Time-Resolved Angiography with a Highly Undersampled Multi-echo 3D Radial Trajectory

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Introduction

3D Time-Resolved MR angiography remains challenging due to the high spatial and temporal resolutions required [1,2]. It was recently demonstrated that the GraDeS algorithm [3] allows for the reconstruction of sparse MRA images from highly undersampled data [4]. It is the goal of the present work to combine a GraDeS reconstruction approach with a highly efficient 3D radial acquisition (VIPR [5]) at 1 mm^3 isotropic resolution. VIPR has previously been shown to have incoherent aliasing artifacts, leading to good image quality even when highly undersampled. To further accelerate the acquisition, multiple radial projections were acquired in each TR interval and shots were ordered to cover k-space in a pseudorandom fashion. In addition, the trajectory is designed in such a way that off-resonance maps for correction of susceptibility artifacts can be derived from the same dataset.

Methods

Four subjects were scanned on a 3T Siemens Verio system with a 12-channel head coil after undergoing informed consent in accordance with local IRB regulations. A single dose (0.1 mmol/kg) of OptiMark (gadoversetamide) was administered at a rate of 3 mL/s via power injection. Subjects were screened to exclude those with impaired renal function or history of kidney disease.

Images were acquired using a non-Cartesian 3D FLASH acquisition (TR=8.68 ms, flip angle=20, 1 mm isotropic resolution). A 2D radial EPI trajectory [6] consisting of 5 projections per shot (duration=6.44 ms) was acquired in each TR interval (Fig. 1a). Pseudo-random rotations of this pattern were used to progressively fill in 3D k-space over multiple shots (Fig. 1b-c shows projection locations after 16, 64 and 256 shots). In total, 4096 unique shots were repeated periodically for 4 repetitions (total scan time: 2 min 10 s). The trajectory was measured in a separate phantom scan using the method of Beaumont et al. [7], employing 2 mm slices offset by 3 cm from isocenter. Contrast injection was performed at 1 minute into the scan, allowing the acquisition of 2 baseline acquisitions (4096 shots each) before contrast arrival. Subtraction of the average of the 2 baseline acquisitions from the post-baseline k-space data was performed to remove static tissue. GraDeS was then carried out on this difference data (corresponding to a sparse images). In the present work, reconstructions were performed at 128 shots / 1.1 s per frame and also at 32 shots / 275 ms per frame. These correspond to acceleration factors of roughly 100 and 400 respectively, relative to a fully sampled 3D radial acquisition.

Gridding operations were performed using NUFFT algorithms with table-based interpolation as provided in the Image Reconstruction Toolbox [8]. A kernel size of 4x4x4 and grid oversampling factor of ~1.4 were chosen to minimize computation time while maintaining acceptable accuracy. The NUFFT routines were modified to take advantage of multiple CPU cores via the OpenMP API (www.openmp.org). For each frame, the GraDeS algorithm was initialized with the result from the previous frame. A zero image was used to initialize the first time frame. The GraDeS γ parameter was set to 1.5 ($1/\gamma$ is the gradient descent step size). A total of 12 GraDeS iterations were performed per frame. No thresholding was performed in the GraDeS algorithm.

To reduce susceptibility artifacts, field-map correction via time-segmented reconstruction [9] with five segments was used. The fieldmap itself was determined from the same 3D radial dataset by reconstructing images corresponding to individual echo times within the multi-echo readout. In this case, all 4096 unique shots were used, and all repetitions (including baseline) were averaged. The radial EPI k-space data was divided up into a series of single-echo datasets corresponding to individual readout lines. The 5-line radial readout of Fig 1a consists of 4 full echoes plus an initial and final half-echo. Images corresponding to each of the 4 full echoes were used in a multi-echo fieldmap estimation scheme [10]. The fieldmap was calculated at a lower, 2 mm isotropic resolution to reduce noise-like aliasing artifacts due to undersampling.

Results and Discussion

Representative sagittal and coronal MIPs corresponding to time-frames from the arterial and venous phases of the GraDeS reconstruction (at 32 shots / 275 ms per frame) are shown in Fig 3. A standard gridding or SENSE reconstruction with only 32 shots per frame is not feasible at this level of acceleration.

