Correction for Concomitant Gradient Field Effects in Refocused SSFP

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Introduction: Concomitant gradients (1,3) are additional magnetic fields that appear whenever we apply linear gradients. Concomitant gradients can produce large frequency offsets, especially in sequences with multiple gradients active, such as refocused SSFP sequences. The effect of concomitant gradients in refocused SSFP sequences is the appearance of a band where the signal is nulled. The following equation models the concomitant gradient field in three-space:

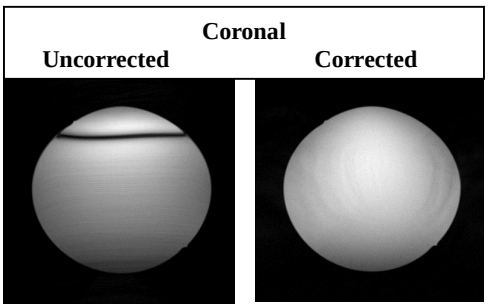
$$B_c(x,y,z) = (G_z^2 / 8B_0)(x^2 + y^2) + (G_x^2 + G_y^2)(z^2 / 2B_0) - (G_xG_zxz + G_yG_zyz)/2B_0 \quad (1)$$

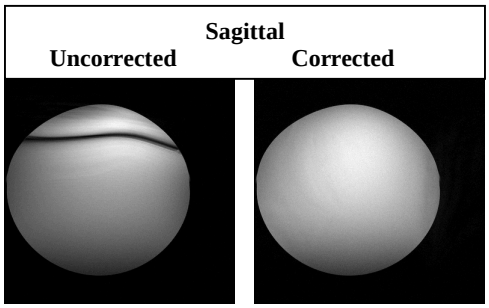
Concomitant gradients are 1) inversely proportional to field strength, 2) quadratic with gradient amplitude and with z, and 3) always positive.

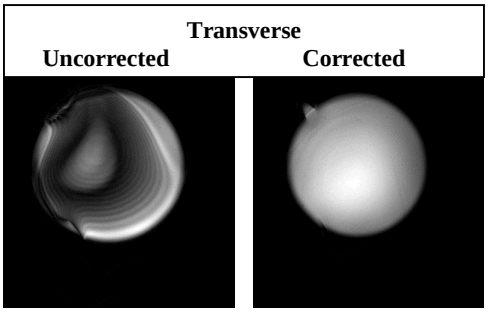
In refocused SSFP sequences such as TrueFISP, FIESTA, and Balanced FFE, the detected magnetization in the steady state is a complex function of TR, TE, T1, T2, flip angle and any inhomogeneities (susceptibility, concomitant gradients, chemical shift) that may exist. The effects of phase accrual are incorporated within the off-resonance precession angle, termed β. For a flip angle of about 70 degrees, there exists a β regime in which the detected magnetization is independent of β, typically from $60 < \beta < 300$ degrees (2). Any inhomogeneity strong enough to cause β to shift out of this regime can lead to a drastic loss in the detected signal from the part of the image that contains that inhomogeneity. Concomitant gradients are strong enough to produce a shift in β of 180 degrees and can lead to significant banding in SSFP images.

Methods: For a given SSFP sequence, a 3D phase map was calculated from its gradient waveform table and the concomitant gradient field equation. This phase map was used to determine the spatial region where the accrued phase due to concomitant gradients reached 180 degrees. Images were acquired in transverse, sagittal, and coronal orientations to demonstrate the concomitant gradient induced banding. To correct the images, two different methods were applied. For the transverse orientation, the offset frequency was altered to limit the phase accrual due to concomitant gradients on a slice by slice basis. For the coronal and sagittal orientations, the phase encoding direction was swapped in order to eliminate the banding. The principle behind this technique is that certain terms will drop out of the concomitant field equation, leading to phase accruals less than 180 degrees across the imaging slice.

Results: Phase map calculations indicate β should be in the vicinity of 180 degrees for a slice 13 cm from isocenter. The phantom scans below were obtained for transverse, coronal, and sagittal orientations. The banding was found to occur in a slice offset around 13.5 cm in the positive z direction, which appears as significant banding in-plane for the transverse image below. In the coronal and sagittal images, the banding appears as dark, broad lines in the image. The images on the right side demonstrate the effect of the correction methods. Swapping the phase encode and readout directions does an excellent job of eliminating the artifact in the sagittal and coronal images. Changing the offset frequency in the transverse image does a good job of eliminating the artifact.







Siemens 1.5 T Sonata, TR 4.3 ms, maximum readout gradient 28 mT/m, 300 x 300 FOV, 0.8 mm by 0.8 mm resolution. FOV offset 7 cm along z.

Conclusion: For reasonable imaging parameters in SSFP sequences, concomitant gradients will lead to banding. In the displayed images the band was found to be at 13.5 cm in Z for a maximum readout gradient of 28 mT/m, but the band will move closer to isocenter if stronger gradients (~40mT/m) are used. Additionally, this artifact is independent of TR, since the phase accrual occurs only when the gradients are active, so shortening the TR alone will not weaken it. Lowering either the gradient amplitude or the time duration for which the gradients are active will move the banding further out. Non-isocenter scans can be particularly susceptible to this artifact. High resolution scans, which use strong gradients, are especially susceptible to this artifact.

References:

1. Bernstein at al. Magn Reson Med, 39: 300-308 (1998)
2. Haacke et al. Magnetic Resonance Imaging: Physical Principles and Sequence Design
3 King K et al. Magn Reson Med 41, 103-112 (1999)