PROPELLER Image Reconstruction Using the Non-Uniform Fast Fourier Transform

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Introduction: Conventional diffusion data acquisitions are based on echo-planar imaging (EPI) techniques, which suffer from significant B_0-related artifacts. In contrast, PROPELLER[1] (Periodically Rotated Overlapping Parallel Lines with Enhanced Reconstruction) imaging is characterized by significantly reduced sensitivity to field inhomogeneity-induced artifacts compared to EPI, and significantly reduced sensitivity to motion compared to conventional fast spin-echo (FSE). However, the minimum imaging time for PROPELLER is 50% longer than that of FSE and markedly longer than that of EPI. Also, for fixed acquisition time, EPI can produce images with significantly higher signal to noise ratio (SNR) than PROPELLER. In this study, a quadratic penalized weighted least squares (QPWLS) reconstruction method was investigated for use with PROPELLER acquisitions, and compared to conventional PROPELLER reconstruction using k-space gridding, in an attempt to increase the SNR without significantly affecting spatial resolution. This reconstruction approach seeks to invert a Non-Uniform FFT[2] (NUFFT) operator that relates the non-uniformly spaced measured k-space samples to the desired image. The trade-off between SNR and spatial resolution was examined for various penalty values.

Methods: PROPELLER data acquisitions for the Shepp-Logan phantom were simulated, using 12 k-space blades, 16 lines per blade, 128 samples per line, and field of view of 20cm. Gaussian noise (mean=0, st.dev.=0.1) was added to k-space data in order to achieve SNR≈20 in the images produced with gridding. A 256x256 image was reconstructed using the QPWLS NUFFT algorithm in an iterative manner using the preconditioned conjugate gradient method. Sampling density compensation was applied to the k-space data to accelerate the iterative procedure. Reconstruction was repeated 1000 times (for different realizations of the noisy data) and SNR was estimated on a voxel-by-voxel basis. The full width at half max (FWHM) of the impulse response function was also calculated[3]. Reconstruction with the QPWLS NUFFT algorithm was repeated for penalty values equal to {0.001, 0.01, 0.03, 0.05, 0.07, 0.1, 0.3, 0.5, 1, 10}. The absolute difference between the ideal and mean reconstructed images was measured for each penalty value. This difference was then averaged over all voxels to compute the mean error per voxel at different penalty values. A 256x256 image was also reconstructed with gridding using a Kaiser-Bessel interpolation kernel of width= ±2/FOV. The SNR, FWHM, and mean error per voxel were estimated for reconstruction using gridding. The QPWLS NUFFT technique was also used in a human experiment.

Results & Discussion: The SNR and FWHM for reconstruction with gridding were 21.46 and 0.216cm, respectively. For the iterative reconstruction, and penalty values less than 0.02, the SNR was lower than that achieved with gridding, while the FWHM was the same (Table 1, Fig.1A). For penalty values greater than 0.02, the SNR and FWHM increased with different rate (Fig.1A). For a penalty value of 0.1, SNR was increased by approximately 20%, while FWHM increased by less than 5% compared to gridding, and therefore blurring was minimal. Further increase in the penalty value increased SNR significantly (105% for a penalty value of 0.5), but also increased FWHM (14% for a penalty value of 0.5) introducing visible blurring (Fig.1A). The mean error per voxel for reconstruction using gridding was 0.0233. The mean error per voxel was lower than that of gridding when using QPWLS NUFFT reconstruction and penalty values from 0.03 to 1 (Fig.1B). However, for very low (<0.03), or very high (>1) penalty values, the mean error per voxel was higher when using the QPWLS NUFFT reconstruction than gridding (Fig.1B). This was probably due to the enhanced noise and the increased blurring for very low and very high penalty values, respectively. Figure 2 shows images of the same axial slice of a human brain reconstructed with gridding and QPWLS NUFFT with different penalty values. The image reconstructed with a penalty value of 0.001 (Fig.2B) exhibits lower SNR than the image reconstructed with gridding (Fig.2A), while for a penalty value of 1 (Fig.2D) the blurring is significant. For a penalty value of 0.1 (Fig.2C), the SNR in a selected white matter region was increased by approximately 17% compared to gridding, and there was no visible blurring. In conclusion, QPWLS NUFFT reconstruction of PROPELLER images with a penalty value of approximately 0.1 provides a significant increase in SNR, negligible loss of resolution, and fewer reconstruction errors than gridding. Alternative penalty values can be selected depending on the application. To our knowledge, this is the first study to examine alternative reconstruction methods that enhance image quality for PROPELLER imaging.

Penalty Value	SNR	% Increase in SNR	FWHM (cm)	% Increase in FWHM
0.001	19.92	-7.17	0.216	0
0.01	20.79	-3.12	0.216	0
0.05	23.11	7.62	0.221	2.41
0.1	25.8	20.22	0.226	4.82
0.3	35.49	65.37	0.237	9.63
0.5	44.1	105.49	0.247	14.45
1	63.11	194.08	0.263	21.68

Table 1. SNR and FWHM values for QPWLS NUFFT PROPELLER reconstruction and various penalty values. The % increases in SNR and FWHM are produced from comparison to the corresponding values in gridding.

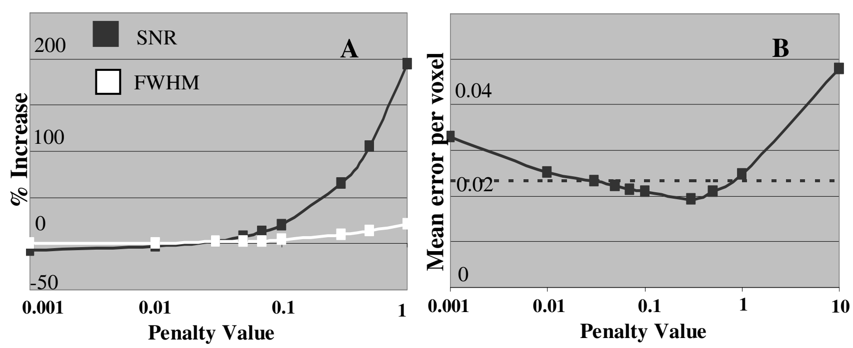

Figure 1. A) Percent increase in SNR and FWHM in QPWLS NUFFT compared to gridding, as a function of penalty values. B) Mean error per voxel in QPWLS NUFFT reconstruction (solid line) as a function of penalty values, and gridding (dotted line).

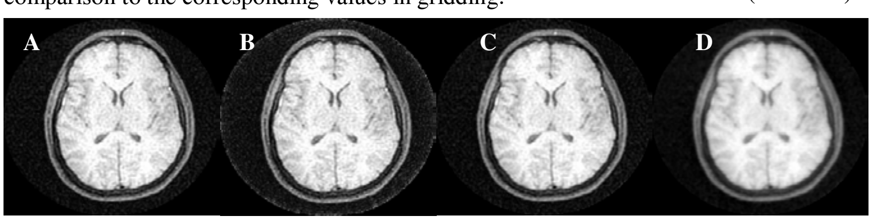

Figure 2. Images of the same slice of a human brain reconstructed by (A) gridding, and QPWLS NUFFT with a penalty value of (B) 0.001, (C) 0.1, (D) 1. The SNR in a selected white matter region is 20.33 for (A), 18.32 for (B), 23.78 for (C), and 47.30 for (D).

References: 1) Pipe J.G., et al. MRM 2002;47:42-52. (2) Fessler J.A., et al., IEEE Trans Signal Proc 2003;51:560-574. (3) Fessler J.A., et al., IEEE Trans Image Proc 1996;5:1346-1358.