Spiral Magnetic Resonance Coronary Angiography With Rapid Real-Time Localization

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OBJECTIVES A spiral high-resolution coronary artery imaging sequence (SH) interfaced with real-time localization system (RT) has been developed. A clinical study of 40 patients suspected of coronary artery disease (CAD) was conducted.

BACKGROUND Segmented k-space acquisition techniques have dominated magnetic resonance coronary angiography (MRCA) over the last decade. Although a recent multicenter trial using this technique demonstrated encouraging results, the technique was hampered by low specificity. Spiral k-space acquisition had demonstrated several advantages for MRCA. Therefore, a first clinical trial implementing spiral high-resolution coronary imaging sequence with real-time localization (SH-RT) was performed.

METHODS A clinical study of 40 patients suspected of CAD undergoing X-ray angiography was conducted to analyze the clinical reliability of this novel imaging system. The SH-RT had been designed to exploit the unique capability of two imaging sequences. The RT allowed a rapid localization of the coronary arteries. Then SH achieved multislice acquisition during a short breath-hold with submillimeter resolution. The MRCA data were analyzed for scan time, anatomic coverage, image quality, and accuracy in detecting CAD.

RESULTS In 40 subjects, SH achieved 0.7 to 0.9 mm resolution with 14-heartbeat breath-holds. Excellent or good image quality was achieved in 78% (263/337) of the coronary segments. Blinded consensus reading among three observers generated sensitivity of 76% and specificity of 91% in the detection of CAD compared with X-ray angiography.

CONCLUSIONS The MRCA imaging sequence implementing a novel spiral k-space acquisition technique enabled rapid and reliable imaging of the CAD in submillimeter resolution with short breath-holds. (J Am Coll Cardiol 2003;41:1134–41) © 2003 by the American College of Cardiology Foundation

Over the last decade, segmented k-space imaging has dominated magnetic resonance coronary angiography (MRCA) (1–4). Although the results of the recent multicenter trial have been encouraging, the technique was hampered by low specificity (5). Application of more complex k-space acquisitions has demonstrated potential advantages over segmented k-space in MRCA (6). Several preliminary studies have reported improved imaging efficacy in MRCA using the spiral k-space trajectory (7–11). Therefore, we conducted the first clinical trial of MRCA utilizing a spiral k-space acquisition strategy optimized for efficient signal read-out and minimum off-resonance artifacts (11).

There are fundamental challenges in MRCA. The coronary arteries are small (<4 mm), tortuous, embedded in tissue with competing magnetic resonance signals, and in aperiodic motion due to cardiac contraction and respiration (2). Although spiral imaging has additional implementation requirements and off-resonance sensitivity, the technique provides improved temporal and spatial resolution, increased signal-to-noise ratio (SNR), and excellent flow properties (11–13). In order to investigate the potential advantages of spirals in MRCA, a spiral high-resolution coronary artery imaging sequence (SH) interfaced with a real-time localization system (RT) has been developed.

Real-time localization of the coronary arteries without cardiac or respiratory gating by RT allowed rapid and complete coverage of the desired coronary plane (14,15). The SH achieved ultrafast, high-resolution image acquisition with spatial resolution of 0.7- to 0.9-mm, temporal resolution of 34 ms, and large volumetric coverage with minimum misregistration (11). Breath-hold intervals for SH were held at 14 heartbeats. The coronary artery and phantom images using SH-RT protocol are shown in Figure 1.

This trial was conducted to test the clinical implementation of the SH-RT system. Forty patients suspected of coronary artery disease (CAD) were studied. The primary end point was to validate this imaging platform by systematic analysis of the scan time, anatomic coverage, image quality, and accuracy in detection of CAD.

