Maxwell Field Terms in Flow Quantifying Phase Images for an Asymmetric Gradient Coil

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Introduction:

As a consequence of the Maxwell equations linear field gradients are accompanied by additional spatially dependent field components. Their effects on MR imaging have been thoroughly studied for the case of a symmetric gradient coil [1]. The resultant magnetic field B can be derived using a Taylor series expansion and can be approximated as:

$$B = B_0 + G_x x + G_y y + G_z z + (G_x^2 + G_y^2)z^2/2B_0 + (x^2 + y^2)G_z^2 /8B_0 - G_x G_z xz/2B_0 – G_y G_z yz/2B_0$$

Here, the additional field components are of 2nd order in space. For an asymmetric coil also components of 0th and 1st order are generated:

$$B = B_0 + G_x x + G_y y + G_z z + (G_x(z+z_{0x}) – G_z\alpha(x+x_0))^2 / 2B_0 + (G_y(z+z_{0y}) – G_z(1-\alpha)(y+y_0))^2 / 2B_0 ,$$

where α, x_0, y_0, z_{0x}, z_{0y} are integration constants reflecting the coil's asymmetry. These additional components can produce severe artifacts [2].

In this contribution, the effect of the Maxwell terms on phase contrast techniques as used for flow quantification is demonstrated and remedied by data post-processing. Flow quantification is based on the velocity-dependent phase evolution of flowing spins in the presence of a field gradient G and typically consists of two successive measurements with gradient schemes of identical 0th, but differing 1st gradient moment. The calculation of the phase difference image results in zero phases for stationary spins and non-zero phases for flowing spins.

Materials and Methods:

The experiments were performed on a Bruker/Siemens MAGNETOM Allegra head scanner. With an inner diameter of 36 cm the gradient coil is of a very compact size to amplify its performance. A special asymmetric gradient design was realized to enable the insertion of the patient's head into the coil while the shoulders remain outside the bore. The z-components of the gradients are symmetric, i.e. they are zero in the isocenter. However, the transversal components have an offset along z-direction (z_{0x}, $z_{0y} \neq 0$). Flow quantification measurements were performed using the Siemens sequence fl_fq which consists of a flow compensated and a flow sensitive sequence part. Phase images were acquired for 9 transversal slices, 5 mm thick, positioned from -80 mm to 80 mm in z-direction, FoV: 220 mm, matrix: 256x256, phase encoding in x-direction, TE from 4.1 to 7 ms, venc: 50 cm/s in through plane direction. A large bottle phantom of 155 mm diameter filled with stationary liquid was used.

Results:

For the chosen phase encoding direction a strong linear phase evolution is observed in y-direction (read direction). In Fig. 1 the phase difference is mounting up to +/- 70 deg over the 15 cm of the object for slice position z = -80 mm. As the read gradient has preceding flow compensating gradients the gradient lobes of G_y and the flow encoding G_z are overlapping. This results in an additional phase evolution due to the Maxwell field terms of which the most dominant one is $\Delta B_{GyGz} = - (1 - \alpha) G_y G_z (y + y_0) (z + z_{0y}) / B_0$. As the gradient schemes between the two consecutive measurements differ, a non-vanishing phase is obtained in the resulting phase difference image. The constants for the Allegra system are $\alpha = -0.22$, $x_0 = y_0 = 0$, $z_{0x} = z_{0y} = -12.7$ cm and thus the effect of the term ΔB_{GyGz} can be much more pronounced than for a symmetric coil. For the example shown below it is more than 6 times larger.

The cross-term can be eliminated by avoiding the gradient overlap, but this also adversely affects the minimum TE. Instead, a correction of the phase image is favourable. Knowledge of the gradient time course allows the calculation of the gradient moments and the phase offsets for which the image can be corrected pixelwise (Fig.1, right image).

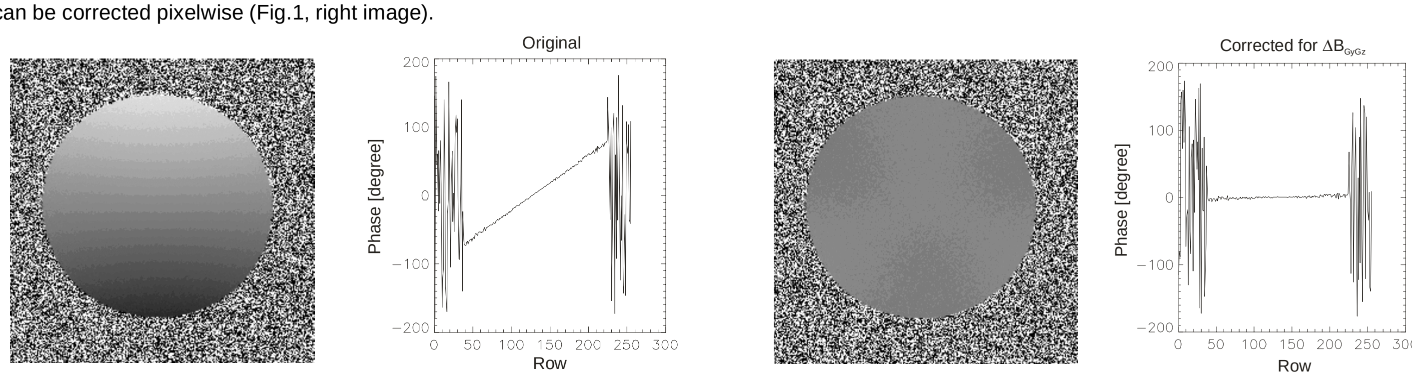

Fig 1: Left: Phase image for TE = 4.1 ms at slice position z = -80 mm and the corresponding line profile. Right: Corrected image.

Conclusions:

Maxwell field cross-terms can cause strong artifacts in flow quantification images, especially for an asymmetric coil design. The observed effects are consistent with the theoretical predictions. As Maxwell fields are predetermined by basic physics a phase correction is possible and represents a well-defined post processing step.

References:

[1] Bernstein et al., MRM 39: 300 (1998), [2] Zwanger, ISMRM 2004, p. 101