Effects of gradient nonlinearity, its correction methods and distortion on diffusion weighted imaging

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Introduction: The apparent diffusion coefficient (ADC) obtained with diffusion weighted imaging (DWI) is a promising, endogenous-contrast, imaging bio-marker for cancer [1-2], which underscores the importance of its accuracy. However, the inherent gradient nonlinearity (GN) that causes 'gradient-warping' in image space also results in spatially-varying ADC [3]. Moreover, these nonlinear characteristics differ between different MRI systems and vendors, and reduce the repeatability and reproducibility in serial, multi-site cancer imaging studies. While an accurate GN correction (GNC) approach has already been demonstrated [4,5], the impact of GNC *in vivo* is not well-understood because of the many confounding effects inherent in the DW-EPI acquisition. By comparing two MRI systems of different inner diameters, this work (i) evaluates the effects of GNC in various anatomies, (ii) explores the parameters needed in GNC, and (iii) decouples the confounding effects of distortion from GN.

Methods: In simulation, the actual gradient field maps of two whole-body 1.5T MRI systems (DSV = 48 cm) of varying bore sizes (Table 1, Row 1) were used as inputs. Ellipsoids of varying sizes and positions (in magnet coordinates) were generated to estimate various regions of anatomy. GNC was applied, using field maps obtained with up to 13 orders of spherical harmonics (SH).

Imaging studies were performed on an ice-bath water phantom [3] with an 8-element cardiac coil. The effects of GN along the left-right axis were evaluated by imaging the phantom at thee positions – the center, displaced to the left and to the right by 11 cm. The first protocol used a single-spin-echo (SSE), three-axes DW-EPI at b = {500, 800, 1000, 2000} sec/mm^2, axial FOV = 24 cm, 128x128, 25x6 mm slices, TR/TE = 8000/96-98 msec. To determine the effects of reducing distortion from both the diffusion-weighted gradients and the EPI readout, imaging was repeated with a second protocol that used parallel-imaging factor R = 2 and a double-spin-echo (DSE) preparation (TE = 79-113 msec) [6]. To determine the effects of imaging gradients, a single b-value vs. the full b-matrix [7] versions of GNC-ADC were compared.

Table 1. Results of peak (RMS) ADC error due to gradient nonlinearity in different anatomies, from two MRI systems of inner-bore diameter D.

System/ Anatomy	1.5T D=60cm	1.5T D=55cm
Brain	14% (0.04%)	29% (0.08%)
Spine	58% (0.46%)	83% (0.75%)
Breasts	14% (0.05%)	30% (0.12%)
Liver	9.9% (0.07%)	22% (0.16%)
Torso	54% (0.05%)	90% (0.10%)
Kidneys	5.7% (0.12%)	13% (0.25%)

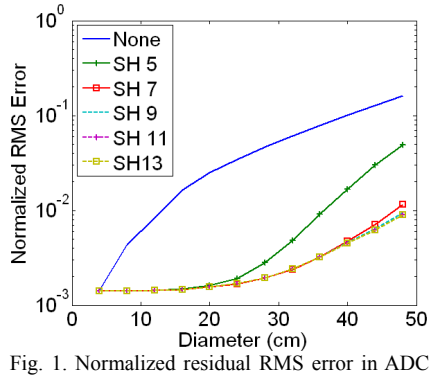

Fig. 1. Normalized residual RMS error in ADC due to GNC vs. diameter of spherical volume evaluated, showing reduced error with higher orders of spherical harmonics (SH).

Results: Table 1 shows that GN can have greater effects in body-imaging than in brain-imaging, and produces greater ADC errors in the narrower MRI system (D = 55 cm). Fig. 1 shows that a 5th-order SH GNC provides about an order of magnitude reduction in error, and that there are diminishing benefits of GNC going beyond 7 orders of SH.

Fig. 2 shows that the ADC values at the three positions converge after GNC in both systems and in both imaging protocols. However, there remains a large mean ADC difference between the two systems with the first protocol (5.4%, P = 0.01). With the second protocol, this difference is reduced (1.2%, P = 0.35). Further analysis shows that reduction in RMSE due to GNC in the second protocol is greater in the narrower bore size (1.2% for D = 60 cm vs. 6.3% for D = 55 cm). In comparison, GNC in the first protocol can result in less RMSE reduction (1.2% for D = 60 cm, 2.8% for D = 55 cm). The RMSE reduction from a full b-matrix computation is 0.02% and is not significant (P = 0.35).

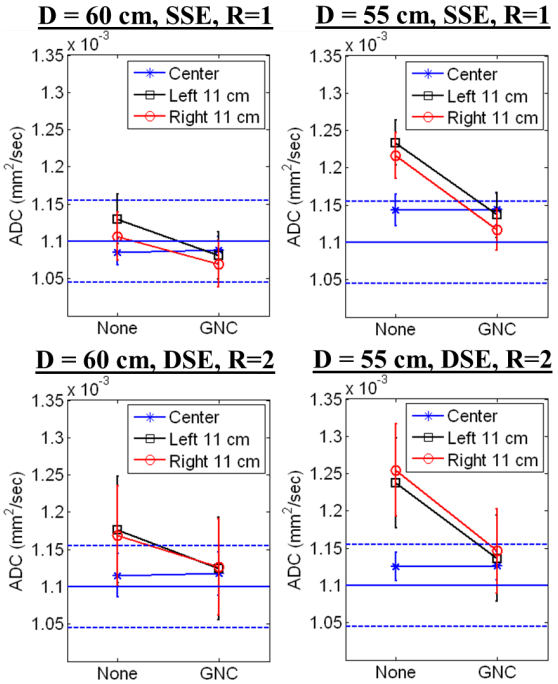

Fig. 2. Mean ADC of iced- water imaged with two systems of inner-bore diameter D using the two (top/bottom) protocols. Results are shown with and without GNC at the central, left and right positions. The expected ADC of 1.1 mm^2/sec (solid line) and the ±5% range (dashed lines) are indicated.

Discussion and Conclusion: The effects of GN and GNC on spatial variation of ADC in two whole-body MRI gradients were evaluated. Distortion due to eddy-currents and susceptibility in DW-EPI could result in confounding inaccuracies in ADC, especially between different MRI systems. Initial tests suggest that the confounding effects of distortion will be greater at 3T. The TE was allowed to vary in the second protocol case, which could result in slightly higher sample variation in computing ADC. GNC will improve both ADC accuracy and repeatability in body-imaging *in vivo* using the same MRI system, even if a full b-matrix is not applied. Further studies with more scanners will be needed to demonstrate the extent of ADC reproducibility between scanners.

References: [1] Padhani et al, Neoplasia, 2009; [2] Thoeny and Ross, JMRI, 2010; [3] Chenevert, NCI Workshop on DWI, 2011; [4] Bammer et al, Magn Reson Med 2003; [5] Markl et al, Magn Reson Med 2003; [6] Reese et al, Magn Reson Med 2003; [7] Mattiello et al, J. Magn Reson Ser A, 1994.

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