METHODS

Patient population. A total of 44 patients (37 men, 7 women; age 40 to 86 years; weight 150 to 250 lbs) were enrolled sequentially in the study. Forty patients (27 dis-
eased and 13 normal coronary anatomy) were included in data analysis. A total of 30 patients had undergone MRCA within one month before X-ray coronary angiography; 10 patients had MRCA after X-ray angiography. The investigators performing MRCA in these patients were blinded to the angiographic results with no prior knowledge of the coronary findings. Four patients who refused the study due to immediate claustrophobia were excluded. The study protocol was approved by the Human Subjects Committee at Stanford University. The patients were enrolled from both Stanford and Palo Alto Veterans Administration Medical Centers. All participants were informed of the study and gave written informed consent. Patients were ineligible if they had arrhythmias, unstable clinical condition, stent, coronary artery bypass graft surgery, or contraindications to undergo magnetic resonance imaging scan as listed on the screening form.

**SH.** A detailed description of spiral coronary artery imaging has been reported by Meyer et al. (11). High-resolution parameters consisted of an 11.8-ms spectral spatial pulse, 60° to 70° flip angle, 6.9-ms echo time, and 16.4-ms acquisition window per slice with one read-out per slice per heartbeat. The slices were acquired in sequential spatial order, and temporal spacing between adjacent slices was 34 ms. The time-varying oscillating x and y gradients traversed a spiral k-space starting at the origin to minimize flow artifact. The multislice spiral imaging sequence allowed two-dimensional acquisition of 5 to 15 slices per breath-hold scan. Imaging protocol consisting of five slices and slice thickness of 5-mm was selected to optimize coverage, SNR, and contrast-to-noise ratio (CNR) of the coronary artery images. Adjustment of imaging plane was performed when necessary. Fourteen interleaves were acquired with cardiac gating during diastole (14 heartbeats) in a single breath-hold with minimal misregistration. Image reconstruction was done on-line. Receiver bandwidth was ±125 kHz corresponding to a data sampling time of 4 ms. There were 4,096 data points per interleaf generating a total number of 57,344 data points per slice (14 × 4,096). A field of view (FOV) of 24 cm and 14 spiral interleaves at gradient strength of 25 to 40 mT/m allowed spatial resolution of 0.7

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**Abbreviations and Acronyms**

- **CAD** = coronary artery disease
- **CNR** = contrast-to-noise ratio
- **FOV** = field of view
- **LAD** = left anterior descending coronary artery
- **LCx** = left circumflex coronary artery
- **LMCA** = left main coronary artery
- **MRCA** = magnetic resonance coronary angiography
- **RCA** = right coronary artery
- **RT** = real-time localization system
- **SH** = spiral high-resolution coronary artery imaging sequence
- **SNR** = signal-to-noise ratio

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**Figure 1.** Representative spiral high-resolution coronary artery imaging sequence (SH) images obtained from normal volunteers at varying resolution and breath-hold duration. (a) Left anterior descending coronary artery and diagonal arteries: 0.7-mm spatial resolution at 14 heart-beat breath-hold duration. (b) Distal right coronary artery: 0.7-mm spatial resolution at 14 heart-beat breath-hold duration. (c) Phantom image obtained using SH. A white block arrow points out the array of fiducial markers at 1-mm resolution.
to 0.9 mm. A timing diagram and \( k \)-space trajectory of SH are shown in Figure 2.

**RT.** A detailed description of the RT has been reported by Kerr et al. (14). The RT required a modest hardware upgrade to a conventional 1.5-T Signa MRI Scanner (GE, Milwaukee, Wisconsin) equipped with high-performance gradients capable of 40 mT/m amplitude and 150 mT/m/ms slew rate. The upgrade consisted of a bus adapter (model 943, Bit 3 Computer Corporation, St. Paul, Minnesota) and a workstation (Sun Sparc, Sun Microsystems, Mountain View, California). The bus adapter allowed rapid access of the raw data. The workstation directly controlled the magnet and its associated hardware to reconstruct, display, and interact with the images in real-time (lag-time <500 ms). An X-window protocol enabled interactive graphical manipulations of scan parameters and images. A gradient-recalled echo pulse sequence (30-ms repetition time, 4.6-ms echo time, and 30° flip angle) utilizing 7.68-ms spectral spatial pulse and 16-ms spiral read-out was implemented. A frame rate of 16 images/s interpolated from 6 complete images/s on the fly allowed a spatial resolution of 2.25-mm with a FOV of 24 cm. Dynamic linear shimming had been incorporated to minimize off-resonance effects.

