Multi-Phase 3D Cones Coronary MRA with 3D Respiratory Motion Compensation

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Introduction: Non-invasive visualization of the coronary arteries *in vivo* is one of the most important goals in cardiovascular MRI, but is challenged by physiologic motion. Recently we have presented a 3D cones whole-heart free-breathing coronary MRA technique [1] which combines *(1)* 3D cones sampling to reduce scan time and improve robustness to motion/flow, *(2)* 2D "navigator images" (iNAVs) of the heart to directly track and compensate for respiratory motion, and *(3)* the acquisition of multiple cardiac phases to improve visualization for different coronary segments. In this work, we extend the iNAV approach to acquire two orthogonal slices every heartbeat and track respiration-induced displacement in all three directions. Tracking results are used to retrospectively compensate *all readouts* before reconstructing the 3D cones dataset for multiple cardiac phases.

Methods: Sequence: A 3D cones (Fig. 1a) alternating-TR (ATR) SSFP sequence is used for whole-heart imaging [1-3]. ATR SSFP achieves steady-state fat suppression and blood-myocardium contrast, which is crucial for multi-phase imaging as contrast preparation wears off over time. The full set of readouts is segmented and acquired over multiple heartbeats (Fig. 1b). Every heartbeat (HB), a leading 2D *sagittal* iNAV of the heart is acquired to track motion in the superior-inferior (S/I) and anterior-posterior (A/P) directions. A trailing 2D *coronal* iNAV is also acquired to track motion in the S/I and left-right (L/R) directions.

Experiments: Whole-heart axial slabs were imaged on a GE Signa 1.5 T system using an 8-channel array and vector ECG triggering. The 3D cones were designed for an FOV of 28x28x14 cm^3 and resolution of 1.2x1.2x1.25 mm^3 using 9142 readouts (*3-fold* reduction vs. 3D Cartesian). Each iNAV was acquired in 68 ms using spirals with 3.1-mm in-plane resolution and a 12^o flip angle to minimize saturation.

Motion Compensation: Leading/trailing iNAVs were processed by: *(1)* identifying a region-of-interest (ROI) on a reference iNAV (Fig. 2, left), *(2)* interpolating 8-fold for 0.4-mm precision, *(3)* least-squares tracking of the ROI over all HBs, and *(4)* calibrating the leading and trailing iNAV tracking results in S/I, by identifying a HB in end expiration and aligning the leading/trailing S/I results at that point to remove any bulk offset between the two traces (Fig. 2, right). A/P displacement obtained from the leading iNAV was assigned to all readouts in that HB and the same was done for L/R based on the trailing iNAV. S/I displacement was estimated for the readouts in each HB by linear interpolation between the leading/trailing S/I tracking results of that HB. All readouts were corrected for 3D displacement by linear phase modulation and used for image reconstruction.

Results: Data from a healthy volunteer is shown in Figs. 2 and 3. This subject's heart rate varied between 75~85 bpm and we imaged during end systole. 14 cone readouts (78 ms) were acquired per phase (IMG) and repeated for 3 cardiac phases. Scan time was 653 HBs (~*8 min* at 80 bpm). While L/R motion is often considered to be much less than that in S/I and A/P, it was actually greater than A/P in this subject (Fig. 2, right). Fig. 3 shows progressive improvement in the depiction of several coronary segments as S/I, A/P, and finally L/R motion are compensated for. In this subject, L/R motion compensation was necessary to achieve the desired image quality. Only cardiac phase 2 of 3 is shown here, as the selected segments are best visualized in this phase.

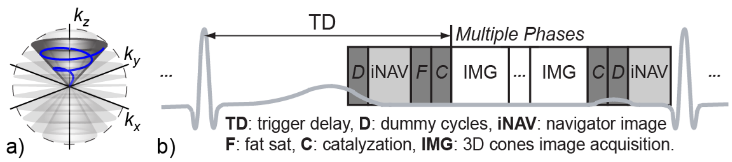

Fig. 1. (**a**) 3D cones *k*-space trajectory. (**b**) Triggered pulse sequence with iNAVs.

