Acceleration of Spiral Fourier velocity encoded MRI using 3D SPIRiT

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Introduction: Fourier velocity encoded (FVE) MRI [1], is useful in the assessment of vascular and valvular stenosis [2] and intravascular wall shear stress [3,4], as it eliminates partial volume effects that may cause loss of diagnostic information in more conventional phase-contrast MRI [5]. FVE MRI has not been adopted for any routine clinical applications, primarily because scan-time is prohibitively long. The spiral FVE method [2] shows promise, as it is substantially faster. Scan-time can be significantly reduced using temporal acceleration [6], and temporal resolution can be improved using parallel imaging [7-9]. Image-domain 2D SPIRiT [10] has been previously used for acceleration of spiral FVE, without temporal acceleration [7,8]. In this work, we investigate the use of 3D SPIRiT to reconstruct temporally-accelerated spiral FVE data.

Methods: **Imaging:** Data were acquired on a GE Signa 3T EXCITE HD system (40 mT/m, 150 T/m/s), using a 4-channel carotid coil. Scan parameters: 1.4×1.4×5 mm^3 spatial resolution, 16 cm FOV, eight 4-ms variable-density spirals, 5 cm/s velocity resolution, 240 cm/s velocity FOV, 12 ms temporal resolution, scan time 146 seconds (256 heartbeats at 105 bpm). The acquired data consist of a temporally resolved stack-of-spirals in k_x-k_y-k_v space [2]. A Cartesian inverse Fourier transform along k_v followed by a non-Cartesian inverse Fourier transform along k_x-k_y produces the spatio-temporal-velocity distribution, $m(x,y,v,t)$. **Evaluation:** Parallel imaging acceleration was evaluated using 4-fold retrospective undersampling of the spiral FVE datasets. Temporal undersampling was performed using three different view-ordering schemes: (i) acquiring only the 1st and 5th spiral interleaves in each k_v-t coordinate [7,8]; (ii) alternating interleaves pairs between k_v levels and cardiac phases (Fig. 1a); and (iii) alternating between half of the interleaves or no interleaves, for each k_v-t coordinate (Fig. 1b) [6]. Each approach yields unique aliasing patterns in v-f space. Undersampled data was reconstructed using three approaches: sum-of-squares (SoS) [11], image-domain 2D SPIRiT [7,8,10,12], and 3D image-domain SPIRiT [13]. For 2D SPIRiT, calibration was performed independently for each k_v-t coordinate, using the fully sampled k-space [7,8]. For 3D SPIRiT, a single calibration step was performed for the entire dataset, using the already undersampled data. The fully sampled SoS result was used as ground-truth reference.

Results: A qualitative evaluation of the time-velocity distributions obtained with 3D SPIRiT (Fig. 2) shows this approach is capable of removing both aliasing from static material in nearby voxels (spurious constant-velocity lines along t), due to spatial undersampling (schemes i-iii), and from flowing spins in the same voxel (shifted replicas of the flow waveforms), due to k_v undersampling (scheme iii). 2D SPIRiT (with scheme i) distorted the entire flow waveform and was unable to successfully remove aliasing artifacts (see error image). 3D SPIRiT was able to almost completely remove aliasing artifacts, and provided less-distorted flow waveforms. Using scheme ii, the distortion appeared temporally modulated across the entire cardiac cycle. Using scheme iii, the distortion appeared only in the cardiac phases associated with peak flow. A quantitative evaluation is presented in Table 1. 3D SPIRiT consistently provided higher signal-to-error ratio, compared to sum-of-squares and 2D SPIRiT. For all evaluated voxels, 3D SPIRiT achieved a signal-to-error ratio (SER) at least 6 dB higher than SoS. Reconstruction time for each approach is shown in Table 2. Reconstruction time for 3D SPIRiT is less than half of that for 2D SPIRiT, however it is still long compared to sum-of-squares reconstruction.

Conclusions: We have demonstrated the potential for 4-fold acceleration of spiral FVE using retrospective undersampling and 3D SPIRiT reconstruction. Results may be further improved using a temporal implementation of SPIRiT (analogous to TGRAPPA [14]), and/or pseudo-random selection of spiral interleaves for each k_v-t coordinate, which would result in incoherent aliasing artifacts in v-t space; and a ℓ_1-norm regularization factor [10]. The general approach also needs to be evaluated prospectively, and in patients.

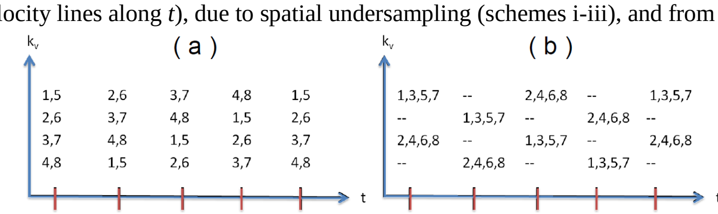

Fig.1: View-ordering schemes: (a) alternate interleaves pairs between k_v levels and cardiac phases (scheme ii); (b) alternating between half of the interleaves or no interleaves, for each k_v-t coordinate [6] (scheme iii).

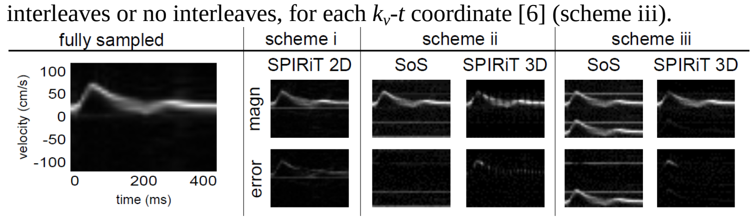

Fig.2: Time-velocity distributions from the left carotid bifurcation of a healthy volunteer, obtained from 4-fold temporally-undersampled data (right), and from the fully-sampled data (left). The undersampled data was obtained using three view-ordering schemes (i-iii) and reconstructed using sum-of-squares, and 2D and 3D SPIRiT (right, top row). The bottom row shows the residual error for each result.

Table 1: Signal-to-error ratio (in dB) for 4-fold undersampled results, with respect to the fully-sampled reference.

View Order	Recon	Right ECA	Right ICA	Left Carotid Bifurcation
i	2D SPIRiT	6.6	7.7	7.5
ii	sum-of-squares	−3.6	0.4	5.0
ii	3D SPIRiT	8.0	10.5	11.3
iii	sum-of-squares	−0.9	−0.5	−0.9
iii	3D SPIRiT	8.6	12.9	12.7

Table 2: Reconstruction time (in minutes) for each approach, using an Intel Core i7 (dual core, 2.67 GHz) with 6GB of RAM.

	2D SPIRiT	3D SPIRiT	SoS
reconstruction time	93	43.5	0.92

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