Real-Time Interactive Coronary MRA

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An interactive real-time imaging system capable of rapid coronary artery imaging is described. High-resolution spiral and circular echo planar trajectories were used to achieve 0.8 × 1.6 mm^2 resolution in 135 ms (CEPI) or 1.13 × 1.13 mm^2 resolution in 189 ms (spirals), over a 20-cm FOV. Using a sliding window reconstruction, display rates of up to 37 images/sec were achieved. Initial results indicate this technique can perform as a high-quality 2D coronary localizer and with SNR improvement may enable rapid screening of the coronary tree. Magn Reson Med 46:430–435, 2001. © 2001 Wiley-Liss, Inc.

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The first successful coronary imaging trials using MRI used images between 1.1 and 1.5 mm in spatial resolution and acquired them over windows of 150–250 ms per cardiac cycle. In these studies, coronary evaluation with sensitivities and specificities on the order of 63–90% were reported (1–3). With the hardware and pulse sequence improvements that have occurred over the past 10 years, commercially available scanners are now capable of acquiring greater spatial and temporal resolution even in real-time. In this article, we discuss the resolution capabilities of three popular fast imaging *k*-space trajectories on a conventional scanner and present a real-time interactive system for rapid coronary imaging.

Real-time interactive (RTI) imaging is a popular and robust cardiac imaging technique because it: 1) does not require gating or breathholding, 2) enables the observation of dynamic motion, and 3) enables the rapid localization of scan planes containing desired cardiac views. However, it is a challenge to achieve high spatial and temporal resolution simultaneously in real time while maintaining a sufficiently high SNR. Real-time coronary artery imaging is particularly difficult due to the small vessel size and the significant vessel motion. However, one notable advantage of real-time acquisition is the availability of multiple images of the same slice. This can be used to selectively average images for improved SNR, as demonstrated by Hardy et al. (4,5). Alternatively, multiple images acquired with asymmetric resolution and high resolution in different directions can be combined in some intelligent way, either computationally or visually by the human observer (6).

A conventional use for RTI imaging is in scan plane localization for high-resolution 2D coronary imaging sequences (7–9). We present a similar high-resolution RTI imaging approach that achieves submillimeter resolution in short acquisition windows. Preliminary results in normal volunteers indicate this is useful as a high-quality 2D coronary localizer and may be used to screen the coronary artery tree.

MATERIALS AND METHODS

Experiments were conducted on a GE Signa 1.5T CV/i scanner (General Electric Co., Milwaukee, WI) equipped with gradients supporting 40 mT/m magnitude and 150 mT/m/ms slew rate, and receiver capable of 4 μs sampling (±125 kHz). A body coil was used for RF transmission and a 5-inch surface coil was used for signal reception. The pulse sequence was implemented within the Stanford RTI imaging environment (9), which provided frameworks for interactive control of scan plane and imaging parameters and for continuous real-time reconstruction and display. Arbitrary scan planes could be interactively localized without the need for gating or breathholding.

The pulse sequence consisted of a water-selective excitation followed by interleaved readouts and a gradient spoiler in the slice select direction. Since coronary arteries lie in areas of epicardial fat, water-selective excitation was used to suppress fat signal. To meet the demands of high spatial and temporal resolution, three readout trajectories (Fig. 1) were explored: Fig. 1a, interleaved spirals; 1b partial *k*-space circular EPI (pkCEPI); and 1c asymmetric pkCEPI. Circular EPI (CEPI) is a variation of the EPI trajectory (10,11) that has a circular *k*-space footprint and therefore a circular image FOV. Partial *k*-space CEPI utilizes the conjugate symmetry of *k*-space and requires the acquisition of slightly more than half of the *k*-space lines and uses a modified reconstruction (12,13). Furthermore, *asymmetric* pkCEPI stretches the pkCEPI trajectory to achieve higher resolution in the readout direction, while sacrificing resolution in the phase-encode direction. We particularly explored using 2:1 *k*-space asymmetry to achieve twice the resolution in the readout direction as in the phase encode direction; however, any arbitrary resolution ratio is achievable and is supported by this system.