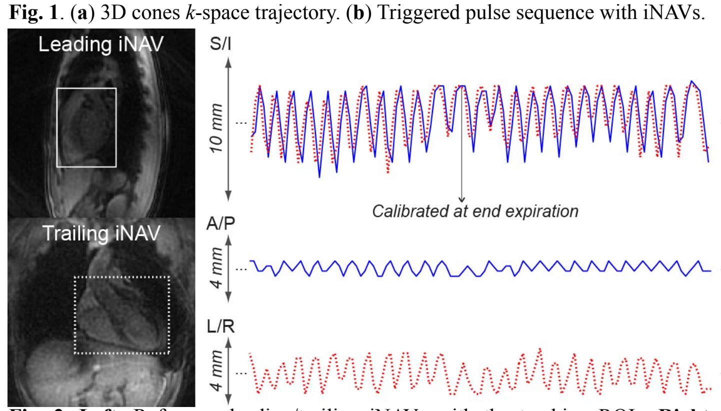

Fig. 2. **Left:** Reference leading/trailing iNAVs with the tracking ROIs. **Right:** Tracking results in S/I (leading and trailing), A/P (leading), and L/R (trailing).

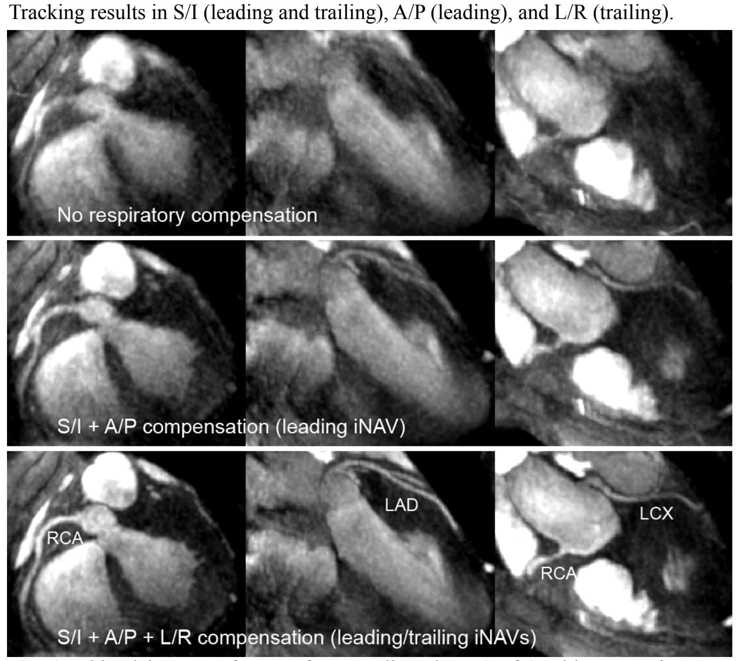

Fig. 3. Thin-slab MIP reformats from cardiac phase 2 of 3 with no respiratory compensation (**top**), S/I and A/P correction using the leading iNAVs (**middle**), and full 3D correction with leading/trailing iNAVs (**bottom**). Note the progressive improvement in image quality. **RCA**: right coronary artery, **LAD**: left anterior descending, and **LCX**: left circumflex coronary artery.

Discussion and Conclusions: Orthogonal leading and trailing iNAVs enable the direct tracking and compensation of respiration-induced displacement of the heart in all three directions (S/I, A/P, L/R). While S/I displacements from the leading/trailing iNAVs are based on different views, they are highly correlated after calibration and can be used together to improve compensation. Combined with the inherent robustness of 3D cones to motion/flow, we can utilize all readouts (100% acquisition efficiency) to achieve 1.2-mm isotropic visualization of the coronary arteries over the whole heart, even when respiratory motion spans up to 10 mm in S/I. As demonstrated by the results, the capability to compensate for motion in all three directions significantly enhances the robustness of 3D cones coronary MRA to more complicated respiratory patterns during free breathing.

References: [1] Wu HH, *et al.*, *Proc. 19th ISMRM*, p. 1261, 2011. [2] Gurney PT, *et al.*, MRM 2006; 55: 575-582. [3] Leupold J, *et al.*, MRM 2006; 55: 557-565.