Compressed Sensing Reconstructed Radial bSSFP with Asymmetric Views for Free-breathing Cardiac Cine MRI

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Introduction: 2D segmented cardiac cine MRI is routinely used for non-invasive assessment of the cardiac function. This technology requires breath-holds and a regular heartbeat. 2D unsegmented real-time bSSFP cine MRI, accelerated by parallel imaging and partial Fourier, is used with reduced quality in problematic cases. bSSFP requires short inter-pulse distance repetition time (TR) for robustness against B0 field inhomogeneities and flow. In Cartesian bSSFP the TR is reduced by partial Fourier acquisition in the readout direction, i.e., the early part of the echo is omitted and the readout is thus shortened. Reconstruction can use zero-filling or data generating algorithms like POCS.[1] The reduction in TR can be either used to increase the frame rate, or to increase the number of views per frame. Recently, the idea of exploiting the compressibility of MR images in some transform domain has generated a flourish in the development of compressed sensing (CS) based iterative image reconstruction techniques,[2] which can further accelerate the acquisition by enabling the reconstruction from highly undersampled k-space data. Radial sampling patterns are particularly well suited for cine MRI because their frequent acquisition of the k-space center region reduces sensitivity to motion and improves visualization of dynamics, and in a CS-type reconstruction, allows exploitation of sparsity along both image dimensions.[3] In conventional radial imaging, the views are placed symmetrically around the k-space center, forming full echoes for acquisition. Yet, since the phase maps are typically smooth, the signals from the outer parts of the k-space connected by point symmetry have complex conjugate symmetry. An asymmetric echo benefits from this redundancy and omits (samples from) the outer part of one side of the view without subsequent data generation. Inspired from these findings and observations, we herein propose to use interleaved-angle radial sampling with asymmetric echoes, instead of the conventional full echoes, for robust fast free-breathing cardiac cine MRI.

Methods: *Acquisition/Measurement Protocol*: We in-house modified a fluoroscopic bSSFP sequence for interleaved-angle radial sampling schemes with echoes at different levels of asymmetry (e.g., full-echo (fe), weak asymmetry (wa), strong asymmetry (sa), and half-echo (he)) as shown in Fig. 1(a)-(d), respectively. Note that the number of samples is inversely proportional to the level of asymmetry. We distribute the views over 2π (instead of π) to make the sampling pattern approximately symmetric. Thus, the sampling density D is a function of the radius r only (and not of the azimuth φ) of the form $D(r) \sim \{1/r \text{ for } r < R; 0.5/r \text{ for } r \geq R\}$, where R is the number of samples on the asymmetric side of the view (e.g., $R = 88$ for sa, $R = 16$ for he). The coil sensitivity maps (CSMs) were calculated using an eigenvector-type approach from the 24×24 central k-space region, making the CSMs independent of the level of asymmetry up to a certain point.

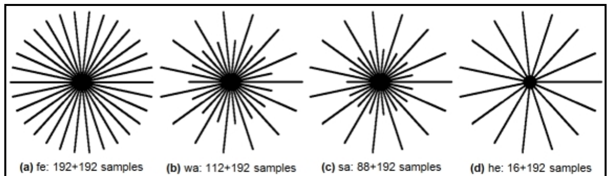

Fig. 1: Interleaved-angle radial sampling with views at different levels of asymmetry.

Reconstruction Protocol: We consider the CS-type MR reconstruction method that applies an L_1 regularization based on the redundant Haar wavelets.[4] Under a parallel imaging scheme with N_c receiver coils, the problem is of the form

$$\min_x \tfrac{1}{2} \sum_{t=1}^{T} \sum_{c=1}^{N_c} ||y_t^c - \Phi_t(s^c \odot x_t)||_2^2 + \|\lambda^{3D} \odot (W^{3D}x)\|_1. \quad (1)$$

In the first (L_2) term, x_t is the 2D image at time t, s^c is the CSM for coil c and, $s^c \odot x_t$ is the coil image of coil c at time t (with $\odot$ denoting the component-wise product of two matrices). Φ_t represents the acquisition operator and y_t^c is the acquired *k*-space data by coil c at time t. In the second (L_1) term, x is the concatenation of $\{x_t\}_{t=1}^T$ into a 3D tensor, $W^{3D}$is the weighted 3D redundant Haar wavelets, and λ^{3D} is the tensor of weights applied on the wavelet coefficients of x. In optimizing (1), Φ_t was implemented using NUFFT[5] with density compensation $D(r)$ applied on k-space data and the problem was solved using a Nesterov-type algorithm.[6] The complete dynamic reconstruction was performed using an overlapping sliding window of length T, where T was set to an integer multiple of the number of interleaves.

