A Novel Post-processing Procedure to Sharpen the ODFs of Different HARDI Datasets by Using Super-CSD

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Introduction

Recently, there were a variety of algorithms proposed to reconstruct orientation distribution function (ODF) based on high angular resolution diffusion imaging (HARDI) data in order to resolve multiple fiber orientations. However, it was found that some fiber orientations were likely lost when fibers intersected at a small angle. A previous study performed the super resolved - constrained spherical deconvolution (super-CSD) to resolve multiple fiber orientations crossing at a smaller angle, but the method was only suitable for diffusion-weighted (DW) datasets acquired in a spherical coordinate [1], such as q-ball imaging (QBI). Other HARDI datasets, such as diffusion spectrum imaging (DSI), acquired in a Cartesian coordinate whose fiber orientation distribution (FOD) could not be obtained by using super-CSD. Hence, the purpose of this study is to propose a post-processing procedure which is suitable for sharpening ODFs of different HARDI datasets and resolving multiple fiber orientations by using super-CSD.

Theory

In spherical harmonic decomposition (SHD), the SH basis set can be designed to form a point-spread function, $PSF(\theta_i)$, which represents a single-fiber function on the sphere pointing at a direction of interest (i) [2]. This study assumed that the coarse ODFs obtained from different HARDI datasets were the results of spherical convolution of $PSF(\theta_i)$ and true fiber orientations; therefore, performing a spherical deconvolution on the original ODF (f) with the inverse of $PSF(\theta_z)$, as shown in Fig. 1, could enhance its true fiber orientations in the sharpened ODF (f'). Afterwards, a planar-shaped $PSF(\theta_{x'})$, as shown in Fig. 2, was designed to estimate the spherical DW data (*e*) [3,4] from the sharpened ODF (f'). Subsequently, the super-CSD was then performed on the estimated spherical DW data to obtain the FODs of different HARDI datasets. The details of above two steps were described below:

$$f' = Z_U PSF(\theta_z)^{-1} Z_U^+ f$$

Fig. 1 $PSF(\theta_z)^{-1}$

$$e = Z_U PSF(\theta_{x'}) Z_U^+ f'$$

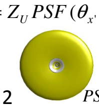

Fig. 2 $PSF(\theta_{x'})$

Step 1: The sharpened ODF (f') was obtained from the operation of spherical convolution, which is a 4-matrix multiplication as shown in Fig. 1, where Z_U is the matrix containing all SH basis functions, $PSF(\theta_z)^{-1}$ is the matrix inverse of single-fiber PSF obtained from all SH basis functions in direction along z-axis, Z_U^+ is the Moore-Penrose pseudoinverse of Z_U, and f is the original ODF estimated from any kind of HARDI data.

Step 2: After obtaining the sharpened ODF (f'), a planar-shaped $PSF(\theta_{x'})$, which is obtained by combining those SH basis functions with order m=0 extracted from $PSF(\theta_x)$ in direction along x-axis, was utilized to estimate the spherical DW signals (e) through the operation of spherical convolution, as shown in Fig. 2. Finally, the super-CSD was performed on the spherical DW signals to obtain the FOD.

