High Angular Resolution Diffusion Imaging (HARDI) with Highly Constrained Back Projection Reconstruction (HYPR)

Y-C. Wu[1], C. A. Mistretta[2], A. L. Alexander[3], T. Andrews[4], P. J. Whalen[5], and J. V. Haxby[5]

[1]Dartmouth Brain Imaging Center, Dartmouth College, Hanover, NH, United States, [2]Wisconsin Institutes for Medical Research, University of Wisconsin-Madison, Madison, WI, United States, [3]Medical Physics, University of Wisconsin-Madison, Madison, WI, United States, [4]College of Medicine, University of Vermont, Burlington, VT, United States, [5]Psychological & Brain Sciences, Dartmouth College, Hanover, NH, United States

Introduction

Structural connectivity is one of the keys to understanding brain neuronal networks, especially integrated with resting-state functional connectivity [1]. Regardless of computation algorithms, structural connectivity often derives from white matter (WM) tractography, which connects voxels of brain images based on the estimated fiber orientation within a voxel. Conventionally, WM tractography uses diffusion tensor imaging (DTI), which suffers from inability to resolve multiple fibers due to its simplified mono-Gaussian model. Many researchers focus on advanced diffusion imaging that imposes higher diffusion-weighting (DW) b-values and substantially more DW directions than DTI. Such approaches, including HARDI (High Angular Resolution Diffusion Imaging), DSI (Diffusion Spectrum Imaging) and HYDI (Hybrid Diffusion Imaging), yield fiber orientation distribution functions (ODF), which predict the probability of all possible fibers within a voxel and increase accuracy of WM tractography [2]. However, a limitation is the long scan time, which is the major obstacle for many applications. In this study, a novel image reconstruction algorithm, HYPR [3], was used to reconstruct HARDI data. HYPR uses undersampled radial lines in k-space to accelerate the scan time and uses composite images to restore signals. Applications of HYPR in DTI have been reported [4,5], which showed comparable scalar maps of fractional anisotropy and mean diffusivity. Herein, we evaluated the feasibility of HYPR-HARDI approach with different acceleration factors (AF) on estimating the directional measure, ODF.

Methods

HARDI [6] was performed on a healthy volunteer at a 3T GE SIGNA scanner with an 8-channel head coil and ASSET parallel imaging. The DW pulse sequence was SS-SE-EPI with cardiac gating. MR imaging parameters: FOV = 256mm, matrix size = 128x128 interpolated to 256x256, 30 slices with slice thickness = 3mm, TE/TR= 122/11700ms and a total scanning time of 15 min. DW parameters: δ/Δ = 45/56 ms, one image at b-value = 0 s/mm^2 and DW images with 50 noncollinear DW directions at b-values = 9375 s/mm^2.

The evaluation of the HYPR approach used a post-processing simulation on the DW EPI data that was first projected to 400 radial lines (Nyquist criteria for a 256x256 Cartesian matrix), and then undersampled according to the HYPR acceleration factor (AF). Unlike time-resolved MR imaging, in the case of diffusion imaging, the DW direction serves as the fourth dimension for the sliding-window composite as well as the sequence of interleaving undersampled radial lines. However, the nature of DW directions is defined on the 2D surface of a unit sphere. Therefore, it is important to "sort" the DW directions in a way that connects the nearest vector sequentially throughout the spherical surface.

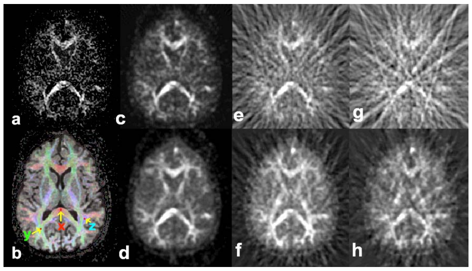

Fig. 1 (a) DW EPI (b) Three voxels in RGB colormap. (c)-(h): FBP (upper) and HYPR-LR reconstructed image (bottom) for AF 4, 20, 40 (L to R).

In addition, this will make sure that the changes of the DW image from one direction to the next direction are "mild" to meet the requirement of HYPR. In this study, we sorted the DW directions into a sequence that was closest to an Archimedean spiral curve from +z to -z. For each DW direction, the undersampled radial lines were filtered-backprojected (FBP) and the sliding-window composite was an average of contiguous FBP images. The window width of composite was equal to AF. Two HYPR image reconstructions were studied: HYPY-O [3] and HYPR-LR [7]. The latter could further reduce cross talk from neighborhood DW directions.

