Compensation of concomitant Maxwell gradient effects in 3D multi-element spatially selective RF excitation

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Introduction

Parallel RF excitation using multi-element transmit coils is of interest to reduce pulse duration for spatially selective excitation. Originally, RF pulse design was formulated in the frequency domain for arbitrary k-space trajectories (Transmit-SENSE, [1]) or in the spatial domain for echo-planar trajectories [2]. Later, Transmit-SENSE was formulated in the spatial domain in [3] allowing to specify a spatial region of interest. Here, we extend this method to compensate for the effects of concomitant Maxwell gradients [4]. They become important especially for a large field of excitation (FoX) and long pulse duration mainly found in 3D RF pulse applications.

Theory

Using the small tip angle approximation [5], the transverse magnetization *m* produced by *R* coils can be written as:

$$m(\mathbf{x},t) = i\gamma m_0(\mathbf{x}) \sum_{r=1}^{R} s_r(\mathbf{x}) \int_0^t b_r(t') e^{i\mathbf{k}(t')\mathbf{x}} e^{-i\Delta\omega(T-t')} e^{-i\Delta\phi(\mathbf{x},t')}\,\mathrm{d}t' \qquad (1)$$

Here, s_r is the transmit sensitivity of coil *r*, b_r is the RF pulse with duration *T*, and Δω is an off-resonance term. The last phase term in Eq. (1) is due to the concomitant Maxwell gradients and is given by:

$$\Delta\phi(\mathbf{x},t') = \frac{\gamma}{2B_0} \int_{t'}^{T} \alpha^2 G_z^2 x^2 + (\alpha-1)^2 G_z^2 y^2 + (G_x^2 + G_y^2) z^2 - 2\alpha G_x G_z xz + 2(\alpha-1) G_y G_z yz \,\mathrm{dt},$$

where **G** = (G_x,G_y,G_z) is the magnetic field gradient and $0<\alpha<1$ is a constant depending on the geometry of the gradient coils (here, using a cylindrical coil α=0.5). It is straightforward to include Δϕ in the RF pulse calculation since it depends only on quantities already known during pulse design. RF pulses are calculated by minimizing $\|m-m_{des}\|^2+\lambda\|b\|^2$, where m_{des} is the target magnetization, λ a regularization parameter, and *b* the concatenated b_r.

In the following, we investigate the influence of the concomitant gradients on the performance of 3D spatially selective excitation at a main field strength of 3T using different FoX.

Methods

A multi-element transmission coil was assumed having 24 elements arranged in 3 cylindrical segments with 8 linear antennas on each segment. The antennas are oriented parallel to the main field direction and equally distributed around the circumference of each segment (see Fig. 1). The sensitivities of the coils were modeled by a static calculation using the Biot-Savart law.

As excitation trajectory, a stack of 12 spirals having 6 revolutions each with an isotropic resolution of 1 cm along the *x,y,z*-direction was used having a total duration of 40 ms.

The used target excitation pattern was a 3D checkerboard pattern with a block size of 2 cm in each direction. The size of the field of excitation was varied from 16^3 voxels to 40^3 voxels keeping the voxel size fixed at 1 cm³. The excitation quality was evaluated using the correlation between the target pattern and a Bloch forward calculation.

Fig. 1: Schematic drawing of the RF coil used in this study: The coil consist of 3 segments with 8 elements each.

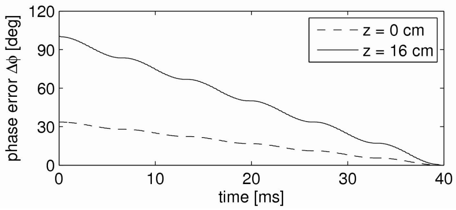

Fig. 2: Phase error due to concomitant gradients for two voxels with x=16, y=16 cm and different z positions. Note, that by definition Δϕ is zero at the end of the pulse.

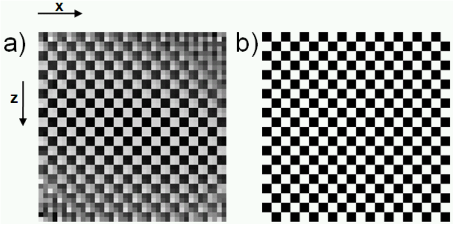

Fig. 3: Sagittal slices of excited patterns a) without and b) with compensation of concomi-tant gradients.

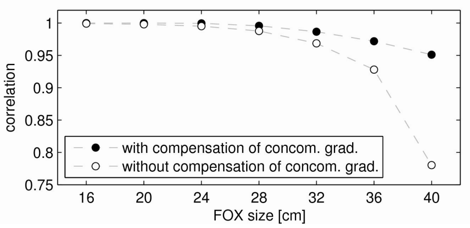

Fig. 4: Influence of concomitant gradients on RF pulse excitation quality for different excitation field of views.

Results and Discussion

As an example, Fig. 2 shows the significant phase error for two voxels at the edge (x = 16 cm, y = 16 cm) of two transversal slices with z = 0 cm and 16 cm, respectively. Fig. 3a) shows a sagittal slice of the excited pattern for a pulse calculated without taking the concomitant gradient term into account; Fig. 3b) shows the pattern taking the additional phase term into account. Fig. 4 shows the impact of the FoX size on the influence of the concomitant gradients: For a small FoX the concomitant gradients can be neglected, whereas the term must be taken into account for a large FoX to produce accurate excitation patterns.

The phase error scales quadratically with gradient strength and inversely with main field strength. I. e., if stronger gradients are used to encode smaller voxels, concomitant gradients would also become important for a smaller FoX. The same is true for a lower main field strength of e. g., 1.5 T.

Conclusion

Concomitant gradients can be taken into account during multi-element RF pulse design at no extra cost. It is important to compensate their effect for a large field of excitation and long pulse duration to achieve high excitation quality.

References

[1] Katscher et al., MRM, **49**, 144-150 (2003)
[2] Zhu et al., MRM, **51**, 775-784 (2004)
[3] Grissom et al., MRM, **56**, 620-629 (2006)
[4] Norris and Hutchinson, MRI, **8**, 33 (1990)
[5] Pauly, JMR, **81**, 43-56 (1989)