

Single-voxel direct Fourier reconstruction of spiral Fourier velocity encoding data on GPGPUs

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Introduction: Fourier velocity encoding (FVE) [1] is useful in the assessment of valvular disease [2], as it eliminates partial volume effects that may cause loss of diagnostic information in phase-contrast imaging [3]. FVE has also been proposed as a method for measuring wall shear rate in the carotid arteries [4,5]. Although the scan-time of 2DFT FVE is prohibitively long for clinical use, the spiral FVE method [2] shows promise, as it is substantially faster. However, the reconstruction of spiral FVE data is time-consuming, due to its multidimensionality and the use of non-Cartesian sampling. This is particularly true for multi-slice/3D and/or multi-channel acquisitions. Spiral FVE datasets consist of temporally-resolved stacks-of-spirals in k_x - k_y - k_z space [2]. The spatial-temporal-velocity distribution, $m(x,y,v,t)$, is typically obtained from the k-space data, $M(k_x, k_y, k_z, t)$, by first using a non-Cartesian inverse Fourier transform along k_x - k_y (e.g., gridding [6], NUFFT [7]), followed by a Cartesian inverse Fourier transform along k_z (Fig. 1a). With this approach, the entire $m(x,y,v,t)$ matrix is calculated. However, we are typically only interested in the velocity distributions associated with a small region-of-interest within the x - y plane.

We propose the use of single-voxel direct Fourier transform (DrFT) [8] to reconstruct spiral FVE data (Fig. 1b). While whole-image DrFT is orders of magnitude slower than gridding and NUFFT algorithms, the DrFT equation allows the reconstruction of individual voxels of interest, which considerably reduces the computation time. Additionally, we propose the use of general-purpose computing on graphics processing units (GPGPUs) to further accelerate computation and achieve seemingly instantaneous spiral FVE reconstruction.

Methods: For the accelerated reconstruction of spiral FVE data, we begin by reducing the dimensionality of the k-space data, $M(k_x, k_y, k_z, t)$, by calculating $M_{xy}(k_z, t)$ for only one select voxel, at position (x,y) . This is performed using the DrFT [8], in which a pixel of the reconstructed image is computed as the weighted correlation of the k-space samples and the phase modulation function for that pixel:

$$m_{xy} = \sum_{n=0}^{N-1} W_n M_n e^{j2\pi(xu_n + yv_n)}$$

where N is the total number of k-space samples, M_n is the raw data acquired at the point (u_n, v_n) on the non-Cartesian grid in k-space, and W_n is the weight attributed to that point. The weights may be calculated based on the Voronoi areas associated with the non-Cartesian k-space sampling grid.

Note that single-voxel NUFFT is not practical, because NUFFT is an iterative algorithm. A 2D-FFT could be calculated for a single pixel of the image, but this would reduce FFT complexity by no more than 50%. Furthermore, gridding of the entire k-space data would still be needed, prior to FFT computation. The proposed approach reduces DrFT's complexity by 99.99%!

The $M_{xy}(k_z, t)$ matrices from each coil element are combined using sum-of-squares, and the time-velocity distribution, $m_{xy}(v, t)$, is obtained by inverse 1D-FFT along k_z . The voxel of interest may be prescribed by clicking on a magnitude image, $m(x,y)$, obtained by reconstructing—using gridding or NUFFT—only the $M(k_x, k_y)$ data associated with $k_z = 0$ and $t = 0$ (this takes only 90 ms) (see Fig. 2).

A multi-slice CINE spiral FVE dataset was acquired on a GE Signa 3T EXCITE HD system (40 mT/m, 150 T/m/s gradients), using a 4-channel carotid coil. Scan parameters: $1.4 \times 1.4 \times 5 \text{ mm}^3$ spatial resolution (8×1012 -sample variable-density spiral readout), 5 cm/s velocity resolution (32 velocity encodes), 12 ms temporal resolution (43 cardiac phases), 5 axial slices, 146-second acquisition per slice (256 heartbeats at 105 bpm). The data were reconstructed on an Intel 2.9 GHz Core i7 CPU with an Nvidia GTX570 graphics card, running MATLAB on Linux. Single-voxel DrFT was implemented in MATLAB, using segments of code written in CUDA, the parallel computing architecture developed by Nvidia for its GPUs.

Results and Discussion: Single-voxel DrFT was able to reconstruct the spiral FVE data in only 5 seconds (per voxel of interest), while reconstruction using NUFFT required 1 minute per slice (5 minutes total). The CUDA implementation of single-voxel DrFT was able to reconstruct the data in only 135 ms, which is seemingly instantaneous. The time-velocity distributions for select voxels are shown in Fig. 2.

The NUFFT approach has the advantage of providing instantaneous visualization of the time-velocity distribution in any voxel, after reconstruction. However, the reconstruction process takes minutes, because the distributions are calculated even for voxels containing no signal or only static material. Typically, only a very small fraction of the voxels contains flows of interest. Also, this approach requires considerable amount of RAM memory (1.4 GB for a $115 \times 115 \times 5 \times 32 \times 43$ $m(x,y,z,v,t)$ matrix). Single-voxel DrFT reconstructs data only for select voxels, prescribed by the user. Since this process is seemingly instantaneous when running on GPGPUs, there is no advantage in using the NUFFT approach.

Conclusions: Single-voxel DrFT allows seemingly instantaneous reconstruction of spiral FVE data. The use of GPGPUs for DrFT computation provided a 37-fold reduction in reconstruction time, compared with the CPU implementation of the same reconstruction algorithm.

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References: [1] Moran PR. MRI 1:197, 1982. [2] Carvalho JLA and Nayak KS. MRM 57:639, 2007. [3] Tang C et al. JMRI 3:377, 1993. [4] Frayne R and Rutt BK. MRM 34:378, 1995. [5] Carvalho JLA et al. MRM 63:1537, 2010. [6] Jackson JI et al. IEEE TMI 10:473, 1991. [7] Fessler JA and Sutton BP. IEEE TSP 51:560, 2003. [8] Maeda A et al. IEEE TMI 7:26, 1988.

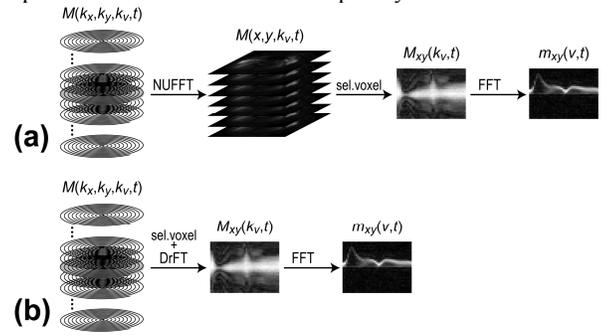


Fig. 1: Reconstruction of spiral FVE data using: (a) NUFFT; and (b) single-voxel DrFT.

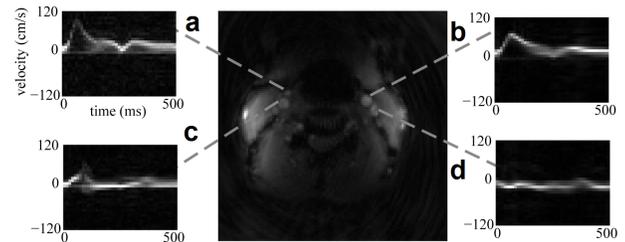


Fig.2: Time-velocity distributions for select voxels from an axial slice prescribed at the neck of a healthy volunteer: (a) right external carotid artery, (b) left carotid bifurcation; (c) right internal carotid artery; and (d) left jugular vein.