In Vivo Comparison of Q-ball, Spherical Deconvolution and Diffusion Orientation Transform HARDI for Fiber Orientation Estimation using the Bootstrap Method

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INTRODUCTION: The failure of DTI to resolve crossing fiber tracts is now well recognized. High angular resolution diffusion imaging (HARDI) offers an attractive solution to this problem given its relatively sparse sampling requirements. Among several methods proposed for reconstruction from HARDI data, q-ball imaging (QBI) [1], spherical deconvolution (SD) [2] and the recently introduced diffusion orientation transform (DOT) [3] stand out for their computational efficiency, sensitivity to multimodal diffusion, and model independence. While the accuracy of QBI and SD has been studied using Monte-Carlo simulations [4], the relative *in vivo* performance of different HARDI techniques has yet to be established. In this study, we apply the bootstrap method to compare fiber orientation estimates obtained using QBI, SD and DOT. This work parallels studies on *in vivo* bootstrap evaluation of fiber orientation uncertainty in DTI [5,6] and spherical deconvolution [7].

METHODS: Whole-brain data were collected from two young adult volunteers using a 3T Signa EXCITE MR scanner (General Electric, Milwaukee, WI). Three identical experiments were performed in each subject, each at 2.2 mm isotropic voxel resolution using an echoplanar spin-echo pulse sequence (TR=8.0s, TE=82ms, NEX=1, SENSE factor 2) with an 8-channel phased array head coil. Diffusion gradients with b=3000 s/mm^2 were prescribed along 55 independent directions determined according to the electrostatic repulsion algorithm. For each subject, the bootstrap method was used to produce 100 diffusion-weighted data sets from the 3 acquisitions. Bootstrap data were used to calculate the QBI orientation distribution function, SD fiber orientation distribution, and DOT angular probability profile. The reconstruction for each method was expressed as a truncated Laplace series of order 4 [2,3,8,9]. Using the same representation for each method avoided biasing the results by differences in implementation. For the SD method, the response function was computed from those voxels in the data with the highest fractional anisotropy. The angular probability radius parameter R_0 for DOT was chosen based on the diffusion time and diffusivity according to heuristics given in [3].

To determine the precision (or reproducibility) of each technique, we used a similar approach to that described by Tournier *et al* [7]. "Gold standard" fiber orientations were derived from the mean of the three measured data sets using a simple simplex search algorithm to identify the three largest peaks in each HARDI reconstruction. A distribution of estimated orientations in each voxel was then obtained by searching for those maxima in the bootstrap HARDI reconstructions closest to the "gold standard" directions. Finally, a 95% confidence interval (CI) was calculated from the population of deviation angles between the bootstrap estimates and the reference orientations. Directional statistics were then used to assess the similarity of the estimated orientations across methods. Specifically, the distributions of bootstrap fiber orientation estimates in each voxel were compared under the hypothesis that the populations had the same mean orientations, according to the F-statistic for comparing directional observations derived in reference [10].

RESULTS & DISCUSSION: The figure depicts typical fiber orientation uncertainties for QBI, SD and DOT in a coronal section through the centrum semiovale in one volunteer. Colors were assigned to reflect the width of the 95% CI in degrees for the fiber orientation estimates in each pixel. Brain regions exhibiting the least uncertainty, shown in darker blue, correspond to white matter with a single well-defined orientation, such as the corpus callosum and internal capsule. In regions where fibers intersect, such as forceps minor, orientation estimates showed a larger 95% CI. The greatest uncertainty is seen within the cortical and deep gray matter. Note the markedly similar appearances of the images and how the 95% CI for each method follows fractional anisotropy. This is expected given the comparatively smaller information content of voxels containing fiber populations with a single orientation. For most regions of the brain, we found little qualitative difference in directional uncertainty between methods. As manifest by the lower uncertainties near the periphery of the brain, DOT did tend to provide slightly higher precision in areas of greater complexity, although this difference was not statistically significant for our data.

	95% CI				*ρ*		
	QBI	*SD*	*DOT*	*DTI*	*QBI:SD*	*QBI:DOT*	*SD:DOT*
Callosal Genu	4.50°	4.57°	4.54°	3.19°	0.96	0.75	0.63
Splenium	6.68°	6.52°	6.83°	5.13°	1.00	0.63	0.63
Forceps Minor	21.83°	22.10°	21.12°		0.95	0.83	0.70
Forceps Major	11.03°	11.47°	10.39°		0.97	0.78	0.72
Centrum Semiovale	14.60°	15.13°	14.23°		0.89	0.75	0.63

The table shows values for the mean 95% CI in several brain regions. Corresponding intervals for DTI in the corpus callosum are provided for comparison. As in the figure, the tightest estimates were obtained for the commissural projections of the corpus callosum. The final three columns express the fraction of voxels, ρ, within each region for which the orientations for the different methods were statistically identical according to the F-statistic (P<0.05). QBI and SD produced equivalent directional information in 89-100% of voxels. However, this fraction fell to 63-83% in comparing QBI and SD with DOT. This difference is felt to be due to the noise properties of DOT, which unlike QBI and SD requires calculation of ADC and thus exhibits a different spread in estimated fiber orientations. In voxels that did not meet criteria for equivalence, however, the maximum difference in mean orientations was only 4.7° between SD and DOT and only 3.1° in comparing QBI and DOT.

CONCLUSION: Our experiments show that despite differences in the theoretical underpinnings of QBI, SD and DOT, the techniques yield similar directional information for sparsely sampled HARDI data that might be acquired in the clinical setting. These results suggest that HARDI fiber tracking should not depend greatly upon the choice of reconstruction algorithm.

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