Spiral SSFP Coronary Artery Imaging
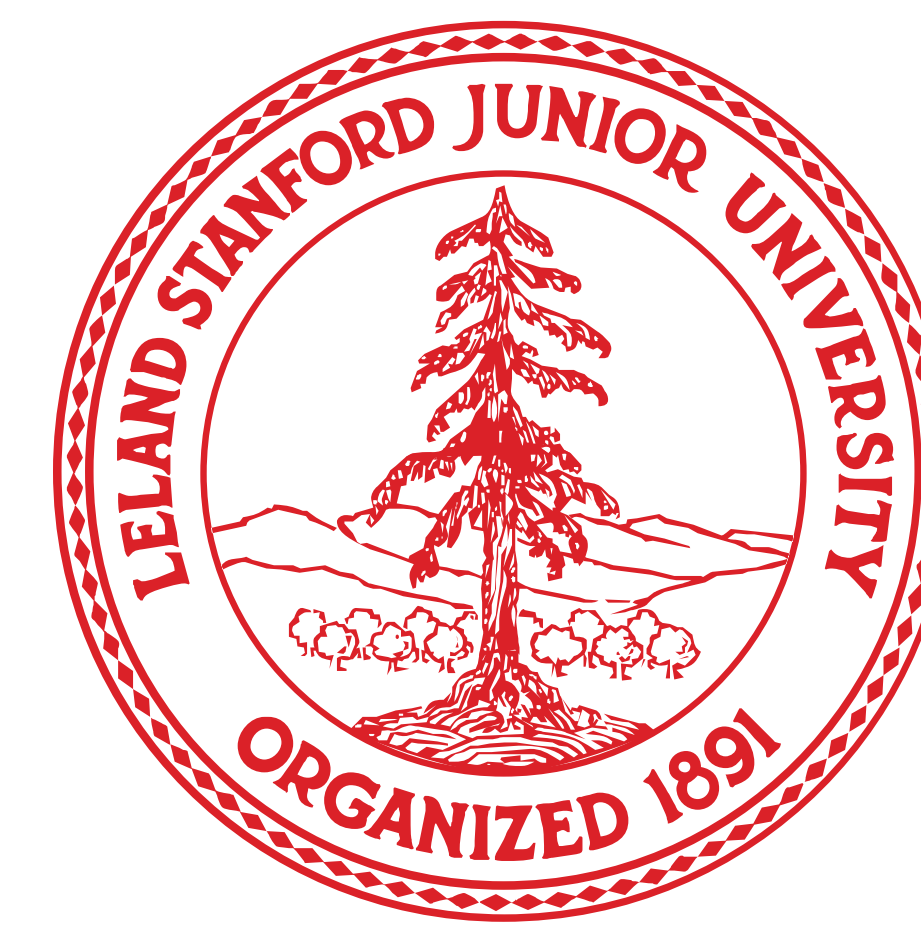
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Introduction

Coronary artery imaging is an important tool for the diagnosis, treatment and monitoring of coronary artery disease. Imaging of coronary arteries requires high signal-to-noise ratio (SNR), high resolution, excellent contrast and suppression of image artifacts due to flow, respiratory motion and cardiac motion.

Recently, there has been a renewed interest in steady-state free-precession (SSFP) imaging, as improved gradient amplifiers now allow reduced sensitivity to resonant frequency variations. SSFP, commercially known as True-FISP, FIESTA or balanced-FFE, provides high SNR efficiency as well as good image contrast. Additionally, developments in magnetization-prepared SSFP [1-3] enable the combination of SSFP with fat-saturation as well as with cardiac gating.

Spiral imaging has been successfully applied to coronary artery imaging [4-5] and recently combined with SSFP for real-time imaging [6]. In this work, we have combined several techniques to develop a breath-held, cardiac-gated, fat-suppressed spiral SSFP sequence for coronary artery imaging.

Methods

The pulse sequence combines cardiac-gated, fat-suppressed SSFP with spiral imaging (Fig. 1). The details of each block are as follows:

Steady-State Free-Precession: SSFP imaging consists of simple slice-selective (or slab-selective) excitation pulses with slice-select and imaging gradients fully rewound over a sequence repetition. Successive excitation pulses alternate in sign.

