spatial resolution.

Timing of DE-CMR Techniques

Subsecond imaging was performed immediately before standard imaging. Because subsecond imaging took <30 seconds to complete, there was little time delay between the 2 techniques, and the potential that time after contrast injection could account for possible differences in the results between the 2 techniques was minimized.

Table 1. Pulse Sequence Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard</th>
<th>Subsecond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution, ms</td>
<td>207</td>
<td>207†</td>
</tr>
<tr>
<td>Field of view, read, mm</td>
<td>320–400</td>
<td>320–400</td>
</tr>
<tr>
<td>Field of view, phase, %</td>
<td>81.3</td>
<td>83.3</td>
</tr>
<tr>
<td>Image matrix</td>
<td>166×256</td>
<td>104×192</td>
</tr>
<tr>
<td>Voxel size, mm³</td>
<td>1.8×1.4×0.6=15.1</td>
<td>2.9×1.9×0.6=33.1</td>
</tr>
<tr>
<td>Interslice gap, mm</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Repetition time, ms</td>
<td>9.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Echo time, ms</td>
<td>3.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Flip angle, degree</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Trigger pulse*</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Bandwidth, Hz/pixel</td>
<td>130</td>
<td>1130</td>
</tr>
<tr>
<td>Breath-hold</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Standard indicates segmented inversion-recovery, gradient-echo sequence; subsecond, single-shot inversion-recovery, steady state free precession.

†With parallel imaging acceleration (factor=2).
Analysis

Clinical Data

ECGs were analyzed for Q waves according to Minnesota codes 1-1-1 to 1-2-7,15 To determine Framingham risk score category, standard score sheets based on total cholesterol level were used (see Figures 3 and 4 of Wilson et al16).

CMR

Scans were placed in random order and scored visually by the consensus of 2 observers who were masked to patient identity and associated clinical information. Standard and subsecond images were read independently during separate sessions. Hyperenhancement was scored on a 17-segment model16 with a 5-point scale (0, no hyperenhancement; 1, 1% to 25%; 2, 26% to 50%; 3, 51% to 75%; 4, 76% to 100%).8 Infarct size as a percentage of LV myocardium was calculated by summing the regional scores (each weighted by the midpoint of the range of hyperenhancement) and dividing by the total number of regions.8 Hypoenhanced regions within hyperenhanced myocardium were interpreted as regions of microvascular obstruction (“no-reflow”) and included in infarct size calculations.12

To assess interobserver variability, images from 68 patients were randomly selected and scored independently by 2 readers. Cine images were evaluated separately from the DE-CMR images and scored for LV ejection fraction by visual inspection.17

Quantitative analysis was performed to evaluate potential mechanisms for differences in the accuracy of subsecond and standard imaging. Twenty-one patients from the infarct group who had hyperenhancement on both techniques were randomly selected. A single short-axis image with the largest hyperenhanced region was selected for each patient. Regions of interest were placed within infarct, remote myocardium, and LV cavity. Signal intensity (SI) ratios between the various compartments were calculated as follows: ratioinfarct/remote=mean SI of infarct/mean SI of remote; ratioinfarct/ cavity=mean SI of infarct/mean SI cavity.

Additionally, a region of interest was placed outside the body to measure the SD of background noise and to generate signal-to-noise ratios (SNR) and contrast-to-noise ratios (CNR) as follows: SNRinfarct=mean SI of infarct/(4.3×SD of background); CNRinfarct-to-remote=(mean SI of infarct−mean SI of remote)/(4.3×SD of background). The correction factor of 4.3 accounts for the underestimation of noise that occurs when noise is measured from magnitude images18 after adjustment for an 8-element coil array.19 This method of measuring noise has limitations in the setting of parallel imaging. On accelerated images such as subsecond images, the noise background varies with spatial position caused by the spatial dependence of noise amplification characterized by coil geometry.20 Thus, SNR and CNR values from subsecond images should be considered only an approximation.