Whereas circular *k*-space coverages result in circularly symmetric resolution elements, elliptical *k*-space coverage results in elliptical resolution elements. Cropped images of a resolution phantom are included in Fig. 1c to demonstrate the effect of asymmetric resolution. When these elliptical resolution elements are oriented parallel to the comb bristles, they appear well-defined; however, when

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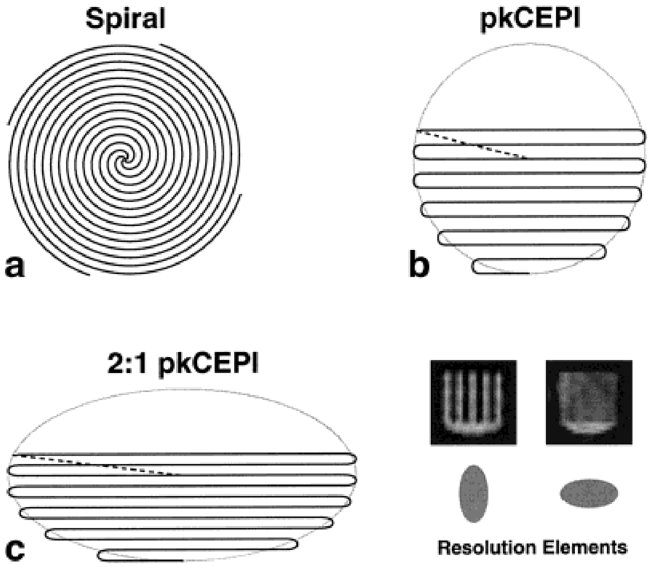

FIG. 1. *k*-Space trajectories for high-resolution real-time imaging. **a:** Interleaved spirals, **b:** Partial *k*-space CEPI. **c:** 2:1 asymmetric partial *k*-space CEPI. Cropped images demonstrate the asymmetric resolution of 2:1 pkCEPI. When the elliptical resolution elements of the asymmetric image are oriented parallel to comb bristles they appear well defined; however, when they are oriented perpendicular to the bristles the features are blurred away.

they are oriented perpendicular to the bristles the features are blurred away. Similarly, in real-time coronary studies the long axis of resolution elements can be interactively placed parallel to the vessel or vessel segment of interest. This enables the quick scouting of even tortuous vessels and takes advantage of the multiple image capability of real-time MRI.

Figure 2 and Table 1 characterize the temporal and spatial resolutions achievable for each of the three trajectories based on our hardware configuration. All comparisons involved optimal trajectory design (14,15) and are based on a 20-cm FOV, 16.384-ms readouts, 27-ms TR, and roughly 56% coverage when using partial *k*-space acquisitions. These are all typical parameters for single-coil real-time cardiac imaging studies. Notice that all three

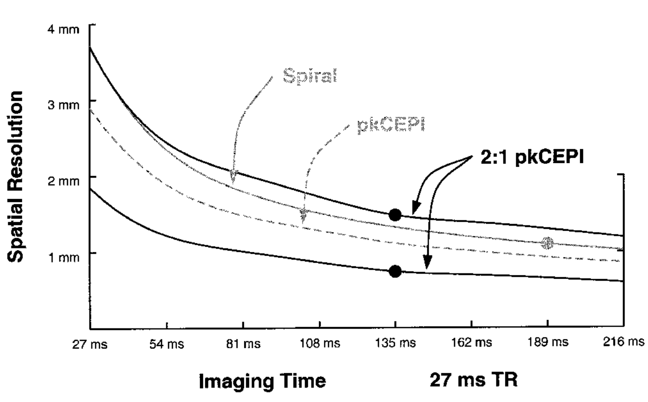

FIG. 2. Temporal and spatial resolution tradeoffs for fast imaging *k*-space trajectories. Acquisitions used in future studies are identified by bullets.

Table 1
Temporal and Spatial Resolution Tradeoff for Fast-Imaging *k*-Space Trajectories

Imaging time	Image resolution (mm)		
	Spirals	pkCEPI	2:1 pkCEPI
27 ms	3.7	3.2	1.85 × 3.70
54 ms	2.3	2.1	1.33 × 2.66
81 ms	1.8	1.7	1.01 × 2.02
108 ms	1.5	1.4	0.89 × 1.78
135 ms	1.3	1.2	**0.80 × 1.60**
152 ms	1.2	1.0	0.70 × 1.40
189 ms	**1.13**	0.94	0.64 × 1.28
216 ms	1.0	0.9	0.60 × 1.20

Acquisitions used in future studies are shown in bold.

trajectories are capable of achieving submillimeter resolution; however, spiral and pkCEPI trajectories require longer imaging times, making them more susceptible to motion artifacts. Figure 3 contains images acquired using 2:1 pkCEPI and spirals of comparable voxel size. Both images achieve high resolution for a real-time system, while exhibiting different types of artifacts. The pkCEPI image is sharper due to its shorter acquisition and relative insensitivity to off-resonance (16), but suffers from flow ghosting in the phase-encode direction. The spiral image exhibits minimally disruptive swirling artifacts from flow, but shows blurring due to off-resonance and the longer image acquisition time (17) (189 ms for spirals vs. 135 ms for 2:1 pkCEPI). The spiral image also has higher SNR because it was acquired over a longer acquisition time.