Spiral Imaging Readout: Spiral imaging gradients provide efficient k-space coverage, and are flow-compensated at the low spatial frequencies. In SSFP, it is important to rewind both the area and the first-moment of imaging gradients [6].

Transitions To and From Steady-State: SSFP with cardiac gating and magnetization-preparation requires rapid transitions to and from steady state [1,2]. Magnetization is manipulated into steady state using a series of excitations increasing in flip angle [7] to minimize transient image artifacts. A single excitation with half the flip angle of the steady-state sequence, placed one full TR after the last steady-state excitation, symmetrically restores signal from water and fat to the longitudinal direction.

Cardiac Triggering: Image acquisition is cardiac-triggered as in [3]. However, following image acquisition, the steady state is maintained until the next cardiac trigger occurs. This reduces signal transients at the start of the acquisition and improves suppression of the myocardium.

Fat Saturation: Fat saturation blocks begin immediately following the cardiac trigger [3] and can be repeated throughout the cardiac cycle in a similar manner to [2] to acquire additional temporal frames. A 100º spectral tip followed by spoiler gradients saturates the lipid signal. Alternatively a spectral-spatial inversion to invert the lipid signal, combined with broad-spectral transitions into and out-of steady state, results in an inversion-recovery type fat-suppression scheme [8].

Our specific implementation uses a breath-hold of 14 heart beats, a repetition time (TR) of 5.0 ms and 84 spiral interleaves resulting in an imaging window or temporal resolution of 30 ms. Additional temporal frames were acquired for roughly half the cardiac cycle, with fat-suppression blocks after every third frame. Imaging parameters included a 2D-slice thickness of 8 mm, in-plane resolution of 1.2 x 1.2 mm over a 24 cm field-of-view. A 60º flip-angle was used to maximize contrast between blood and myocardium. The approach to steady-state consists of four slice-selective excitations spaced TR apart, with flip angles of 9º, -22º, 37º, -49º using the method described in [7].
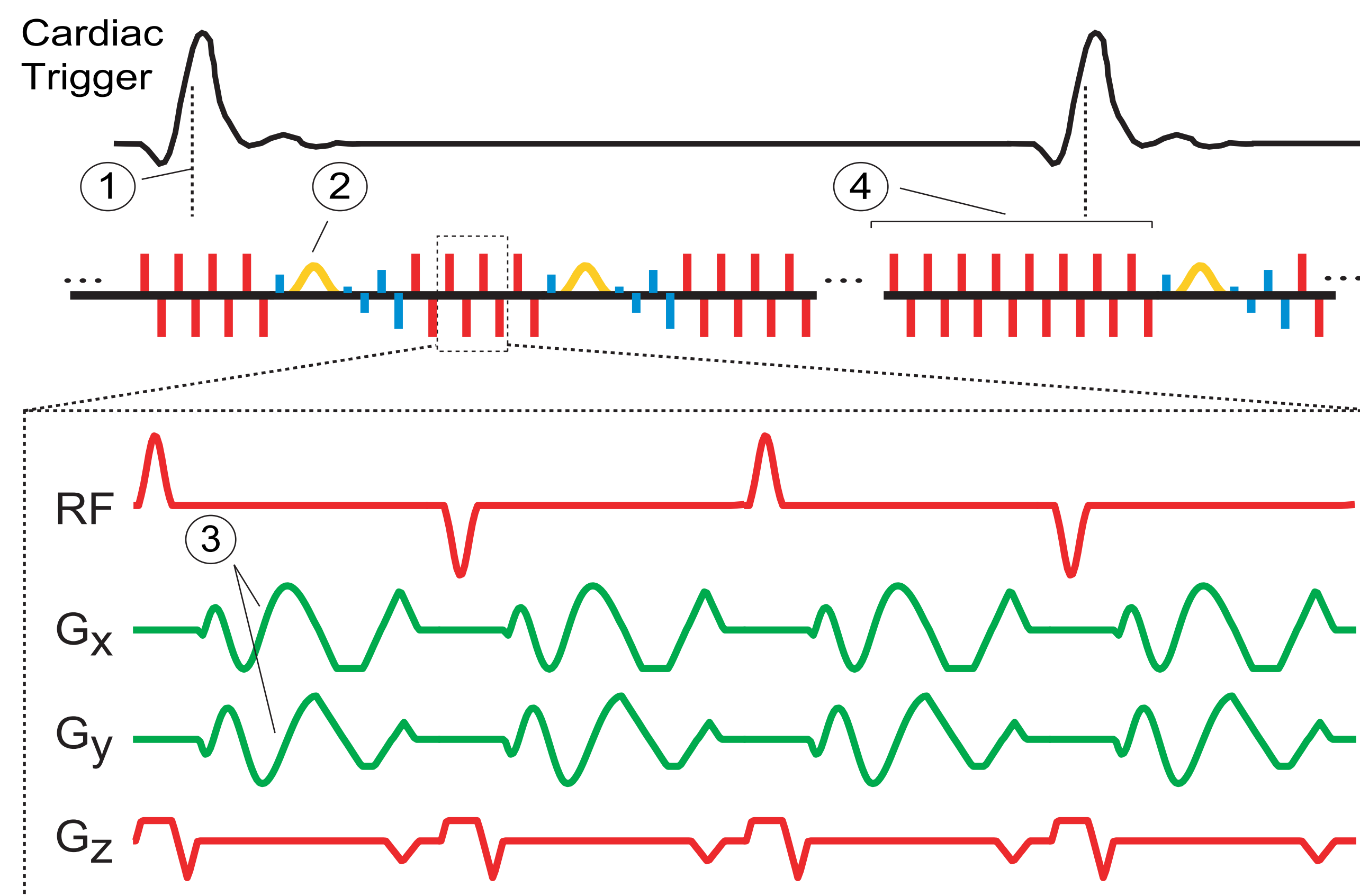

