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

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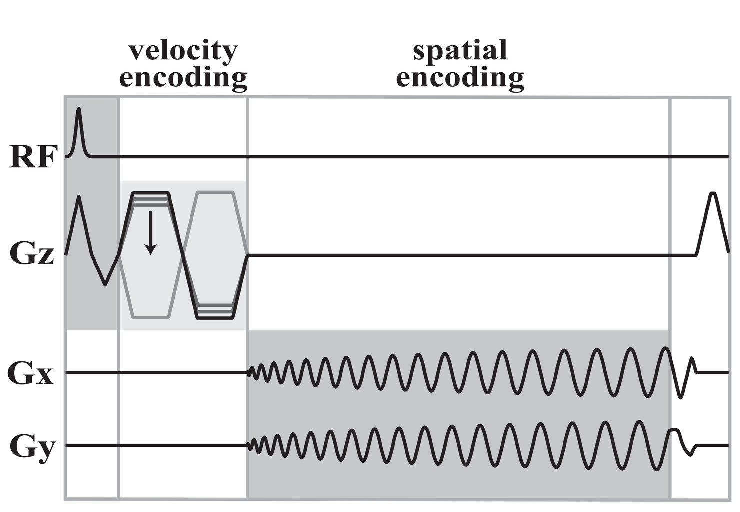
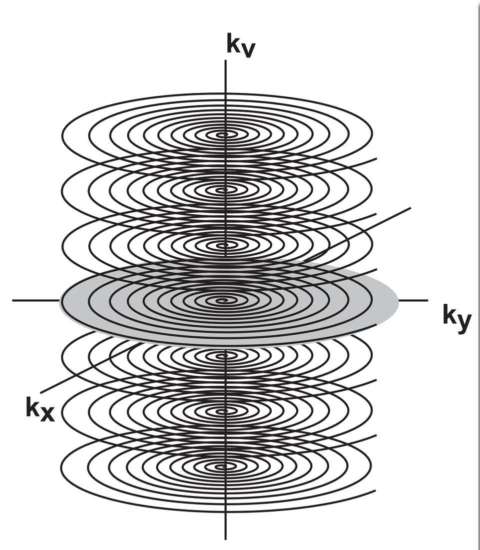
Introduction

- Phase contrast: fast, but has issues with partial voluming [1]
- Fourier velocity encoding [2]: robust to partial voluming, but slow
- Spiral FVE [3]: fast acquisition, but long reconstruction time
  - High dimensionality + non-Cartesian sampling = SLOW!
- We are interested in $\mathbf{m(v,t)}$ for small ROIs, but the entire $\mathbf{m(x,y,v,t)}$ matrix is calculated
- We propose single-voxel direct Fourier transform (DrFT) [4] for reconstruction of spiral FVE data
  - DrFT allows reconstruction of individual voxels
  - GPGPU implementation further accelerates computation
  - Seemingly instantaneous spiral FVE reconstruction!

Spiral FVE



Spiral FVE pulse sequence [3]



Spiral FVE k-space trajectory: a stack-of-spirals in $\mathbf{k_x}$-$\mathbf{k_y}$-$\mathbf{k_v}$ *[3]*

- Traditional reconstruction:
  - NUFFT [5] along $\mathbf{k_x}$-$\mathbf{k_y}$
  - FFT along $\mathbf{k_v}$

