Multi-Phase Coronary MR Angiography Using a 3D Cones Trajectory

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Introduction: Non-invasive visualization of the coronary arteries *in vivo* is one of the most important goals in cardiovascular imaging. Compared to other paradigms for coronary MR angiography (MRA), a 3D whole-heart iso-resolution free-breathing approach simplifies prescription effort, requires less patient cooperation, and supports retrospective reformats at arbitrary planes. However, this technique requires longer scan times and must account for respiratory and cardiac motion. In this work, we present a 3D whole-heart iso-resolution free-breathing coronary MRA technique based on the 3D cones readout trajectory [1, 2], which can reduce the scan time compared to conventional 3D Cartesian encoding and exhibits greater robustness to motion/flow. To further improve robustness to motion, 2D "navigator images" are acquired to compensate for respiratory motion and multiple cardiac phases are resolved to support retrospective selection of the best phase for visualizing the coronary arteries.

Methods: Acquisition: The 3D cones trajectory samples a spherical volume in *k*-space with a set of nested conical surfaces. Each surface is sampled by a series of spiraling readouts that start from the center of *k*-space (Fig. 1a). We implement the 3D cones in an alternating-TR (ATR) SSFP sequence (TR_2/TR_1 = 1.15/4.36 ms, FA = 50°) (Fig. 1b) [3] to achieve steady-state fat suppression and blood-myocardium contrast. The full set of cone readouts is divided into sequential segments and acquired over multiple heartbeats with a cardiac-triggered sequence (Fig. 2). Right before starting image acquisition (at TD), a 2D sagittal spiral "navigator image" (NAV) containing the left ventricle is acquired to track respiratory motion. Catalyzation cycles (*C*) are then played out to establish the steady state for 3D cones image acquisition (IMG), where data is collected to resolve multiple cardiac phases. Finally, catalyzation cycles exit the steady state in anticipation of the next heartbeat. Data from multiple passes of this sequence can be combined to further enhance respiratory compensation.

Reconstruction: The 2D navigator images are processed using a least-squares algorithm to track 2D displacement of the heart in S/I and A/P. The data from multiple passes are combined by accepting the readouts that have the least S/I displacement from the respiratory mode. Accepted readouts are then corrected for 2D displacement (linear phase modulation) and used for 3D gridding reconstruction. Multiple cardiac phases are reconstructed, with the option of sliding window reconstruction of intermediate cardiac phases. Sum of squares is used to combine data from multiple coils.

Experiments: Setup: Axial slabs covering the whole heart were imaged on a GE Signa 1.5 T Excite system using an 8-channel cardiac array. Cardiac triggers were obtained from a pulse oximeter. The 3D cones trajectory in this experiment supported an FOV of 24x24x16 cm^3 and resolution of 1.2x1.2x1.25 mm^3 using 8942 readouts (3-fold acceleration vs. 3D Cartesian), where 18 readouts were acquired per segment (100 ms/phase) and repeated for 3 cardiac phases. Spiral navigator images were acquired with 3-mm in-plane resolution (12 interleaves) using a gradient-echo sequence. TD was selected from a 4-chamber cine prescan to coincide with the start of diastole. Scan time for a single pass was 497 heartbeats (~8 min) and 2 passes were acquired.

Results: Fig. 3 shows reformatted thin-slab maximum-intensity-projected (MIP) images containing the proximal right coronary artery (RCA) and left main coronary artery (LM) obtained from a healthy volunteer for cardiac phase 1. While the RCA and LM are already recognizable before motion correction due to the inherent robustness of cones, respiratory motion correction substantially improves image quality. Fig. 4 displays reformats containing the proximal RCA and left anterior descending coronary artery (LAD) after motion correction at the 3 fully resolved 100-ms cardiac phases and one intermediate phase (phase 1.5) from sliding window reconstruction. In this subject, the RCA is sharpest in early diastole (phase 1) and becomes blurred in late diastole (phase 3). The LAD has a longer rest period but also becomes blurred in late diastole. Interestingly, the LAD is sharpest in phase 1.5, which was obtained by sliding window reconstruction.