**Protocol.** Study patients underwent both RT and SH in the supine position. The RT allowed rapid localization of the four main coronary arteries without any breath-holding or cardiac gating. The scan-plane prescription of each coronary artery was then saved and transferred to the SH. Representative RT images are shown in Figure 3.

The SH triggered to the cardiac cycle using a plethysmogram and required breath-holding over 14 heartbeats. With each coronary prescription, SH imaging was performed on the fly. Five slices, each 5-mm thick, were obtained with each breath-hold. Imaging parameters including prescription plane, slice-offset, gradient strength, and number of slices were adjusted as needed. A 5-inch diameter surface coil was used for signal reception in both RT and SH.

**Data evaluation.** All MRCA images were evaluated independently by a total of four observers experienced in MRCA. The MRCA image sets were analyzed using the original MRCA source images. First, the scan time for each imaging sequence was measured. Second, the coverage of coronary anatomy was based on the number of the coronary segments seen in each coronary artery by MRCA compared with X-ray coronary angiography. One observer studied the MRCA image sets, and another observer analyzed the coronary angiogram. The coronary segments were identified according to the American Heart Association classification system (16,17). Side branches were not included. Third, image quality of each coronary segment was judged using a grading scale based on the extent of the contiguity of the vessel border of a given segment with minimum artifact (measured in percentage) and the amount of artifact present in the segment (interruption of the vessel border definition). The scale ranged from 1 to 4 (1 = excellent quality, >91% contiguity of the vessel border of a given segment with minimum artifact; 2 = good quality, 75% to 90% contiguity with minimum to mild artifact; 3 = fair quality, 51% to 74% contiguity with minimum to moderate artifact; and 4 = nondiagnostic quality, <50% contiguity). Finally, three observers who were blinded from the findings on the coronary angiogram reviewed the SH images of the four major coronary arteries to identify the coronary lesions. A coronary lesion was identified by the degree of signal loss compared with an adjacent normal segment. This signal loss may be either smooth or irregular, and symmetric or asymmetric in appearance (2,4). In both readings, any disagreement in the presence or absence of a coronary lesion among the observers was resolved in consensus.

**Coronary angiography.** In all patients, coronary angiography was performed by the transfemoral Judkins approach. Angiograms documented in digitized format allowed spatial resolution of 0.3 mm. Classification of the coronary segments was described above. All stenoses >50% constituted
CAD. The X-ray angiogram was analyzed by the interventional cardiologists who performed the procedure.

**Statistical analysis.** The visualization of coronary segments and the detection of diseased and normal coronary arteries were given in percent, specificity, and sensitivity values. The image quality for the coronary segments was given in mean grade value/SD. Kappa value was calculated to assess interobserver agreement. A p value <0.05 was considered significant.

**RESULTS**

**Scan time.** The scan time to prescribe all four coronary arteries using RT ranged from 3 to 12 min; the high-resolution scan obtained by SH ranged from 5 to 40 min. Because we allowed optimization of the image quality during the scan, scan time duration of each study was not kept to minimum. Duration and frequency of breath-hold was another major consideration. The acquisition time for each coronary scan was considered optimal at 14 heartbeat breath-hold time or/15 s (18). The mean number of breath-holds per patient (coronary scans) was 10 ± 6. All patients tolerated the 14-heartbeat breath-hold.

**Coverage of coronary anatomy.** Coronary angiography revealed a total of 337 coronary segments. The SH-RT imaged 94% (317/337) of the main coronary segments seen with coronary angiography. The mean percentage of the coronary segments seen in each coronary artery was the following: 1) right coronary artery (RCA) 99% (100/101); 2) left main coronary artery (LMCA) 100% (40/40); 3) left anterior descending coronary artery (LAD) 95% (111/116); and 4) left circumflex coronary artery (LCx) 82% (66/80).

Table 1 details the number and percentage of each coronary segment seen in the coronary arteries.