Proposed Reconstruction

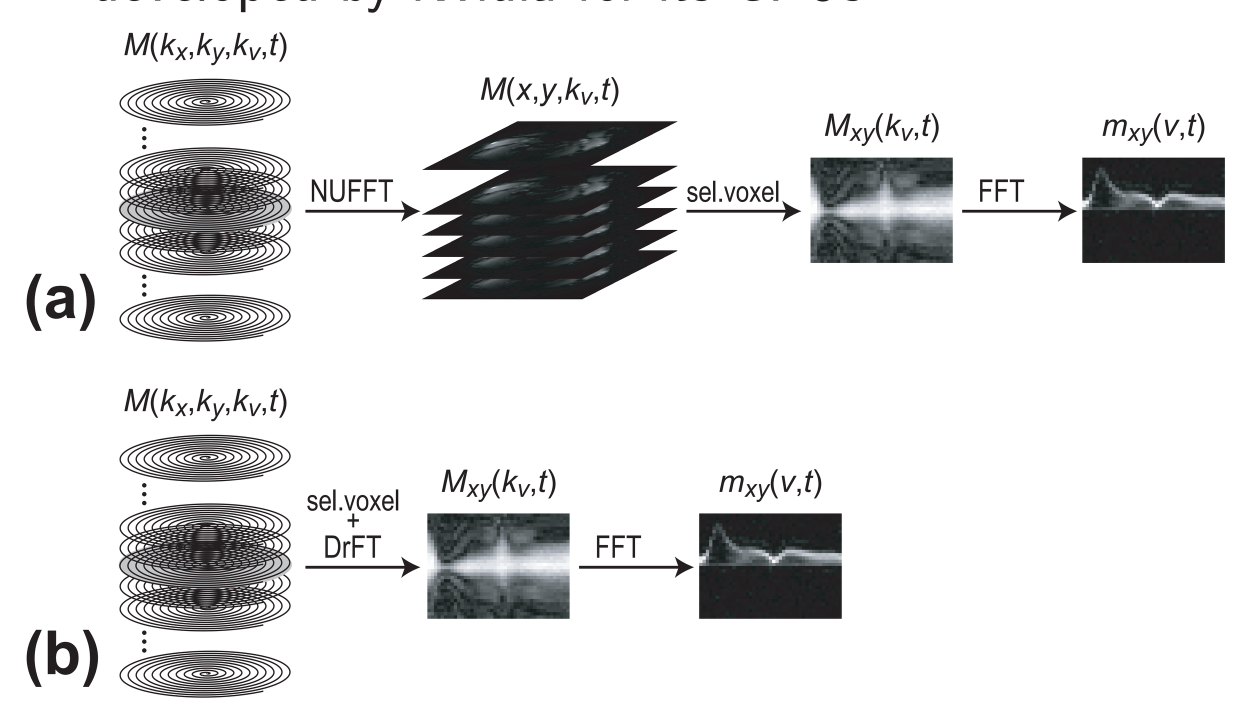
- K-space dimensionality is reduced by calculating $\mathbf{M(k_v,t)}$ for a select voxel at position $\mathbf{(x,y)}$ using the DrFT [4]:

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

  - $\mathbf{N}$ is the total number of k-space samples
  - $\mathbf{M_n}$ is the data acquired at k-space position $\mathbf{(u_n,v_n)}$
  - $\mathbf{W_n}$ is the weight attributed to that k-space position
- Single-voxel computation reduces DrFT's complexity by 99.99%!
  - Single-voxel FFT would still require gridding of the entire k-space
  - Single-voxel NUFFT is not practical, because NUFFT is an iterative algorithm
- $\mathbf{M_{xy}(k_v,t)}$ matrices from each coil element are combined using sum-of-squares
- $\mathbf{m_{xy}(v,t)}$ is obtained by 1D-FFT along $\mathbf{k_v}$

