A Rotation-Invariant Spherical Harmonic Decomposition Method for Mapping Intravoxel Multiple Fiber Structures

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Introduction

An important advantage of diffusion tensor imaging (DTI) over traditional diffusion-weighted imaging (DWI) is its rotation-invariant property that justifies the quantitative comparison of diffusion structures between different parts of the brain or across different subjects (1). However, the validity of DTI is confounded by the fact that the primary eigenvector of the diffusion tensor may be seriously biased from the actual fiber direction if multiple fibers share a single voxel (2). A strategy for handling intravoxel multiple fibers is to characterize the measured high angular resolution diffusion (HARD) profile in each voxel, e.g. using spherical harmonic decomposition (SHD) to characterize the 3-D apparent diffusion coefficient (ADC) profile (3-4). However, a major disadvantage of the SHD method is that the calculated components are rotation-variant, i.e. the decomposed SH (1st order or higher) changes with the rotation of the diffusion profile with respect to the coordinate system (4). We previously proposed a "diffusion circular spectrum mapping" (DCSM) method for characterizing the HARD profiles by examining only the ADC distribution along the circle spanned by the major and medium eigenvectors (5-6). Unlike the regular SHD method, DCSM utilizes the local diffusion tensor eigenvectors to determine the plane where the circular decomposition is performed, and therefore it inherits the rotation-invariant property from the diffusion tensor model. In this paper, a new rotation-invariant SHD technique is presented also based on the inherent rotation-invariant property of DTI. Diffusion-weighted MRI experiments were performed on human subjects to validate this method.

Methods

Theory. A regular SHD can be regarded as a spherical correlation between the measured ADC profile $D_{app}(\theta,\phi)$ and the SHD kernel functions $Y_l^m(\theta,\phi)$, such that $a_{lm}=\int_0^{2\pi}\int_0^{\pi} D_{app}(\theta,\phi)Y_l^m(\theta,\phi)\sin(\theta)d\theta d\phi$. Due to the generally anisotropic shapes of both the ADC profile and the kernels, any rotation of $D_{app}(\theta,\phi)$ with respect to the coordinate system (θ,ϕ) may lead to the change of magnitude and/or phase of the SHD component a_{lm}. In the proposed rotation-invariant SHD method, a reorientation of the measured ADC profile is performed in each voxel such that the reoriented profile $D'_{app}(\theta',\phi')$ corresponds to a diffusion tensor whose major, medium and minor eigenvectors are parallel with x-, y- and z- axis, respectively. Thus, the rotation-invariant SHD is obtained by $a'_{lm}=\int_0^{2\pi}\int_0^{\pi} D'_{app}(\theta',\phi')Y_l^m(\theta',\phi')\sin(\theta')d\theta' d\phi'$.

Experiments. Experiments were performed on healthy volunteers on a 3T Siemens Allegra scanner, and a diffusion-weighting EPI sequence was used to acquire 2 coronal imaging slices (4 mm thickness and 1 mm gap) approximately parallel to the extension of the brain stem and covering the pons region. Equally-spaced 256 directions (diffusion encoding scheme $\mathbf{E}_1$) were used to apply the diffusion-weighting gradients with b factor of 2500 (s/mm^2). Another diffusion encoding scheme $\mathbf{E}_2$ was also used, which was obtained by rotating $\mathbf{E}_1$ about the x-, y- and z- axis at angles ($\alpha=0$, $\beta=\pi/2$, $\gamma=\pi/4$), respectively.

Date Processing. For each diffusion-weighted dataset, the following procedures were performed: i) a procedure to correct the geometrical distortion due to the susceptibility-induced field inhomogeneities on the EPI images; ii) the diffusion tensor eigen-system for each voxel, and several DTI-based index maps, such as fractional anisotropy (FA), were calculated; iii) the 0th, 2nd and 4th order DCSM maps were calculated (5-6); iv) the regular SHD maps were used to calculate the magnitude maps of lower orders ($0\le l\le 6$); and v) the proposed rotation-invariant SHD method was used to calculate the rotation-invariant SHD maps at the same lower orders. Only the first scheme $\mathbf{E}_1$ was used for all datasets, because the diffusion-weighted images acquired with scheme $\mathbf{E}_2$ can be regarded as an equivalent one acquired with scheme $\mathbf{E}_1$ while the head is correspondingly rotated with angles ($\alpha=0$, $\beta=-\pi/2$, $\gamma=-\pi/4$).The obvious advantage of generating an equivalent rotation is to avoid the difficulties of repositioning the imaging slices.

