Accelerating PROPELLER-MRI by Means of Under-Sampling and Iterative Image Reconstruction using the Non-Uniform Fast Fourier Transform

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Introduction: PROPELLER-MRI[1] is a multi-shot fast spin-echo (FSE) data acquisition technique that is gaining popularity due to its reduced sensitivity to motion and B_0 inhomogeneities. However, k-space sampling in PROPELLER is performed on a set of parallel lines forming a blade, which is rotated to cover k-space. This sampling pattern oversamples the central region of k-space, and PROPELLER acquisitions are at least 50% slower than conventional FSE. Often in MRI, imaging time is reduced by under-sampling k-space. In PROPELLER, the most significant reduction in acquisition time can be achieved by reducing the number of blades/acquisition while increasing the distance between lines[2]. However, this violates the Nyquist criterion and leads to severe image artifacts when images are reconstructed with conventional gridding. Iterative reconstruction techniques are known to provide superior image quality when k-space is not sufficiently sampled. In this study, we investigated the trade-off between imaging time, artifacts and noise for under-sampled PROPELLER acquisitions with iterative reconstruction using the NUFFT[3-5] operator.

Methods: Simulations using different PROPELLER k-space sampling patterns were performed. The Shepp-Logan phantom[6] was used in the simulations, since its k-space representation is known analytically. The field of view (FOV) in image space was 24cm x 24cm, and the image matrix was 256x256. The following k-space sampling patterns were tested: number of blades ={12, 11, 10, 9, 8, 7, 6}, and distance between lines in each blade = {1.00/FOV, 1.14/FOV, 1.26/FOV, 1.39/FOV, 1.57/FOV, 1.79/FOV, 2.00/FOV}, respectively. The number of lines per blade and samples per line were equal to 16 and 128 respectively. The pattern with 12 blades was fully sampled, and all other patterns were under-sampled. Zero mean Gaussian noise was added to the real and imaginary part of k-space to achieve SNR≅25 in the fully sampled case. All images were reconstructed using iterative reconstruction with NUFFT and a quadratic weighted least squares penalty. The penalty value was 0.1, and reconstruction was terminated after 50 iterations. All images were also reconstructed with conventional gridding. For every sampling pattern, the simulation was repeated 1000 times and the variance was measured on a voxel-by-voxel basis. To quantify the amount of artifacts, the ideal Shepp-Logan phantom image was subtracted from the mean image reconstructed for each sampling pattern, and the mean error per voxel was estimated by averaging the difference for all voxels. The mean error per voxel and mean variance were plotted as a function of the number of blades per sampling pattern. Human brain k-space data were also simulated for all PROPELLER sampling patterns[5], from a T_2-weighted image of a normal human brain. Images were reconstructed using iterative reconstruction, as well as gridding.

Results and Discussion: Figures 1a1, b1 show a fully sampled and a 50% under-sampled pattern with 12 and 6 blades, respectively. For the fully sampled case, both reconstruction methods produced similar, artifact-free, results for the Shepp-Logan phantom (Fig. 1a2, a3) and human brain (Fig. 1a4, a5). As the distance between lines increased to reduce the number of blades and increase the degree of under-sampling, images reconstructed with gridding exhibited severe artifacts caused by Nyquist holes (Fig. 1b2, b4). In contrast, images reconstructed with iterative reconstruction showed significantly reduced artifacts (Fig. 1b3, b5). However, reduction in the number of blades increased image noise. Figure 2 shows the relationship of noise and artifacts in images reconstructed iteratively using NUFFT, as a function of the number of blades in the sampling pattern. Also, Table 1 shows the percent increase in noise, and in mean error per voxel, as well as the percent decrease in imaging time with respect to full sampling, for various under-sampled patterns and iterative reconstruction using NUFFT. According to Figure 2 and Table 1, one can use an under-sampled PROPELLER k-space pattern and iterative reconstruction with NUFFT to obtain images with minimal image artifacts, unaffected spatial resolution in significantly reduced acquisition time (e.g. 8 blades, 33% reduction in acquisition time, only 1% increase in the mean error per voxel compared to the fully sampled case). The approach introduced in this work essentially minimizes the main disadvantage of PROPELLER-MRI, namely longer acquisition time, without altering image quality. Therefore, the technique presented here may soon become the main image reconstruction method for PROPELLER imaging.

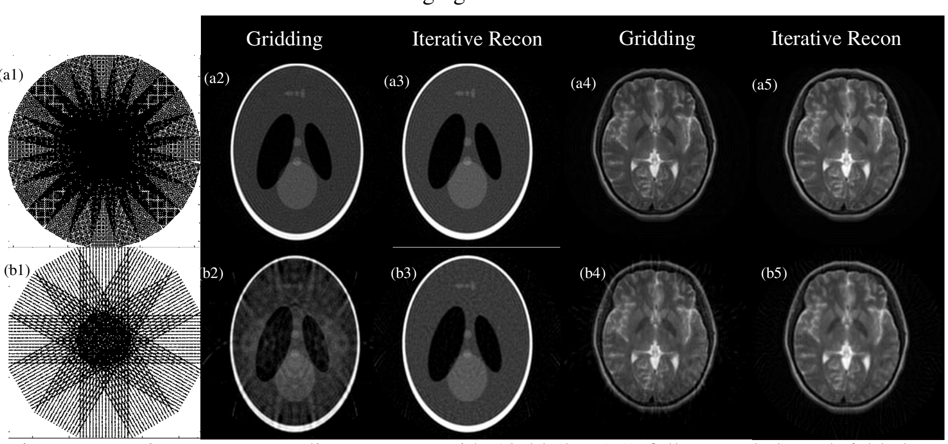

Figure 1. PROPELLER sampling patterns with 12 blades (a1)(fully sampled) and 6 blades (b1)(under-sampled). Images a2, a3, a4, a5 are produced with sampling pattern (a1) while b2, b3, b4, b5 are produced with sampling pattern (b1). Images a2, b2, a4, b4 are reconstructed with gridding, and a3, b3, a5, b5 with iterative reconstruction using NUFFT.

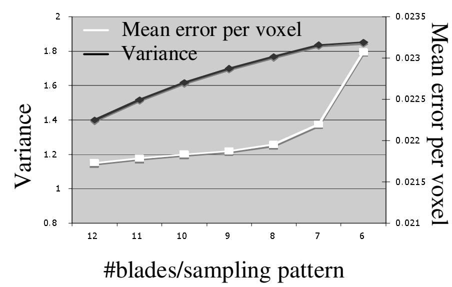

Figure 2. Plot of the variance (black) and mean error per voxel (white) as a function of the number of blades per sampling pattern, for images obtained with iterative reconstruction.

# of blades	% decrease acq. time	% increase variance	% increase mean-error
12	0	0	0
11	8.33	8.48	0.26
10	16.66	15.64	0.47
9	25	21.42	0.65
8	33.33	26.36	1.02
7	41.66	31.18	2.15
6	50	32.28	6.19

Table 1. Percent reduction in acquisition time, increase in variance and mean error per voxel with respect to the number of blades.

References: 1) Pipe J.G., et al. MRM 2002;47:42-52. (2) Arfanakis KA, et al MRM 2005;53 :675-683 (3) Fessler J.A., et al., IEEE Trans Signal Proc 2003;51:560-574. (4) Fessler J.A., et al., IEEE Trans Image Proc 1996;5:1346-1358. 5) Tamhane AA, et al ISMRM 2007;p.2. 6) Shepp LA, Logan BF, IEEE Trans Nucl Sci NS-21:21 (1974).