Joint Reconstruction for Phase-Cycled Balanced SSFP

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INTRODUCTION: Balanced steady state free precession (bSSFP) is an SNR-efficient technique that has found widespread use in cardiac, abdominal and brain imaging. Despite being a rapid sequence with unique T_2/T_1 contrast, it suffers from banding artifacts due to its sensitivity to B_0 inhomogeneity. To mitigate these artifacts, multiple images at different off-resonance frequencies can be acquired and combined with maximum intensity projection (MIP). Such phase-cycled acquisition increases the total scan time, counteracting the inherent efficiency of bSSFP. Parallel imaging [1] and simultaneous multislice (SMS) [2] employ sensitivity encoding to reduce the scan time, and have been recently deployed in phase-cycled bSSFP [3]. Herein, we propose to jointly reconstruct the phase-cycled images, and report up to 3-fold decrease in maximum g-factor and 47% reduction in reconstruction error. This is achieved by GRAPPA kernels [1] that are fit jointly across channels and phase-cycles, analogous to *k-t* and virtual coil approaches tailored for dynamic [4] and diffusion imaging [5].

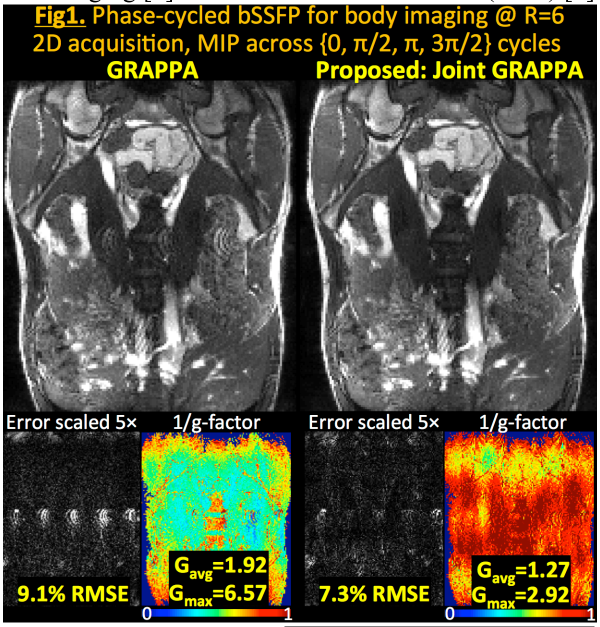

Fig1. Phase-cycled bSSFP for body imaging @ R=6 2D acquisition, MIP across {0, π/2, π, 3π/2} cycles

METHODS: We propose Joint GRAPPA, which reconstructs all phase-cycles simultaneously to exploit their mutual information. This creates virtual coils by stacking the phase-cycles along the channel axis, where all coils and all cycles contribute to the reconstruction of a particular channel. Similar to *k-t* acquisition, the sampling pattern is shifted across the cycles to provide complementary k-space coverage. By creating virtual coils out of the phase-cycles, Joint GRAPPA makes use of the intensity and phase modulations due to B_0 inhomogeneity, and converts these artifact sources into useful, additional spatial encoding.

Fig1: A single abdominal slice of a volunteer was imaged with bSSFP using four cycles (0, π/2, π, 3π/2) at 3T. Parameters were: FOV=380×380 mm^2, mtx=160×160, 5 mm slice, TR/TE=3.3/1.54 ms, FA=37°, BW=822 Hz/px, 34-channel reception. For GRAPPA, each cycle was reconstructed separately with a 9×3 kernel. Joint GRAPPA used a 7×3 kernel and undersampling patterns were shifted by (0,3,0,3) samples for the four cycles to create complementary k-space information.

