Steady-state Free Precession Diffusion Tensor Imaging in Human Brain Fixed and In Vivo Tissue

E. E. Sigmund[1], M. F. Falangola[1], and K. McGorty[1]
[1]Radiology, New York University, New York, NY, United States

Background

Diffusion tensor imaging (DTI) is a mainstay neuroscience technique whose outputs (average diffusivity <D>, fractional anisotropy (FA)) have wide scientific and clinical application. The most common DTI modality is echo-planar imaging (EPI). While very fast, EPI contains numerous artifacts (signal dropouts, blurring, N/2 ghosting) that can limit its application, particularly at high field (3 T, 7 T). Prior work showed a variation on the SSFP-echo sequence for DTI[1]. Motion (respiration, pulsation) combined with this steady-state sequence's unbalanced diffusion gradients usually causes ghosting, an effect which has been addressed with navigator correction schemes[2, 3]. The gradient-alternated (GASP) modality (Figure 1), which alternates the diffusion gradient polarity in successive TR cycles, reduces ghosting somewhat *in vivo* without a dramatic reduction in diffusion weighting. In this sense it is partially self-navigated. The present work has continued the development of this approach, including verifying the advantages of the steady-state modality over EPI in fixed phantoms and tissue, as well as comparing SSFP and GASP *in vivo*. The majority of the work was performed at 3 T; 7 T pilot data was also collected for fixed tissue.

Methods

Three systems were investigated to compare three DTI methodologies: bipolar-gradient echo-planar imaging (EPI), steady state free precession (SSFP), and gradient alternated SSFP (GASP). The systems were: (a) asparagus stalks in water, (b) a formalin-fixed normal human brain slice in agarose, and (c) a normal human volunteer brain. Phantom and fixed tissue data were collected in a Siemens Trio 3 T system with 8 channel head coil and a GRAPPA acceleration factor of 3; in vivo data were collected in a TIM Trio system with 4 channel head coil. Additional fixed brain SSFP DTI data was collected in a 7 T system with a birdcage head coil. SSFP and GASP were run in 3D mode, with 6/8 partial Fourier (phase and slice). The asparagus slice was coronally oriented, while the fixed tissue and in vivo slices were axial. Parameters for the DTI scans are listed in Table 1. The 6 directions used in all cases were: ((1,0,1),(-1,0,1),(0,1,1),(0,1,-1),(1,1,0),(1,-1,0)), in either physical coordinates (XYZ, in EPI), or logical coordinates (RPS, in SSFP). ADC map analysis for SSFP images was done via published steady state expressions including effects of flip angle and relaxation[4]. In some cases, this analysis incorporated separately measured T_1 and T_2 maps; this correction was found to significantly influence the calculated Trace(D) values, but minimally affected the FA maps.

Table 1 : DTI Sequence Parameters.

	EPI				SSFP / GASP				
	Voxel(mm)	Matrix	b (s/mm^2)	TE(ms)	Voxel (mm)	Matrix	Diff.Moment(mT/m ms)	α(°)	TR(ms)
Asparagus	0.8x0.8x3	256x256x30 (*)	0, 500, 1000	72	1.7x1.7x3	128x128x30	0,50,100,150,200,250	30	30
Fixed brain	1.7x1.7x3	128x128x16	0, 500, 1000	93	1.1x1.1x3	192x144x14	0,100,200,300,400,500	30	30
Fixed brain(7T)					1.1x1.1x3	192x144x16	0,50,100,150,200,250	30	30
In vivo brain	2.3x2.3x5	128x128x16	0, 500, 1000	138	2.2x2.2x3	128x96x40	0,50,150,250	30	30

(* interpolated)