Example time-courses for voxels in the ACA, MCA and superior sagittal sinus are shown in Fig. 2. These timecourses correspond to the reconstruction at 128 shots (1.1 s) per frame. Good separation between the arterial and venous phases can be seen. A separate, standard gridding reconstruction at 512 shots (4.4 s) per frame is shown for validation of the timecourse behavior.

The GraDeS algorithm only requires a single forward and adjoint NUFFT operation in each iteration. This makes it substantially faster than existing L1-based compressed sensing reconstructions [11] which employ a nonlinear conjugate gradient algorithm that requires a linesearch at each iteration. Despite this advantage, long reconstruction times still remain a challenge for such large, non-Cartesian datasets. In our present implementation, reconstruction with field map correction and 12 GraDeS iterations requires approximately 25 minutes per frame on an 8-core workstation with 2.33 GHz Intel Xeon processors. Angiograms nearly identical in appearance to those in Fig 3 are possible with as few as 2 GraDeS iterations, but this results in overly smooth temporal uptake curves (although good arterial/venous separation is preserved). Eliminating the need for field map correction by the use of shorter readouts or alternative trajectories will substantially improve the reconstruction time.

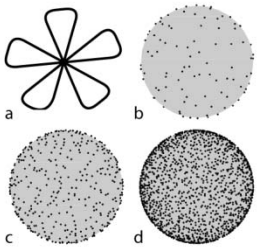

Fig 1. a) single shot. b-d) projection locations after 64, 128, and 256 shots

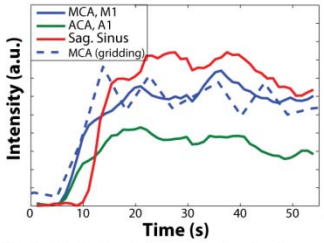

Fig 2. GraDeS uptake curves for single voxels. A gridding reference is also shown.

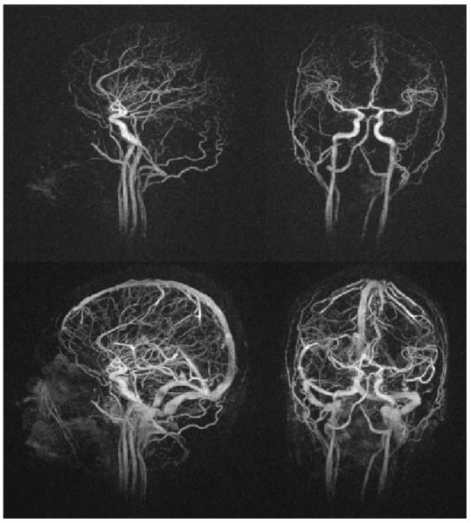

Fig 3. Representative sagittal (left) and coronal (right) MIPs during late arterial (top) and mixed arterial/venous (bottom) phases.

Conclusions

The combination of GraDeS and a multi-echo 3D radial acquisition enables time-resolved 3D CE-MRA at an unprecedented combination of spatial and temporal resolution. MRAs acquired at 1mm^3 isotropic resolution maintain high quality even for acceleration factors over 400. With further improvement, this method could become competitive with conventional x-ray DSA for many applications.

References: 1. Mistretta et al. MRM 2006;55(1):30-40. 2. Haider et al. MRM 2008;60(3):749-760. 3. Garg R and Khandekar R. Proc. 26th Int. Conf. on Machine Learning, Montreal, Canada, 2009. 4. Seiberlich et al. Proc. ISMRM 2010, p.4873. 5. Barger et al. MRM 2002;48(2):297-305. 6. Silva et al. JMR 1998;135(1):242-247. 7. Beaumont et al. MRM 2007;58(1):200-205. 8. http://www.eecs.umich.edu/~fessler/code 9. Noll et al. IEEE TMI 1991;10(4):629-637. 10. Lu et al. MRM 2008;60:236-244. 11. Lustig M, et al. Magn Reson Med. 2007 Dec;58(6):1182-95.

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