**Image quality of the coronary segments.** Excellent or good (grade 1 to 2) image quality was obtained in 78% of all the coronary segments as shown in Figure 4 (panels a, c, e, g, i, k). These segments were LMCA, proximal-LAD, mid-LAD, proximal-RCA, mid-RCA, distal-RCA, and proximal-LCx. Fair image quality (grade 3) was obtained in 17% of all the coronary segments mostly located in the distal-LCx and -LAD. Nondiagnostic (grade 4) image quality was demonstrated in approximately 5% of the coronary segments also located in distal-LCx and -LAD. Table 2 details the mean image quality in each coronary segment.
Figure 4. Representative spiral high-resolution coronary artery imaging sequence (SH) and X-ray angiographic images of mild, moderate, severe, and totally occluded coronary lesions (white solid arrow). (a and b) Mild proximal-left anterior descending coronary artery (LAD) lesion, (c and d) mild proximal-LAD lesion, (e and f) totally occluded mid-right coronary artery (RCA) lesion, (g and h) moderate distal-RCA lesion, (i and j) mild proximal-left circumflex coronary artery (LCx) lesion, and (k and l) severe proximal-LCx lesion and poststenotic dilation. Continued on next page.
Detection of the coronary lesions. A total of 41 coronary lesions were seen on the X-ray coronary angiography. There were 21 proximal-, mid-, and distal-RCA; 16 proximal-, mid-, and distal-LAD; and 4 proximal-LCx lesions. Consensus analysis of the coronary arteries generated overall sensitivity of 76% and specificity of 91%. Interobserver agreement (kappa) was 0.59 (p < 0.05). On per patient basis, the sensitivity and specificity were 78% (21/27) and
85% (11/13), respectively. The frequency of CAD in the population was 63% (27/40). Additional sensitivity and specificity data on the individual RCA, LMCA, LAD, and LCx arteries are detailed in Table 3. Representative SH images and corresponding conventional angiograms of the coronary lesions are demonstrated in Figure 4.

**DISCUSSION**

In this study the primary objective was to investigate the reliability of spiral k-space imaging through a systematic analysis of the data obtained from patients suspected of CAD. The study design enabled methodical investigation of clinical application of this technique by assessing scan time, coronary coverage, image quality, and accuracy in detecting CAD.

Issues in MRCA include temporal and spatial resolution, SNR, CNR, and spatial coverage. Our current MRCA protocol was designed to address these issues. Spiral imaging has been reported to provide several advantages over commonly used segmented approaches (7–11). High temporal resolution was achieved through efficient data collection and rapid k-space coverage resulting in short acquisition time (12). Blurring from coronary artery motion often seen in segmented strategy with extended acquisition window was minimized (19–21). Improved spatial resolution was obtained through full k-space coverage instead of partial k-space coverage in segmented approach (12). Image artifact was reduced through excellent flow characteristics of spirals due to short TE and small phase shifts in the k-space origin (13). Also, the requirement of fewer excitations per heart-beat allowed larger flip-angle excitation generating higher SNR (12). Furthermore, CNR was enhanced by more robust fat suppression through spectral-spatial excitation rather than conventional fat saturation (22). Finally, accurate localization of desired coronary plane in fluoroscopic mode enabled by RT and multislice imaging capability of SH provided precise and wide spatial coverage.

Clinically, this study demonstrated robustness and reliability of the technique. The combination of real-time localization and short breath-hold imaging enabled visualization of high percentage of coronary segments and produced consistent image quality. We found that the breath-holds kept to 14 heartbeats were well-tolerated even when done consecutively for 10 breath-holds. Furthermore, the sensitivity and specificity data represented potential clinical reliability. Although the overall exam time was not kept to minimum in this study, the technique demonstrated the potential of completing each exam in <30 min.

