

STAGES: Dynamic Shimming by Nonlinear Phase Preparation and K-Space Parcellation in Steady-State MRI

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Introduction: Dynamic shimming in MRI is a method to homogenize the static magnetic field variation across a set of slices (1) or, conceptually, image space parcels (2). Homogenizing the field in real time has the potential to reduce many confounding issues in MRI, such as intravoxel dephasing, image distortion and balanced steady-state free precession (bSSFP) stop band artifacts, among others. One limitation of this approach is that the spatially encoded gradient echoes arise simultaneously across the entire excited and received image volume, such that the local shim may be improved, but only to the deterioration of image quality elsewhere. Here we present a technique steady-state gradient echo shimming (STAGES) for dynamic shimming within a single spatially encoded volume in steady-state sequences using a combination of nonlinear phase preparation and a k-space parcellation algorithm. The techniques are demonstrated to eliminate bSSFP stop band artifacts along the direction of phase encoding in simulations and experiments.

Theory: Consider the special case of a steady-state experiment in which spatial encoding was performed using a combination of quadratic phase preparation and linear spatial encoding. The acquired MRI phase encoded signal $S(k)$ is the Fourier transform of the spin density function $\rho(x)$, SSFP frequency response function $m(x,k)$, and a Gaussian phase function $g(x)$, $S(k) = \int \rho(x)m(x,k)g(x)e^{-ikx}dx$. The Gaussian is a complex function e^{-iqx^2} whose coefficient q is determined by the relationship $q = k_{max}/FOV$. This relationship repositions the gradient echo originating from the edge of the field-of-view (FOV) to the maximally encoded spatial frequency. In general, the SSFP function m is a complex function of the sequence parameters echo time (TE), repetition time (TR), RF pulse flip angle θ , and RF pulse duration, and spatially-dependent parameters of the object T1, T2 and frequency offset $\Delta\omega$. These parameters affect the projection of the magnetization trajectory into the transverse plane following each RF pulse n . The important feature of the signal equation is that, since the SSFP function depends on the local shim, it can be progressively updated during spatial encoding using a k-space parcellation approach in the presence of nonlinear phase preparation.

Methods: Hardware. Experiments were performed on a 3 T MRI device (TIM Trio Model, Siemens Healthcare, Erlangen, Germany, Trio Model) equipped with an insert comprised of two custom quadrupolar, magnetic fields (a PatLoc system) (3,4). Each magnetic field could produce $2.5 \text{ mT/m}^2/\text{A}$ with a maximum rise time 400 A/ms . A birdcage RF transmit and 8-channel receive coils were positioned inside the custom fields for signal reception. **MRI.** A customized bSSFP imaging sequence (Fig. 1) was implemented with the following imaging parameters: matrix = 256×256 , FOV = 210 mm , TE/TR = $6/12 \text{ ms}$, flip angle = 45° . The duration of the pulsed nonlinear field was $600 \mu\text{s}$. Tukey window filtering ($\alpha=0.05$) was applied to suppress Gibb's artifacts. **K-Space Parcellation Algorithm.** A sliding window k-space parcellation approach was used for selection of the shim coefficients (Fig. 2). An object subvolume (parcel) of width w and height h was locally shimmed by L2 norm minimization of the magnetic field (5) and a set of shim coefficients up to second order could be updated throughout spatial encoding at sequence run time (Fig. 1). For initial experiments (Fig. 4), only carrier frequency adjustment was performed.

Results and Discussion: The STAGES method was simulated for a 1D object using linear and Gaussian field heterogeneities across a range of frequency offsets (two of which are shown in Fig. 3). bSSFP stop bands were eliminated for a 450 Hz frequency range across the FOV, with progressive deterioration of resolution with increasing field heterogeneity and a decreasing number of shim coil corrections. Images were acquired to test the feasibility of the approach with or without nonlinear phase preparation and dynamic shimming in the presence of a 0.1 mT/m magnetic field gradient and correction using only adjustment of the RF and ADC carrier frequencies (Fig. 4). Fig. 3 and 4 demonstrate that bSSFP stop bands can be

eliminated in the presence of modest static variations along the direction of k-space parcellation using only adjustment of the carrier frequency. We expect that robustness to field heterogeneity can be considerably increased by using dynamic first and second order shim coils (Fig. 3B) and k-space parcellation along more than one direction. The latter is more difficult to implement and depends on the particular k-space trajectory. On the existing experimental system, shim coils up to second order along the axial direction are available for correction. There is an inherent compromise between spatial resolution and elimination of bSSFP stop bands. The reduction of spatial resolution may be resolved by improvement of the k-space trajectory or parcellation algorithm or coil sensitivity information. Although and application for bSSFP is shown, this technique can be applied analogously to other steady-state sequences.

