An improved Maxwell term compensation method for FSE images

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Purpose It is well known that a high–order spatial Maxwell field, or Maxwell term, exists when an imaging gradient is activated on MR system. This unwanted high order field causes additional phase error for excited spins, which has large impact on FSE. Several methods have been developed to reduce or compensate the Maxwell term to eliminate the phase error [1]. The main compensation method for FSE is to reshape the gradient waveforms for each gradient axis. Under the assumption that the Maxwell terms from left side and right side of refocus RF pulse are equal after compensation, the net phase errors due to Maxwell term from the two sides cancel each other due to phase reversal effect of the refocus RF pulse[2]. However, reshaping the gradient axis may result in a prolonged echo space (ESP) that leads to additional T2 decay artifact in FSE images. This is especially predominant on scanners with higher gradient, which are becoming widely used.

In this abstract, we propose an improved method for Maxwell compensation which compensates slice gradient (Gx) and readout gradient (Gy) mutually. This method has the benefit of zero or minimum ESP prolonging to reduce additional T2 decay artifact.

Methods To acquire T2 weighted sagittal spine images with a large FOV, it is typical to scan FSE with a readout gradient set to anterior-posterior (AP) direction to avoid moving artifact from beating and breathing. Eqs.[1] shows the Maxwell term from all gradient axes, whereas the dominant Maxwell term is contributed by Gx and Gy with Z^2 term written in bold. The main goal is to compensate for the dominant Maxwell term for the first echo, as the Maxwell terms for the other echoes are generally neglectable due to the symmetric gradient waveforms.

$$B_M(x,y,z,t) = \frac{1}{2B_0}\left\{(\boldsymbol{G_x^2} + \boldsymbol{G_y^2})\boldsymbol{z^2} + G_z^2\frac{x^2+y^2}{4} - G_xG_zxz - G_yG_zyz\right\} \quad [1]$$

$$M_G(x,y) = \int_0^t G^2 dt \quad [2]$$

The compensation method is described as following to minimize ESP prolonging effect.

1. Generate FSE waveform with max gradient amplitude to get min ESP. Calculate Maxwell term with Eqs.[2] for every gradient M_left(Gx), M_right(Gx), M_left(Gy) and M_right(Gy). (Fig.1)
2. Sum Gx and Gy Maxwell terms for left side and right side of RF refocus pulse as Eqs.[3] and [4]. Assuming M_left > M_right for below steps.
   M_left = M_left(Gx) + M_left(Gy) [3]
   M_right = M_right(Gx) + M_right(Gy) [4]
3. Derate gradients Gs180l, Gs180r, Gr1 and Gr2 in Fig. 1 without ESP prolonging. Calculate M_left and M_right again after derating.
   M_left_derate = M_left(Gx_{derate}) + M_left(Gy_{derate}) [5]
   M_right_derate = M_right(Gx_{derate}) + M_right(Gy_{derate}) [6]
4. If M_left_derate < M_right_derate, reduce the derating scales for left gradients (Gr1 and Gr2) until M_left_derate = M_right_derate. In this case, Maxwell term compensation will not prolong ESP.
5. If M_left_derate > M_right_derate, there are two conditions.
   a) M_right >M_left_derate > M_right_derate
      In this case, the derating scale for right gradients (Gr2 and Gs180r) should be reduced to increase the Maxwell term from left gradients until M_left_derate = M_right_derate. ESP will not be prolonged in this case.
   b) M_left_derate > M_right > M_right_derate
      In this case, we have to prolong ESP to derate left gradients (Gr1 and Gs180l) until M_left_derate = M_right. The right gradients should use the max gradient amplitude.

