Increasing Spatial Resolution of Real-Time Cardiac Cine MRI Using Radial k-space Undersampling with Golden Angle Ratio and Block-Wise Low Rank Contraint

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Purpose: Real-time cardiac cine MRI is clinically useful for imaging patients with arrhythmia and/or reduced breath-hold capacity [1]. We have developed an 8-fold Cartesian k-space undersampled real-time cine MRI [2] with nominal spatial resolution of 2.5 mm x 2.5 mm and temporal resolution of 46 ms and validated it in large animals [3]. In this study, we sought to increase the spatial resolution further using a combination of radial k-space sampling with golden angle ratio [4] and block-wise low-rank (BWLR) constraint [5,6].

Methods: (*Phantom Experiment*) We imaged a resolution phantom with 2 mm fins [7] to compare the effective spatial resolution produced by fully sampled (Nyquist) cine and accelerated cine with radial k-space undersampling with two different constraints (see below). (*Human Experiment*) We imaged 14 patients and 1 volunteer in 12-14 short-axis planes using real-time cine with radial k-space undersampling. Both phantom and human experiments were conducted on a 3T MRI system (Siemens, Verio). Relevant imaging parameters were: image acquisition matrix = 160 x 160, spatial resolution = 2.0mm x 2.0mm, FOV = 320 mm x 320 mm, TR = 2.96 ms, number of rays per image = 14, temporal resolution 41ms, flip angle = 45°. (*Image Reconstruction*) Undersampled data were reconstructed using hybrid constraints. A hybrid BWLR (hBWLR) reconstruction uses BWLR as the primary constraint (normalized weight =0.31) and temporal total variation (TTV) as a secondary constraint (normalized weight =0.0075). A hybrid TTV (hTTV) reconstruction uses TTV as the primary constraint (normalized weight =0.06) and temporal fast Fourier transform (TFFT) as a secondary constraint (normalized weight =0.006). These regularization weights were determined empirically to achieve a good balance between data fidelity and artifact suppression as described in [2]. (*Quantitative Image Analysis*) For the resolution phantom, a region with 2mm fins and spacing was analyzed by measuring the intensity profiles to reflect edge sharpness. For in vivo reconstructed results, given the difficulty in identifying good regions to draw intensity profiles, the energy of the outer regions of k-space, defined as a square ring with 16 k-space points at each outside edge, was calculated relative to the energy of the total k-space, where energy is defined as the sum of squares. This approach is justifiable, since both TTV and BWLR constraints do not favor one particular spatial frequency over another (i.e., invariant in spatial frequency). (*Qualitative Image Analysis*) Two experienced cardiologists independently graded the cine images on a Likert scale of 1-5 (worst-best), where the categories were image quality, diagnostic confidence of wall motion, artifact level, and noise [2,3]. The scores from two readers were averaged, and then the two groups were compared statistically.

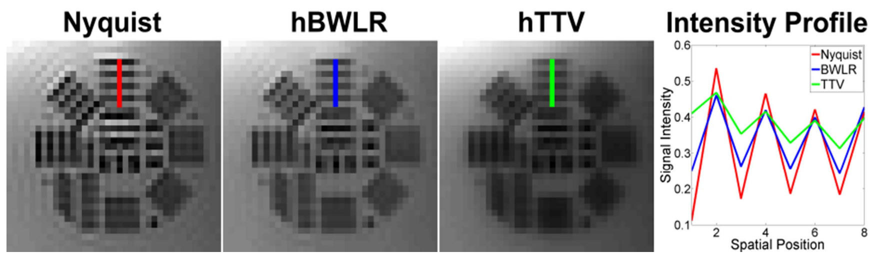

Figure 1: Resolution phantom results: Nyquist (column 1), hBWLR (column 2), and hTTV (column 3).

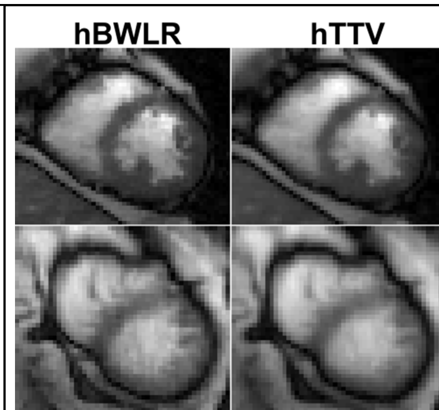

Figure 2: Cine images from two different patients: hBWLR (left) and hTTV (right). Compared with hTTV, hBWLR produced higher apparent spatial resolution.

Table 1. Mean reader scores over 15 subjects.

Category	hBWLR	hTTV	p value
Image quality	3.6 ± 0.6	3.6 ± 0.5	0.97
Wall Motion	3.8 ± 0.7	4.0 ± 0.4	0.25
Artifacts	3.6 ± 0.6	3.4 ± 0.5	0.81
Noise	3.7 ± 0.7	3.7 ± 0.8	0.68

Results: Figure 1 shows the resolution phantom results produced by Nyquist sampling and radial undersampling with hBWLR and hTTV reconstructions. The mean peak-to-peak intensity was 0.29, 0.17 and 0.08 for Nyquist, hBWLR, and hTTV, respectively. Compared with Nyquist, hBWLR had 41% less, and hTTV had 74% less relative peak-to-peak intensity. The relative energy in the outer k-space ring was 0.25, 0.11, and 0.06% for Nyquist, hBWLR (54% lower compared with Nyquist), and hTTV (74% lower compared with Nyquist), respectively. Figure 2 shows representative short-axis planes of two different patients, where hBWLR produced sharper edges than hTTV. Averaging the results over 15 subjects, the relative energy in the outer k-space ring was 0.29 ± 0.09 and 0.24 ± 0.07% for hBWLR and hTTV, respectively, where the difference was statistically significant ($p < 0.05$). These correspond to 17% higher relative energy in the outer k-space ring for hBWLR over hTTV. Reader scores are summarized in Table 1; compared with validated hTTV, hBWLR was not significantly different in all four categories ($p \geq 0.25$).

Conclusion: This study demonstrates that hBWLR produces higher effective spatial resolution than hTTV in real-time cine MRI with radial k-space undersampling and golden angle ratio, without sacrificing diagnostic image quality. A future study is warranted to evaluate the clinical utility of rapid real-time cardiac cine MRI with radial k-space undersampling and hBWLR reconstruction.

References: **[1]** Aandal G, et al. JCMR. 2014 Oct 1;16(1):79 **[2]** Feng L, et al. MRM. 2013 Jul; 70(1):64-74. **[3]** Bassett EC, et al. NMR Biomed. 2014 Feb;27(2):175-82. **[4]** Winkelmann S., et al. IEEE TMI. 2007 Jan;26(1):68-76. **[5]** Chen X, et al. MRM. 2014 Oct;72(4):1028-38. **[6]** Trzasko J, 2011 ISMRM Proceedings p. 4371. **[7]** Kaggie JD, et al. MRM. 2014 Jun;71(6):2231-42. **Funding:** NIH (HL116895-01A1), American Heart Association (14GRNT18350028).