Experimental Methods

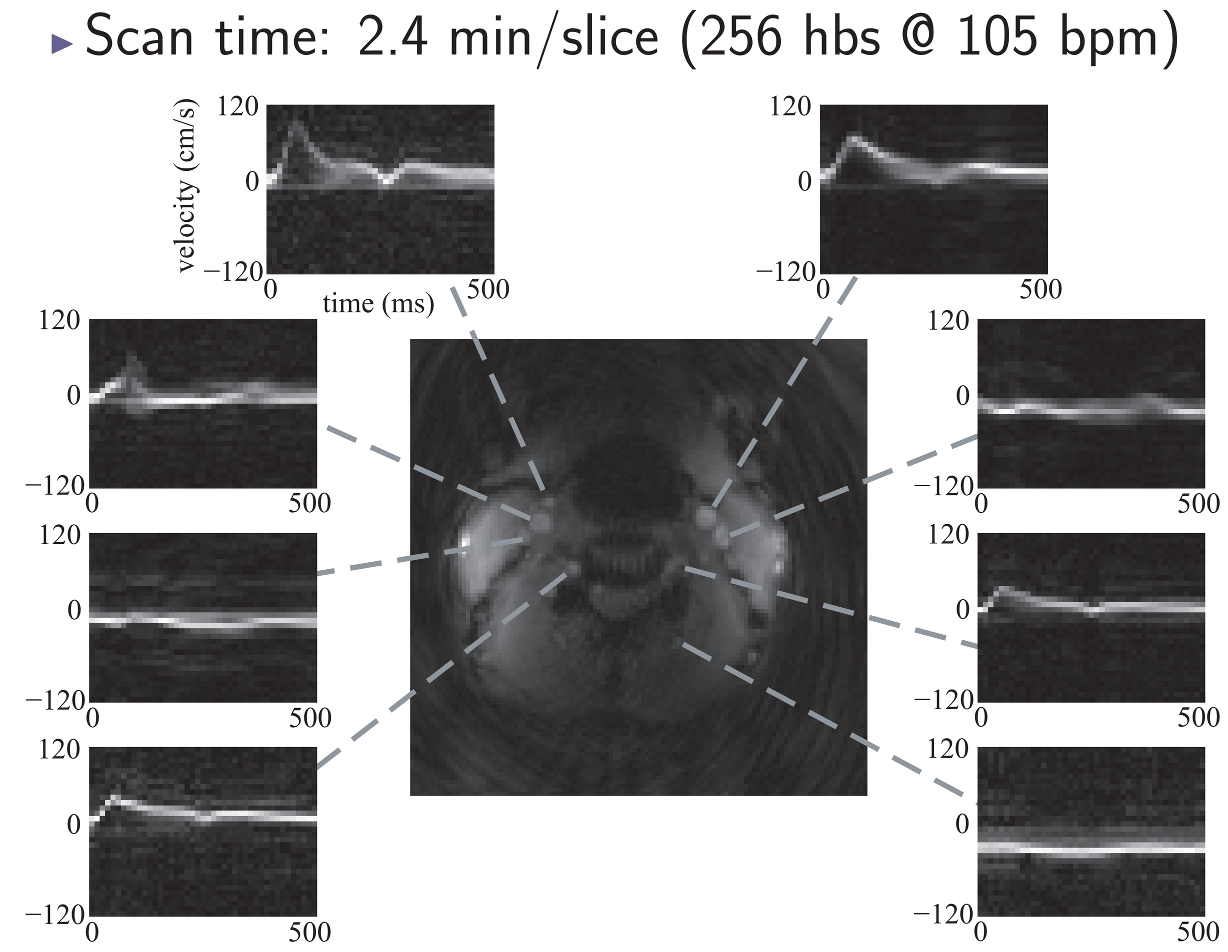
- Data were reconstructed on an Intel 2.9 GHz Core i7 CPU with an Nvidia GTX570 graphics card, running MATLAB on Linux
- Single-voxel DrFT was implemented in MATLAB, using segments of code written in CUDA, the parallel computing architecture developed by Nvidia for its GPUs



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

Reconstructed Data

- Multi-slice CINE spiral FVE scans
- Spatial resolution: 1.4×1.4×5 mm^3
- 8 variable-density spiral readouts (4 ms each)
- Velocity resolution: 5 cm/s (32 velocity encodes)
- Temporal resolution: 12 ms (43 cardiac phases)
- 5 axial slices
- Scan time: 2.4 min/slice (256 hbs @ 105 bpm)



Time-velocity distributions for select voxels of interest from an axial slice prescribed at the neck of a healthy volunteer

Results and Discussion

- Reconstruction using NUFFT required 1 minute per slice (5 minutes total)
  - Only a tiny fraction of the voxels contains flows of interest, but distributions are calculated even for voxels containing no signal or only static material
  - Requires considerable amount of RAM memory: 1.4 GB for a 115×115×5×32×43 $\mathbf{m(x,y,z,v,t)}$ matrix
- Single-voxel DrFT was able to reconstruct the spiral FVE data in only 5 seconds (per voxel)
- The CUDA implementation of single-voxel DrFT was able to reconstruct the data in only 135 ms! (per voxel)

Conclusion

- 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
- Single-voxel DrFT can be used for any non-Cartesian FVE method

References

[1] Tang C et al. JMRI 3:377, 1993
[2] Moran PR. MRI 1:197, 1982
[3] Carvalho JLA, Nayak KS. MRM 57:639, 2007
[4] Maeda A et al. IEEE TMI 7:26, 1988
[5] Fessler JA, Sutton BP. IEEE TSP 51:560, 2003

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