Quantitative Comparison between Hybrid Diffusion Imaging and Diffusion Spectrum Imaging

Y-C. Wu[1], A. L. Alexander[1,2]

[1]Medical Physics, University of Wisconsin-Madison, Madison, WI, United States, [2]Psychiatry, University of Wisconsin-Madison, Madison, WI, United States

Background

At higher levels of diffusion-weighting, the diffusion tensor model is inadequate for describing non-Gaussian diffusion that arises from complex tissue architecture (e.g., crossing white matter (WM) fiber groups). Complex diffusion behavior in brain tissue may be studied with different approaches including diffusion spectrum imaging (DSI) [1], q-ball imaging (QBI) [2], and diffusion model fitting (CHARMED) [3]. Hybrid diffusion imaging (HYDI) combines the approaches of diffusion tensor imaging, high angular resolution, multiple diffusion-weighting levels [4]. The HYDI q-space method consists concentric shells of icosahedral encoding directions at different diffusion-weightings (DW) (b values). While the whole dataset may be used for DSI, the inner shell is suitable for diffusion tensor imaging (DTI), and the outer shell with higher angular sampling resolution may be used for QBI. In this study, several diffusion distribution measurements derived from HYDI, DSI and QBI were compared quantitatively. Monte Carlo noise simulations with different complex diffusion patterns (single and crossing WM with "fast" and "slow" diffusing signal components) were used to study the compare of image noise on DSI, HYDI, QBI for different SNR and q-space ranges.

Methods

Reported diffusion measurements in corpus callosum were used to simulate fast and slow Gaussion diffusion functions [5]. Simulations included single-fiber groups with four spatial orientations (azimuthal angle: 0°, 30°, 60° and 90°) and two-crossing WM fiber groups at four intersection angles (45°, 60°, 75° and 90°). For each geometry, six levels of SNR were evaluated using either 90 or 150 Monte Carlo trials. The q-space noised diffusion signal was sampled and processed using both DSI and HYDI encoding schemes. The DSI q-space sampling was a 7x7x7 Cartesian lattice with a spherical aperture giving 100 total diffusion-encoding directions. The HYDI sampling scheme (Table 1) consisted of four icosahedron shells also with 100 encoding directions. The outer shell was used to evaluate a QBI experiment with 50 encoding directions. Four maximum b values (4000, 6000, 8000 and 10000 sec/mm^2) were studied. The b value of each HYDI shell was decreased propotionally with the maximum b value. For both DSI and HYDI, the diffusion distribution probability density function (PDF) was estimated by Fourier Transform of the q-space samples [1]. Three displacment PDF measures were calculated including the zero displacement probability (Po), the second momentum of PDF ($\iiint PDF(\vec{R}) \times \vec{R}^2 d\vec{R}^3$, where R is the diffusion displacement)[4], and the orientation distribution function (ODF) calculated from the radial integral of the PDF. For HYDI, the QBI ODF was calculated using the Funk-Radon transform of the q-space samples from the outer shell [2]. The number of fibers and the estimated fiber orientation were extracted from the ODF using a maximum likelihood algorithm [6].

Table 1. HYDI encoding scheme

HYDI	Ne	g (mT/m)	b value (s/mm^2)
Shell	1	0	0
1st	12	6	1500
2nd	12	16	4000
3rd	25	28	7000
4th	50	40	10000
Total	100		