Figure. 1. *Cardiac-gated spiral-SSFP pulse sequence. After a cardiac trigger (1) and delay, a fat-saturation block (2) precedes an SSFP spiral imaging sequence (3). Additional fat-saturation blocks can be included. Following imaging, the steady state is maintained for the duration of the cardiac cycle (4) to suppress signal from the myocardium.*

Results

We have verified this method with normal volunteers using a 1.5 T GE LX scanner with CV/i gradients (40 mT/m maximum amplitude, 150 T/m/s maximum slew rate) and a 5-inch surface coil placed over the chest.

Short-axis cardiac images were acquired to verify the contrast characteristics of the sequence, as shown in Fig. 2. Three cases were tried: (a) the sequence described above with spectral-spatial inversion for fat suppression and maintaining the steady state through systole, (b) the sequence with a 100º fat-saturation pulse instead of the inversion and (c) the sequence without maintaining steady state through systole. Figure 2 shows that the spectral-spatial inversion improves fat suppression, and that maintaining the steady state reduces signal from the myocardium by 30%.

Coronary images were acquired using the same parameters. Sample temporal images are shown in Figure 3, along with an image averaged over three frames to improve SNR. The right coronary artery is clearly depicted with very minimal artifacts from either motion or the approach to steady-state.

Discussion

Spiral imaging can achieve similar resolution and field-of-view to Cartesian imaging in 30% as many repetitions, and has the advantage of low first-moments during imaging. However, moment nulling of spiral gradients over a sequence repetition costs some SNR efficiency as well as increased sensitivity to field variations due to a longer TR (compared with Cartesian acquisitions). Spiral imaging is also more sensitive to steady-state transient artifacts than standard Cartesian imaging, but with effective transitions into the steady state these artifacts are not significant.