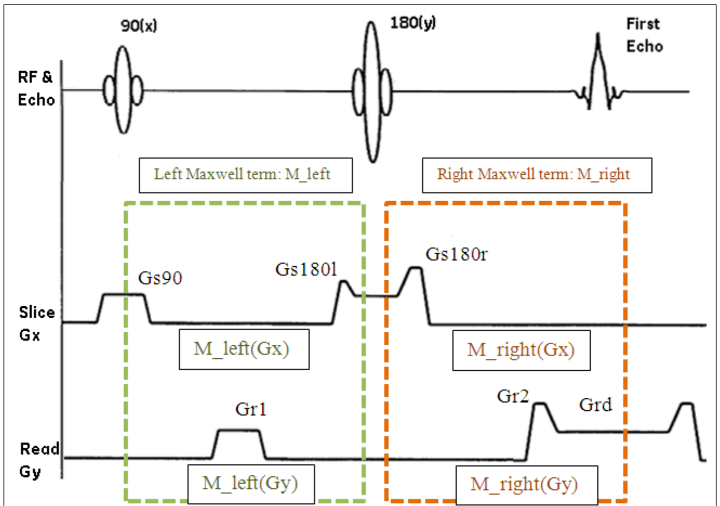

Fig 1. Mutual Maxwell term compensation for slice axis and readout axis in FSE. The Maxwell term is calculated before and after gradient derating for each axis.

Results The proposed method was implemented on a 1.5T GE Healthcare Optima360 whole body system. In-vivo sagittal spine images with 48cm FOV were acquired before and after Maxwell term compensation are shown in Fig. 2. Consent form has been obtained prior to scans. It is seen that Maxwell term compensation improves image quality significantly at the edge of FOV. The shading artifact at the edge of FOV in SI direction on Fig. 2(b) and 2(c) is obviously reduced compared to 2(a).

This new compensation method results in a shorter ESP compared to those in the conventional methods. As the example shown in Fig. 2, the ESP using the new method is 10,520 us in Fig. 2(c) compared to 11,496 us in Fig. 2(b), which amounts to a reduction of 8.4%.

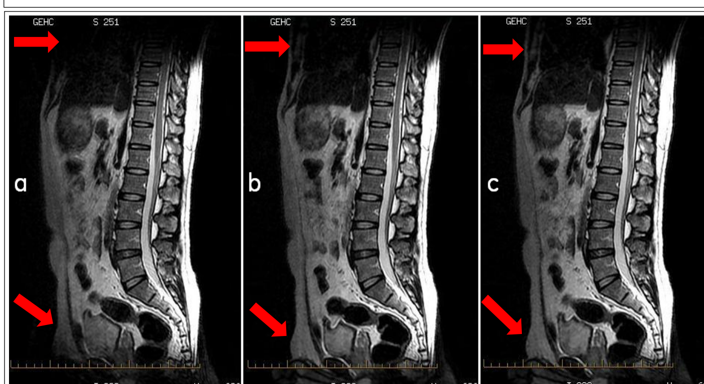

Fig 2. Image quality is improved by Maxwell term compensation.
(a). Image acquired without Maxwell term compensation.
(b). Image acquired with Maxwell term compensation on Gx and Gy independently. ESP = 11,496 us.
(c). Image acquired with Maxwell term compensation on Gx and Gy mutually. ESP = 10,520 us.

Discussion A novel method for Maxwell term compensation in FSE is proposed, in which the gradients on slice and readout axes are mutually compensated. The benefits of this method are: (1) Special attention is paid on minimizing the ESP prolonging. (2) The gradients are derated as much as possible without prolonging the ESP, which helps to reduce the cross axis Maxwell term and eddy current. (3) Mutual compensation makes the Maxwell compensation for FSE with flow compensation more effective. Since in this case the de-phase gradient is at the right of refocus RF pulse if flow compensation is in the readout direction, independent compensation for Maxwell term on read gradient normally requires additional gradient waveform on readout gradient at left of refocus RF pulse, which may prolong the ESP significantly. Whereas in mutual compensation this issue is avoided as the compensation could be achieved by reshaping the gradient waveform in another axis.

Although the example illustrated in this work was on sagittal plane with swapped readout gradient to AP direction, this method can be applied for any scanning plane.

References

1. X Zhou, Matt A Bernstein, Steve Tan. Strategies to Minimize Phase Errors Induced by Maxwell Field. ISMRM; 1998
2. X Zhou, Matt A Bernstein, Guosheng Tan. Method for reducing Maxwell term artifacts in fast spin echo MR images. US Patent: 6011392