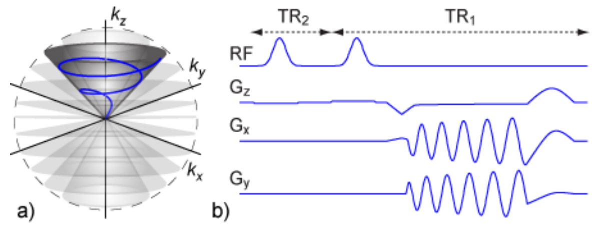

Fig. 1. (**a**) 3D cones trajectory. (**b**) ATR SSFP imaging sequence.

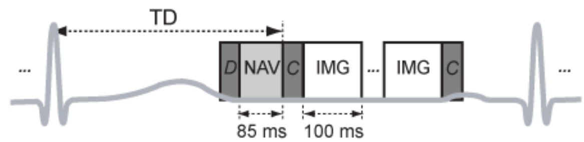

Fig. 2. Triggered pulse sequence. **TD**: delay to start of diastole, ***D***: 10 dummy cycles for navigator imaging, **NAV**: 2D spiral navigator image, ***C***: 10 catalyzation cycles for 3D cones imaging, **IMG**: 3D cones image acquisition for one cardiac phase.

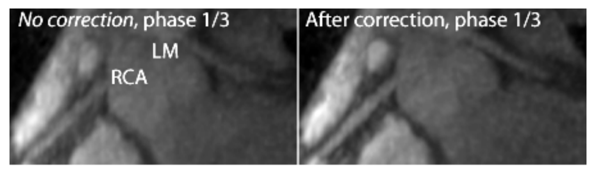

Fig. 3. Reformats displaying the proximal RCA and LM before (left) and after (right) motion correction at cardiac phase 1/3.

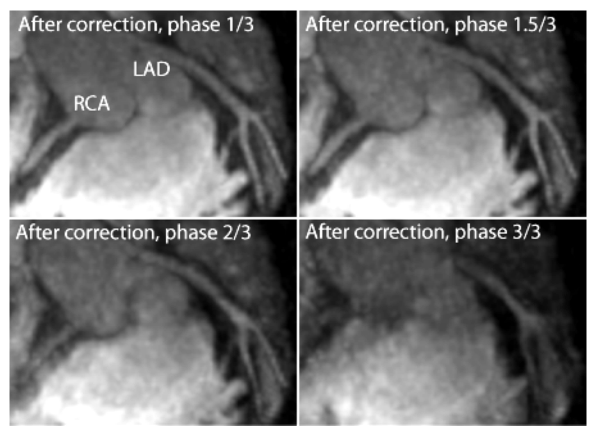

Fig. 4. Reformats displaying the proximal RCA and LAD at the 3 fully resolved cardiac phases and one intermediate phase.

Discussion: We have presented a 3D cones whole-heart iso-resolution free-breathing coronary MRA technique that reduces scan time 3-fold vs. 3D Cartesian and improves robustness to motion. Navigator images directly measure 2D respiratory motion of the heart and provide robust compensation even when reconstructing only a single pass (results not shown). Multiple passes were combined using a basic algorithm and the efficiency can be improved by adopting methods such as the diminishing variance algorithm [4]. In addition to respiratory compensation, multiple resolved cardiac phases provide robustness to the initial choice of TD and subsequent heart-rate variations. This sequence can be extended to resolve cardiac motion over a greater span of the cardiac cycle, thereby producing a volumetric cine of the coronary arteries. Since the left and right coronary trees may have different rest periods [5], such a dataset could allow retrospective selection of the best cardiac phase for visualizing each coronary segment.

References: [1] Gurney PT, et al., MRM 2006; 55: 575-582. [2] Gurney PT, PhD Thesis, Stanford University, 2007. [3] Leupold J, et al., MRM 2006; 55: 557-565. [4] Sachs TS, et al., MRM 1995; 34: 412-422. [5] Jahnke C, et al., Radiology 2006; 239: 71-78.