A Method for Gradient Calibration in Diffusion Weighted Imaging

O. Posnansky[1], Y. Kupriyanova[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. Conventional gradient calibration procedures do not exclude significant bias in the diffusion-weighted (DW) signal during MR experiments. The error, arising from imperfections in the DW gradients, varies among the different gradient directions and exhibits different extent of offsets. We propose a calibration method for DW imaging using a homogeneous water phantom, presuming that its ADC profile is uniform and does not depends on the orientation of diffusion gradients. Our approach includes not only rescaling of the DW signal distributed among different diffusion encoding directions so as to minimise an angular error in ADC [1-3], but also an optimisation of balancing times for DW gradients among each diffusion direction. Such a technique corrects all possible diffusion gradient errors in a single protocol. The correction protocol was applied to a phantom and *in vivo* at 3T. Our results show the effectiveness of our approach and demonstrate that the described scheme of systematic error reduction is a valid method for quality control studies of gradient system performance for DW imaging.

Methods and Results. In our study we used the twice-refocused spin echo sequence [4]. Our method involves high angular resolution DW imaging on a homogeneous water phantom and consists of two serial procedures: **1.** First, the balancing times of the DW gradients for each diffusion gradient direction were optimised. This was achieved by measuring the DW signal for directions together with a variation of duration of one of the diffusion gradient lobes (See Figure 1: δ_4^n is a variable parameter for every gradient direction). **2.** From DW signals, acquired with the optimised gradients durations, a set of errors in the ADC values, distributed among different diffusion directions, was determined. This set of values, required to rescale the DW signal among different directions, forms the correction curve. Such a rescaling procedure is similar to the methods introduced in [1-3]. However, using the optimised gradients as a first step in the calibration procedure can greatly improve the results. Thus, both steps, gradients duration optimisation followed by DW signal rescaling among different directions, should be used for proper gradients calibration.

Two kinds of experiments were performed in order to validate our correction scheme. First, a spherical water phantom provided by the scanner manufacturer was used to carry out the calibration procedure. Second, *in vivo* data from a healthy volunteer were acquired with and without the application of the calibration procedure. Both kinds of experiments were performed on a 3T MRI system (whole-body, Tim-Trio, Siemens). The gradients system is capable of a maximum of 40 mT/m. The sequence parameters were common for phantom and *in vivo* studies and had the following values: TE = 90 ms, TR=11200, resolution = (2 mm)^3, slices = 75, field-of-view (FOV) = 256×256 mm^2, b-value=1000 s/mm^2, 60 unique non-collinear diffusion-encoding directions uniformly distributed over an icosahedron. As a reference, non-diffusion-weighted images were also acquired and used in post-processing. The spherical water phantom was stored in the scanner room with air conditioning on to maintain a constant temperature. Before every experiment the phantom was placed in the scanner about 20 min prior to experiment to reduce effects of random fluxes. Experiments with the phantom involved variation of δ_4^n by adding a free parameter ξ in the interval [-3; 3] ms with step 0.3 ms for every diffusion gradient direction (Figure 1). After acquiring the data, we performed post-processing to obtain an optimised set of parameters. Optimised parameters correspond to minimum error in ADC estimation for the prescribed balanced time of the diffusion gradient. These parameters were put in a basic sequence and phantom data were acquired again. The calculated ADC values, from data acquired with the standard diffusion sequence and with the optimised diffusion gradients durations, are shown in Figure 2a and Figure 2b, respectively. The thick white line in the middle is a mean value of the ADC for the specific DW gradient direction. Upper and lower thick white lines depict the standard deviation of the ADC distribution for the selected direction. The thin white line is a mean ADC for all applied directions. It is clear that for properly calibrated gradients the mean curve should not have a distinct modulation otherwise it needs to be corrected. In the Figure 2b, we observe less modulation in the ADC values among different directions in comparison with the Figure 2a and the ADC distribution in Figure 2b was closer to the expected value [5]. However, the balancing procedure alone does not compensate imperfections entirely due to background gradients. The second step of our correction method is the rescaling of the DW signal among different directions. It was applied to the phantom data acquired with the optimised gradient duration. We calculated the differences between the mean ADC value for all diffusion gradient directions (flat line in Figure 2b) and mean ADC for a specific direction. The difference curve is the correction curve and it was used for the second calibration step. The ADC distribution after rescaling with the correction curve is shown in Figure 2c. Phantom measurements were repeated several times in order to increase the number of degrees of freedom for statistical analysis. The correction procedure showed stability in parameter estimation. Phantom experiments corroborated the necessity of diffusion gradient calibration for accurate diffusion data acquisition. Optimised diffusion gradient balancing times and the correction curve, computed with the phantom, were used for further experiments with volunteers.