In our coronary studies, we elected to use the 2:1 asymmetric pkCEPI trajectory with five interleaves achieving 0.8×1.6 mm^2 resolution in 135 ms and spiral trajectories with seven interleaves achieving 1.13×1.13 mm^2 resolution in 189 ms. These two trajectories were specifically chosen because they have roughly the same voxel size (for comparison purposes).

Both used a 20-cm FOV and 5-mm slice thickness. The pulse sequence consisted of a 7-ms water-selective excitation followed by interleaved readouts and a gradient spoiler. For noncontrast studies a flip angle of 30° was used and for contrast-enhanced studies a flip angle of 60° was used. Using a sliding window reconstruction (18), we were able to produce an image after each acquired interleave (every 27 ms), thereby achieving image display rates of up to 37 images/sec.

RESULTS

Our initial study consisted of 15 normal volunteers scanned using the 2:1 pkCEPI acquisition. Each volunteer was scanned for roughly 20 min with the goal of visualizing segments of both right and left coronary trees. As a result, the right coronary artery (RCA) was visualized in all volunteers and some part of the left coronary system was visualized in 9 of the 15. We believe that greater difficulty was experienced viewing the left coronary system because of the smaller vessel sizes and lower SNR due to distance from the surface receiver coil. Figure 4 contains single frames captured from real-time video acquired with this sequence. Figure 4a,b depicts the right coronary and origin

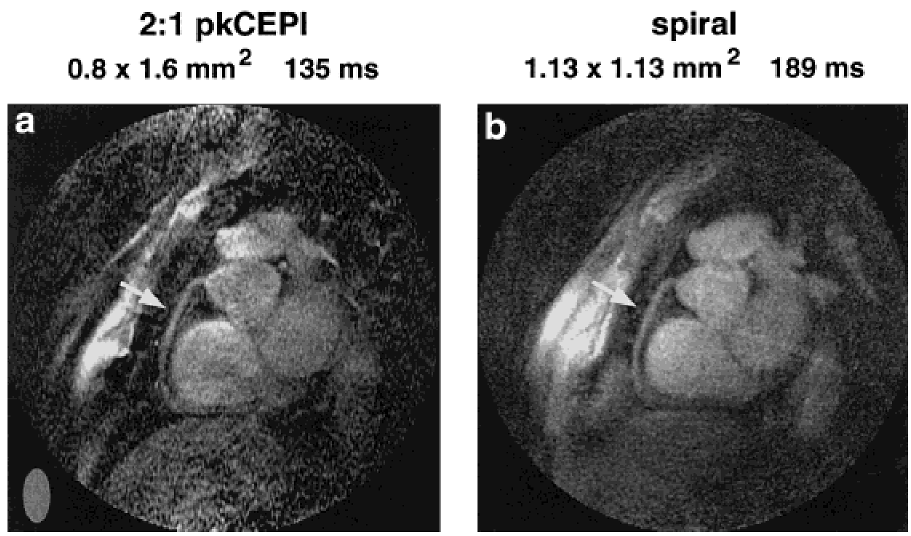

FIG. 3. Comparison of 2:1 pkCEPI and spiral images. The right coronary from a normal volunteer is shown using (**a**) 2:1 pkCEPI with the ellipse indicating the orientation of resolution elements and (**b**) interleaved spirals. The pkCEPI image is sharper due to its shorter acquisition and insensitivity to off-resonance, but suffers from flow ghosting in the phase-encode direction. The spiral image exhibits minimally disruptive swirling artifacts from flow, but shows blurring due to off-resonance and the longer image acquisition time. The spiral image also has higher SNR because it was acquired over a longer acquisition time.

