Practical aspects of correcting ADC bias due to gradient nonlinearity in media of arbitrary anisotropy

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Introduction

Significant spatial bias observed for off-center DWI measurements [1] confounds quantitative studies that employ ADC as a clinical marker. This platform-dependent bias is primarily caused by DWI gradient nonlinearity, which can be described by a nonlinearity tensor. Previously, a framework was proposed [2] to correct for the bulk of the ADC bias error for medium of arbitrary anisotropy using three orthogonal DWI measurements and projecting the nonlinearity tensor onto the corresponding DWI directions. In present work, the proposed ADC bias correction was tested for isotropic and highly anisotropic media on a clinical scanner. Different implementation scenarios correcting for DWI intensities, b-value, or ADC bias were compared.

Methods

DWI measurements were performed on a clinical 3T MRI scanner for an isotropic phantom of known diffusivity (ice-water) and highly anisotropic tissue (brain) near isocenter and offset superiorly by 120mm. System nonlinearity scale was estimated along laboratory (LAB) axes for a regular grid phantom using ratio of inter-grid spacing with and without vendor's nonlinearity correction. Spatial dependence of gradient coil fields was modeled using spherical harmonic expansion to the 7th order [2,3], and numerically differentiated and scaled to characteristic system dimensions to produce gradient nonlinearity tensor ($\hat{L}(\vec{r})$ [4]). The square of nonlinearity tensor projection onto kth DWI direction was used to generate bias corrector map [2], $C^k(\vec{r}) = [\vec{R}_k^T \hat{L}(\vec{r}) \vec{R}_k\,]^2$, on a Cartesian grid sampled every 3.6mm within a 360 mm FOV. For experimental data, each corrector was obtained by interpolation of the $C^k(\vec{r})$ map according to DICOM header information on specific imaged volume and DWI direction. This corrector was then applied pixel-by-pixel to yield corrected DWI intensities, $S_b^c = S_0^{\frac{C^k(\vec{r})-1}{C^k(\vec{r})}} S_{b'}^{\frac{1}{C^k(\vec{r})}}$ or b-maps, ${}^c b_k(\vec{r}) = b_0\, C^k(\vec{r})$, and produce unbiased ADC for isotropic and anisotropic medium with LAB and non-LAB DWI gradient encoding.

Results

The original spatial bias for off-center locations was calculated as deviation from true (known) diffusion value for ice-water [1], and as deviation from the value measured for the same anatomy close to isocenter for brain tissue. At the same spatial location, different measured bias was observed for isotopic versus anisotropic medium, as well as, for different DWI directions, as predicted by the model [2]. For the isotropic phantom, unidirectional bias scale for LAB DWI gradients was consistent with characteristic system nonlinearity scale obtained from grid phantom measurements. Application of a single corrector map per DWI direction was sufficient to effectively reduce the bias down to 2% at extreme offsets (~130 mm) both for isotropic and anisotropic medium. DWI intensity correction before ADC derivation or ADC calculation using corrected b-values produced identical results. As expected, the degree of correction using direction-average corrector map applied to the trace DWI was reduced for anisotropic media.

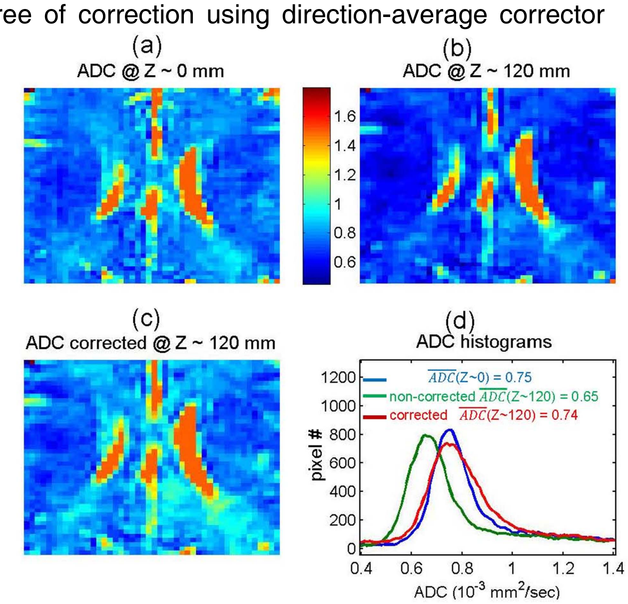

Figure 1: ADC bias correction efficiency is illustrated for the brain region close to isocenter Z~0 (a) and offset by Z~120 mm in superior direction before (b) and after (c) correction. (d) shows ADC histograms for all pixels of four slices in the vicinity of isocenter (blue) and superior offset (green). The original median $\overline{ADC}$ bias of 13% (d-green) was reduced to 1.5% after correction (d-red), which is below measurement (pixel) noise.

Conclusion

System specific corrector maps that account for gradient nonlinearity were generated for orthogonal LAB and non-LAB DWI gradients. Application of these correctors effectively removed ADC bias for off-center measurements both in isotropic and highly anisotropic media. Identical performance was achieved using corrected DWI intensities or b-values.

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References: [1] D. Malyarenko, et. al. JMRI epub (2012); [2] T. Chenevert, et.al. ISMRM #3550 (2011); [3] A Janke, et.al. MRM 52:115 (2004) [2] R Bammer, et.al. MRM 50:560 (2003).