Diffusion Gradient Calibration for DTI

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Background The self-diffusivity of water molecular may be measured using diffusion sensitizing gradient pulses. For DWI, errors or miscalculations in the diffusion-weighting gradients may lead to errors in diffusion quantitation. In this study, we developed and evaluated a simple protocol to calibrate the gradients for DTI and methods for retrospectively correcting DTI measurements. The approach may be used to monitor and compare DTI performance either over time between scanners or between pulse sequences.

Theory Pulsed diffusion weighting gradients are commonly used for DWI [1]. Errors in the estimated diffusion weighting may arise from a combination of background gradients, G_o, residual gradients, G_r, gradient scaling factors, c, and imaging gradients, G_i. The effects of G_o and G_i can be minimized by acquiring two datasets with opposite diffusion polarities and calculating the geometric mean [2]. G_r and the c can be estimated by linear three-parameter fit of the geometric DW mean versus gradient strength using a phantom with known isotropic diffusivity, D_{true}. $\ln(\sqrt{S_+ \cdot S_-} / S_o) = \beta_1 G^2 + \beta_2 G + \beta_o + \varepsilon$ (1)

where S_+ and S_- are the signals with +G and –G diffusion gradients. Expanding Eq. (1):

$$\ln(\sqrt{S_+ \cdot S_-} / S_o) \approx D_{true}[B(\delta,\Delta)c^2G^2 + R_1(\delta,\Delta,t_2)G_r cG] = D_{cal}[B(\delta,\Delta)G^2 + R_1(\delta,\Delta,t_2)G_r G] \approx D_{true}B(\delta,\Delta)c_{effR}^2 G^2 \quad (2)$$

D_{cal}, c, G_r, and c_{effR} may be estimated by

$$D_{cal} = \beta_1 / B(\delta,\Delta)\ ; \quad c = \sqrt{D_{cal} / D_{true}}\ ; \quad G_r = \beta_2 / (cD_{true}R_1)\ ; \quad \text{and} \quad c_{effR}^2 = c^2[1 + R_1(\delta,\Delta,t_2) / B(\delta,\Delta)cG] \quad (3,4,5,6)$$

Then the signal attenuation is refit to the corrected gradient strength, $G_c = c_{effR}\, G$ using the model $\ln(S_+ / S_o) = \beta_{c1}G_c^2 + \beta_{c2}G_c + \beta_{co} + \varepsilon$. (6)

The relationship of the signal attenuation to the corrected gradient strength is $\ln(S_+ / S_o) \approx D_{true}[B(\delta,\Delta)G_c^2 + O_1(\delta,t_1,t_4)G_o G_c]$ (7)

$$\ln(S_+ / S_o) \approx D_{true}B(\delta,\Delta)c_{effO+}^2 G_c^2 = D_{true}B(\delta,\Delta)c_{effO+}^2 c_{effR}^2 G^2 = D_{true}B(\delta,\Delta)c_{eff+}^2 G^2 . \quad (8)$$

The strength of background gradient and the total effective scaling factor can be estimated by $G_o = \beta_{c2} / (D_{true}O_1)$ and $c_{eff\pm} = c_{effO\pm} \cdot c_{effR}$, respectively. (9,10)

Analytic expressions of $B(\delta,\Delta)$, $R_1(\delta,\Delta,t_2)$ and $O_1(\delta,t_1,t_4)$ are obtained by integrating the gradient errors [3]. To retrospectively correct the DTI, the diffusion-encoding vector must be corrected back to the real value by applying the total effective scaling vector, $c_{eff\pm}$ to the diffusion-encoding vector $\vec{h}_{corr} = [c_{effx}^2 g_x^2 \;\; c_{effy}^2 g_y^2 \;\; c_{effz}^2 g_z^2 \;\; 2c_{effx}c_{effy}g_x g_y \;\; 2c_{effx}c_{effz}g_x g_z \;\; 2c_{effy}c_{effz}g_y g_z]$ [4].

