Three Minute Whole-heart Magnetic Resonance Angiography with Prospective Heart Tracking and Compressed Sensing Parallel Image Reconstruction

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Synopsis

To accelerate whole-heart magnetic resonance angiography, we implemented a variable density Poisson disc undersampling pattern and compressed sensing parallel image reconstruction, and compared it to a standard parallel image (SENSE) acquisition in 15 patients. The compressed sensing technique was faster (mean 3.4±1.0 minutes vs 7.6±1.7 minutes) and had similar objectively measured sharpness in 4 designated regions (all p>0.05) but a lower subjective image quality scores (all p≤0.05).

Introduction

Electrocardiogram and respiratory navigator (NAV)-gated 3D whole-heart magnetic resonance angiography (MRA) acquired with an intravascular gadolinium-based contrast agent and a non-selective inversion recovery (IR) pulse to null the myocardial signal generates a high-resolution anatomic dataset allowing for a comprehensive evaluation of intra-cardiac, coronary, and vascular abnormalities [1]. To improve respiratory motion compensation with this sequence, we previously implemented the "Heart-NAV" technique, which prospectively tracks the heart position rather than hemi-diaphragm location. Still, an important limitation of this sequence is a relatively long acquisition time lasting 5-15 minutes [2]. During longer acquisitions, the patients' heart-rate, breathing pattern, and body position may change leading to reduced image quality or incomplete scans. Therefore, we sought to reduce the imaging time of this sequence by implementing a variable density Poisson disc undersampling technique that randomly samples k-space lines and using compressed sensing (CS) reconstruction algorithm to complete the scan in ≈3 minutes.

Materials and Methods

The schematic diagram of the whole-heart IR 3D SSFP MRA sequence with Heart-NAV is shown in Fig. 1. One of the startup pulses for the 3D SSFP acquisition was used to collect the centerline of k-space, and its 1-dimensional reconstruction was fed into the conventional navigator signal analysis process to prospectively gate and track respiratory-induced heart displacement. A variable density Poisson disc undersampling pattern was implemented on the scanner to randomly sample k-space lines with a variable sampling rate. The most central 2% of k-space was fully sampled. The sampling rate was then exponentially decreased from the center to periphery of k-space to sample 16-18% of the k-space lines in a radial order on Cartesian grids (Fig. 2). A nonlinear iterative CS reconstruction algorithm, L1-ESPIRiT [3], with L1-wavelet penalty and random shifting as implemented in Bart [4] was used to estimate the unacquired k-space lines and reconstruct the images. The regularization parameter was optimized on one dataset and kept constant for the whole study. To assess this approach, 15 patients (7 females; age 19±9 years) underwent 2 Heart-NAV IR 3D SSFP acquisitions on a 1.5T MR scanner (Philips Ingenia) after the administration of 0.03 mmol/kg gadofosveset trisodium (Ablavar) contrast. The first acquisition used parallel-imaging (SENSE) and the second used variable density Poisson disc k-space filling with CS reconstruction. Imaging parameters were FOV ~310(SI)×140(AP)×130(RL) mm, spatial resolution 1.2-1.5 mm; α/TE/TR 90°/2/4 ms, bandwidth 1.06 kHz, Heart-NAV acceptance window 3 mm, tracking factor 1, 28-element phased-array coil, and a reduction factor of 2 for SENSE and ~6 for CS. CS image reconstruction was performed offline (processing time 5.3±2.1 minutes). To assess the image quality, the border sharpness of the lower pulmonary vein (LPV), right pulmonary artery (RPA), ascending aorta (AAO), and ventricular septum (VS) was subjectively graded by 2 clinicians based on a 5 point-scale (1-poor/non-diagnostic; 2-fair/moderate blurring; 3-acceptable/mild blurring; 4-Good/sharp image; and 5-excellent), and objectively measured (MediaCare tool, range 0-infinity with higher values being sharper) [5]. Subjective and objective measures for the 2

acquisitions were compared using the signed-rank test and paired student t-test, respectively, and a p-value ≤0.05 was considered statistically significant. Informed consent was obtained from all subjects.

Results

Fig. 3 shows representative 3D whole-heart MRA images acquired from 2 patients using SENSE and CS. The scan time for CS was significantly shorter (3.4±1.0 vs. 7.6±1.7; p<0.05). As shown in Table 1, there was no significant difference in the objectively measured border sharpness at all 4 locations between SENSE and CS (all p>0.05). The subjective image quality score for CS was lower than that for SENSE at all 4 locations (all p≤0.05, mean 3.46±0.64 vs. 4.33±0.83). The minimum image quality score for all locations using CS was 3.

Conclusions

Compared to a SENSE rate of 2, our variable density Poisson disc undersampling with CS reconstruction method for the whole-heart IR 3D SSFP MRA reduced scan time by a factor of 2.2. Objectively measured border sharpness was not significantly different but subjective image quality was reduced by approximately 1 grade. The latter finding may be related to more extensive undersampling of the k-space (18-20% vs. 50%) and the resulting reduction in signal-to-noise ratio. Future work will assess this CS approach in a larger group of children and adults, and extend it to a 3D cine acquisition.

Acknowledgements

Authors acknowledge support from Translational Research Program (TRP) fellowship and office of faculty development from Boston Children's Hospital and Harvard Catalyst from Harvard Medical School.

References

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Figures

Fig. 1: Schematic diagram of the Heart-NAV respiratory motion compensation for whole-heart IR 3D SSFP MRA sequence. IR = inversion pulse. Fat Sup = fat suppression. FOS = fold-over suppression. SP = startup pulse. SSFP = steady-state free precession sequence. Trigger delay = onset of the ventricular motion rest period. Inversion time = time when the signal of myocardium is nulled. TR =repetition time.

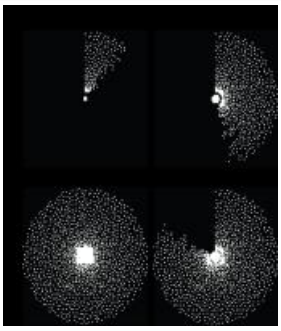

Fig. 2: K-space profile ordering. The central 2% of the k-space lines are fully acquired and 16-18% of peripheral k-space is randomly acquired using a variable density Poisson disc undersampling pattern.

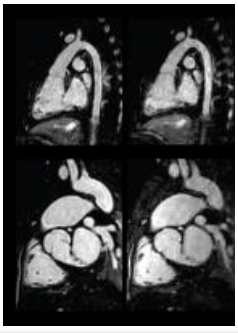

Fig. 3: Heart-NAV with SENSE and Heart-NAV with CS in whole-heart IR 3D SSFP MRA acquisitions with sagittal reformats in 2 patients, ages 2 and 8 years.

Table 1: Values are mean ± standard deviation. Visual score: 1-poor to 5-excellent. Sharpness measure: 0-blurred to infinity-sharp. LPV, lower pulmonary vein; RPA, right pulmonary artery; AAO, ascending aorta; VS, ventricular septum.