SPIRiT^{mc} - Autocalibrating parallel imaging with non-rigid motion correction

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Introduction: Scan acceleration and motion compensating techniques are invaluable to reduce acquisition times and breathing artifacts in cardiac imaging. Respiratory motion compensation with navigator (NAV) based gating or breathholding is widely used, but may be limited in non-compliant patients. Based on the matrix formulation of general motion correction proposed earlier [1], various approaches have been presented permitting data acquisition during free breathing of the subject [2,3]. It has also been demonstrated that the method can be combined with different undersampling techniques [4,5]. Among the parallel imaging (PI) portfolio SPIRiT [6] has gained interest as an autocalibrating PI technique for arbitrary k-space trajectories generalizing GRAPPA [7].
In this work, the SPIRiT reconstruction framework is extended by incorporating linear motion operators into the signal model allowing for scanning during the entire breathing cycle in cardiac imaging. Simulation and in-vivo phase-contrast (PC) data demonstrate the benefits of the technique.

Theory: In SPIRiT a Cartesian multi-coil image $\boldsymbol{\rho}$ is reconstructed by minimizing $\|\mathbf{d} - \mathbf{E}\boldsymbol{\rho}\|^2 + \lambda^2\|(\mathbf{G} - \mathbf{I})\boldsymbol{\rho}\|^2 + \mu^2 R(\boldsymbol{\rho})$ (1), with the measured k-space trajectory $\mathbf{d}$, encoding matrix $\mathbf{E}$, calibration consistency operator $\mathbf{G}$, identity $\mathbf{I}$, regularization parameters λ and μ, and further regularization $R(\cdot)$. The data consistency term is extended with a bilinear interpolation matrix $\mathbf{T}$ warping the coil images into the different motion states corresponding to the respiratory positions during data acquisition: $\|\mathbf{d} - \mathbf{ET}\boldsymbol{\rho}\|^2 + \lambda^2\|(\mathbf{G} - \mathbf{I})\boldsymbol{\rho}\|^2 + \mu^2 R(\boldsymbol{\rho})$ (2). The encoding operator then maps the motion state images to the acquired profiles.

Methods: Dynamic short axis view data (256x256 image matrix) was generated from the XCAT human anatomy model [8] simulating realistic cardiac and non-rigid respiratory motion. Thirty cardiac phases of 30ms covering the whole cardiac cycle were calculated for a number of heart beats corresponding to an undersampling factor R relative to radial Nyquist. Complex valued coil sensitivities and Gaussian noise (SNR=30) were added. The dynamic 8-coil array data was then projected onto a 2D Golden angle (GA) radial trajectory [9] with a TR of 3ms per profile.
Fully sampled 2D radially (GA) encoded 4-point cine PC data (5mm NAV window, FOV 250x250mm^2, voxel size 2x2x10mm^3, V_{enc} 200cm/s, TR/TE 5.4/2.9ms, temporal resolution 28ms) was acquired in a healthy volunteer during free-breathing on a 3T Philips scanner (Philips Healthcare, Best, The Netherlands) with six receiver coils. The same scan was repeated without NAV gating during free-breathing with 4x radial undersampling.
Reconstruction was performed with and without motion correction using equations (1) and (2) with L1 total variation (TV) regularization: $R(\boldsymbol{\rho}) = \|\mathbf{B}\boldsymbol{\rho}\|_1$, $\mathbf{B}$ being the image gradient. The 7x7 interpolation kernels in $\mathbf{G}$ were fitted to a 30x30 calibration area extracted from a temporal average image of the reduced k-space data. Motion state images at each heartbeat and phase were assigned by reconstructing low resolution images using equation (1) with TV from a 50 projections window around each heart phase. $\mathbf{T}$ was obtained by non-rigid registration of the motion state images relative to a reference heartbeat using the ITK based elastix framework [10].

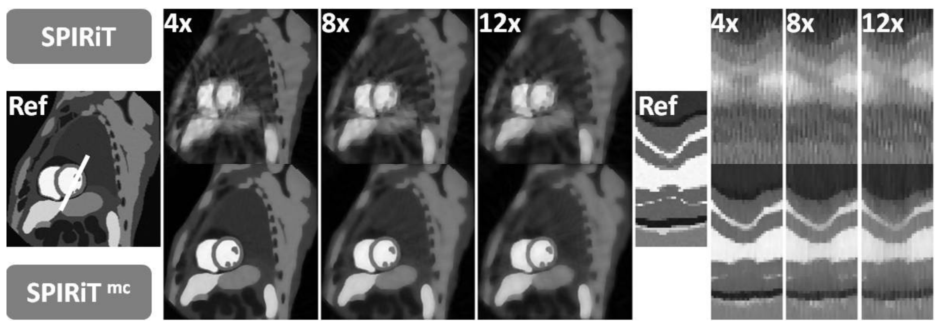

Figure 1 Cardiac frame of heart model (Ref) and reconstructed images for different undersampling factors without (SPIRiT, top row) and with (SPIRiT^{mc}, bottom row) motion correction. The corresponding temporal profiles are plotted along the indicated line.

Results: Fig.1 compares images and temporal profiles of the heart model reconstructed from 4, 8 and 12x radially undersampled data without (SIPRiT) and with motion correction (SPIRiT^{mc}) relative to the fully sampled reference. Fig.2 shows a comparison of the in-vivo fully sampled NAV gated reference and SPIRiT^{mc} reconstructions from 4x undersampled data acquired without respiratory gating.

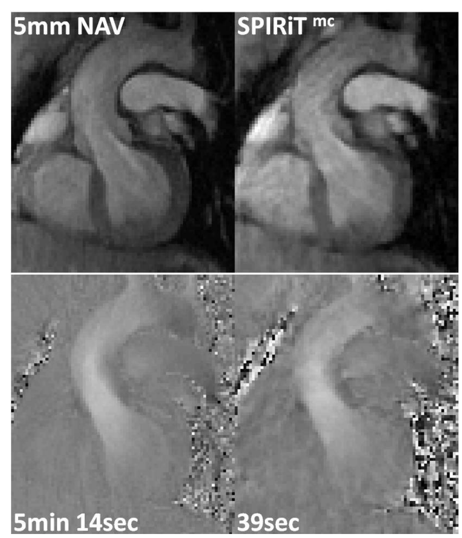

Figure 2 Systolic magnitude and in-plane velocity component images of NAV gated scan (left). Reconstructed images of non-gated 4x radially undersampled measurement with motion compensation (right). The corresponding acquisition times are also depicted.

Discussion: In this work, the SPIRiT reconstruction framework has been extended with a linear operator for retrospective non-rigid motion correction. The proposed method has been applied to a dynamic heart model simulating both cardiac and respiratory motion and PC in-vivo data. Image artifacts induced by respiratory motion are well corrected for with SPIRiT^{mc}. In conjunction with significant undersampling the method holds considerable potential for accelerating free-breathing cardiac imaging protocols.

References: [1] Batchelor PG, MRM (54) 2005, [2] Odille F, MRM (60) 2008, [3] Schmidt JFM, MRM (66) 2011, [4] Hansen MS, MRM (68) 2012, [5] Usman M, MRM (online) 2012, [6] Lustig M, MRM (64) 2010, [7] Griswold MA, MRM (47) 2002, [8] Segars WP, Med Phys (37) 2010, [9] Winkelmann S, IEEE TMI (26) 2007, [10] Klein S, Staring M, IEEE TMI (29) 2010