**Study limitations.** Despite these promising findings, the SH-RT still has limitations for routine clinical implementation. First, SH must achieve higher SNR and CNR, particularly for the distal vessels. As the image quality data indicate, the distal segments of the LCx and LAD arteries continue to be problematic. Techniques including threedimensional stack of spirals and improved coil design may address SNR issues for the LCx artery coverage along the lateral and posterior walls (23). While fat was well-suppressed, strategies to improve CNR by suppressing the competing signals from the surrounding myocardium would be necessary in the LAD artery along the distal anterior wall. Contrast mechanisms including magnetization transfer, T2-prep, steady-state free precession, and inversion preparation would be useful for suppression of the surrounding structures to enhance the visualization of the coronary arteries (24–27). Second, the 2.25-mm spatial resolution of the RT limited the ability to localize the imaging plane of coronary lesions. A prototype RT sequence with spatial resolution in the 1-mm range is currently undergoing optimization (28); RT imaging at higher spatial resolution will allow a more accurate localization of the coronary plane to provide enhanced SH images of the coronary lesions. Recently, adaptive real-time architecture enabling seamless transition from RT to gated SH imaging has been developed. This technique provides flexibility in imaging protocol to enable more accurate and rapid imaging (29). The third limitation consisted of breath-hold duration. While all patients tolerated the breath-holds in this study, even shorter breath-holds would lead to better patient tolerance and, ultimately, better data. Alternatively, we are continuing investigation of navigator-enhanced three-dimensional spiral coronary sequences to allow for improved free-breathing MRCA (23,30). In addition, the sensitivity data demonstrated a need for more accurate detection of the

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**Table 2.** Mean Image Quality (1 to 4) of Each Coronary Segment

<table>
<thead>
<tr>
<th></th>
<th>p-RCA</th>
<th>m-RCA</th>
<th>d-RCA</th>
<th>LMCA</th>
<th>p-LAD</th>
<th>m-LAD</th>
<th>d-LAD</th>
<th>p-LCx</th>
<th>d-LCx</th>
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<tbody>
<tr>
<td>MIQ</td>
<td>1.13</td>
<td>1.27</td>
<td>1.78</td>
<td>1.24</td>
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<td>1.38</td>
<td>2.53</td>
<td>1.53</td>
<td>2.68</td>
</tr>
<tr>
<td>±SD</td>
<td>0.24</td>
<td>0.43</td>
<td>0.86</td>
<td>0.40</td>
<td>0.39</td>
<td>0.55</td>
<td>0.77</td>
<td>0.69</td>
<td>1.01</td>
</tr>
</tbody>
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d = distal; LAD = left anterior descending artery; LCx = left circumflex artery; LMCA = left main coronary artery; m = mid; MIQ = mean image quality; p = proximal; RCA = right coronary artery.

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**Table 3.** Sensitivity and Specificity (Total Number) of SH-RT Images in the Detection of Lesions in Individual Coronary Artery and of Patients With Coronary Artery Disease

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity</th>
<th>Specificity</th>
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<tbody>
<tr>
<td>RCA</td>
<td>76% (16/21)</td>
<td>79% (15/19)</td>
</tr>
<tr>
<td>LMCA</td>
<td>NA</td>
<td>100% (40/40)</td>
</tr>
<tr>
<td>LAD</td>
<td>87% (14/16)</td>
<td>88% (21/24)</td>
</tr>
<tr>
<td>LCx</td>
<td>25% (1/4)</td>
<td>89% (32/36)</td>
</tr>
<tr>
<td>Overall (artery)</td>
<td>76% (31/41)</td>
<td>91% (108/119)</td>
</tr>
<tr>
<td>Overall (patient)</td>
<td>78% (21/27)</td>
<td>85% (11/13)</td>
</tr>
</tbody>
</table>

LAD = left anterior descending artery; LCx = left circumflex artery; LMCA = left main coronary artery; NA = not applicable; RCA = right coronary artery; SH-RT = spiral high-resolution coronary artery imaging with real-time localization.
coronary lesions. Improved SNR, CNR, coverage, and motion sensitivity would improve the delineation of the lesions. Furthermore, a more detailed definition of the fair quality in image scale would have provided more information on the visualization of the distal coronary segments, a known limitation in MRCA. Finally, patient recruitment may have been problematic. The pre-test probability of the subjects was high, as they were patients referred for cardiac catheterization. A cohort with lower prevalence of CAD would reduce such bias.

Conclusions. In conclusion, our study represents the first clinical evaluation of spiral $k$-space imaging in MRCA. This study provides data supporting the potential clinical implementation of this technique. The unique capabilities of the combined real-time and high-resolution spiral sequences have been exploited to enable rapid, accurate, and robust imaging of CAD.

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