Gradient-Alternated SSFP (GASP) Diffusion Imaging

E. E. Sigmund[1,2], T. B. Parrish[2]

[1]NMR Research, Schlumberger-Doll Research, Ridgefield, CT, United States, [2]Radiology, Northwestern University, Chicago, IL, United States

Background

Diffusion tensor imaging[1] (DTI) uses restricted diffusion to study anisotropically oriented biological media. Apparent diffusion coefficient (ADC) maps along different directions are combined to calculate the diffusion tensor at each voxel, which provides the orientation and degree of anisotropy of the underlying tissue. Outputs of this analysis include scalars such as fractional anisotropy (FA) or directionality for fiber-tracking in brain white matter. The most common clinical DTI modality is bipolar gradient (BPG) diffusion weighting followed by echo-planar imaging (EPI). While this technique offers high speed, it suffers from magnetic susceptibility signal dropouts, N/2 ghosting, and image distortions. An alternate scheme is the steady-state free precession (SSFP) readout. This methodology allows high signal to noise ratio, 3D acquisition and avoids susceptibility artifacts, providing enhanced resolution. However, the diffusion gradients providing microstructural sensitivity also make the SSFP sequence sensitive to patient motion (bulk and physiologic), which disrupts the steady-state magnetization and leads to image artifacts. Recent work has addressed this issue through diffusion weighting prior to the SSFP readout.[2] We have developed and executed an alternative variation of the SSFP sequence in which the diffusion gradient polarity is alternated in successive cycles of the sequence. (Fig. 1) This gradient-alternated SSFP, or GASP, modality demonstrates marked reduction of motional artifacts while retaining all other advantages of the SSFP modality.

Methods

Three systems were investigated to compare three DTI methodologies: bipolar-gradient echo-planar imaging (BPG-EPI), steady state free precession (SSFP), and gradient alternated SSFP (GASP). The systems were: (a) a spherical water phantom (uniform, isotropic diffusion), (b) a bundle of asparagus stalks (uniform, anisotropic diffusion), and (c) a normal human volunteer brain (nonuniform, anisotropic diffusion). All images shown were collected on Siemens Trio 3 T scanner and a birdcage head coil for both transmission and reception. The parameters of the BPG-EPI acquisition were as follows. Water phantom: diffusion weighting ($0 < b < 500$ s/mm^2), 6 diffusion gradient directions, 1.45 mm x 1.45 mm x 4 mm voxel, 2D acquisition. Asparagus: diffusion weighting ($0 < b < 500$ s/mm^2), 6 diffusion gradient directions, 0.86 mm x 0.86 mm x 4 mm voxel, 2D acquisition. Brain: diffusion weighting ($0 < b < 500$ s/mm^2), 6 diffusion gradient directions, 1.45 mm x 1.45 mm x 4 mm voxel, 2D acquisition. The parameters of the SSFP acquisitions were as follows. Water phantom : diffusion gradient moment $0 < M < 250$ (mT/m ms), TR = 30 ms, $\alpha = 30$ deg., 6 diffusion gradient directions, 0.86 mm x 0.86 mm x 2 mm voxel, 3D acquisition. Asparagus: diffusion gradient moment $0 < M < 250$ (mT/m ms), TR = 50 ms, $\alpha = 60$ deg., 6 diffusion gradient directions, 0.35 mm x 0.35 mm x 2 mm voxel, 3D acquisition. In vivo brain images for the SSFP and GASP case were conducted as follows: diffusion gradient moment $0 < M < 250$ (mT/m ms), axially oriented diffusion gradient, TR = 30 ms, $\alpha = 30$ deg., 0.86 mm x 0.86 mm x 2.7 mm voxel, 3D acquisition. ADC map analysis for SSFP images was done via published steady state expressions[3] including effects of flip angle and relaxation. In some cases, this analysis incorporated separately measured T_1, T_2, and flip angle maps. H_2O phantom data was used to empirically adjust this theory for the GASP sequence variation. Finally, semiclassical isochromat simulations were performed to elucidate the SSFP / GASP comparison.