Results

Figure 2 shows an array of results comparing the DTI modalities. Each image is a primary eigenvector colormap(see diagram; all directions relative to the magnet axes), weighted by the FA. The top row shows a phantom of asparagus stalks in several orientations in a water bath. The expected diffusion anisotropy along the stalk axes is reproduced in both EPI and SSFP images. The FA contrast between asparagus and water is greater for SSFP, although large scale water motion produced artifacts in the SSFP images. The second row shows results from a fixed normal human brain coronal slice taken through the anterior thalamic nucleus (see photo, Figure 2). The EPI image highlights the white matter but is of low quality; the SSFP image successfully resolves the orientations of several white matter (WM) regions, such as the corpus callosum(CC), inferior fasciculi (IF), and corona radiata (CR). The fractional anisotropy is also small in the gray matter (GM), as expected. A similar DTI image is evident from the 7 T scan. *In vivo* normal volunteer brain results at 3 T are shown in the bottom row. The EPI results show the expected WM anatomy as along with susceptibility-based artifacts. The SSFP DTI data is completely scrambled by motional ghosting, while the GASP DTI data recovers some of the expected structure (e.g. corpus callosum) but still suffers major artifacts along the superior-inferior direction.

Discussion

The advantages of the SSFP/GASP DTI modalities are clearly born out in the stationary phantom and fixed tissue scans. Larger diffusion weighting was used in the fixed tissue due to its smaller average diffusivity (WM : 0.1 μm^2/ms, GM : 0.4 μm^2/ms) and faster relaxation rates (WM:T_1/T_2 = 180 / 40 ms, GM:T_1/T_2 = 250 / 80 ms) than *in vivo* values. The *in vivo* SSFP and GASP data show significant motional ghosting artifacts, but less so in the GASP case. There are several potential reasons for this partial correction. Simulations have suggested[1] GASP limits *phase* buildup from motion and thus reduces ghosting, but echo *magnitudes* can also be modulated (e.g. due to intravoxel incoherent motion). Work is in progress comparing k-space data from *in vivo* SSFP vs. GASP DTI scans to understand and fully exploit the GASP motion correction.

References

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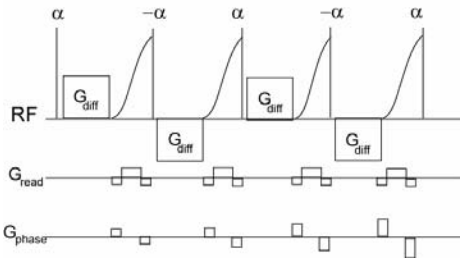

Figure 1: GASP Diffusion imaging sequence.

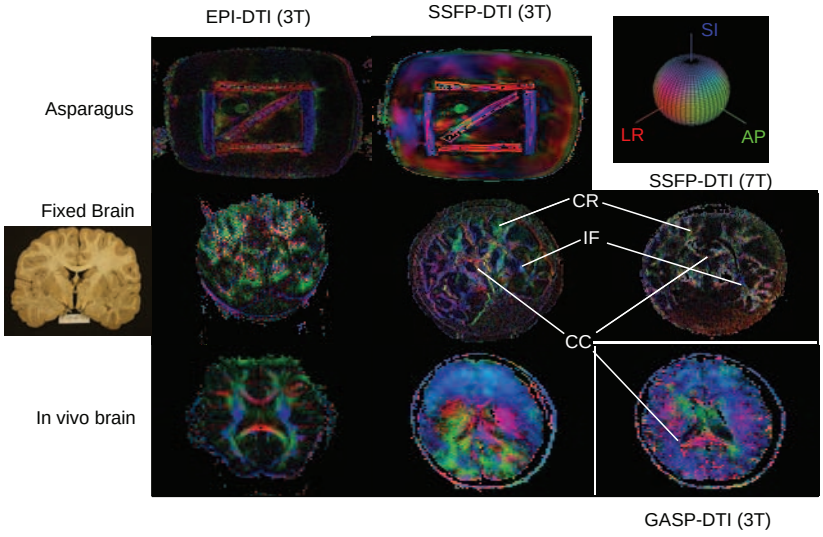

Figure 2: DTI FA-weighted eigenvector colormaps for several image modalities and systems (described in text).