Data: The proposed framework is evaluated on phantom and real data (from a healthy volunteer) acquired on a 1.5T clinical MR scanner (MAGNETOM Aera, Siemens AG Healthcare, Erlangen, Germany). Dynamics in the phantom was generated by shifting the slice position by 0.1mm along the slice normal between frames. The k-space data for the phantom was measured using different radial trajectories with the asymmetries given in Fig. 1, 15 views per frame, 23 interleaves, 30 coils, and FOV = 250mm×250mm. A series of 100 images of size 192×192 was reconstructed. The volunteer cardiac data was acquired using protocols with asymmetries fe and sa, 15 views per frame, 20 interleaves, and 32 coils (slice thickness = 7mm, FOV = 250mm×250mm) to reconstruct two series of 3700 short-axis images of size 192×192. Table 1 shows the asymmetries (%) and the RF spacing (as TR) for these two datasets.

Table 1: Datasets with information on radial asymmetries and the RF spacing

Data Type	Asymmetry (%)	TR (ms)
Phantom (fe/wa/sa/he)	0/42/54/92	3.45/3.09/2.98/2.66
Clinical (fe/sa)	0/54	2.80/2.45

Results: Experiments on phantom data demonstrate that reconstruction from all asymmetries shows qualitatively comparable image quality (Fig. 2(a): fe,wa,sa) and temporal dynamics visualization (see x-t plots in Fig 2(a)) with reduced TR, whereas we observe a noticeable degradation in quality (i.e., increased blurring and streaks, arising from bright bands around bSSFP stop bands where the slowly varying phase condition is violated) for the half-echo k-space data (Fig. 2(a): he, red arrows). These findings demonstrate that radial CS imaging with echo asymmetries of about 50% is feasible. In Fig. 2(b) we compare 102 time phases of the cardiac data with asymmetries sa and fe. Although radial streaks in the background are slightly increased, the reconstruction from sa views offers a similar image quality and sharpness in dynamics due to the reduced TR (or higher frame rate). These results support our hypothesis that sampling the k-space using radial asymmetric views (assuming we sample ~46% (i.e., 88/192) of one side of the view) can accelerate the overall acquisition with a tolerable degradation in reconstruction quality.

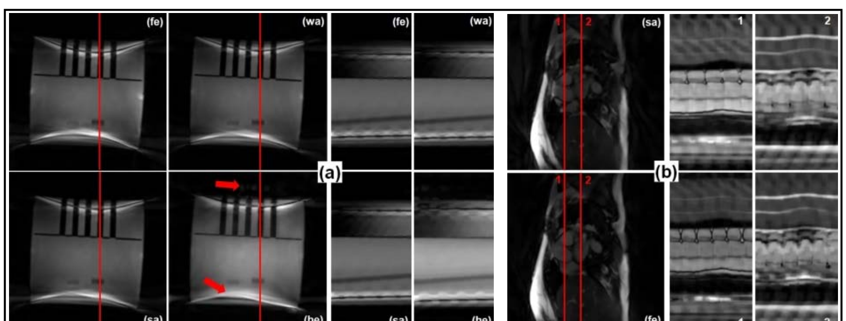

Fig. 2: Reconstructed images and x-t plots for (a) phantom data and (b) volunteer cardiac data.

Discussion and Conclusion: In this work, we propose to use interleaved-angle radial sampling with asymmetric views for fast free-breathing cardiac cine MRI. Our experiments show that the proposed schemes, combined with a state-of-the-art CS-type reconstruction method, can speed up data acquisition and stabilize bSSFP signals by reducing TR by about 12% with only minor degradation in image quality compared to the conventional full echo schemes.

References: 1. Bauschke H, Borwein J. SIAM Review. 1996; 38(3):367-426. 2. Lustig M, et al. Mag Reson Med. 2007; 6:1182-1195. 3. Feng L, et al. Proc Intl Soc Mag Reson Med. #1117; 2012. 4. Liu J, et al. Proc Intl Soc Mag Reson Med. #4249; 2012. 5. Fessler J, et al. IEEE T Signal Process. 2003; 51:560-574. 6. Beck A, Teboulle M. SIAM J Imag Sci. 2009; 2:183-202.