Statistical Analysis

Continuous data are expressed as mean±SD, except where noted. Comparisons between patient groups were made with the use of the 2-sample t test for continuous data and χ² test for discrete data. Comparisons between imaging sequences were made with the paired t test for continuous data and McNemar test for discrete data. Bland-Altman21 and linear regression analyses were performed to assess the relationship between the 2 DE-CMR techniques for infarct size. Interobserver agreement for the presence of hyperenhancement was calculated with the κ statistic. All statistical tests were 2-tailed; P<0.05 was considered significant. Statistical analysis was performed with S-PLUS 6 (Insightful Corporation, Seattle, Wash).

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Patient Characteristics

Baseline characteristics for both patient groups are shown in Table 2. Slightly less than half (45%) of the infarct group had acute infarcts at the time of imaging. Twelve-lead ECGs were acquired in all patients from the infarct group and in 64 from the no-infarct group. The interval between ECG and CMR was 1±1, 5±14, and 6±11 days in acute MI, chronic MI, and no-infarct patients, respectively, and no patient had any cardiac events during this interval. Q waves were present in 46% of the infarct group and 0% of the no-infarct group. Cardiac enzyme values were available in 70% (95/135) of the infarct group. The remainder were referred from outside hospitals, and although the medical records of these patients clearly documented prior MI according to European Society of Cardiology/American College of Cardiology consensus criteria,2 including reference to the fact that enzyme levels were abnormal, the specific values were not available.

Infarct Detection

Both DE-CMR techniques were performed in all 238 patients. The overall diagnostic performance of the 2 techniques is displayed in Figure 1A. Standard imaging performed well in this highly selected cohort with a sensitivity of 98% and specificity of 100% for the diagnosis of MI.

The sensitivity of the subsecond technique was modestly lower at 87% (P<0.0001). Of the 17 MI patients who were missed, 2 were also missed by the standard technique. Of the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Infarct Group (n=135)</th>
<th>No-Infarct Group (n=103)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>60.2±13.5</td>
<td>43.1±16.5</td>
</tr>
<tr>
<td>Gender</td>
<td>Male</td>
<td>93 (69)</td>
</tr>
<tr>
<td>CHD risk factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diabetes</td>
<td>41 (30)</td>
<td>6 (6)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>85 (63)</td>
<td>22 (21)</td>
</tr>
<tr>
<td>Hyperlipidemia</td>
<td>59 (44)</td>
<td>16 (16)</td>
</tr>
<tr>
<td>Smoking</td>
<td>51 (38)</td>
<td>19 (18)</td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>71.3±14.0</td>
<td>71.8±13.3</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td>5 (4)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>LV ejection fraction, %*</td>
<td>41.9±12.7</td>
<td>64.7±5.6§</td>
</tr>
<tr>
<td>12-lead ECG (Q wave†)</td>
<td>59/135 (46)</td>
<td>0/64 (0)</td>
</tr>
<tr>
<td>Infarct characteristic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac enzymes on admission‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CK, U/L</td>
<td>891 (394, 2331)</td>
<td>…</td>
</tr>
<tr>
<td>CK-MB, ng/mL</td>
<td>99 (49, 204)</td>
<td>…</td>
</tr>
<tr>
<td>Troponin T, ng/mL</td>
<td>3 (1.2, 6.1)</td>
<td>…</td>
</tr>
<tr>
<td>Acute (&lt;14 d)</td>
<td>61 (45)</td>
<td>…</td>
</tr>
<tr>
<td>Chronic (&gt;14 d)</td>
<td>74 (55)</td>
<td>…</td>
</tr>
</tbody>
</table>

Values are expressed as mean±SD, n (%), or median (25th, 75th percentile). CHD indicates coronary heart disease; CK, creatine kinase.

* Determined by cine CMR.
† According to Minnesota codes 1-1-1 to 1-2-7.
‡ Cardiac enzyme values were available in 95 patients.
§ All with normal LV ejection fraction and no regional wall motion abnormalities.

