Application of UNFOLD to Real-Time Fourier Velocity Encoding

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Introduction: To measure velocity spectra at high temporal resolution, a real-time Fourier-velocity encoding (FVE) method has previously been developed [1]. This method uses a two-dimensional (2D) spatially-selective excitation with an oscillating 1D readout gradient to measure the velocity spectrum every TR. Modified sampling strategies have been proposed using variable-density (VD) k-space trajectories to improve acquisition efficiency [2]. However, a smoothly-varying sampling density is needed to avoid coherent artifacts from the under-sampled regions of k-space, which again limits acquisition efficiency. To overcome this constraint, we have developed and experimentally tested a method using UNFOLD [3] to suppress the aliasing artifacts resulting from more aggressive VD trajectories.

UNFOLD was first developed to improve the efficiency of the MR acquisition of dynamic data [3]. By alternating between two interleaved and under-sampled k-space trajectories, this method imparts a temporal frequency to aliased signals which can then be filtered out. However, this strategy cannot be applied directly to real-time FVE data because the measured flow patterns already possess large temporal bandwidths that would interfere with UNFOLD encoding. Here we show that it is possible to suppress the signal modulation related to flow by pre-processing the FVE data, which then allows artifact removal using UNFOLD.

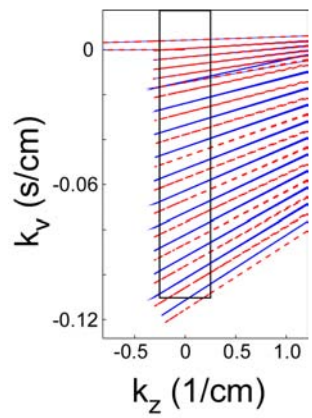

Fig. 1: Partially interleaved k-space trajectories. Box = bounds of the data used for homodyne recon.

Methods: A two-interleaf real-time FVE sequence was implemented on a 1.5 T MR system (Twinspeed/EXCITE III, GE Healthcare). Relevant portions of the experimentally measured k-space trajectories are shown in Fig. 1. Similar to partial-Fourier imaging studies using UNFOLD, the trajectories shared a common path near the origin of k-space (aliasing velocity = 125 cm/s) before diverging [4].

With this sequence, pulsatile flow was studied using a flow phantom constructed from a gear pump (Hypro Corp.) and computer-controlled servo motor (Baldor Electric Co.). Water was pumped at a fundamental frequency of 1 Hz through a rubber tube (inner diameter = 10 mm) fed through the bore of the magnet. Peak velocities of approximately 1 m/s were used. Other relevant acquisition parameters were: TR = 40 ms, BW = ±125 kHz, velocity resolution = 4.5 cm/s, scan time = 640 spectra in 25.6 s. Acquired data were gridded to a Cartesian matrix using a 2×2 sinc-weighted kernel and Kaiser-Bessel windowed (β = 3.5) before homodyne reconstruction. Spectra from one spatial location were then concatenated to generate a flow waveform.

Pulsatility was removed from the velocity waveform by tracking the peak intensity at each time point (dashed line in Fig. 2a) and shifting each spectrum along the velocity axis to align these peaks (see Fig. 2b). Velocity spectra were first interpolated to 128 points to allow sub-pixel alignment. The 1D Fourier transform of the aligned data was then computed in the temporal dimension (Fig. 2c), and a frequency band of ±4 Hz about the Nyquist frequency was set to zero to suppress the aliased components (Fig. 2d). The filtered data were then inverse Fourier transformed and the resulting spectra shifted back along the velocity axis to their original offsets (Fig. 2e).

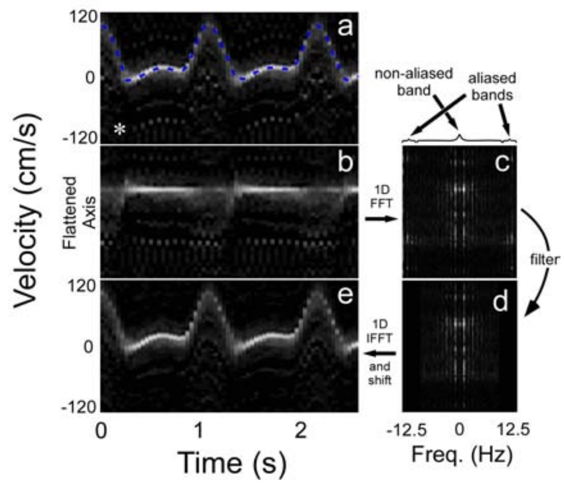

Fig. 2: Modified UNFOLD processing of FVE spectra. See text for description.

Results & Discussion: Spectra acquired using the interleaved trajectories contained artifacts due to undersampling of k-space (asterisk in Fig. 2a). These artifacts were modulated in time by the alternating k-space trajectory (Nyquist) as well as by the pulsatile flow pattern (1 Hz fundamental). To correct for the latter modulation, spectra were registered based on their peak intensity. This simple approach performed well for the given waveform, which had a well-defined peak over most of the flow cycle. As expected, artifacts in the flattened waveform possessed strong temporal frequency components centered at the Nyquist frequency (Fig. 2c) that could be successfully filtered (Fig. 2d). Harmonics about the Nyquist frequency (and DC) resulted from residual flow information in the flattened waveform. The reconstructed flow waveform (Fig. 2e) showed good artifact suppression without degradation of the primary waveform. Some residual artifact remained due to imperfect alignment of the spectra prior to Fourier transformation, and from artifact from the conventional real-time FVE analysis itself.

In summary, interleaved real-time FVE data were pre-processed to reduce flow-related signal modulation, which enabled application of UNFOLD to suppress artifact from k-space undersampling. This approach will enable more aggressive undersampling of k-space without compromising flow measurement. Artifact associated with other differences between the interleaved trajectories would also be suppressed by this method.

References: [1] Hu *et al*. Magn Reson Med (1993) p.393; [2] DiCarlo *et al*. Magn Reson Med (2005) p.645; [3] Madore *et al*. Magn Reson Med (1999) p.813; [4] Madore. Magn Reson Med (2002) p.493