THE SIGNAL INTENSITY MUST BE MODULATED BY THE DETERMINANT OF THE JACOBIAN WHEN CORRECTING FOR EDDY CURRENTS IN DIFFUSION MRI

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INTRODUCTION: The problem of eddy current (EC) induced distortions is well known in MRI. Eddy current (EC) induced distortions are particularly problematic for diffusion MRI, when fast readouts such as EPI are commonly used, as this renders the 'pixel bandwidth' in the phase encode direction to be very low. Moreover, the ramp-up and ramp-down of the diffusion-sensitizing gradients are much further apart than they would normally be for spatial encoding gradients, so the resulting eddy currents do not tend to self-cancel. If the time-constant of the eddy current is long (so that it remains constant during the readout), then the distortions are readily characterized, with a shift, shear and scale of the image resulting from residual eddy currents on the slice, read and phase gradients respectively. Since Haselgrove and Moore's publication in 1996[1], the problem of residual EC distortion in diffusion MR data has largely been handled with post-processing, applying an affine transformation to map each raw diffusion-weighted image to an image acquired with no diffusion weighting. However, there is an additional step that is not so common-place – that is modulating the intensity of the signal according to the volumetric change occurring during the affine mapping. When the voxel is stretched, the signal intensity in the voxel is reduced (in proportion to the change in the volume). This will be 'interpreted' in subsequent analysis as a higher rate of diffusion. In this work, we wished to characterize the nature of the problem – and the consequences of neglecting to correct for this signal modulation due to residual eddy currents.

METHOD: *Simulating Diffusion-Weighted Signals:* To model the phenomenon in a controlled setting, we first simulated prolate diffusion tensors with the same trace (2.1×10^{-3} mm^2s^{-1}), and different fractional anisotropies. For a given orientation of the tensor – and for a standardized set of optimal sampling schemes, (e.g. 'Jones30'[2]) and b-value of 1000 s mm^{-2}, we derived the noise-free diffusion weighted intensities. *Simulating the Effect of Eddy Currents:* Without loss of generality, we arbitrarily assumed that *applying* a gradient along the read axis, would lead to EC's along the phase axis. We therefore modeled the stretch of the voxel to be linearly proportional to the x-component of the different encoding vectors (as done previously[1]) and modulated the intensity of each DWI accordingly, to simulate the effect of the EC-induced dilation/compression. Horsfield[3] has previously measured typical EC-induced distortions in gel-phantoms and reported a stretch of DW-images up to 8%, so we took this as the maximal volume change when the x-component of the gradient was at its maximum. *Assessing the Consequences:* We then derived the difference between the trace, fractional anisotropy and principal eigenvector of the input tensor and the computed tensor (for Tr / FA, the difference and for principal eigenvector – the angular deviation. The tensor orientation was then changed – and the whole process repeated. This was done in 3° increments in each of the spherical co-ordinates (θ, ϕ) to consider a range of 61x31 different tensor orientations.

RESULTS: Figure 1 shows a typical result and depicts show how the error in the principal eigenvector depends both on anisotropy and fibre orientation when neglecting to account for the modulation of signal intensity.

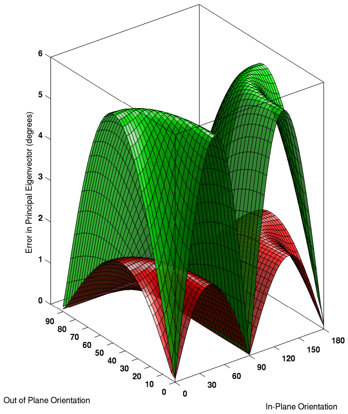

Figure 1: Plot of the angular deviation between the true eigenvector orientation and the computed eigenvector orientation when neglecting to account for the volumetric change induced by eddy currents. The horizontal axes correspond to in-plane (θ) and out-of-plane orientation (ϕ), the vertical axis is the angular deviation. Green and red surfaces correspond to FA = 0.3 and FA = 0.7, respectively. Maxima are of the order of 5° for FA = 0.3, and 1.2° for FA = 0.7

The maxima / minima are independent of anisotropy located, and occur when θ = 45° and 135°, and ϕ = 45°. Similarly, the minima always occur when the fibre is oriented along one of the three logical axes (i.e. θ = 0° and 90°,ϕ = 0 and 90°). The magnitude of the error, however, scales inversely with the anisotropy – as suggested in Figure 1.

DISCUSSION: The observation that the size of the error depends on the anisotropy is, with hindsight, not unexpected. Imagine two extremes: tensor_A has FA = 1, and is aligned along the y-axis. If we now have additional signal attenuation when applying a gradient along the x-axis, this will appear as slightly increased diffusion along the x-axis – but the impact will be minimal and the peak diffusion will still be along the fibre. In contrast, tensor_B has an anisotropy close to zero, but nevertheless the principal eigenvector points along the y-axis. Now, increased signal loss when applying an x-gradient has a far more severe effect, and can cause the principal eigenvector to change to point along the x-axis.

Despite the step to account for modulation of signal intensity being trivial to implement, a quick survey of several leading diffusion MR labs and assessment of software packages widely used for EC correction in diffusion MR data, reveals that this is not commonly implemented. Despite this, however, there are clearly far reaching consequences. An error in fibre orientation of 5° at each point in space, for example, would make any fibre-tracking experiment non-sensical. Note that there is increasing trend to extend fibre-tracking / connectivity analyses to gray matter regions, where FA is already low, and particularly to use higher b-values for HARDI-style acquisitions, which will exacerbate the problem. The problem is multiply compounded in that the errors also depend on fibre orientation (Figure 1) – so the artifact is extremely heterogeneously distributed throughout the brain.

CONCLUSION: Despite being a very trivial step in post-acquisition eddy-current distortion correction, the correction of signal intensity for the volumetric change appears to be largely ignored by the diffusion MR community. However, the consequences of neglecting this step can be severe – particularly in regions of low anisotropy – and would render inferences based on fibre orientation, for example, meaningless. Therefore, we conclude that one must perform this simple step when correcting for eddy-current induced distortions in diffusion MRI.

REFERENCES: 1. Haselgrove JC, Moore JR. Magn Reson Med. 1996;36:960–964; 2. Jones DK et al. Magn Reson Med. 1999 42: 515-525; 3. Horsfield MA. Magn Reson Imaging. 1999;17:1335–1345