EGCs were obtained in 64 of the no-infarct group subjects within 10 weeks of CMR.

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remaining 15 patients, the majority (13/15; 87%) had either small (≤10% of LV myocardium) or subendocardial (≤50% transmural extent) infarcts (Figure 1B). Two patients were exceptions in that the missed infarcts were both large and transmural. One had an acute infarct with an extensive no-reflow zone, and the other had a very patchy infarct. The sensitivity of the subsecond technique was lower for both acute (85% versus 98%; \(P=0.005\)) and chronic infarcts (89% versus 99%; \(P=0.008\)). Additionally, in patients with acute infarcts (n = 61), the subsecond technique detected fewer no-reflow zones than the standard technique (14/61 [23%] versus 25/61 [41%]; \(P=0.0009\)). Representative patient images, demonstrating concordance and discordance of hyperenhancement patterns between the 2 techniques, are shown in Figures 2 and 3.

The specificity of the subsecond technique was excellent at 96%. In the few patients (n = 4) in whom false-positive infarcts were detected, the presumed infarct region was near high-SI epicardial fat in all cases (Figure 3c).

**Global Infarct Size**

Infarcts were generally smaller on the subsecond technique compared with the standard technique (12.1 ± 9.3% versus 17.0 ± 11.2% of LV; \(P<0.0001\)). By Bland-Altman analysis (Figure 4A), the average underestimation of infarct size by the subsecond technique was 4.9% of LV, and the 95% limits of agreement were −7.1% and 17.0% of LV. The plot, however, was partially skewed in that the bias was less for smaller infarct sizes. By linear regression analysis (Figure 4B), the subsecond technique underestimated infarct size by 31 ± 4% (slope = 0.69 ± 0.04). When the infarcts were assigned to coronary territories according to the 17-segment model, infarct size was moderately underestimated by the subsecond technique in all 3 (left anterior descending coronary artery, 13.0 ± 17.8% versus 18.4 ± 23.9%; left circumflex artery, 9.1 ± 13.2% versus 12.8 ± 14.3%; right coronary artery, 13.8 ± 16.3% versus 19.4 ± 18.4% of LV; \(P<0.0001\) for all).

In the subcohort of 68 patients in whom interobserver variability was assessed for the presence of hyperenhancement, there

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**Figure 1.** Sensitivity, specificity, and diagnostic accuracy of standard and subsecond DE-CMR for the detection of MI (A). The sensitivity of subsecond imaging was reduced primarily in small or subendocardial infarcts (B).
was excellent agreement ($\kappa=0.97$). The difference in mean infarct size between the 2 readers was not significant (0.4±3.3% of LV; $P=0.3123$). By Bland-Altman analysis, the 95% limits of agreement were −6.1% and 6.9% of LV.

### Transmural Extent of Infarction

Table 3 displays the comparison of the transmural extent of infarction (TEI) between the 2 techniques on a regional basis. This analysis was based on 2294 regions (135 patients×17 regions=2295 regions; in 1 patient the true apex, region 17, was not imaged). Overall, the concordance was high at 91% (2083/2294). However, there was a systematic, albeit modest, underestimation of TEI by the subsecond technique (Figure 3B). Whereas 536 regions (23%) by the subsecond technique had TEI scores less than that of the standard technique (360 of which were 1 grade less), only 150 (6.5%) had higher scores. In regard to the 337 regions that were deemed predominantly infarcted (>50% TEI) by the standard technique, 51 (15%) were considered predominantly viable (≤25% TEI) by the subsecond technique.

### Influence of Time After Contrast Injection, Heart Rate, and Arrhythmia

In the subgroup of 11 patients in whom the subsecond technique was performed immediately before and after the standard technique, infarct size was virtually identical (22.1±9.8% versus 22.2±10.7% of LV). Bland-Altman analysis demonstrated narrow limits of agreement (−2.5% and 2.3% of LV). The heart rate in patients in whom infarction was detected by the subsecond technique was not significantly different from those in whom infarction was missed (71.4±13.8 versus 70.7±15.4; $P=0.84$). Only 5 patients had arrhythmia. All 5 had atrial fibrillation and were from the infarct group. In these 5, infarcts were detected by both techniques.