The ODF was reconstructed using the q-ball algorithm (integral of equator) [8] without any noise treatment, model assumption or spherical harmonic decomposition. This may simplify and help to appreciate direct effects of HYPR approach. Seven AFs (1 4 5 10 20 40 50) were simulated. The root mean square error (RMSE) of diffusion signals, the deviation angles and profiles of ODF were studied. Herein, we present preliminary results of three representative voxels in Fig. 1(b); each contained a single fiber orienting along x, y and z axis, respectively.

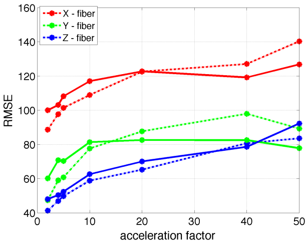

Fig. 2 RMSE vs. AF; dash: HYPR-O; solid: HYPR-LR.

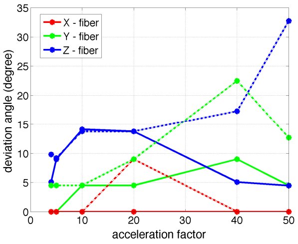

Fig. 3 Deviation angle v.s. AF dash: HYPR-O; solid: HYPR-LR.

Results Fig. 1(a) shows the original EPI image with DW direction at [-0.15 0.05 0.99]. Fibers perpendicular to the encoding, e.g. corpus callosum in this case, had higher DW signals. The undersampled FBP images of AF 4, 20 and 40 are shown in Fig. 1(c), (e) and (g), respectively, and the HYPR-LR reconstructed images are in (d), (f) and (h) with restored WM signals. Although WM signals were restored from the composite, it may also introduce errors resulting in angular deviation and false positive peaks of ODF. Not surprisingly, the RMSE of DW signals on a gridded spherical surface increased with AF (Fig. 2). Note that the maximum and mean signal intensities of WM were about 500 and 150, respectively. Fig. 3 plots the deviation angle of ODFs and shows that in general z-fibers were the most sensitive to HYPR AF whereas x-fibers were the most resistant. The different response of intrinsic fiber orientation is also shown in RMSE in Fig. 2, where x-fibers were more sensitive than y and z fibers. The ODF profiles in Fig. 4 may give a possible explanation. As the AF increased, although the major direction along the x-axis did not change, the side lobe along the y-direction was increasingly exaggerated (Fig. 4 upper row). The similar trend could be seen in y-fibers, but with smaller scales. This directional discrepancy may relate to the predominant axis (z in this case) of the spiral sorting sequence and the number of DW directions. The HYPR-LR method appears to successfully reduce the RMSE and angular deviations at large AF (solid lines in Fig. 2 & 3). The ODF profiles appear improved for HYPR-LR in Fig. 5.

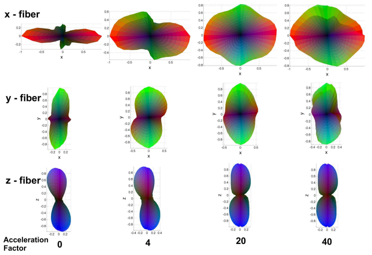

Fig. 4 ODF along x, y and z axis v.s AF

Discussion We have shown that HYPR HARDI is feasible. With some tolerance of error and angular uncertainty, the HARDI scan time may be reduced. Note that AF doesn't directly equal to the reduction factor of the scan time if EPI sequence is used, but the reduction factor of the read out time. More studies are necessary to optimize AF and the number of directions. The HYPR and ODF reconstruction algorithms used in this study were very basic. In addition, 50 DW directions was the minimum required number to resolve crossing fibers. Therefore, any improvements such as iterative HYPR (HYPR-IT), imposing ODF models, spherical harmonic decomposition and increasing DW direction may improve the performance, hence increase angular accuracy and decrease side lobes.

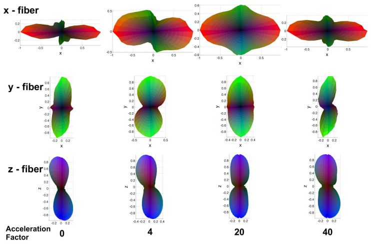

Fig. 5 ODF along x, y and z axis v.s AF

References 1.Hagmann P et al. PloSBio 2008;6(7):159. 2.Behrens TEJ et al. NeuroImage 2007;34:144. 3.Mistretta CA et al. MRM 2006;55:30. 4.Alexander AL et al. ISMRM 2006;858. 5.Samsonov AA et al. ISMRM 2008;342. 6.Tuch DS st al. MRM 2002;48:577. 7.Johnson KM et al. MRM 2008;59:456. 8.Tuch DS et al. Neuron 2003;40:885.