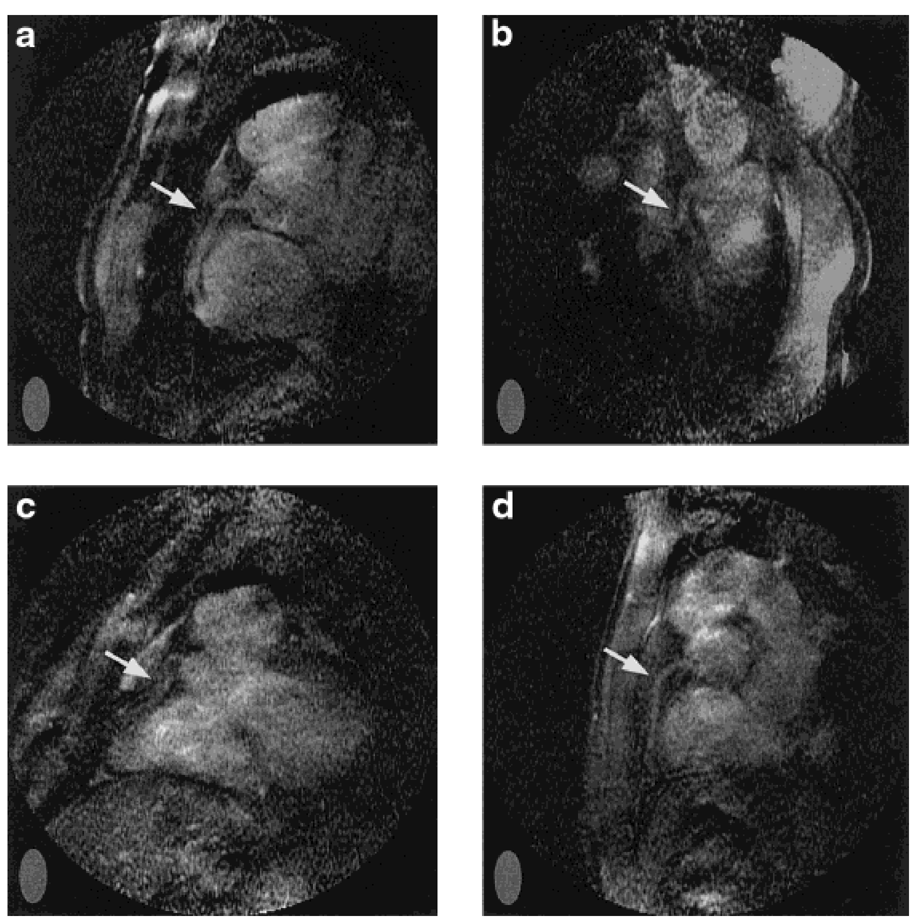

FIG. 4. Real-time 2:1 pkCEPI images of the (**a**) right coronary and (**b**) left coronary in one volunteer, and the (**c,d**) right coronaries of two other volunteers, using five-interleave 2:1 pkCEPI acquisitions. Each image is a single still frame taken from a real-time video sequence.

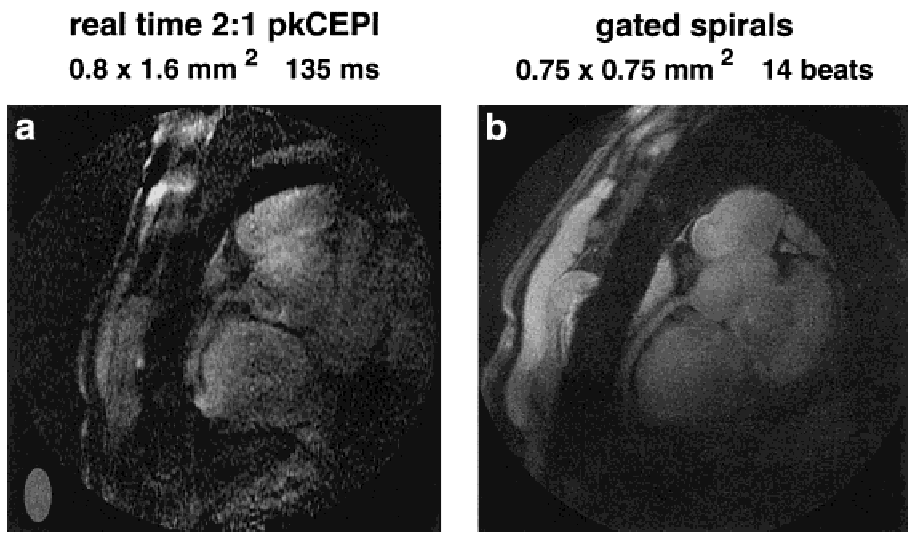

FIG. 5. RCA images acquired in (**a**) real-time and (**b**) using a gated spiral technique on the same healthy volunteer. The SNR improvement using gated techniques is significant; however, the resolution achieved in real-time is sufficient for visualization.