### Quantitative Analysis

Table 4 displays the quantitative analysis performed in the randomly selected cohort of 21 patients with infarction detected by both techniques. The SNR values of both infarct and remote myocardium were moderately lower for the subsecond technique. Likewise, the CNR values of infarct-to-remote and infarct-to-cavity were also lower. The SI ratios demonstrate that the subsecond technique led to reduced differences between infarct and remote myocardium and between infarct and LV cavity.

### Discussion

The main finding of this study is that MI can be accurately detected (91% accuracy) with the use of an ultrafast DE-CMR technique that can acquire snapshot images during free breathing. Importantly, the technique was robust and provided full coverage of the heart in ≤30 seconds, and specificity was excellent at 96%. However, there were some limitations compared with the standard approach. Sensitivity was 11% lower (87% versus 98%), and there was a tendency to underestimate both global infarct size and the transmural extent of infarction.

Despite these limitations, the development of subsecond imaging has important clinical implications. For instance, although CMR is a highly attractive modality for the assessment of MI and viability, some practical drawbacks potentially limit the impact of this technology for general clinical practice. In comparison to other imaging modalities, standard
CMR is more complex: Patient and protocol setup times are longer, and multiple breath-holds and longer scanning times are necessary. These conditions limit clinical throughput and the types of patients that can be scanned and increase the complexity and length of training required for CMR operators. On the other hand, single-shot CMR techniques such as subsecond imaging could potentially overcome a number of these drawbacks. As we have demonstrated in the present study, breath-holding is not necessary, and although we performed subsecond imaging with ECG gating to allow a precise comparison of the 2 techniques, we note that gating is not required for single-shot techniques. Indeed, one could imagine a scenario in which a patient is given intravenous gadolinium contrast while outside the scanner, then 5 to 10 minutes later is placed on the scanner table with minimal preparation (no ECG leads, no breath-holding instructions). Then a relatively fixed subsecond protocol is run without adjustment of parameters for breath-hold time or ECG gating, with rapid assessment of MI performed in under a minute. In this scenario, DE-CMR becomes a quick “push-button” technique with the ability to scan a wide range of patients, including those more acutely ill or with dyspnea.

Although subsecond imaging had reduced sensitivity compared with standard imaging, to place this result in context, we note that current methods for the detection of MI have significant limitations. For example, according to the European Society of Cardiology/American College of Cardiology consensus document, the 12-lead ECG is one of the fundamental tools for the diagnosis of chronic MI. However, Q waves, on which the diagnosis is based, are often absent in small or lateral wall infarcts. In fact, in the present study, only 49% of patients with chronic MI (36/74) and 16% of patients with lateral wall MI (4/25) had Q waves. In contrast, subsecond imaging had markedly higher sensitivity at 89% (66/74) and 80% (20/25), respectively.

One potential reason for the disparity in diagnostic sensitivity between the 2 DE-CMR techniques may be the difference in spatial resolution. Typical voxel sizes for the subsecond technique were 2.2-fold larger than for the standard technique. This reduction in spatial resolution and subsequent increase in partial volume effects may in part be responsible for both inconsistent identification of small infarcts and less accurate characterization of the transmural extent of infarction. Additionally, it is perhaps not surprising that no-reflow zones were particularly difficult to identify on the subsecond technique. Because partial volume effects are pronounced at the borders between different tissues, the multiple transitions