Fat-saturated SSFP imaging could benefit greatly from more robust fat-suppression, which is currently quite sensitive to field variations. Interactive shimming capabilities would thus improve reliability. Image SNR may be improved by temporal averaging, or 3D imaging as in [3]. Temporal resolution could be traded for increased spatial resolution at the cost of some robustness to cardiac motion.
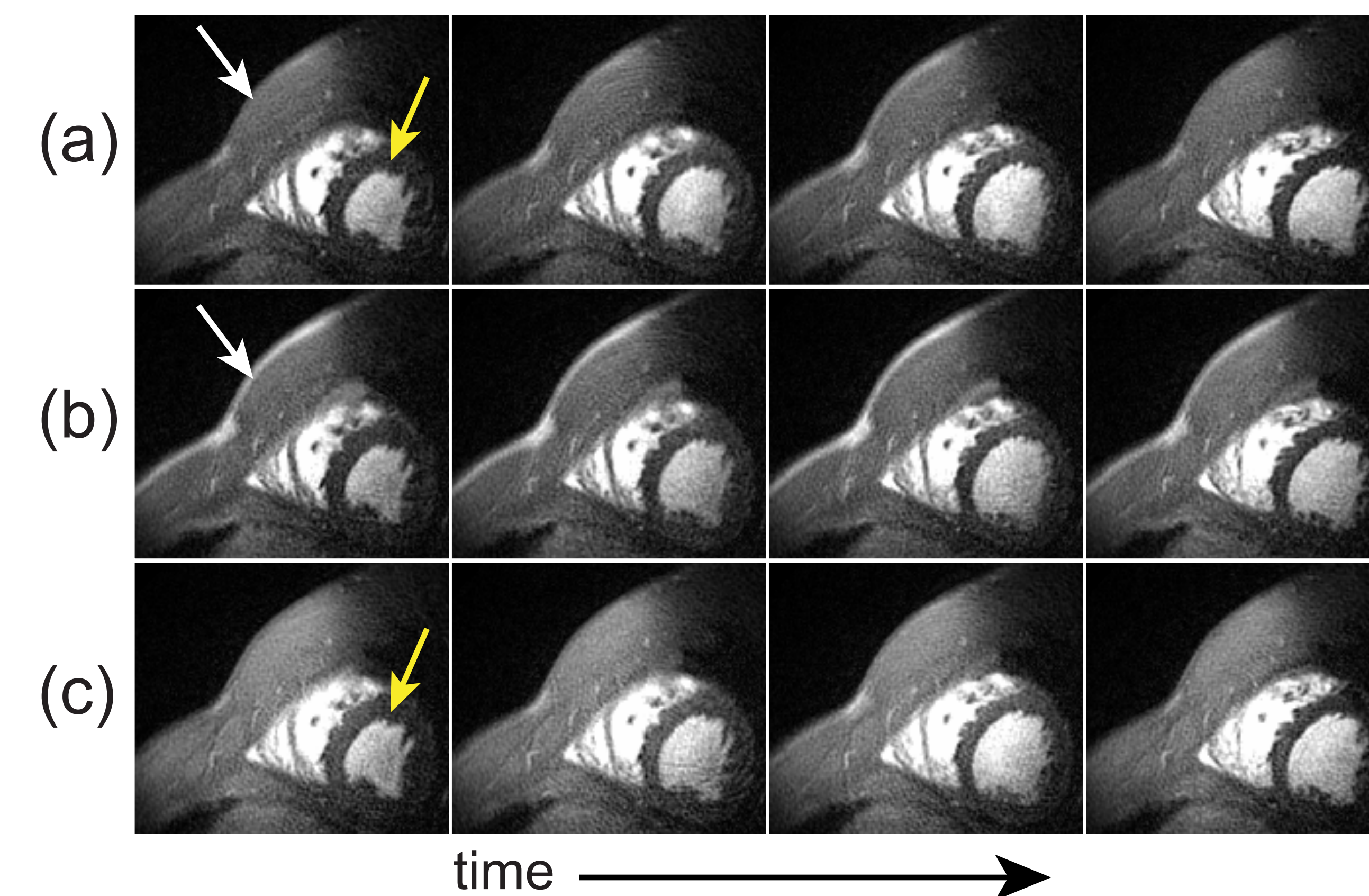