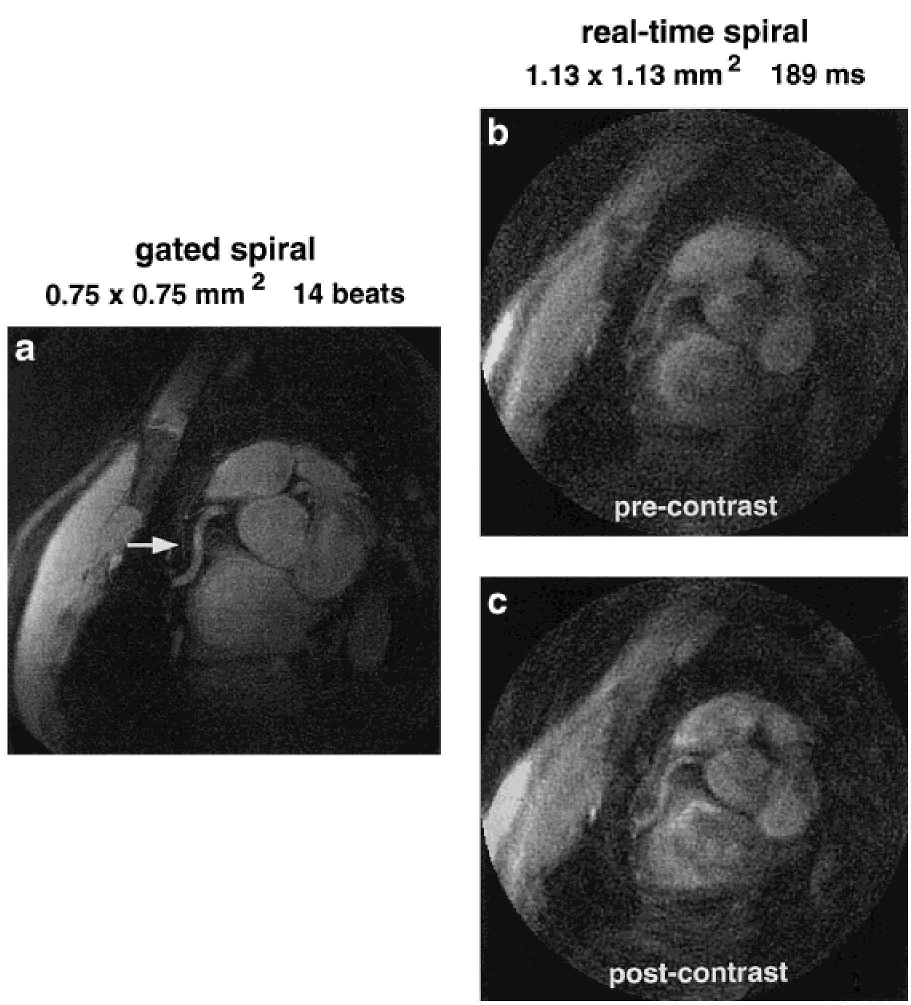

FIG. 6. Right coronary artery images from a normal volunteer imaged using (**a**) gated spirals, and real-time spirals both (**b**) before and (**c**) 1 min after a bolus injection of gadolinium.