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**Figure 3.** Representative images in patients showing discordant hyperenhancement patterns between standard and subsecond imaging. A shows typical examples of infarcts that were missed by subsecond imaging (false-negative) either because of small size (patient 4), only subendocardial involvement that was difficult to distinguish from the LV cavity (patient 5), or the presence of a large central no-reflow zone (patient 6). B shows an infarct that was detected by both DE-CMR techniques; however, the transmural extent of infarction was significantly less on subsecond compared with standard imaging (patient 7; also see cartoon). C shows 2 patients without MI who were incorrectly diagnosed with MI by subsecond imaging. In both cases, the presumed infarct region was near high-SI epicardial fat, either apically (patient 8) or near the atrioventricular groove (patient 9).
that characterize no-reflow zone–type MI—dark no-reflow zone to bright infarct to dark noninfarcted myocardium—within a limited space likely render this pathophysiology more susceptible to partial volume effects (Figure 3A). Partial volume effects also likely explain the 4 patients without MI who were incorrectly scored positive by the subsecond technique. In all 4 cases, the presumed infarct region was near epicardial fat, which is high in SI.

Another potential reason for the reduced sensitivity of the subsecond technique may relate to differences in tissue contrast between the 2 techniques. Quantitative analysis demonstrated reduced CNRs between infarct and remote myocardium and between infarct and LV cavity. Interestingly, in retrospect, we found that tissue contrast between infarct and LV cavity was of particular importance. Although, on average, SI differences between infarct and LV cavity were modest for both techniques, for the standard technique the infarct was brighter than cavity in the majority of patients (90%), whereas for the subsecond technique the relationship was reversed, and cavity was brighter than infarct in 90%. In the absence of infarction, the normal progression of SIs for both techniques is as follows: dark myocardium, gray transition zone between myocardium and cavity, then bright cavity. In the presence of subendocardial infarction, the progression of SIs for the subsecond technique—dark epicardium, gray subendocardial infarction, then bright cavity—was occasionally difficult to distinguish from normal. In hindsight, in many cases of “missed” subendocardial infarction by subsec-

Figure 4. Bland-Altman (A) and regression analyses (B) comparing infarct size (percentage of LV) between standard and subsecond imaging. See text for details.

<table>
<thead>
<tr>
<th>TABLE 3. Regional Analysis</th>
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<tr>
<td></td>
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<tr>
<td>Standard (TEI)</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Subsecond (TEI)</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>0%</td>
</tr>
<tr>
<td>1%–25%</td>
</tr>
<tr>
<td>26%–50%</td>
</tr>
<tr>
<td>51%–75%</td>
</tr>
<tr>
<td>76%–100%</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

*TEI scores that are concordant between the 2 techniques (defined as TEI scores that are within 1 category of each other).
ond imaging, the infarct was clearly distinct and brighter than noninfarcted myocardium. Instead, the error was in considering the subendocardial infarct as part of the LV cavity (Figure 3A, patient 5). The use of a multicontrast version of DE-CMR that acquires both T1 and T2 contrasts within a single acquisition may improve the discrimination between MI and LV cavity.24

In part, the differences in tissue contrast may be due to inherent properties of the standard and subsecond pulse sequences. For both sequences, data readout is preceded by an inversion-recovery pulse for strong T1 weighting. However, unlike the spoiled gradient-echo readout of the standard sequence, the steady state free-precession readout of the subsecond sequence can also lead to significant T2 weighting, especially at higher flip angles.11,25 Steady state free precession was used because it provides intrinsically high signal-to-noise ratios.11,25 This advantage was utilized by incorporating high bandwidth (9-fold higher than standard) and parallel image acquisition,14 both of which reduce SNR, to provide sufficient temporal and spatial resolution. New approaches in which SNR is improved further by averaging multiple single-shot images after motion correction may hold promise.26