References: (1) Blamire, et al. Magn Reson Med (1996); 36:159-65. (2) Poole, et al. Magn Reson Mater Phy (2008); 21:31-40. (3) Schultz, et al. Magn Reson Med In Press. (2010); (4) Gallichan, et al. Magn Reson Med. In Press. (2010); (5) Prammer, et al. J Magn Reson (1988); 77:40-52. **Acknowledgements:** This work is part of the INUMAC project supported by the German Federal Ministry of Education and Research Grant No. 13N9208.

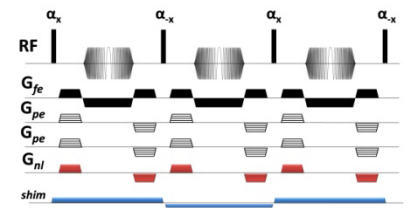


Fig. 1: Three kernels of the STAGES pulse sequence are shown and illustrate 2 features: nonlinear phase preparation (red), and varying shim adjustments.

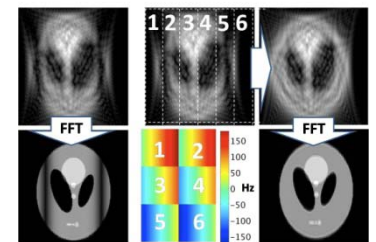


Fig. 2: Method for k-space parcellation. A subvolume or 'stage' (shown here as volumes 1-6) is continuously shifted across the k-space during each SSFP kernel and the field gradient corresponding to the k-space subvolume is minimized. Spatially encoded data is acquired in the presence of nonlinear magnetic fields and the stage is updated for the next SSFP kernel. The final dynamically shimmed k-space data (upper right) is free of artifacts.

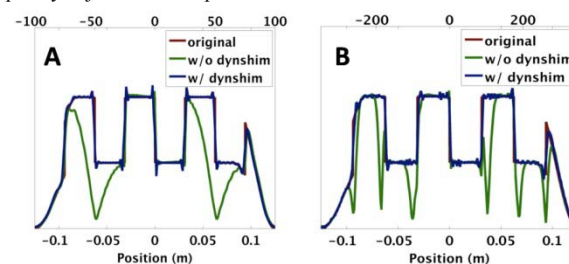


Fig. 3: Simulated 1D objects encoded and reconstructed using phase alternating bSSFP without static field heterogeneity (red) or using STAGES (blue) and conventional bSSFP (green) in the presence of (A) 200 Hz linear magnetic field gradient and (B) 350 Hz FWHM Gaussian field gradient. In (A) STAGES was performed with k-space parcellated shimming using only correction of the carrier frequency and in (B) using zero, first and second order frequency correction. Top Axis: (Hz).

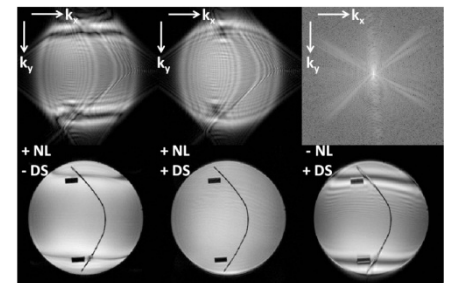


Fig. 4: Experimental data acquired on a doped saline phantom ($T_2/T_1 = 200 \text{ ms}/300 \text{ ms}$), using nonlinear preparation (+NL) and dynamic shimming (+DS). (Left) +NL and -DS shows k-space dispersion without correction for stop band artifacts. (Middle) +NL and +DS locally corrects the shim eliminating artifacts. (Right) -NL and +DS is unable to correct for artifacts within a single spatially encoded volume.