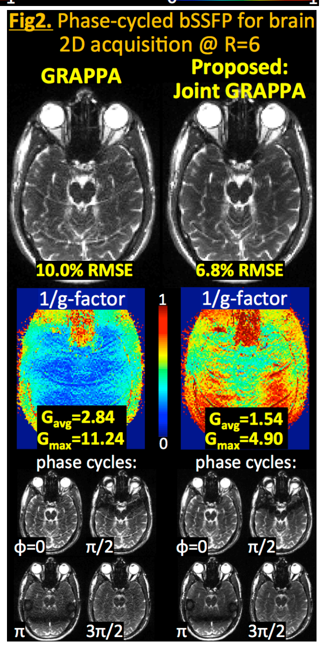

Fig2. Phase-cycled bSSFP for brain 2D acquisition @ R=6

Fig2: A volunteer underwent a brain scan using 2D-bSSFP with four cycles at 3T. Parameters were: FOV=240×240 mm^2, mtx=160×160, 4.5 mm slice, TR/TE=3.37/1.57 ms, FA=47°, BW=845 Hz/px, 32-channel reception. Kernel sizes were 13×3 for GRAPPA and 9×3 for Joint GRAPPA. Undersampling patterns were staggered by (0,3,0,3) for joint reconstruction.

Fig3: Eight individual slices were acquired with four cycles using the same parameters in Fig2. These were shifted by multiples of FOV/4 and collapsed retrospectively. Since alternating the RF phase leads to a shift in both FOV and frequency [3], a collapsed slice group has contribution from all phase-cycles. As such, slices from the appropriate cycles were selected and shifted for this simulation. Slice- and Joint Slice-GRAPPA used 13×13 kernels with leak-block [6].

All experiments used 32 ACS lines, 12 GCC compressed channels [7] and 300 Monte-Carlo iterations for g-factor calculation [8]. Kernel sizes were selected for optimal RMSE.

RESULTS: **Fig1:** At R=6 acceleration, GRAPPA led to **9.1%** RMSE in the MIP image while the error was **7.3%** for Joint GRAPPA. The g-factors were $\mathbf{g_{avg}=1.92/1.27}$ and $\mathbf{g_{max}=6.57/2.29}$ for GRAPPA/Joint GRAPPA. **Fig2:** At R=6, the reconstruction errors were **10.0%** and **6.8%**. G-factor analysis revealed $\mathbf{g_{avg}=2.84/1.24}$ and $\mathbf{g_{max}=11.24/4.90}$. Bottom panel displays the individual cycles. **Fig3:** SMS reconstructions at MB=8 had **13.3%** and **10.2%** error. G-factor statistics were $\mathbf{g_{avg}=2.24/1.52}$ and $\mathbf{g_{max}=36.17/10.23}$ for GRAPPA/Joint GRAPPA.

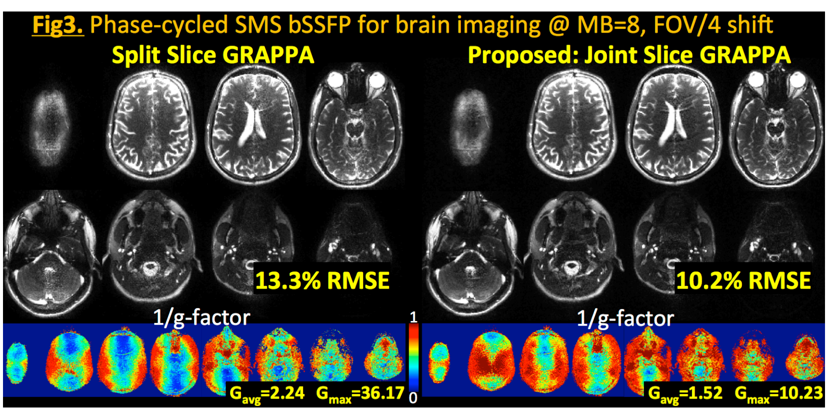

Fig3. Phase-cycled SMS bSSFP for brain imaging @ MB=8, FOV/4 shift

DISCUSSION: Joint GRAPPA employed the banding artifacts as additional spatial encoding to improve g_{max} by at least 2.3-fold relative to GRAPPA. The improvement in g_{avg} was at least 1.5-fold, i.e. the SNR improvement is similar to two averages of GRAPPA reconstruction. The proposed Joint GRAPPA could thus mitigate the scan time burden of phase-cycling while producing banding-free images.

REFERENCES: [1] M Griswold MRM'02; [2] DJ Larkman JMRI'01; [3] Y Wang MRM'15; [4] F Huang MRM'05; [5] E Dai MRM'16; [6] SF Cauley MRM'14; [7] T Zhang MRM'13; [8] FA Breuer MRM'09.