Diffusion Gradient Calibration Influences the Accuracy of Fibre Orientation Density Function Estimation: Validation by Efficiency Measure

Y. Kupriyanova[1], O. Posnansky[1], and N. J. Shah[1,2]

[1]Medical Imaging Physics, Institute of Neuroscience and Medicine - 4, Forschungzentrum Juelich, Juelich, Germany, [2]Department of Neurology, Faculty of Medicine, RWTH Aachen University, Aachen, Germany

Introduction. Diffusion-weighted (DW) MRI provides important information regarding the arrangement of white matter fibres. However, imperfections in the DW gradients may cause errors in the estimation of diffusion parameters. The sources of the gradient errors are various and may arise from long-term eddy currents, background gradients, imaging gradients, and spatial non-linearity and non-uniformity of the gradients. We present results demonstrating the influence of these errors into the accuracy of the fibre orientation density function (ODF) estimation. A DW gradient calibration scheme, which can be used to mitigate the gradient errors, is also described. We compare the reconstructed fibre ODFs from two datasets, acquired *in vivo* with and without the application of the diffusion gradient calibration scheme [1, 2] and calculated the statistical efficiency [3] of the unbiased fibre ODF estimators for these datasets.

Methods. Several approaches for reconstructing fibre orientations from high angular resolution diffusion imaging (HARDI) have been proposed as alternative methods to diffusion tensor imaging (DTI) [4-8]. Here, we obtained the fibre ODF combining the general idea of spherical deconvolution [6] with the Funk-Hecke theorem [7], which leads to:

$$S^k = 2\pi F^k \int_{-1}^{1} P_{l_k}(t) R(t) dt \qquad (1),$$

where S^k and F^k are two vectors, representing the spherical harmonic (SH) decomposition of the signal and the fibre ODF, respectively, P_{l_k} are the Legendre polynomials of the degree l_k, where l_k is the order associated with the kth SH basis element. The response function R is the signal profile of an individual white matter fibre and was determined from the data directly [6]. We compared the reconstructed fibre ODFs from two datasets, acquired *in vivo* with and without the application of the diffusion gradient calibration scheme [1, 2]. The key point of our scheme is the rescaling of the DW signal distributed among different diffusion encoding directions by means of the correction curve. The correction curve was obtained using an isotropic spherical water phantom following the algorithm given below: **1.** First, the balancing times δ_4^n for each diffusion gradient direction were optimised (see Figure 1). This was achieved by measuring the DW signal for different directions together with variation of duration of one of the diffusion gradient lobes. **2.** From DW signals, acquired with optimised gradient durations, a set of errors in the apparent diffusion coefficient (ADC) values, distributed among different diffusion directions, was determined (see Figure 2). This set of values, required to rescale the DW signal among different directions, forms the correction curve [1, 2, 9].

To compare reconstructed fibre ODFs quantitatively, we have used a recently introduced measure - statistical efficiency of the unbiased fibre ODF estimator [3]. Statistical efficiency of the fibre ODF is an accuracy with which microstructural information can be inferred from the diffusion measurements in a given amount of imaging time. Ideal efficiency of the unbiased fibre ODF estimator is a function of the b-value, the ADC of the single-fibre response, and the SNR at b=0. The relationship between the fibre ODF estimation efficiency and the angular resolution is inversely proportional. In other words, increasing the order l of the SH expansion in Equation (1) allows one to distinguish fibre separation angles more accurately, but decreases the efficiency.

Results. Two HARDI datasets (with and without the application of the diffusion gradient calibration procedure) were acquired on a 3T scanner (Tim-Trio, Siemens) from a healthy adult with identical spatial parameters: TE/TR=90/11200 ms, resolution=(2.0 mm)^3, FOV=256x256 mm^2, b-value=1000 s/mm^2, 60 directions distributed over an icosahedron.