Results

In the H_20 phantom, ADC maps showed appropriately spatially uniform results for both EPI and SSFP images. In the SSFP case, this result was obtained only when the spatial variation of the imaging flip angle α (obtained from the intercept of separate inversion recovery data with the same pulse type) was taken into account. Quantitatively, the two scans produced results within 10% of each other. In the asparagus bundle, 6-direction DTI scans were performed with both image modalities. Qualitatively similar diffusion results were obtained by both image methods. Both sequences showed nominally unidirectional diffusion bias along the asparagus stalk, as evidenced by a uniform fractional anisotropy (FA) map, similar spread of eigenvalues, and a preferentially high component of the primary diffusion eigenvector along the stalk direction. However, the EPI based method suffered from distortions. In the in vivo brain scans, the EPI images showed the expected anatomical white matter structures, while the SSFP DTI scans were scrambled by image ghost artifacts from motion-induced steady-state disruption. These artifacts were significantly reduced in GASP images acquired under identical conditions. Simulations qualitatively reproduced this artifact reduction as well.

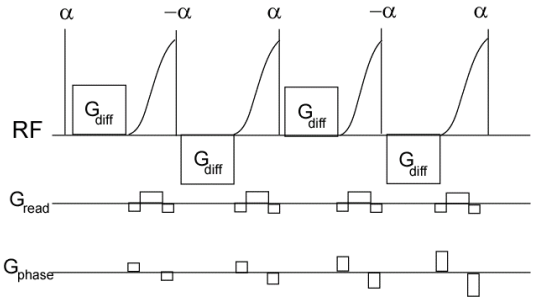

Figure 1: GASP diffusion imaging sequence. The structure is a variation of the basic SSFP diffusion sequence with alternation in polarity of the diffusion gradient in each cycle.

Discussion

In all three systems, the resolution in the SSFP scans showed marked improvement over that of the EPI, due to 3D acquisition and the absence of susceptibility and N/2 ghost artifacts. The flip angle map correction, required in the water phantom to obtain a uniform diffusivity map, was applied in other asparagus images (not shown) with little effect, likely due to the smaller uniform "tissue" regions relative to the RF penetration depth for this case. The processed EPI FA maps in the asparagus bundle suffer from lower resolution and susceptibility artifacts; the SSFP and GASP scans are better resolved, but smaller voxel size (factor of 8) gives a lower SNR. In the in vivo human brain scans, the EPI DTI images showed the expected anatomical white matter structure and orientation.

The SSFP images were severely compromised by motion-induced steady-state disruption artifacts, scrambling the information in the 3D DTI dataset. A comparison of SSFP and GASP diffusion-weighted images collected under identical conditions (Fig. 2) showed a dramatic reduction in image artifacts, allowing accurate diffusivity measurement in the cerebrospinal fluid (CSF): $D = 3.0 +/- 1.0$ μm^2/ms. While the GASP diffusivities in the parenchyma showed marked improvement from the SSFP case and were of the correct order ($0.5 < D < 1.0$ μm^2/ms) , the SNR was not sufficient for a full 3D DTI map. These results imply that with higher SNR, such as is provided in higher field scanners where EPI susceptibility artifacts are even more pronounced, the GASP sequence is a viable option for diffusion tensor imaging.

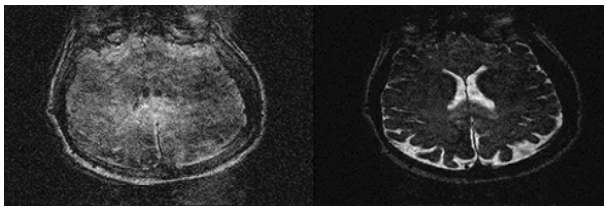

Figure 2: Diffusion weighted images (b ~ 100 s/mm^2) w/ axially oriented diffusion gradient. Left: SSFP ; Right: GASP.

References

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3. Wu, E. X. et. al. JMR 90**:** 243-253, 1990.