In summary, subsecond imaging has both advantages and disadvantages compared with standard imaging. Therefore, the results suggest that the choice of technique should be based on multiple factors, including logistical issues at the CMR center, the technical knowledge level of the CMR operators, and patient-specific concerns such as the presence of arrhythmia, ability to breathe-hold, and acuity of illness. Despite some limitations, the development of subsecond imaging is a significant advance for the clinical practice of CMR. Now there is a potential alternative to images with motion artifacts or no images at all in patients who were not referred to CMR because of dyspnea or inability to undergo a prolonged examination. Indeed, the speed and ease of use of subsecond imaging are such that even in patients for whom the standard technique should be preferred, eg, for the evaluation of myocardial viability for revascularization decisions, the common practice in our laboratory is to perform subsecond imaging first. This preference is based on the minimal cost (because the total scan time is virtually the same) and the potentially large benefit in patients who have their scans prematurely terminated before standard imaging is completed (because of fatigue or illness) or in patients for whom findings can be confirmed when motion artifacts are troublesome on the standard images.

Sources of Funding
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Disclosures
Drs Kim and Judd are inventors of a US patent on delayed enhancement MRI, which is owned by Northwestern University. Drs Kim and Judd have previously received grant support from Siemens Medical Solutions and have been consultants for Mallinckrodt/Tyco, Inc. Dr Rehwald is an employee of Siemens Medical Systems, Inc.

References

### Table 4: Quantitative Analysis

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Subsecond</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR Infarct</td>
<td>24.8±7.2</td>
<td>15.3±7.7</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>SNR Remote</td>
<td>4.7±1.2</td>
<td>3.3±0.8</td>
<td>0.0003</td>
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<tr>
<td>CNR Infarct-to-remote</td>
<td>20.1±6.6</td>
<td>12.0±7.2</td>
<td>&lt;0.0001</td>
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<tr>
<td>CNR Infarct-to-cavity</td>
<td>3.6±3.7</td>
<td>-2.5±2.7</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Ratio Infarct/remote</td>
<td>5.1±1.4</td>
<td>4.3±1.6</td>
<td>0.0037</td>
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<tr>
<td>Ratio Infarct/cavity</td>
<td>1.1±0.2</td>
<td>0.9±0.1</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

*Twenty-one patients from the infarct group who had hyperenhancement on both techniques were randomly selected for quantitative analysis.*


**CLINICAL PERSPECTIVE**

Cardiovascular magnetic resonance (CMR) is a highly attractive modality for the assessment of myocardial infarction and viability because of high spatial resolution and accuracy. However, some practical drawbacks potentially limit the impact of this technology for general clinical use. In comparison to some imaging modalities, standard CMR is more complex: Patient and protocol setup times are longer, and multiple breath-holds and longer scanning times are necessary. These conditions limit clinical throughput and the types of patients that can be scanned and increase the complexity and length of CMR training. A new delayed contrast-enhancement CMR technique that can acquire subsecond, “snapshot” images during free breathing (subsecond technique) could potentially overcome a number of these drawbacks and provide myocardial infarction imaging with complete left ventricular coverage in <30 seconds. In the present study, we compared the accuracy of subsecond delayed contrast-enhancement CMR with standard delayed contrast-enhancement CMR in 238 patients. We found that with the subsecond technique, the sensitivity for detecting myocardial infarction was mildly reduced (87%), but specificity and accuracy were excellent (96% and 91%, respectively). There was a tendency to underestimate the transmural extent of infarction, but overall, the techniques were highly concordant. Together, these results demonstrate that myocardial infarction can be detected rapidly by subsecond delayed contrast-enhancement CMR during free breathing with high accuracy. The clinical implication is that delayed contrast-enhancement CMR can become a quick “push-button” technique with the ability to scan a wide range of patients, including those who are more acutely ill, those with dyspnea, or those unable to undergo a prolonged examination. Moreover, clinical throughput could be increased multifold.
Rapid Detection of Myocardial Infarction by Subsecond, Free-Breathing Delayed Contrast-Enhancement Cardiovascular Magnetic Resonance

Burkhard Sievers, Michael D. Elliott, Lynne M. Hurwitz, Timothy S.E. Albert, Igor Klem, Wolfgang G. Rehwald, Michele A. Parker, Robert M. Judd and Raymond J. Kim

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