Radial Fourier velocity endcoding (rFVE) with SPIRiT exploiting temporal correlations in k-t space

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Introduction: Fourier velocity encoding (FVE) [1] resolves the distribution of velocities within a voxel by acquiring a range of k_v-points. The long acquisition times, however, have excluded the method from clinical use so far. SPIRiT [2] provides a very general reconstruction framework for non-Cartesian undersampled data. Prior assumption of Gaussian velocity spectra additionally allows undersampling along the velocity encoding dimensions [3]. In this work, we extended non-Cartesian SPIRiT to include the temporal dimension thereby additionally exploiting temporal correlations in k-t space. The k-t method is applied to non-uniformly undersampled k_v-encodes to reconstruct mean and standard deviation (SD) of the velocity spectra for each voxel in aortic flow measurements.

Theory: The SPIRiT interpolation operator **G**, enforcing consistency between calibration data from a fully sampled centre of k-space and reconstructed Cartesian k-space points, **x**, is extended for dynamic MRI by including temporal correlations between adjacent data frames (Fig.1a). Data consistency is imposed using gridding-operator **D** relating **x** to the measured k-t trajectory **y** (Fig.1b). Then, **x** is recovered by solving the minimization problem $\text{argmin}_{\mathbf{x}}\ \|\mathbf{D}\mathbf{x} - \mathbf{y}\|^2 + \lambda\|(\mathbf{G} - \mathbf{I})\mathbf{x}\|^2$ with identity operator **I** and regularization parameter λ.

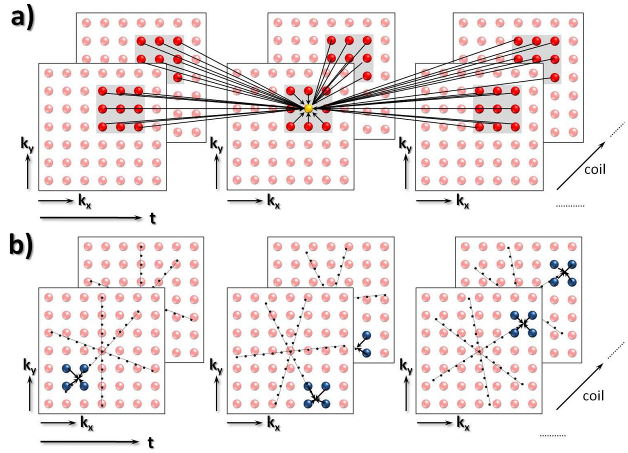

Figure 1: a) Every Cartesian k-t sample point is expressed as a linear combination of neighboring points in k-t space across all coils.
b) Dynamic Golden angle acquisition of radial profiles.

Methods: 2D radial (FOV=250x250mm^2) fully sampled cine FVE data of the ascending and descending aorta (aA and dA) for 3 orthogonal velocity components were obtained from a healthy volunteer on a 3T Philips scanner (Philips Healthcare, Best, The Netherlands). Six receiver coils were used. 17 k_v-points were acquired symmetrically around k_v=0 with $\Delta k_v = \pi/V_{enc}$ (V_{enc} = 200cm/s). Data in 5 healthy volunteers were acquired with the same parameters but only 3 k_v-points corresponding to encoding velocities of 200cm/s, 50cm/s, and 25cm/s along with the reference (k_v=0) for the Gaussian prior data. Undersampled radial data sets for every first gradient moment were simulated by re-gridding the data onto Golden angle profiles [4] (Fig.1b). Reconstruction was performed for every k_v-point separately (λ=0.125) using dedicated software implemented in Matlab (Natick, MA, USA). A 7x7x3 neighborhood in k_x-k_y-t direction was chosen for the k-t space interpolation kernel. The weights were calculated from a 30x30x(nr cardiac phases) calibration area. For the resulting coil-combined images, mean and SD of velocity distributions for each component (M-P-S) were calculated using a 3-point method [5] and least-squares fit to the 4-point measurements.

