SUPPLEMENTARY MATERIAL

Spiral acquisition and reconstruction methods

A 3D stack-of-spirals was implemented with Fourier sampling in the slice direction. The in-plane spiral trajectory was accelerated in two ways, using variable-density sampling (linearly decreasing from fully sampled at the center of k-space to 0.2 of Nyquist condition at the edge) as well as acquiring only 2 interleaves out of 6. This resulted in a reduction factor of R=6 compared to a fully sampled spiral. Each 3D partition could be acquired in only 2 spiral shots, resulting in 12 partitions acquired in 24 heartbeats, which can be performed in a breath hold. In order to mitigate spiral blurring artifacts, fat suppression was achieved using water-selective excitation (1), and the readout duration was kept small (7.43ms). We selected dynamic compressed sensing to perform the reconstruction of undersampled spiral data. Such methods have previously been applied to successfully accelerate Cartesian cine 2D up to R=6 (2, 3). A variable-density spiral was chosen for its relatively flat point spread function (4). Dynamic variations in aliasing artifacts were generated by rotating the spiral trajectory by a random angle uniformly distributed between 0 and 2π for each dynamic frame (see **Fig. 1**). Reconstruction routines were implemented using Matlab (Matlab, R2012b; Mathworks, Natick, Mass) and took about 3h on a desktop computer (12-core Intel Xeon, 64 GB RAM, no algorithm parallelization) to complete for each subject. Multiple coil information was included in the compressed sensing framework, as described previously (5). Individual coil sensitivity maps were computed from the acquired series without need for extra calibration scan, by combining all dynamic volumes acquired with different random rotation angles. Temporal principal component analysis was selected to improve sparsity

of the 4D flow data (2, 3). After optimizing reconstruction parameters on a test dataset, the weight between data sparsity and consistency (6) was set to 0.1, which was found to eliminate residual artifacts while providing negligible temporal filtering of the flow waveforms. Following compressed sensing reconstruction, phase difference images (**Figure 2**) were computed and residual phase offsets were eliminated by fitting a 3rd order polynomial to static tissue (7) for each of the 3 velocity-encoding directions, using Matlab fit function.

Table S1: Sequence parameters for Cartesian 4D flow, Spiral 4D flow and 2D cine phase contrast.

	Cartesian 4D Flow	Spiral 4D Flow	2D phase contrast
FOV	400 x 400 mm^2	400 x 400 mm^2	319 x 270 mm^2
Velocity Encoding (x, y, z)	(60, 60, 60) cm/s	(60, 60, 60) cm/s	(0, 0, 60) cm/s
Matrix size	160 x 160 x 12	160 x 160 x 12	192 x 160 x 1
Interpolated matrix	320 x 320 x 24	320 x 320 x 24	384 x 320 x 1
Phase resolution	63 %	100 %	50 %
Acquired voxel size	2.5 x 3.9 x 5 mm^2	2.5 x 2.5 x 5 mm^2	1.7 x 3.3 x 7 mm^2
Interpolated voxel size	1.3 x 1.3 x 2.5 mm^2	1.3 x 1.3 x 2.5 mm^2	0.9 x 0.9 x 7 mm^2

Lines per cardiac phase	3	1	3
Slice thickness	5	5	7
Flip angle	9	10	20
Fat suppression	none	Binomial 1-1	none
Echo time	3.3 ms	3.8 ms	4.1 ms
Repetition time	5.7 ms	16.5 ms	6.9 ms
Temporal resolution	68.4 ms	66.2 ms	41.8 ms
Acceleration	R=2 GRAPPA	R=6	R=2 GRAPPA
Acquisition time	11:21 min (6:12 – 20.37)	24 R-R (18-25 s)	17 RR (12-18 s)

1. Sigfridsson A, Petersson S, Carlhall CJ, Ebbers T. Four-dimensional flow MRI using spiral acquisition. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2012;68(4):1065-73.
2. Kim D, Dyvorne HA, Otazo R, Feng L, Sodickson DK, Lee VS. Accelerated phase-contrast cine MRI using k-t SPARSE-SENSE. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2011.
3. Feng L, Otazo R, Jung H, et al. Accelerated cardiac T2 mapping using breath-hold multiecho fast spin-echo pulse sequence with k-t FOCUSS. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2011;65(6):1661-9.
4. Lustig M, Donoho DL, Santos JM, Pauly JM. Compressed sensing MRI. Ieee Signal Proc Mag. 2008;25(2):72-82.

5. Otazo R, Kim D, Axel L, Sodickson DK. Combination of compressed sensing and parallel imaging for highly accelerated first-pass cardiac perfusion MRI. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2010;64(3):767-76.
6. Lustig M, Donoho D, Pauly JM. Sparse MRI: The application of compressed sensing for rapid MR imaging. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2007;58(6):1182-95.
7. Walker PG, Cranney GB, Scheidegger MB, Waseleski G, Pohost GM, Yoganathan AP. Semiautomated method for noise reduction and background phase error correction in MR phase velocity data. Journal of magnetic resonance imaging : JMRI. 1993;3(3):521-30.

MOVIE LEGENDS

Movie S2: Example of a sample slice of the 4D flow spiral acquisition, showing magnitude image of the velocity-compensated volume. The movie is played along the cardiac cycle. On the left is the zero-filled reconstruction of undersampled spiral data, which suffers from severe artifacts. On the right is the series after dynamic compressed sensing reconstruction adopted in this work.

Movie S3: Flow visualization with Cartesian 4D flow acquisition. Particle-tracking was performed to visualize flow mixing from the superior mesenteric vein and splenic vein, into the portal vein. This was acquired in a 30 year-old healthy subject. The segmented vessels are visualized on top of the 3D time-averaged phase contrast angiogram (static volume).

Movie S4: Flow visualization with spiral 4D flow acquisition, in the same subject as Movie 2.