Compensation for Maxwell Cross-Terms in Diffusion-Weighted Imaging

M. S. Zwanger[1], D. Porter[1], T. Feiweier[1], P. Heubes[1], T. G. Reese[2], T. Benner[2], J. E. Kirsch[3]

[1]Siemens Medical Solutions, Erlangen, Germany, [2]Athinoula A. Martinos Center, Charlestown, MA, United States, [3]Siemens Medical Solutions, Malvern, PA, United States

Introduction: As a consequence of Maxwell's equations, additional spatially-dependent field components are generated when applying a linear gradient. The resultant field **B** can derived using a Taylor series expansion[1]. For symmetric gradient coils, the undesired contributions from Maxwell effects have a high-order spatial dependence (2^{nd} order or higher):

$$\mathbf{B} = B_0 + G_x x + G_y y + G_z z + G_x^2 z^2/2B_0 + G_y^2 z^2/2B_0 + G_z^2 x^2/8B_0 + G_z^2 y^2/8B_0 - G_x G_z\, x z / 2B_0 - G_y G_z\, y z / 2B_0 \quad .$$

However, if an asymmetric gradient coil design is used, there are also 1^{st} order terms which result in a deviation from the ideal field:

$$\mathbf{B} = B_0 + G_x^2 z_{0x}^2/2B_0 + G_y^2 z_{0y}^2/2B_0 + G_x x + G_y y + G_z z + G_x^2\, z\, z_{0x}/B_0 + G_y^2\, z\, z_{0y}/B_0 - G_y G_z\, y\, z_{0y}/B_0 + G_x^2 z^2/2B_0 + G_y^2 z^2/2B_0 + G_z^2 y^2/2B_0 - G_y G_z\, y\, z/B_0 \quad ,$$

where z_{0x} and z_{0y} are constants describing the coil asymmetry.

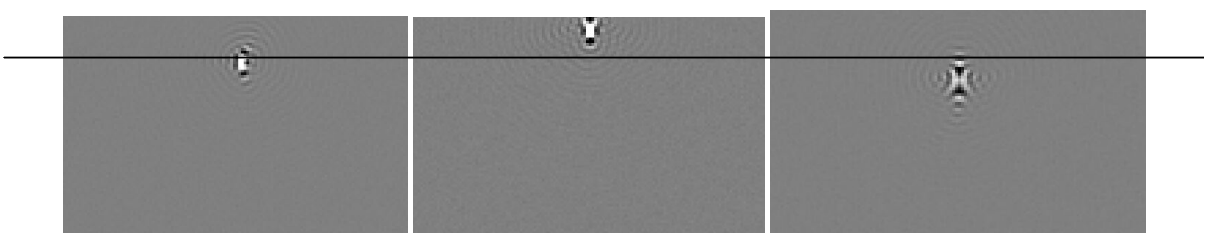
This paper describes a situation in which these additional terms have a significant detrimental effect on image quality in diffusion weighted EPI. The following description relates to the case of a transverse image plane, but similar effects are also observed with other slice orientations. Diffusion imaging requires switching long-lasting diffusion gradients with a high amplitude on different axes at the same time. This technique is prone to Maxwell gradient induced artifacts, associated with cross-terms between the G_y and G_z gradients:

$$\mathbf{B}(x,y,z) = B_0 + \mathbf{G} \cdot \mathbf{r} - G_y G_z\, y\, (z + z_{0y}) / B_0 \quad .$$

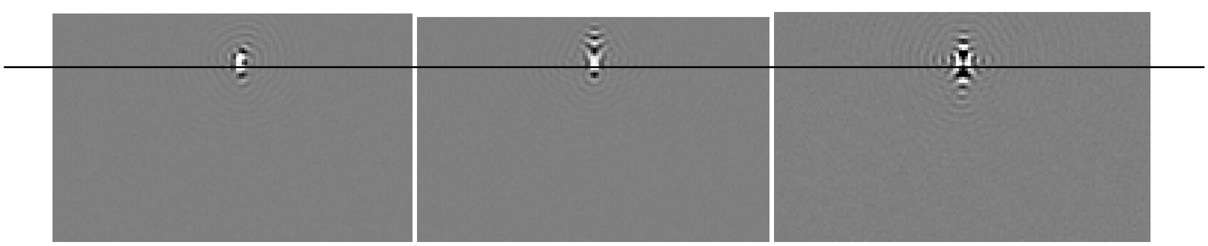
For a standard Stejskal-Tanner encoding scheme, the Maxwell gradients induced by the diffusion gradients are identical for both lobes and are compensated inherently. However, this compensation does not apply for a dual bipolar encoding scheme, in which both positive and negative polarity gradient pulses are used (such as [2,3]). In this case, the cross-terms induce a field gradient in the y direction which generates a shift of the echo in the k_y direction. If the shifted echo is too close to the edge of k-space (e.g. due to phase partial fourier), a localized loss of image intensity may be observed. In this case, the concomitant gradient can be compensated for by applying an additional gradient in the opposite direction on the G_y axis.

Material and Methods: The experiments were carried out using a DWI sequence with dual bipolar diffusion gradients on a SIEMENS Magnetom Allegra head scanner. This system has an asymmetric gradient coil design, in which the centre of the applied z-gradient field is offset along the z-direction to accommodate a cut-out for positioning the shoulders. These gradients were applied in the following directions: (1,0,0) (left figures), (0,1,1) (middle) and (0,1,-1) (right). Phantom data were acquired with and without a compensation for Maxwell cross-terms and the position of the echo was visualised in the raw data.

Results: The real part of the k-space data shown in the figures clearly reveals a shift of the echo position, which comes close to the edge of the acquisition window when sampling with 5/8 phase partial fourier. Without Maxwell correction, the echo is shifted in the phase-encoding direction when both y and z axes are active. As shown in the lower figures, the shift can be successfully corrected.



In the first experiment, data were acquired without Maxwell compensation.
The black line denotes the central line in k-space.



In a second experiment, the correction was applied.

Conclusion: Using an asymmetric gradient coil and a DWI sequence with dual bipolar diffusion gradients, the first order Maxwell cross-terms can cause artifacts in diffusion-weighted images. The observed effects are consistent with theoretical predictions derived from Maxwell's equations and can be compensated for by using the theoretical expressions to modify the applied gradients. Currently, these Maxwell effects are rarely taken into account in sequence design; this study demonstrates that it is necessary to do so with certain sequence types. In addition to the diffusion application described here, a similar correction may also be required for flow quantification sequences.

References:

[1] MA Bernstein et al., MRM 39:300 (1998)
[2] O Heid, ISMRM 2000, p. 799
[3] TG Reese et al, MRM 49:177 (2003)