Results and Discussions

A typical slice from one subject is used to illustrate the experimental results. The magnitude maps of the $|a_{00}|$, $|a_{22}|$ and $|a_{44}|$ components calculated from the regular SHD method are illustrated in Fig.1, and the upper and lower rows correspond to the datasets acquired with the encoding scheme $\mathbf{E}_1$ and $\mathbf{E}_2$, respectively. It is observed that the $|a_{22}|$ and $|a_{44}|$ maps change significantly with the rotation of the encoding scheme while map $|a_{00}|$ remains unchanged. The $|a_{00}|$, $|a_{22}|$ and $|a_{44}|$ maps calculated from the proposed rotation-invariant SHD method are illustrated in Fig.2 with the same subfigure arrangement as used in Fig.1. Clearly, all the maps remain unchanged with the rotation of the diffusion encoding scheme, indicating the rotation-invariant property of the proposed method. As a comparison, the 0th 2nd and 4th order DCSM maps are illustrated in Fig.3 with a similar subfigure arrangement. It is demonstrated that the DCSM method is rotation-invariant. The clear consistency between the $|a_{00}|$, $|a_{22}|$ and $|a_{44}|$ maps from the proposed rotation-invariant SHD method and the 0th 2nd and 4th DCSM maps indicate that the $|a_{00}|$, $|a_{22}|$ and $|a_{44}|$ maps from the proposed method can be used to map the diffusion patterns of isotropic, single fiber and orthogonal fiber crossing, respectively. It is also observed that the SHD component maps from the proposed method exhibit higher signal-to-noise ratios (e.g. SNR ≈ 50 for the $|a_{44}|$ map) than those of the corresponding DCSM maps (e.g. SNR ≈ 30 for the 4th order DCSM map).

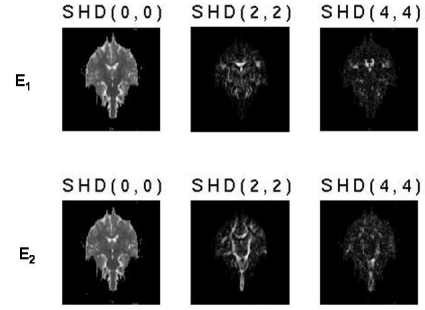

Fig.1: Selected component maps from the regular SHD method.

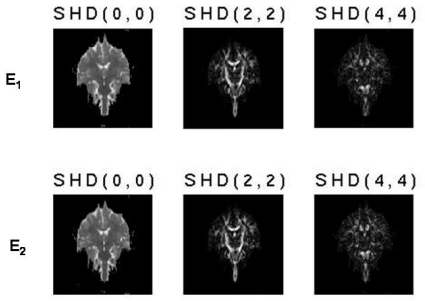

Fig.2: Selected component maps from the rotation-invariant SHD method.

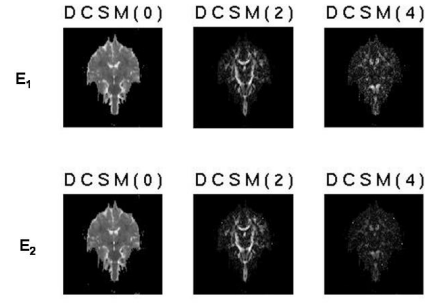

Fig.3: The 0th 2nd and 4th order DCSM

The rotation-invariant property of the DCSM method and the method are based on an equivalent ADC profile reorientation according to the diffusion tensor eigenvectors before the decompositions are performed. That is, both methods inherit the rotation-invariant property of the diffusion tensor model. Compared with regular SHD methods, the proposed method is superior in characterizing the multiple fiber structures between different brain regions or across subjects.

References

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