Methods A computer simulation was use to estimate the impact of c and G_o on DTI measurements. DTI calibration experiments were performed using a phantom with n-undecane, a test liquid with low flammability, chemical stability, small temperature coefficient, and a known diffusion coefficient similar to brain [5]. Diffusion calibration imaging was performed on a 3T GE SIGNA using a SS-SE-EPI sequence with diffusion encoding in three orthogonal directions ($\pm x$, $\pm y$, and $\pm z$). Along each direction and polarity, 23 images were accquired over equal steps in b value from 0 to 10^3 s/mm^2. Other imaging parameters were slice thickness = 5 mm, matrix size= 100x100, FOV= 18cm and TE/TR= 74/3000ms. The diffusion gradient parameters, δ/Δ, were 21/32 ms. Estimates of c, G_o, G_r, and c_{eff} were obtained using Equations (1-10). To test the calibration protocol, we performed imaging experiments with six different simulated gradient scaling conditions with or without the background gradients, which were introduced using linear shims. The estimated and prescribed c, G_o and G_r were compared. Cardiac gating brain DTI experiments were also performed under same simulated conditions. The diffusion gradient parameters, δ/Δ and gradient amplitude were 21/32 and 3.5 mT/m, respectively. The other imaging parameters were TE= 74ms, FOV=18cm, matrix size=100x100. The DTI data were decoded using both uncorrected and corrected diffusion encoding vectors.

Results and Discussion Errors in ADC and FA for c=1.10 in G_x are plotted in Figure 1. The errors vary substantially both as functions of FA and the orientation of the tensor. For the isotropic case, the estimated FA value was consistently overestimated for any degree of error. The estimated ADC was also overestimated for $c > 1$ and underestimated for $c < 1$. As the ideal tensors became more anisotropic, the estimated FA values showed a wide spread as a function of tensor orientation, but this spread decreased for highly anisotropic tensors. Significant errors in the estimated major eigenvector direction were observed for low anisotropy tensors, especially those that were highly oblique to the gradient error direction. Comparisons of the estimated and prescribed gradient scaling, c, for the phantom data are in Table 1. The estimated c are accurate to the third decimal with standard deviation = 0% to 1% of the prescribed c. When a linear gradient shim was applied in the y direction, the calibration technique detected highly significant background gradients of 3.46% to 4.48% of the maximum diffusion gradient. When the linear and higher order gradient shims are optimized in our system, no significant residual gradients were detected during the repeated calibration imaging or across time. Maps of FA and RGB color eigenvector with one gradient scaling condition are shown in Fig. 2. The standard maps (Fig 2(a)) were acquired without gradient scaling factors (c=1). For Fig 2(b,c), the gradient scaling condition is c =[1.10 1 1] and no introduced background gradients. Before correction, overestimation of the x direction in the eigenvector colormap (a red "bias" in the RGB map) and increasing values of FA in most gray mater regions were noticed in Fig 2(b). After retrospective correction, the overestimation of both FA and the colormap are eliminated in Fig 2(c). Histograms of FA revealed that the corrected data in Fig 2(c) was similar to the "standard" data in Fig 2(a). Although this study focused on the application to DTI, the calibration approach could easily be adapted to higher b value for general DWI methods. To generalize this technique for a wide range of DW, a phantom containing multiple fluids with a broad range of diffusivities may improve the utility.

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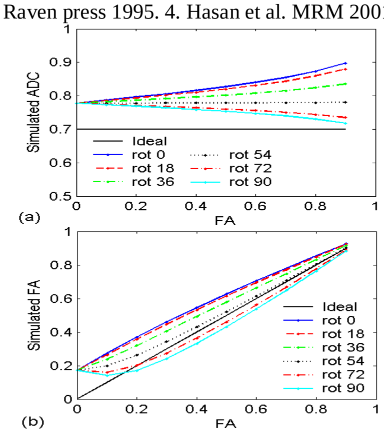

Table 1 Comparison of prescribed c to the estimated c

Exp.#	x (presc / esti)	y (presc / esti)	z (presc / esti)
1	1 /1.000±0	1 /1.000±0	1 / --
2	1.05 /1.052±0.005	1 /1.004±0.006	1 /1.001±0.002
3	1.10 /1.106±0.002	1 /1.004±0.005	1 /0.999±0.002
4	1 / 1.000±0	1.10 /1.103±0.011	1.05 /1.057±0.002
5	1 / 1.000±0	1.05 /1.056±0.009	1.10 /1.108±0.004
6	1 / 1.004±0.006	1.10 /1.105±0.008	1 /1.004±0.007

FIG. 1 (left) Computer-stimulated errors of ADC (a) and FA (b). The simulated gradient scaling c=1.10 in G_x. The rotation degree denotes the orientations of the ideal diffusion tensor to x-axis.

FIG 2. (right) DTI measures: FA and RGB eigenvector maps. (a). The standard maps were acquired at c= 1. (b). Maps at c=1.10 in G_x before correction. (c). The retrospectively corrected maps of (b) using the total effective scaling vector, $c_{eff\pm}$.