The Deleterious Effect of Concomitant Gradient Fields on Diffusion Imaging

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Introduction. Concomitant fields are small unavoidable magnetic field components that exist during the application of imaging gradients [1]. These fields can usually be ignored for common pulse sequences; however, specific pulse sequences can be susceptible to error from them [2,3]. In diffusion tensor imaging (DTI), large gradients are required to sensitize the MR signal to the diffusion of water. While the change in b-value from concomitant gradient fields is negligible [4], phase accrual from concomitant fields can lead to image artefacts, especially for modern systems utilizing strong gradients. This is of particular concern for diffusion preparations that have gradients unequally distributed about refocusing RF pulses, such as those routinely used for eddy current cancellation [5,6]. It has been shown that concomitant fields can lead to shifting of k-space data, which causes signal loss when partial Fourier techniques are used [7]. The purpose of this work is to test for additional DTI errors that result from concomitant gradient fields, and we demonstrate that an erroneous increase in apparent diffusion coefficient (ADC) that worsens for slices far from isocenter can occur, even when partial Fourier acquisition is not used. We propose and validate a prospective correction for these errors.

Theory. When a combination of gradients, $\{G_x, G_y, G_z\}$, are applied, concomitant gradient fields (B_C) cause B_0 to increase by [7]:

$$B_C \approx \frac{(G_x^2 + G_y^2)z^2}{2B_0} + \frac{G_z^2(x^2+y^2)}{8B_0} - \frac{G_x G_z xz}{2B_0} - \frac{G_y G_z yz}{2B_0} \quad (1)$$

Net phase accrual occurs over the cumulative duration, τ, of diffusion gradients that are not symmetrically placed about RF refocusing pulses. There are two resulting categories of image artefacts for a slice: signal loss caused by through-plane dephasing (focus of this work) and k-space distortions caused by in-plane dephasing (e.g. k-space shifting error in Ref. [7]). In DTI, this signal loss is misattributed to diffusion and ADC values are increased erroneously.

Materials and Methods. Axial images were acquired using a Varian Unity Inova 4.7 T MRI system. Both Stejskal-Tanner (ST) [8] (phase accrual from B_C fully refocused) and split gradient (SG) [5] (phase accrual from B_C not fully refocused) diffusion preparations were utilized (Fig. 1) with echo planar imaging, *FOV* = 24 cm, 96 × 96 matrix, 3.0 mm slices, TE = 80 ms. For the SG preparation τ = 26.3 ms (required for 50 ms eddy current cancellation). For both SG and ST, x- and y-diffusion gradients were applied simultaneously (60 mT/m each; b = 1000 s/mm^2) for a water phantom and a healthy human volunteer. There is no in-plane dephasing because $G_z = 0$ (Eq. 1). The error in ADC, δD, from through-plane dephasing was calculated using two steps: (1) ADC_{SG} (sensitive to B_C) - ADC_{ST} (insensitive to B_C) per voxel, (2) calculate the mean of the result of step (1) for each slice. To prospectively correct for the dephasing from concomitant fields, an additional slice-dependent gradient lobe (area based on prediction from Eq. 1) was applied (Fig. 1).

Results. Fig. 2 shows brain images acquired using both a ST and SG diffusion preparation. Despite similar appearance of the images, through-plane dephasing leads to an overall increased δD that worsens with distance from isocenter for both the human brain and phantom (Fig. 3). At 10 cm, δD is approximately 0.3×10^{-3} mm^2/s for both cases, which corresponds to ~30% error in typical human brain tissue. The results highlight that δD is independent of material; therefore, regions with lower ADC will have higher percent error. With the application of our prospective correction, δD has been drastically reduced. We note that errors of this magnitude have not yet been reported at clinical field strengths because of the comparatively lower gradient strengths and a smaller τ for Reese's twice refocused preparation [5] compared to the SG preparation used here [6]; however, with high performance gradient hardware these ADC errors will likely become problematic.

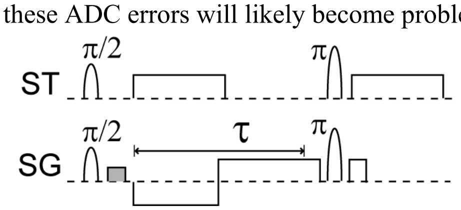

FIG 1. Diffusion gradient timing for Stejskal-Tanner (ST; insensitive to concomitant fields) [8], and split-gradient (SG; sensitive to concomitant fields) [6], preparations, where τ is the duration of gradients asymmetric about a refocusing RF pulse. To perform a prospective correction, phase accrual from concomitant fields is refocused by the shaded gradient in the SG case (gradient area is slice dependent).

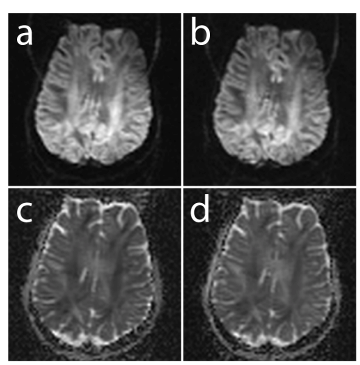

FIG 2. Diffusion-weighted images (a,b) and ADC maps (c,d) for a slice at z_S = 7 cm for ST (a,c) and SG (b,d) preparations.

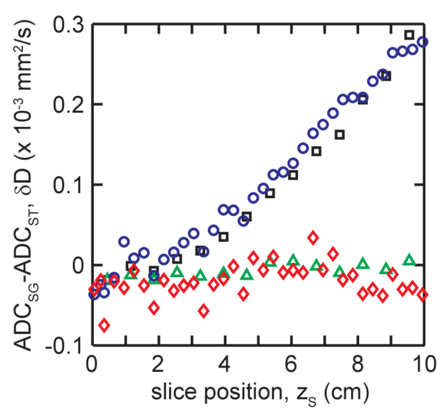

FIG 3. Mean error in ADC, δD, caused by through-plane concomitant field phase accrual, for a phantom (squares - no correction, triangles - corrected) and human brain (circles - no correction, diamonds - corrected). Dephasing from concomitant gradient fields leads to error in ADC that increases with distance from isocenter (z_S = 10cm-superior; z_S = 0cm-inferior).

References. [1] Norris DG *MRI* 1990;8:33. [2] Bernstein MA *MRM* 1998;39:300. [3] Sica CT *MRM* 2007;57:721. [4] Liu C *Proc. of ISMRM*. 2003. p 264. [5] Reese T *MRM* 2003;49:177-182. [6] Finsterbusch J. *MRM* 2009;61:748. [7] Meier C *MRM* 2008;60:128. [8] Stejskal EO *J. Chem. Phys.* 1965;42:288.