Improved spoiling efficiency in dynamic RF-spoiled imaging by ghost phase modulation and temporal filtering

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Target audience: Users of RF-spoiled steady-state imaging for, e.g., dynamic contrast-enhanced MRI or T1 mapping.

Purpose: To reduce ghosting in dynamic (or averaged) RF-spoiled steady-state 3D imaging.

Introduction: RF-spoiled steady-state sequences (SPGR/T1-FFE/FLASH) offer rapid data acquisition and T1-weighting, and are used for, e.g., dynamic contrast-enhanced imaging and quantitative T1 mapping. The unbalanced gradient lobes ("spoiler gradients") in these sequences are generally chosen empirically to be sufficiently large to achieve good spoiling and suppress ghosting artifacts. However, the required spoiler gradient size for "good" ghost suppression is subjective and application-dependent. For example, quantitative T1 mapping may require spoilers several msec in duration [1], which increases the sequence repetition time (TR) and hence the total imaging time significantly. Furthermore, in non-cartesian SPGR imaging such as stack-of-spirals, it may be difficult to assess visually whether good spoiling is achieved. Here we present a strategy for improved spoiling efficiency in dynamic (or averaged) SPGR imaging, by dynamically modulating the phase of the ghosts at the Nyquist frequency and removing that frequency component in pre-processing.

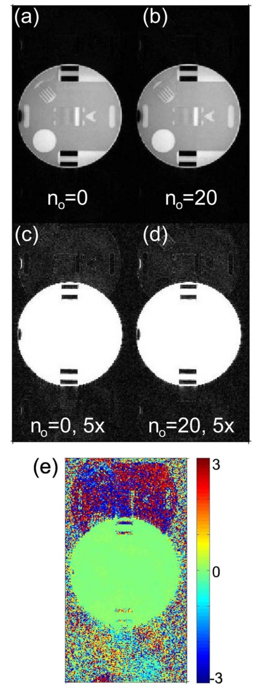

Figure 1: SPGR images of a stationary phantom obtained with TR counter starting values (a) 0 and (b) 20. (e) Phase difference between the two images. The ghosts are 180° out of phase.

Theory: In RF-spoiled imaging the RF phase increment from one TR to the next increases linearly as $\Psi\times n$, where Ψ is a constant (typically 117°) and n is the "TR counter". Typically $n=0,1,2,3,\ldots$, however we may offset the counter by an arbitrary integer value n_0 without loss of generality, i.e., $n= n_0+0, n_0+1, n_0+2, n_0+3, \ldots$. Our method is based on the observation that the phase of the ghost in 3D SPGR images is a function of the initial value n_0 of the TR counter. This is because the ghost phase lags the main (FID) signal phase by [2]

$$\Psi\times n = \Psi\times n_o + \Psi\times(0,1,2,3,\ldots). \qquad (1)$$

The second term in (1) causes the ghost to appear shifted in the image, while the constant term determines the phase of the ghost relative to the main object. Therefore, for Ψ=117° the ghosts described by Eq. (1) in two images acquired with n_0=0 and n_0=20, respectively, will be mod(117x20,360)=180° out of phase (Fig. 1). We propose to exploit this for ghost removal in dynamic SPGR imaging, by resetting the TR counter every dynamic frame to one of two predetermined values, making the ghosts oscillate at the Nyquist frequency.

Methods: We acquired a dynamic 3D SPGR time-series of a stationary resolution phantom [Ψ=117°; flip angle 20°; 2x2x2 mm^3 isotropic voxels; matrix size 120x120x26; 24 temporal frames; one cycle of spoiling along z, and zero cycles of spoiling along x and y]. The TR counter was reset at the beginning of each timeframe, with n_o=0 (20) for every odd (even) frame. After 3D inverse Fourier transforming into image space, the image time-series for one slice was Fourier transformed along the temporal dimension, the Nyquist component was set to zero, and the spectrum was inverse FFT'd.

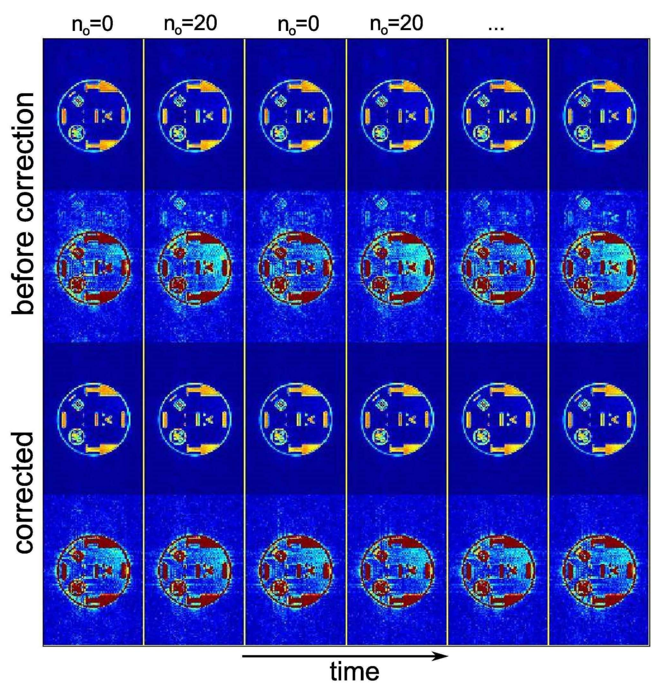

Figure 2: Proof-of-principle demonstration of ghost removal in dynamic SPGR imaging by ghost phase modulation and temporal filtering. Six consecutive time-frames from a dynamic 3D SPGR scan are shown (Ψ =117°), both before (rows 1 and 2) and after (rows 3 and 4) removal of the Nyquist temporal frequency component. The TR counter was reset at the beginning of each frame, with n_o=0 (20) for every odd (even) frame. Only one of the 26 acquired slices is shown.

Results: Figure 2 shows six consecutive frames from the dynamic SPGR scan, both before and after removal of the Nyquist component. Ghosts have been effectively suppressed with our method.

Discussion and Conclusions: We have demonstrated a simple method for more effective ghost suppression in dynamic SPGR imaging, based on frame-to-frame modulation of the ghost phase. Our approach does not increase scan time, is easy to implement, and may allow for robust dynamic (or averaged) SPGR imaging even with spoiler gradients as small as one cycle applied along a single gradient axis. This approach may be particularly useful in situations where large spoiler gradients on multiple axes would increase the TR significantly, or pose other sequence challenges. One example is stack-of-spirals 3D imaging with multiple within-platter segments, in which each spiral leaf should be fully balanced (zero net gradient area) so as not to rotate the spoiler gradient with each spiral leaf, which would violate the conditions for steady-state. Another application of interest is dynamic imaging using the recently proposed "small-tip fast recovery" steady-state sequence, which relies on RF-spoiling to suppress the SSFP-echo signal from outer-volume spins [3]. Potential limitations of our approach include the possibility that resetting the TR counter can cause small transient oscillations at the beginning of each temporal frame, which needs to be evaluated further.

Conclusion: Effective ghost suppression in dynamic SPGR imaging is possible, even with minimal gradient dephasing.

[1] Yarnykh MRM 2010; [2] Leupold and Hennig MRM 2011; [3] Nielsen et al. MRM 2013.

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