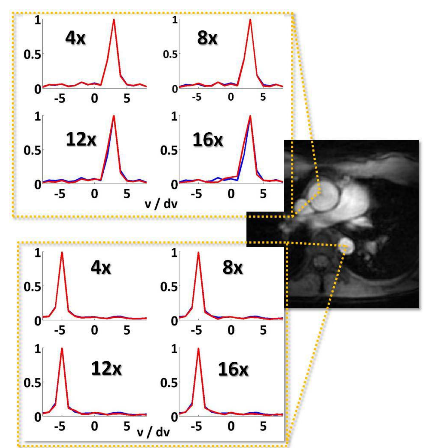

Figure 2: Velocity spectra at peak systole for two voxels in the ascending and descending aorta for the fully sampled k_v-axis data.

Results: Fig.2 shows the magnitude image at peak systole from the fully sampled in-vivo reference data and compares kt-rFVE reconstructed normalized through-plane velocity distributions for different undersampling factors (red) relative to the fully sampled reference (blue). Fig.3 displays in-plane streamlines reconstructed from the acquired mean velocities and turbulence intensity maps calculated from SD values for the non-uniformly k_v-undersampled data. Additionally, mean root-mean-square errors (RMSE) of the reconstructed mean velocities and standard deviations in the aortic arch for different undersampling factors and for each flow direction are compared.

Discussion: In this work, an extension of SPIRiT has been developed for dynamic radial FVE. The algorithm was successfully tested on in-vivo data for two different k_v-sampling schemes. Results show that up to 12-fold radial undersampling provides accurate quantification of mean velocities and turbulence intensities.

References: [1] Moran PR, MRI (4) 1982, [2] Lustig M, MRM (64) 2010,[3] Dyverfeldt P, MRM (56) 2006, [4] Winkelmann S, IEETransMedIm (26) 2007, [5] Lee AT, MRM (33) 1995, [6] Dyverfeldt P, JMRI (28) 2008.

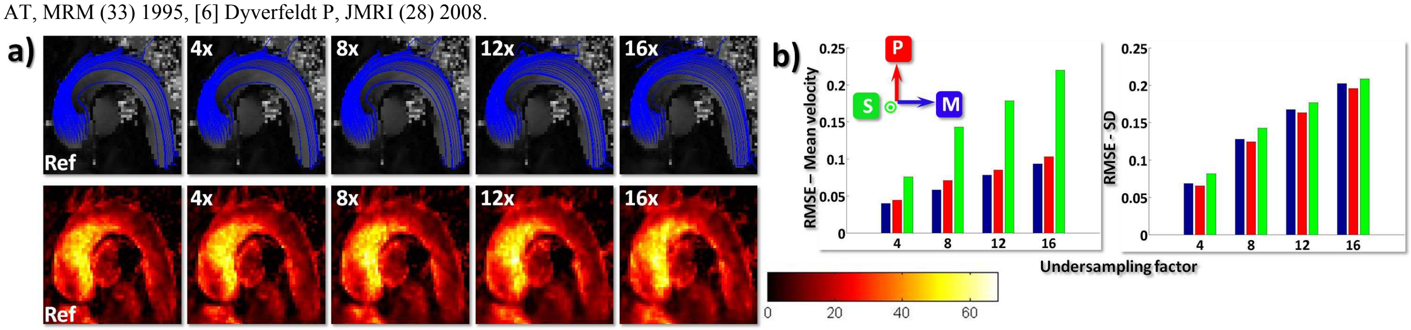

Figure 3: a) Top row: Stream lines derived from reference and undersampled systolic data. Bottom row: Corresponding turbulence intensity maps [J/m^3] calculated according to [6]. The streamlines are congruent with the turbulence and phase dispersion maps, respectively. **b)** The RMSE of reconstructed mean velocities and SDs from a ROI placed over the aortic arch and averaged over all time frames and volunteers.