Results and Discussion

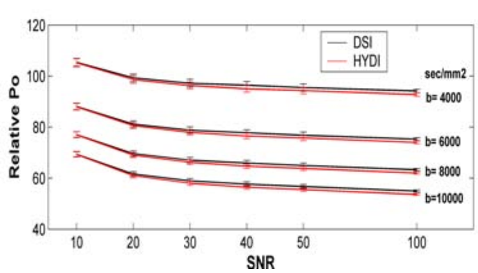
As shown in Figure 1, the measured Po for both DSI and HYDI are very similar. In general, Po was overestimated for both lower maximum b-values and/or decreased SNR. The second momentum of PDF was similar for both HYDI and DSI at lower maximum b-values and higher SNR, but was overestimated for HYDI relative to DSI, otherwise (results not shown). For the case of two-crossing WM tracts with intersection angle of 60° and 75°, DSI did very poorly at detecting more than a single fiber group, while the ODF from either HYDI or HYDI-QBI demonstrated a 20 - 50% increased chance in detecting and characterizing two crossing fibers (Figure 2). Both methods were more adept at detecting and characterizing crossing white matter orientations at higher diffusion weighting. For intersection angle of 90°, all methods (DSI, HYDI and QBI) were able to detect and characterize two fibers, across all SNR and maximum b values (results not shown). For intersection angle of 45°, all methods detected only one fiber from two-crossing-fiber geometry. The accuracy of estimating single fiber orientation for all methods (DSI, HYDI and QBI) is shown in Figure 3. The degree denotes the estimated angular deviation between the estimated and true fiber orientations. Both DSI and HYDI QBI had roughly 1.5° of angular error in estimating oblique fiber orientations (azimuthal angle of 30° and 60°), whereas HYDI demonstrated angular errors of 2-2.5° (Fig3 (a)). For the case of orthogonal fiber orientations (Fig 3(b)), both DSI and HYDI-QBI had smaller than 1° angular errors, whereas HYDI demonstrated 2.5-5° errors. The maximum b value had very little effect on estimating the fiber orientation.

Conclusion

In this study, we demonstrated that a hybrid diffusion-encoding scheme with shells of increasing diffusion-weighting and high angular resolution in the outer shell is quite promising for characterizing complex diffusion distributions. Estimates of the diffusion function measures, Po and the second momentum of PDF were similar for both HYDI and DSI. However, the outer QBI shell of the HYDI data appears to yield the most accurate estimates of both fiber number and orientation. Consequently, this approach is very promising for both complex diffusion characterization and resolving complex tissue architecture in moderate scan times.

References 1. Wedeen VJ et al. Proc. ISMRM 2000:82. 2. Tuch DS et al. NeuronImag 2003;40:885-95. 3. Assaf Y et al. MRM 2004:52;965-78. 4. Wu YC & Alexander AL Proc. ISMRM 2005:578. 5. Maier SE et al. MRM 2004:51;321-30. 6. Campbell JSW et al. Proc. ISMRM 2002:1130.

FIG. 1
The estimated Po across SNR and max. b values. The errorbar denotes one standard deviation across 150 Monte Carlo noise simulation trials.



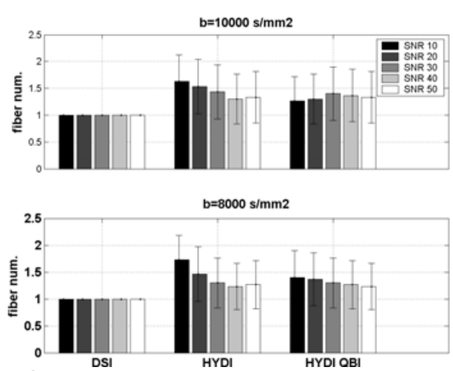


FIG 2.
The detectable fiber numbers using ODF of DSI, HYDI and HYDI-QBI on two-crossing-fiber system with 60° intersection angle. The errorbar denotes one standard deviation across 90 Monte Carlo noise simulation trials.

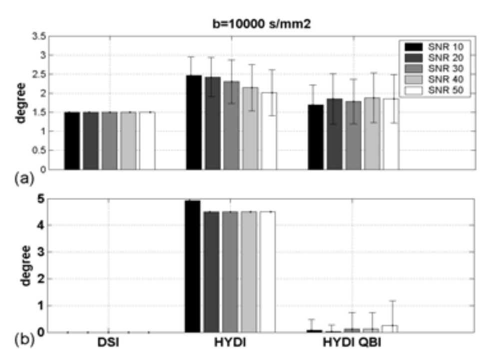


FIG 3. The estimated angular deviation of fiber orientation using ODF of DSI, HYDI and QBI on single-fiber system. (a) Oblique fiber with 30° azimuthal angle. (b) Orthogonal fiber (0°). The errorbar denotes one standard deviation across 90 Monte Carlo noise simulation trials.