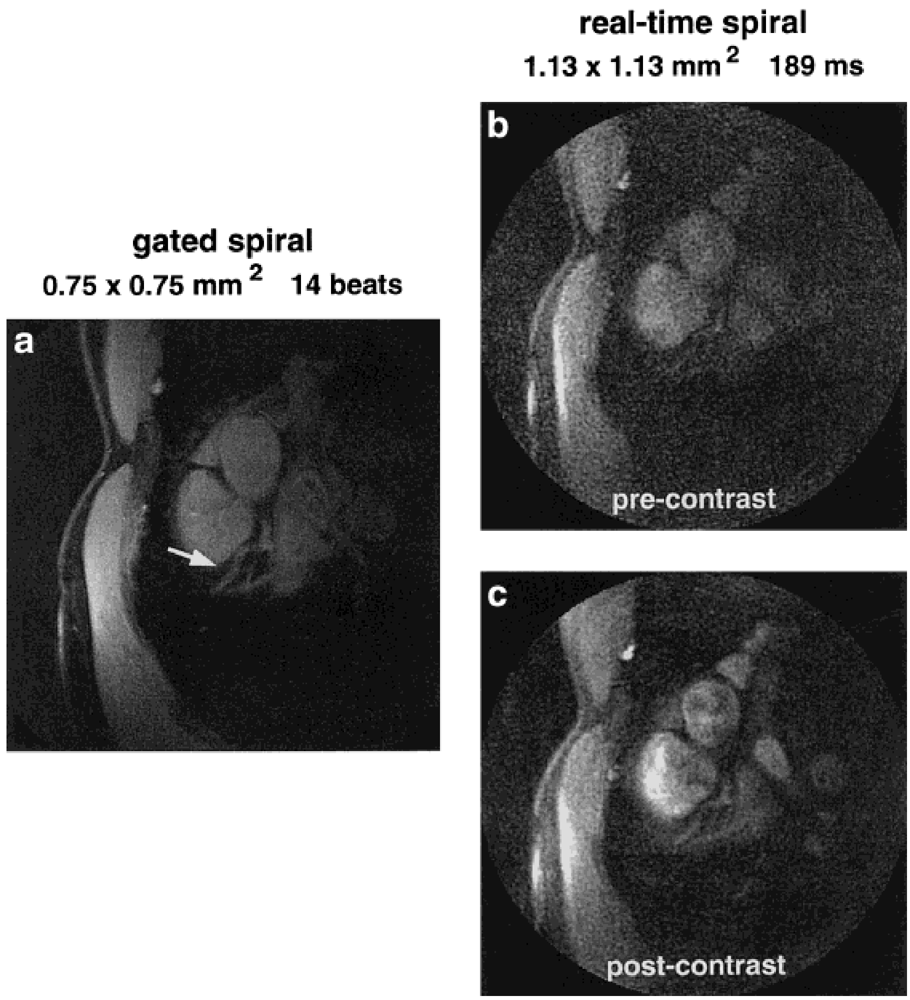

FIG. 7. Left coronary artery images from a normal volunteer imaged using (**a**) gated spirals and real-time spirals both (**b**) before and (**c**) 3 min after a bolus injection of gadolinium.

of the left main in one volunteer, 4c depicts a tortuous RCA from a second volunteer, and 4d depicts the RCA in a third volunteer. While images here show vessel segments at single instances, a longer vessel length is observed in a real-time video due to segments passing through the imaging slice in different time frames. Also note that while viewing video, noise from successive frames is mostly uncorrelated and temporally averages down.

One immediate application of this technique is as a high-quality localizer for 2D sequences. Figure 5 contains views of an RCA from the same volunteer during the same scan, first imaged with the real-time system, and then with a gated breathheld 2D spiral technique (19). The gated image clearly has higher SNR and achieves better resolution due to the longer integration time; however, the real-time image provides reasonable resolution and can be used to achieve very accurate scan plane localization.

As SNR is a major limiting factor in real-time acquisition, this system could greatly benefit from the use of T_1 shortening contrast agents. In addition to improving SNR, blood-flow-induced artifacts will be reduced due to the more consistent blood pool signal. This should significantly improve both EPI and spiral-based acquisitions. In a preliminary trial, two normal volunteers were scanned with both acquisition schemes following bolus injections of Gadolinium-DTPA (10 cc; Magnevist, Berlex Laboratories, Wayne, NJ). Figure 6 contains right coronary images acquired before and 1 min after contrast injection. Figure 7 contains images of the left anterior descending (LAD) and left diagonal branches before and 3 min after contrast injection. In these preliminary studies, vessel depiction was significantly improved and diagonal branches became visible with the SNR enhancement provided by contrast agents. SNR could also be improved in other ways, including the design of more sensitive receiver coils or coil arrays.

SUMMARY

We have demonstrated submillimeter resolution real-time interactive 2D coronary imaging with currently available scanner hardware. Novel *k*-space trajectories such as asymmetric pkCEPI can be used in conjunction with an RTI system to provide higher resolution in one preferred direction. In vivo studies show that real-time images can achieve submillimeter resolution, but have low SNR compared to gated images. However, preliminary studies suggest that contrast agents may significantly improve SNR. While patient studies are needed to further validate this technique, this sequence can be immediately used for accurate 2D coronary localization and may be useful for the rapid initial screening of coronary lesions and for the guidance of high-resolution scans.

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