Ideal efficiencies, E, of the fibre ODFs for the data sets, acquired with (red line) and without (blue line) the gradients calibration procedure as a function of different SH expansion orders l are shown in Figure 3. It is clear that for the data set, acquired with the gradient calibration procedure (red line), efficiency is higher for every order of SH expansion. Moreover, for this data set efficiency for SH expansions up to l=8 (corresponding to the theoretical angular resolution of the fibre ODF estimator 36˚ [8]) is approximately equal for the efficiency at l=6 (corresponding angular resolution is 46˚ [8]) for data set, acquired without the calibration procedure. Thus, the application of the calibration scheme allows one to infer microstructural information from DW images more accurately.

Typical ODFs for *in vivo* data, acquired with and without the diffusion gradient calibration scheme are shown in Figure 4 (a,c) and Figure 4 (b,d), respectively. No regularization techniques were used to suppress noise in the raw data during the reconstruction of ODFs, and even then the ODFs, reconstructed from the data acquired after the diffusion gradient calibration procedure, are sharper and features are more distinguishable (see Figure 4). This is especially important for regions with crossing fibres.

Conclusion. DW gradient imperfections can markedly interfere with measurements of diffusion anisotropy. We have shown that a diffusion gradient calibration procedure can improve the results of studies that rely on the DW signal such as fibre ODF estimation. Fibre ODFs, reconstructed from data, acquired after the diffusion gradient calibration scheme, are sharper and distinguish more complex structures. For approximately the same values of efficiency, an angular resolution of the fibre ODF estimator is higher for data acquired with the calibration procedure. The presented method of DW gradient calibration is fast enough to be used on a routine basis and can recover the fibre ODFs more accurately and precisely. This holds promise for applications such as tractography.

References: [1] Posnansky et al. 2008, Proc. ESMRMB, 624. [2] Posnansky et al. 2009, Proc. ISMRM, 3570. [3] White and Dale 2009, HBM, in press. [4] Tuch et al. 2002, MRM, 48: 577. [5] Tuch 2004, MRM, 52: 1358. [6] Tournier et al. 2004, NeuroImage, 23: 1176. [7] Descoteaux et al. 2007, MRM, 58: 497. [8] Hess et al. 2006, MRM, 56:104. [9] Nagy et al. 2007, MRM, 58: 763.

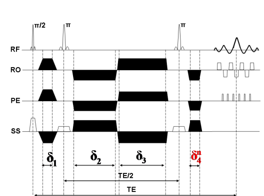

Figure 1. Basic diffusion preparation twice-refocused spin echo sequence diagram. Diffusion gradients are depicted in black. Durations of diffusion gradient lobes are $\delta_1, \delta_2, \delta_3, \delta_4^n$, where δ_4^n is a parameter which may be adjusted for every n-th gradient direction, n=[1,60].

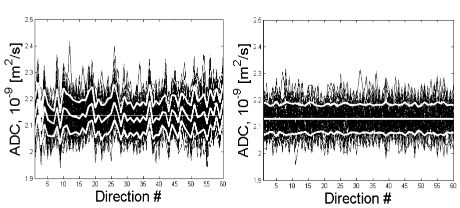

Figure 2. Distribution of the ADCs as a function of diffusion gradient direction (left – before the calibration procedure, right – after the calibration procedure). The thick white line in the middle is a mean value and upper and lower thick lines are standard errors for the ADC distribution depending on gradient direction. Thin flat line is a mean ADC for all applied directions.

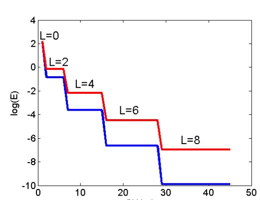

Figure 3. Ideal efficiency, E, of the ODFs for the data sets, acquired with (red line) and without (blue line) the gradients calibration procedure as a function of different SH expansion orders L.

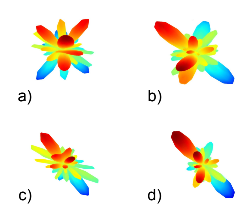

Figure 4. Typical ODFs, obtained from data, acquired without diffusion gradient calibration (a, c), and with the application of calibration (b,d).