Optimal imaging parameters for fibre-orientation estimation in diffusion MRI

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Introduction

This abstract investigates the optimal imaging parameters for estimating white-matter fibre orientations using diffusion MRI with a spherical sampling scheme [1]. We simulate diffusion MRI measurements from brain tissue with one and two dominant microstructural fibre orientations using simple models of the particle-displacement density \( p \). We map the models to the synthetic data to recover the fibre orientations. In the one-fibre case, we use a zero-mean Gaussian density, as in diffusion-tensor MRI [2], and in the two-fibre case, we use a mixture of two zero-mean Gaussians, as in [3, 4]. We study the error in the fibre-orientation estimates in the presence of noise as a function of the parameters of the imaging sequence in order to identify optimal settings for brain imaging.

In earlier work, Xing et al [5] show that the optimal strategy for measuring the diffusion coefficient \( d \) uses a two-point sampling scheme, which acquires \( N \) repeated measurements at \( b_1 \) and \( M \) repeats at \( b_2 < b_1 \). For \( N = M = 1 \), \( d(b_1 - b_2) = 1.11 \) maximizes the signal to noise ratio of the measured \( d \). As the number of available measurements increases, the optimal \( d(b_1 - b_2) \) increases asymptotically to 1.28 and the optimal \( N/M \) tends to 3.6. Jones et al [1] extend Xing et al’s analysis to measurement of the full diffusion tensor. They acquire the \( N \) measurements at \( b_1 \) with gradient directions spread evenly over the sphere and the \( M \) measurements at \( b_2 = 0 \). Jones et al note that higher \( b_2 \) requires higher TE, which reduces signal to noise. They model this effect (for a specific, but fairly typical, EPI-based pulse sequence) and show numerically that, for an approximately isotropic diffusion tensor \( D \) and \( T_E = 0.08 \) s, the sum of the variances of the elements of \( D \) is minimum when \( b_1 = 0.85 \times 3/\text{Tr}(D) \) and \( M(N + M) = 0.103 \). Here, we use simulations to determine \( b_1 \) in Jones’ spherical sampling scheme that minimizes the variance of the principal eigenvalue of anisotropic diffusion tensors over a large number of independent noise trials. The simulations take into account the reduction in signal as TE increases.

Methods

We assume the standard PGSE measurement sequence with EPI readout. To synthesize measurements with a particular \( b \), we choose the gradient pulse-width \( \delta \) and separation \( \Delta \), TE and \( k \)-space-sampling fraction that maximize the signal to noise at \( b = 0 \). We fix gradient strength and image resolution and thus the time \( R_0 \) required to readout the second half of \( k \)-space after the echo centre. The SNR at \( b = 0 \) is then \( S/R = \exp(TE/T_2) \) (R + Rm)^1/2, where \( S/R \) is a constant and \( R \) is the time available within \( T_E \) to sample some or all of the first half of \( k \)-space. At fixed TE, a range of choices for \( \delta \) and \( \Delta \) provide the required \( R \). We choose \( \delta \) as large as possible, since this maximizes \( R \). To select the optimal TE for \( b \), we determine \( \delta, \Delta, R \) and hence \( S/R \) separately at each TE and choose the TE that maximizes \( S/R \).

We use variations of two simple test functions: \( p_1 = G(x; D_1, \iota) \) (one-fibre case) and \( p_1 = G(x; D_0, \iota) + (1 - \alpha) G(x; D_2, \iota) \) (two-fibre case), where \( \alpha \in [0, 1] \) is a mixing parameter, \( G(x; D_i, \iota) \) is the zero-mean Gaussian function with covariance \( \iota = \iota/2 \) and the diffusion tensors are \( D_1, D_2 \) with \( \iota = \iota/2 \) and \( \iota = \iota/2 \) respectively. For each experiment over 500 random rotations of the test function and mixing parameter \( \alpha \), we compute the mean dyadic tensor \( Y = \lambda_0 \mathbf{1} \) and an EPI sequences with maximum gradient strength 0.04 T m^-1 and in the two-fibre case, we use a mixture of two zero-mean Gaussians, as in 

\[ Y = \lambda_0 \mathbf{1} \]


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