Figure. 2. *Temporal frames showing breath-held, cardiac-gated short-axis views that compare (a) sequence using spectral-spatial inversion fat-suppression and steady-state maintained through systole. (b) same sequence, but using a 100º fat-saturation as in [2,3]. (c) sequence with spectral-spatial inversion, but steady-state is not maintained during systole. Sequence (a) shows improved fat-suppression (white arrows) compared with (b), and approximately 30%-reduction in myocardium signal (yellow arrows) compared with (c).*
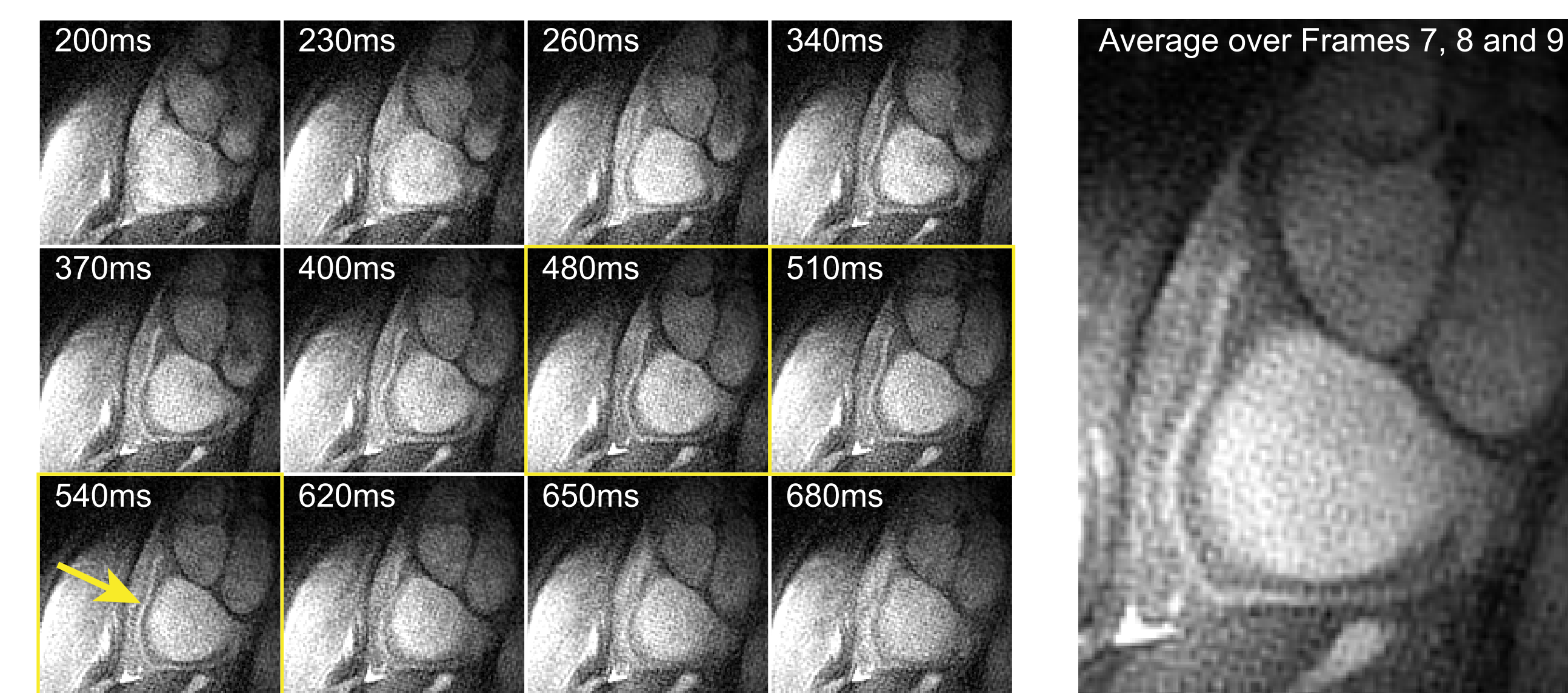

Figure. 3. *Temporal frames showing the right coronary artery (arrow) in a normal volunteer. Each frame is acquired in a 30 ms window, with a 50 ms-duration fat-saturation after every third frame. The time after cardiac trigger is shown for each frame. The frame at right is a complex average of the three frames outlined in yellow, and depicts the right coronary artery with good SNR.*

Conclusion

The combination of spiral imaging with fat-suppressed SSFP provides excellent contrast, speed and motion-insensitivity for coronary artery imaging. High-resolution cardiac gated images can be obtained in a 30 ms imaging window over a 14-heart beat breathhold. With some improvements to robustness, spiral-SSFP shows high potential for coronary artery imaging.

References

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