Measuring and Correcting Errors That Occur In Diffusion Weighted Images Due To Non-Ideal Gradient Linearity

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Introduction: The MR signal is sensitive to diffusion (1). This effect is exploited in diffusion-weighted imaging by including large, bipolar gradients into the pulse sequence (2) (3) which allows the measurement of the apparent diffusion coefficient (ADC) (4).The voxelwise accuracy of this measurement depends on how well the gradient systems produce the required magnetic field at each spatial location within the object. Due to the known non-linearity of the gradients it is expected that at positions away from the isocentre the actual error in the produced magnetic fields will be spatially dependent (5). This error produces a variation in the diffusion weighting b-value and in turn results in erroneous values in the calculated diffusion coefficient. Here we provide a method to measure the error terms and provide a simple correction for subsequent diffusion weighted imaging experiments.

Methods: *Theory:* In order to calculate an ADC image, two images with different diffusion weighting b and b_o are used

$$\ln(S_o/S)/(b-b_o)=D \qquad [1]$$

where S and S_o are the respective signal intensities in a voxel. When the b-values are not correctly played out the signal is due to the incorrect b-values (i.e. S^{err} and S^{err}_o) but in the calculations the ideal b-values are still included

$$\ln(S^{err}_o/S^{err})/(b-b_o)=D^{err} \qquad [2]$$

leading to the erroneous ADC value, D^{err}. Knowledge of the incorrect b-values could be included in the calculations to achieve the correct ADC value as in [1].

$$\ln(S^{err}_o/S^{err})/(b^{err}-b^{err}_o)=D \qquad [3]$$

If equations [2] and [3] are rearranged and equated the following relationship results:

$$(b^{err}-b^{err}_o)D = (b-b_o)D^{err} \qquad [4]$$

To represent the error in the gradient amplitude (G) due to nonlinearity let $G^{err}= kG$. Given that the b value is proportional to G^2, equation [1] can be solved for

$$k = \mathrm{sqrt}(D^{err}/D) \quad \rightarrow \quad b^{err} = k^2 b \qquad [5]$$

Then with the knowledge of the true diffusion constant, the factor 'k' quantifies the deviation in the calculated ADC at any given voxel position.

Data collection and correction procedure: A 1.5T whole body scanner was used (Magnetom Sonata, Siemens Medical Erlangen, Germany) with b_o=100 s/mm^2 for the first 7 images and b=1000 s/mm^2 for 61 diffusion encoding directions which were distributed over a semi-sphere. The voxel size was 2.3 mm isotropic. The slice-to-slice TR and the TE were 350ms and 90ms respectively. Twelve complete datasets of the 68 images were collected on a water phantom and averaged. Two representative ADC maps based on this mean dataset are displayed in **Figure 1**. Because the calculated ADC values vary smoothly we convolved all volumes with a 5x5x5 voxel Gaussian filter. This smoothed mean dataset was used to provide the voxelwise estimates of the D^{err} in equation [5]. The true diffusion constant in equation [5] can be obtained in two ways: either by monitoring the temperature and calculating the corresponding diffusion constant according to Mills (6), or by estimating it from the isocentre of the image. We used the latter method because the temperature was changing during the course of the experiment and we are primarily interested in the spataial variation of the diffusion weighting but not the exact absolute value. Once the k-factor is obtained it can be used in equation [1] while replacing $(b-b_o)$ with $k^2(b-b_o)$.

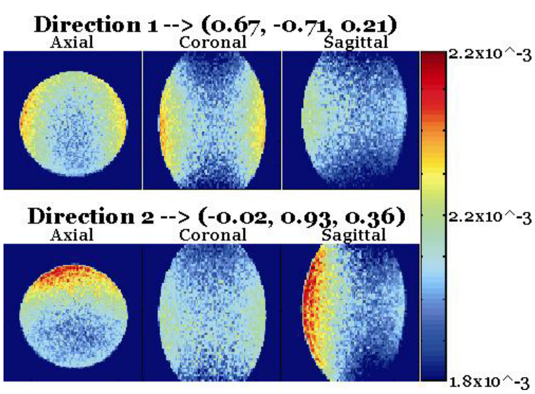

Figure 1 – Mean ADC maps used for calculating the k-factors in equation [5]

Results: ADC maps of a single measurement of the two representative directions are displayed in **Figure 2**, both before and after correction. Note that a single measurement is noisier than the maps from Figure 1 but still the underlying smoothness of the error allows for the correction to be performed. At the edges of the field of view the error in the ADC value can be up to ±10% possibly causing a severe bias the tensor estimation since even errors of 2-3% can have adverse effects (7).

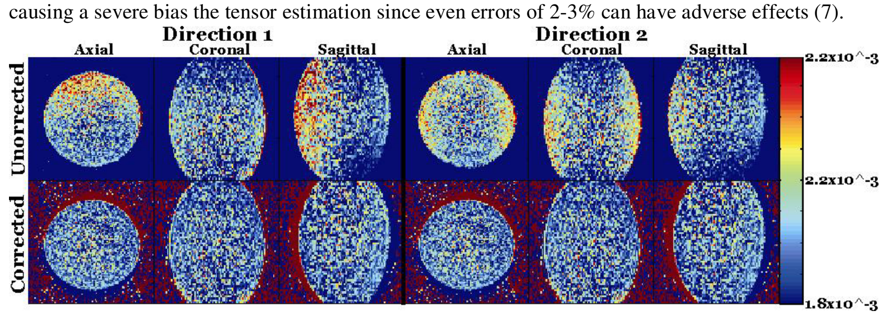

Figure 2 – A single measurement of the two representative directions in Figure 1. The error can be up to ±10% (top row) but can be corrected for (bottom row)

Discussion: We demonstrated that non-linear gradients can produce erroneous measurements of ADC values and provided a simple method for correction. The error is most worrying when a single or a few diffusion directions are used. In diffusing tensor imaging, involving dozens of measurements the error propagated to derivatives of the tensor (fractional anisotropy, direction of main eigenvector) is less significant. Note that this problem has been recognized and discussed before. For example Bammer at al. (5) provided an elegant theoretical framework for the correction of ADC images which is based on the knowledge of the gradient non-linearities. We instead measured these errors and extracted simple correction factors which allows for voxelwise correction of ADC maps. This approach is advantageous if the information on the spatial nonlinearity is not available or if it is expected to change over time. Furthermore, as gradient non-linearity is machine-specific, the above simple procedure can be used to compare the performance of different scanners without the need for specifics.

References

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