Magnitude-Weighted Complex-Sum SSFP

T. Cukur[1], N. K. Bangerter[2], and D. G. Nishimura[1]

[1]Electrical Engineering, Stanford University, Stanford, CA, United States, [2]Radiology, Stanford University, Stanford, CA, United States

Introduction: Balanced steady-state free precession (SSFP) imaging sequences offer high signal-to-noise ratio (SNR) efficiency, but suffer from characteristic banding artifacts where field inhomogeneity is large. Banding is more severe at higher field strengths and longer repetition times (TR). However, decreasing TR is not always possible due to resolution and specific absorption rate (SAR) considerations. Instead, multiple SSFP data sets, each with a different RF phase increment between subsequent excitations, are often combined to reduce banding artifacts [1-5]. Several such combination methods have been proposed, including maximum-intensity (MI) [3,4], complex-sum (CS) [5], and sum-of-squares (SOS) [6]. The SOS method gives the highest SNR efficiency, whereas the CS method is the most effective at banding removal.

In this work, a new combination method (magnitude-weighted complex-sum or MW-CS) is proposed that approaches the SNR efficiency of SOS while preserving the band-reduction robustness of the CS methods. The SNR and band-reduction performance of the new technique is analyzed for various tissue parameters.

Theory: In its general form, the MW-CS image Y can be expressed as a function of N separate phase-cycled SSFP images: $|\mathbf{Y}| = |\sum(|\mathbf{X_i}|^p\mathbf{X_i})|^{1/(1+p)}$, where $\mathbf{X_i}$ denotes the ith SSFP image and *p* is a constant that determines the tradeoff between SNR efficiency and band reduction. Optimal SNR efficiency is achieved when *p* is unity, while increasing *p* improves banding artifact reduction at the expense of SNR. Note that the MW-CS method converges to MI for very large *p*, and to CS as *p* goes to zero. The spectral response of a combined data set can be formed by appropriately combining *N* SSFP data sets that are shifted by $2\pi/N$ radians as outlined in [6]. Average SNR and percent ripple across the profile (a good measure of band reduction) can be computed from this profile to assess the performance of each combination method.

Results: The theory was partially verified by generating simulated SSFP images with different phase-cycling schemes and combining the images with each method (Fig. 1). Simulation parameters were: $\alpha = 30^o$, TR/TE = 10/5 ms, T1/T2 = 270/85 (fat), 870/47 (muscle), 100/200 (blood) ms. Bivariate Gaussian noise was added to the data. MW-CS with *p* = 1 is more successful at reducing banding artifact than both CS and SOS. If *p* is further increased (Fig. 1.d), banding artifacts become less evident with an accompanying decrease in SNR. The measured values of ripple and SNR are listed in Table 1.

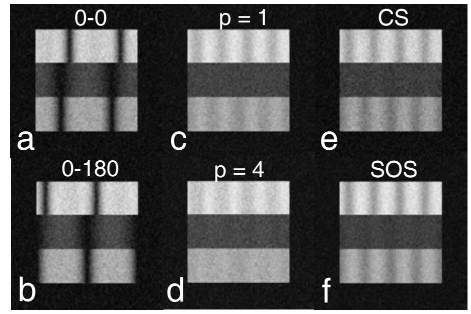

Figure 1. a-b: *Field homogeneity simulated SSFP phantoms (tissues from top to bottom are fat, muscle and arterial blood), with 0-0 and 0-180 phase cycling.* ***c-d:*** *MW-CS images with the constant p equal to 1 and 4 respectively.* ***e-f:*** *CS and SOS combination results.*

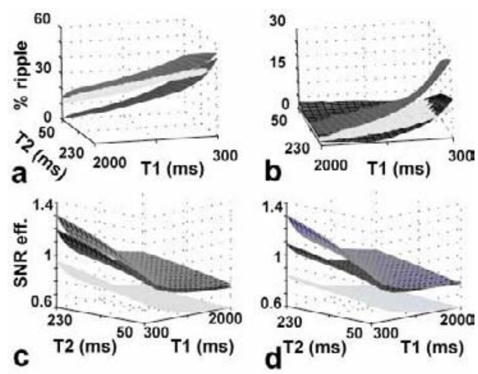

Figure 2. *The percent ripple and relative SNR efficiency for CS (light gray), MW-CS (p=1) (black) and SOS (dark gray) methods for* ***a,c:*** *N=2 and* ***b,d:*** *N = 4 respectively.*

The SNR efficiency and percent ripple of CS, SOS, and MW-CS (*p* = 1) are also compared (Fig. 2). Simulation parameters were: $\alpha = 30^o$, TR/TE = 10/5 ms, T1 = 300-2000 ms, T2 = 50-230 ms, and N (the number of data sets to be combined) = 2 and 4. An SNR of 15 was assumed at the center of the passband of a single SSFP acquisition. The results show that the MW-CS method achieves more robust banding artifact reduction than the other methods for a range of T1 and T2 values typically found in vivo, without a significant reduction in SNR efficiency compared to the SOS method. The tissue contrast of MW-CS is very similar to normal SSFP contrast for the range of T1 and T2 values considered.

	p = 1	p = 4	CS	SOS
Fat	34%, 29.6	30%, 28.6	31%, 26.4	44%, 32.1
Muscle	16%, 12.5	10%, 12.6	24%, 11.0	28%, 13.0
Blood	31%, 24.0	22%, 23.7	40%, 20.5	44%, 26.4

Table 1. *The percent ripple and relative SNR for MW-CS (p=1 and 4), CS, and SOS.*

A phantom experiment was performed to further validate the method. Four phase-cycled SSFP acquisitions of three $MnCl_2$-doped water phantoms were combined with the CS, MW-CS (p=1), and SOS methods (Fig. 3). The MW-CS method is as effective as CS in reducing banding artifacts, but achieves SNR efficiency comparable to that of the SOS method.

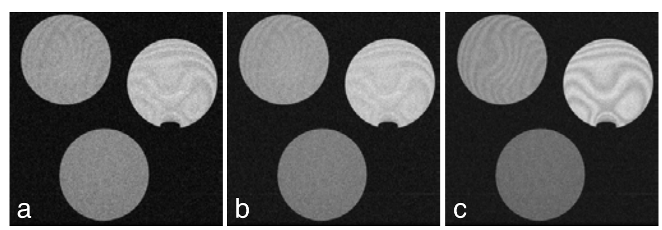

Figure 3. *3DFT - SSFP images of 3 phantoms with T1/T2 = 1300/900 (upper-right), 800/375 (upper-left), 250/50 (lower) ms, were acquired with $\alpha=30^o$, 16 cm FOV, 0.5x0.5x2 mm resolution, TR/TE=20/10 ms, ±15 kHz bandwidth and 4 different phase-cycling schemes. Combination images are displayed for* ***a:*** *CS,* ***b:*** *MW-CS (p=1) and* ***c:*** *SOS methods.*

Conclusion: MW-CS is a novel SSFP combination technique that can achieve the banding artifact reduction of the CS method with an SNR efficiency close to that of the SOS method. Variation of the parameter p allows the degree of banding artifact reduction to be traded off against SNR efficiency on an application-specific basis.

References:

1. Schwenk A, JMR 5:376-89, 1971.
2. Zur Y, MRM 16:444-59, 1990.
3. Haacke E, Rad 175:545-52, 1990.
4. Casselman J, AJNR 14:47-57, 1993.
5. Vasanawala S, MRM 43:82-90, 2000.
6. Bangerter N, MRM 51:1038-47, 2004.