Diffusion Tensor Encoding Schemes Optimized for White Matter Fibers with Selected Orientations

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Introduction

The accuracy of diffusion tensor imaging (DTI) measurements depends on the gradient encoding scheme used [1]. Most current acquisition schemes contain diffusion directions uniformly distributed in 3D space, in order to provide equal noise levels for fibers in any orientation [2]. However, when considering specific fiber-bundles, such as the corticospinal tract (CST), or parts of fiber-bundles, the range of fiber orientations is limited. Based on this observation, we have developed a method to produce encoding schemes that minimize the noise of fractional anisotropy for tensors with primary eigenvector orientations within a cone with a specified opening angle. When compared to a conventional acquisition scheme with the same number of diffusion directions [3], the new scheme significantly reduced the standard deviation of fractional anisotropy (*STD(FA)*) for tensors with primary eigenvectors oriented within the optimized cone. Similar results were obtained in simulations and experiments on humans. The same technique could be used to minimize the noise in the measurement of any other diffusion characteristic of the selected fibers.

Methods

Simulations: A large number of cylindrically symmetric tensors with diffusivities 1.7 x 10^{-3} mm^2/s, 0.2 x 10^{-3} mm^2/s, and 0.2 x 10^{-3} mm^2/s, and primary eigenvectors uniformly distributed in 3D space, were simulated [4]. An optimization algorithm based on the downhill simplex method was used to identify the 6 diffusion directions that minimize the total variance of FA (*TV(FA)*) for tensors whose primary eigenvectors were included within a cone with 30° opening angle around the z-axis. The starting point of this iterative procedure was the ICOSA6 acquisition scheme [1]. In each iteration, the 6 diffusion directions were modified and the new encoding scheme was used in order to produce the DW signals for each of the simulated tensors. The signal with no diffusion weighting (b=0sec/mm^2) was set to 1000 for all tensors. Then, noise with a standard deviation of 30 was added to all signals and the tensors were re-estimated. This process was repeated 1024 times for each tensor and the variance of FA was measured each time. At the end of each iteration, the *TV(FA)* was estimated for the group of tensors with orientations within the selected cone, and the 6 diffusion directions were modified for the next iteration. This iterative process was terminated when the decrease in *TV(FA)* between two iterations was less than 10^{-6}%. The algorithm was restarted 10 times in order to verify the stability of the minimization. A plot of *STD(FA)* as a function of the orientation of the primary eigenvector was produced for the optimized and conventional ICOSA6 acquisition schemes. In addition, the conventional scheme was simply rotated so that the minimum *STD(FA)* was achieved for tensors having their primary eigenvector parallel to the z-axis. This scheme was called $ICOSA6_{min}$. Similarly, a scheme called $ICOSA6_{max}$ was created by rotating the conventional scheme so that the maximum *STD(FA)* was achieved for tensors with primary eigenvector parallel to the z-axis.

Human studies: A healthy human subject was scanned on a 3T GE MRI scanner using a spin-echo echo-planar DTI sequence and the ICOSA6 acquisition scheme (TR=5.4secs, TE=71.8ms, FOV=24cm x 24cm, slice thickness=3mm, image matrix=256 x 256, NEX=5, b-value=900sec/mm^2). At the end of the sequence a region of interest (ROI) was selected in the right CST. The primary eigenvectors for voxels included in that ROI were averaged in order to estimate the mean orientation of the underlying fibers. Then, the optimal 6-direction scheme from the simulations was rotated so that the optimized tensors were not those around the z-axis, but those around the mean orientation of the fibers and within a cone with a 30° opening angle. The same rotation was applied to the $ICOSA6_{min}$ and $ICOSA6_{max}$ schemes. DTI scans using the rotated optimized scheme, and the rotated $ICOSA6_{min}$ and $ICOSA6_{max}$ schemes were performed. Data were also acquired using a minimum energy scheme with 30 directions (ME30) and NEX=1. The mean FA and standard deviation in the selected ROI were estimated for all scans.

Results and Discussion

The six diffusion directions of the optimized and conventional schemes are shown in Figure 1. The values of *STD(FA)* for the conventional and optimized acquisition schemes are plotted in Figure 2 as a function of the orientation of the primary eigenvector of the tensors. In the simulations, the *STD(FA)* of the tensors with primary eigenvectors within the selected cone was reduced by 48% maximum when using the optimized scheme compared to the $ICOSA6_{max}$. The mean FA value (*M(FA)*) of the tensors with primary eigenvectors within the selected cone remained unchanged. In the human study, the process of determining the appropriate rotation for the optimized acquisition scheme lasted less than 10 minutes. This time could be significantly reduced by fully automating this process. The results of the human study were in agreement with the simulations (Table 1, Fig. 3). The *STD(FA)* of tensors in the selected ROI was reduced by 47% when using the optimized compared to the $ICOSA6_{max}$ scheme. When compared to the $ICOSA6_{min}$ scheme, the *STD(FA)* obtained with the optimized scheme was decreased by 24%.

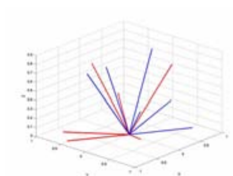

Figure 1. Gradient directions of the optimized (red) and conventional schemes (blue).

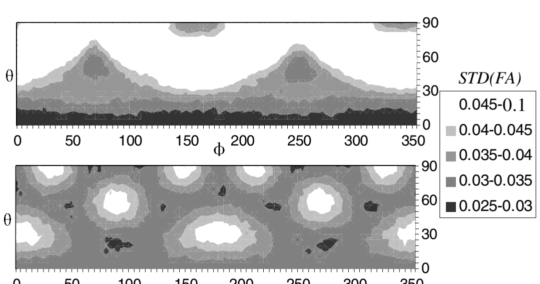

Figure 2. Graph of *STD(FA)* as a function of the orientation of the primary eigenvector of tensors [in spherical coordinates (θ, φ)], for the conventional (top) and optimized (bottom) 6-direction schemes.

Table 1. Mean FA and standard deviation in the selected ROI using five acquisition schemes.

Acquisition scheme	*mean FA*	*STD(FA)*
ICOSA6	0.808	0.03
Optimized 6-direction	0.806	0.019
ME30	0.783	0.03
$ICOSA6_{min}$	0.806	0.025
$ICOSA6_{max}$	0.802	0.036

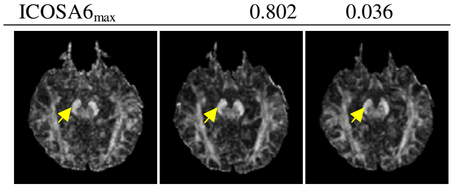

Figure 3. FA maps obtained using the: optimized 6-direction (A), $ICOSA6_{min}$ (B), and $ICOSA6_{max}$ (C) schemes. The arrows are pointing to the location of the selected ROI in the right CST.

In conclusion, we have presented a method for producing DTI data acquisition schemes that minimize the noise in the measurement of a selected property (e.g. FA, trace etc.) of white matter fibers oriented within a cone with a specified opening angle. Once the scheme is produced using simulations, it can be used in actual scans after appropriate rotation. Furthermore, hybrid schemes can be developed which maintain sufficient SNR for any fiber, but improve SNR for fibers with specific orientations.

References: [1] Hasan KM, *et al. J Magn Reson Imaging* 2001;13:769-780. [2] Skare S, *et al. J Magn Reson* 2000;147:340-352. [3] Pierpaoli C, *et al. Radiology* 1996;201:637-648. [4] Papadakis NG, *et al. J Magn Reson* 1999;137:67-82.