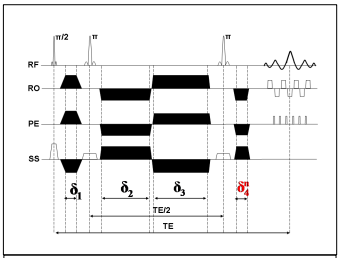

Figure 1.Basic diffusion preparation twice-refocused spin echo sequence diagram [4]. Diffusion gradients are depicted in black. The durations of diffusion gradient lobes are $\delta_1, \delta_2, \delta_3, \delta_4^n$, where δ_4^n is a parameter which may be adjusted for every *n*-th gradient direction, *n*=[1,60].

One healthy male volunteer was recruited in the study. Two DW data sets were acquired for comparison. First, a data set was acquired with the optimised diffusion gradient durations in the pulse sequence and then additionally corrected according to the second step of the calibration procedure. The second data set was obtained with a standard pulse sequence product from manufacture. Post-processing and data analysis was carried using FSL [6]. FA maps computed from both data sets are shown in Figure 3a,b. It is clear that the FA map computed from data acquired with the diffusion gradient calibration looks more accurate, has less distortions, and anatomical features are easily distinguishable.

Discussion and Conclusion. Our study shows that DW gradient imperfections can markedly interfere with measurements of diffusion anisotropy. The presented two-step calibration algorithm can effectively minimize effects of the miscalibration in the diffusion gradients and improve the results of studies that rely on the DW signal. The proposed calibration procedure was demonstrated in phantom and *in vivo* measurements. Our method can be applied to general DW MR data and can be performed regularly to monitor the systematic drifts in diffusion gradient and pulse sequence performances. In addition, our method could enhance available tools for the comparison studies between scanners.

References: [1] Posnansky et al. 2008, Proc. ESMRMB, 624. [2] Posnansky et al. 2009, Proc. ISMRM, 3570. [3] Nagy et al. 2007, MRM, 58:763. [4] Reese et al. 2003, MRM, 49:177. [5] Mills 1973, J. Phys. Chem, 77:685. [6] Smith et al 2004, Neuroimage, 23:208.

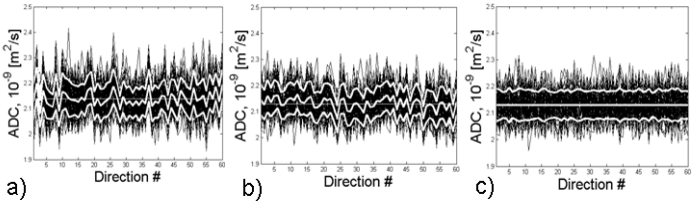

Figure 2. Distribution of the ADCs as a function of diffusion gradient direction.

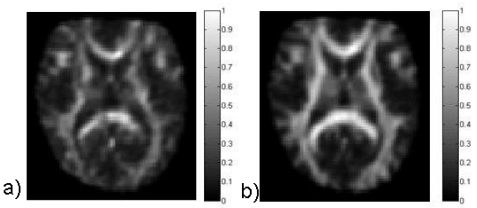

Figure 3. FA map calculated for *in vivo* data: a) acquired without the calibration procedure; b) acquired with the calibration procedure.