Materials and Methods

Computer Simulation: A two-tensor model (FA=0.8 and ADC=950*10^{-6} mm^2/s) was constructed to simulate DSI signals lying on a 17x17x17 Cartesian grid with the following parameters: crossing angle=50°, amplitudes of two fibers=1:1, SNR=30 (Rician distribution), max b-value=6000 s/mm^2, q-radius=3.7 m^{-1}, simulation # = 100. *Human Brain Experiment:* A 23-year-old volunteer was scanned on a 3T MRI system (Trio, Siemens, Erlangen, Germany) to acquire a set of whole-brain DSI data by using spin-echo echo-planar DW pulse sequence with the following parameter settings: TR/TE=9100/142 ms, max *b*-value=6000 s/mm^2, DW directions=203 (including b0), NEX=1, matrix size=128*128, voxel size=2.9*2.9*2.9 mm^3, slice #=45, total scan time was about 43 minutes [5]. *Data Processing:* To demonstrate the feasibility of the proposed method in sharpening the ODF of different HARDI datasets, the generalized q-sampling imaging (GQI), SH-QBI and QBI datasets were interpolated from the grid-wise DSI dataset. For two-shell GQI dataset [6], the *b*-values for the first and second shells were 1500 and 3000 s/mm^2 applied in 30 and 60 non-collinear directions respectively. For single shell SH-QBI and QBI datasets, a *b*-value of 3000 s/mm^2 and 60 non-collinear directions were used. The ODFs of four different HARDI datasets were firstly reconstructed using their original reconstruction methods. Subsequently, the original ODFs were then processed using the proposed sharpening procedure to obtain their FODs. For human brain data, generalized fractional anisotropy map was also obtained by calculating the standard deviation of the normalized ODFs. For computer simulation, the successful rates of resolving 50° crossing fibers were defined as the percentage of successfully separating two fiber orientations having amplitude > 0.5 in 100 simulations. The angular errors were also obtained by calculating the angles between the estimated and true fiber orientations. In this preliminary study, the max degree of spherical harmonics (l_{max}) was set as 10 for both $PSF(\theta_z)$ and $PSF(\theta_{x'})$, and was set as 16 for super-CSD.

Results

In computer simulation, the left panel of Fig. 3 showed the original ODFs of four different HARDI datasets with two fibers crossing at 50° angle (top) and their corresponding estimated spherical DWIs (middle) and FODs (bottom). It is obvious that the original ODFs in both DSI and GQI have lost true fiber orientations (top row), while SH-QBI and QBI still preserved them. After applying the proposed sharpening method, the true fiber orientations of four HARDI datasets were susucessfully detected (bottom row). The opaque surfaces correspond to the mean ODF/FOD/spherical DWI in 100 simulations, while the transparent surfaces indicates their standard deviations. Under SNR=30, the successful rates of detecting 50° crossing fibers were 0%, 0%, 92%, and 91% for original ODFs of DSI, GQI, SH-QBI, and QBI respectively. By using the proposed method, the successful rates were increased to 100% for all HARDI datasets, and their mean angular errors were 8.4, 8.7, 5.6, and 5.6 degrees respectively. The right panel of Fig. 3 showed the results of the original ODFs (top row) and FODs maps (bottom row) of four HARDI datasets of human brain. The enlarged region showed the intersection between corpus callosum (red) and internal capsule (green). The voxels which contain the two fibers cannot be clearly identified from the original ODF maps, but they were successfully resolved in the FOD maps by using the proposed method, as indicated by green arrows.

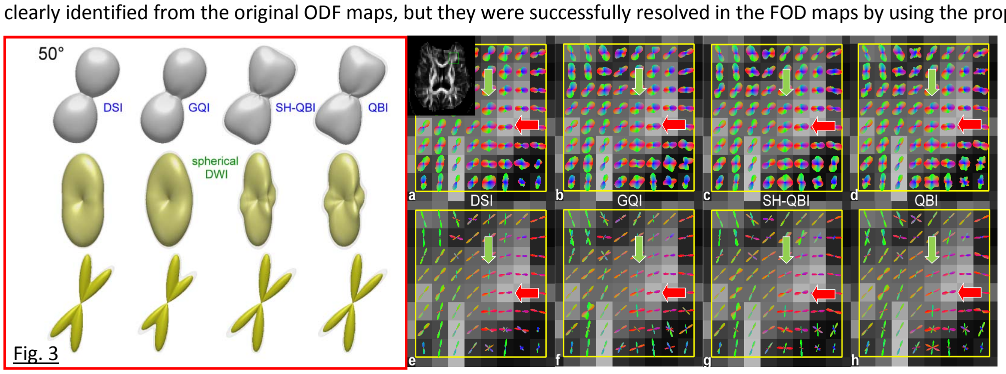

Fig. 3

Conclusion

This study performed the computer simulation and human brain experiment to demonstrate the feasibility of the proposed method in sharpening the ODFs of different HARDI datasets. The results showed that the proposed method can improve the detection of crossing fibers in both computer simulation and human brain experiment. Therefore, we concluded that the proposed sharpening procedure is a helpful adjunct to the post-processing of HARDI datasets.

References

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