Error analysis and correction of ADC measurements for gradient non-linearity

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Introduction: Significant spatial-dependent error in ADC measurement has been demonstrated on commercial MRIs using a temperature-controlled (ice water) phantom for a precisely known diffusion fluid [1]. Gradient non-linearity is the primary source of the error leading to a spatially-dependent b-value and subsequent ADC error that can exceed 10-20% on some systems [1]. Previous research on non-linearity correction [2] described an approach that requires full spatial mapping of the gradient fields. Complete description should further consider diffusion gradient cross-terms as well as imaging gradients [3]. Our work seeks a practical procedure that both builds on comprehensive physical system characteristics and achieves minimal algorithm complexity for quantitative control of experimental error.

Methods: Spatial dependence of gradient fields was modeled using spherical harmonic expansion to the 7th order [4]. Nine 3D-elements of the gradient non-linearity tensor [2] were calculated by numerical differentiation of the model gradient fields in Cartesian coordinates. Spatial dependence of b-matrix was calculated for three orthogonal DWI gradient directions applied along lab X, Y, Z , as well as for an orthogonal combined X+Y+Z axes scenario (eg. “overplus”). Gradient cross-terms were included through (1) 3D-dependence of the non-linearity tensor [2] producing gradients in orthogonal directions in respect to applied DWI pulses, and (2) inclusion of imaging gradients [3] and their spatial dependence. Diffusion properties of the media were modeled using diffusion tensor with tissue-like characteristics: ADC =1.0 and FA = 0.0, 0.3, 0.5, 0.7 and 0.9. Tensor orientation was varied in respect to the lab (gradient) system. A correction was devised using only the leading terms of the spatial dependence of diagonal b-matrix elements. Assumed (uncorrected) ADC was obtained using b-values at the gradient iso-center where non-linearity is zero. ADC errors were calculated as deviation from true value for each pixel in 3D-volume within 30 cm FOV (Fig.1). Error statistics histograms were compared for ADC with and without b-correction.

Results: Contribution of gradient cross-terms to b-tensor was modest (<10 % of the diagonal values) in case of DWI gradients applied along the primary lab-axes, but were amplified for the over-plus (i.e. simultaneous X+Y+Z) DWI gradients. Increasing ADC non-uniformity errors were observed with higher anisotropy of the simulated medium. For isotropic case, the calculated errors were consistent with our experimental observations on clinical systems [1]. Leading b-correction terms were consistent with cylindrical symmetry of the original gradient field model. After leading-term correction, residual error-distribution for ADC was dependent on anisotropic properties of the media and relative orientation of gradient fields. The absolute error reduction for ADC achieved through leading-term correction procedure was from 75 to 95% as illustrated in Figure 1. That is, the spatially-dependent ADC error was effectively removed.

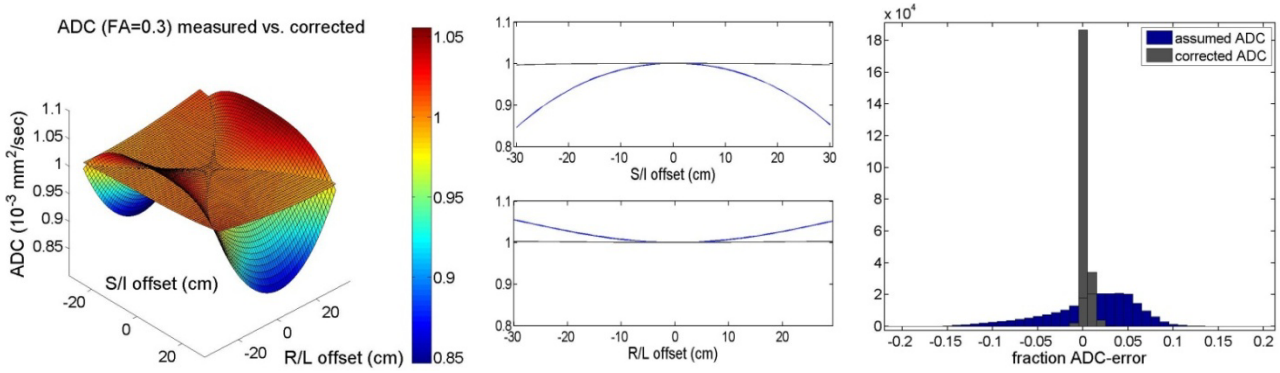

Figure 1: Comparison of measured and corrected ADC for gradient over-plus mode and FA = 0.3. Left: ADC surface for Y = 0 (flat after correction); middle: cross-section through iso-center for the ADC surface; right: histograms of residual ADC-error for all voxels within FOV= 30 cm (blue = assumed, gray = corrected).

Conclusion: Spatial dependence of diagonal b-terms accounts for the bulk (75-95%) of ADC non-uniformity error. Residual error depends on FA of the medium and the DWI gradient direction/mode. ADC non-uniformity errors are amplified for anisotropic diffusion and gradient over-plus mode. Simplified b-correction algorithm, including spatial dependence of diagonal b-terms rotated into lab-gradient system, is found to be sufficient to control ADC measurement error in clinical studies.

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References: [1] T Chenevert, et. al. ISMRM 19th Proc (2011); [2] R Bammer, et.al. MRM 50:560 (2003); [3] J Mattiello, et.al., MRM 37:292 (1997); [4] A Janke, et.al. MRM 52:115 (2004)