On the Effects of Random Subject Rotation on Icosahedral Diffusion Sampling Schemes in DT-MRI

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Introduction: The choice of the number (N) and orientation of diffusion sampling gradients required to measure accurately the water diffusion tensor remains contentious. Monte Carlo studies have suggested that between 20 and 30 uniformly distributed sampling orientations are required to provide robust estimates of water diffusions parameters. These simulations have not, however, taken into account what effect random subject motion, specifically rotation, might have on optimised gradient schemes, a problem which is especially relevant to clinical diffusion tensor MRI (DT-MRI). Here this question is investigated using Monte Carlo simulations of icosahedral sampling schemes. These simulations involve randomly rotating the prescribed gradient orientations of icosahedral sampling schemes with N between 6 and 40 (Icosa6 to 40) and determining how this affects the mean fractional anisotropy (FA) and its standard deviation (SD). Icosahedral sampling schemes, which have the advantage that large N can be created from optimised subsets of smaller N, appear to be ideal for the study of restless subjects since if scanning needs to be prematurely terminated it should be possible to identify a subset of images that have been acquired with a near optimised sampling scheme.

Methods: The effect of random subject rotation on Icosa6, 15, 21, 31 and 40 was investigated by rotating each of the original orientations of these schemes by a fixed angle α (= 1, 3, 5, ..., 19°), with the direction of the rotation applied to each gradient direction being random and independent of the others. Figure 1 shows 50 random rotations of the gradient directions of the Icosa6 scheme with α = 9°. Since the rotation angle α is fixed, all the random rotations of each original gradient direction lie on the surface of a cone with opening angle 2α. For each sampling scheme, a total of 100 random rotations of the gradient orientations were performed for each of the 10 values of α. For each random rotation, a new **B**-matrix (**B′**) was calculated; this represents the *actual* acquisition matrix for a gradient scheme when random subject rotation of magnitude α takes place during the scan. For each **B′**, new diffusion-weighted signals were calculated from $S=S_0e^{-\mathbf{BD0}}$ with 100 different orientations of the principal diffusion direction of $\mathbf{D_0}$. $\mathbf{D_0}$ is a baseline water diffusion tensor created using a constant trace value typical of that found in normal human brain, *i.e.* $\mathrm{Tr}(\mathbf{D}_0) = 2100 \times 10^{-6}$ mm^2/s, for five different values of FA (= 0.1, 0.3, 0.5, 0.7 and 0.9) [1].

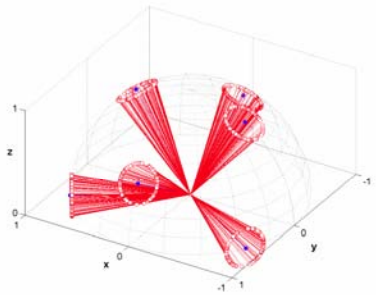

Figure 1

Diffusion tensors estimated from these numerical signals were calculated by multivariate linear regression using the *original* **B**-matrix. This permits the assessment of the error present in the measurement of **D** if the **B**-matrix is not re-calculated when subject motion occurs during the scan. To assess the rotational variance of diffusion anisotropy measurements made from these data, the mean and SD of the estimated FA (FA_{est}) was then determined from all 100 rotations of $\mathbf{D}_0$ and 100 random rotations of the gradient directions for each α and the five original FA values.

Results: Figure 2 displays plots of mean FA_{est} (first column) and its SD (second column) obtained by randomly rotating the diffusion gradient orientations of Icosa6 (first row), Icosa21 (second row) and Icosa40 (third row). This figure shows the errors introduced into the estimation of **D** and FA when the **B**-matrix is not corrected for random subject rotation during scanning. At the lowest diffusion anisotropy values, mean FA_{est} is close to its expected value for the investigated range of α for the three schemes. Conversely, for medium to high FA at values of α greater than approximately 10°, the mean FA_{est} is underestimated and this effect becomes more pronounced as N increases. SD{FA_{est}}, and hence the rotational variance of estimated **D**, increases with α for the three displayed schemes, particularly for higher diffusion anisotropy values, although this increase becomes progressively less as N becomes larger.

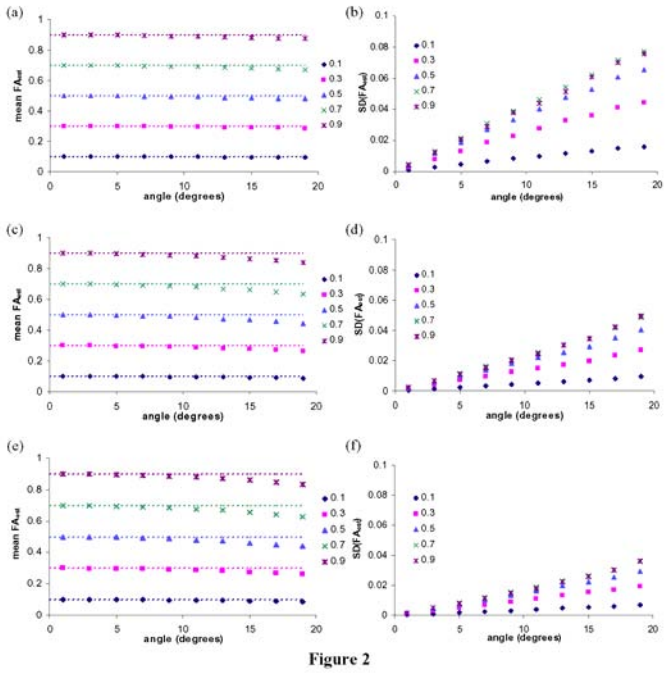

Figure 2

Discussion: The Monte Carlo simulations presented here show that the effects of random subject rotation on the optimisation of icosahedral sampling schemes and measurements of diffusion anisotropy made from them are most significant for small N. Thus, for Icosa6, the results show increased rotational variance of the estimated FA compared with higher N schemes. Conversely, schemes with larger N are less affected by random rotations with the rotational variance of diffusion anisotropy estimates becoming progressively less dependent on α as N increases. For large N, however, the simulations also show that higher values of FA are underestimated when α is greater than approximately 10°. It is not entirely clear why this is so, although it may be due to the increased chance of two or more unique gradient orientations coinciding when the angle between them is small and the subject's head rotations are large. This would result in the two different gradient orientations producing the same measurement of *S*, an error which would cause **D** estimated using the original **B**-matrix to be more isotropic than it actually is. This suggests that in the case of large subject rotations, *i.e.* above approximately 10°, the **B**-matrix should be corrected to avoid underestimation of FA in anisotropic brain structures.

References

[1.] Jones DK. *Magn Reson Med* 2004;**51**:807-815.

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