Banding Reduction in SSFP imaging through Accurate, Image-based Estimation of the SSFP Sensitivities

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Introduction: Balanced steady-state free precession (SSFP) imaging offers high SNR efficiency, but suffers from banding artifacts due to field inhomogeneities. A common solution is to combine multiple phase-cycled SSFP data [1-4]. SSFP induces a complex image weighting, which depends on T1, T2, off-resonance and phase cycling, on a reference image with center-of-the-pass-band SSFP contrast. If these SSFP sensitivities (weightings) can be estimated accurately, then multiple SSFP data can be linearly combined to yield banding-free images with optimal SNR. Estimating the sensitivities from low-resolution SSFP data was recently proposed [5]. However, that method relies on the sub-optimal banding-reduction performance of an initial maximum-intensity (MI) image and performs poorly in regions of fast susceptibility change.

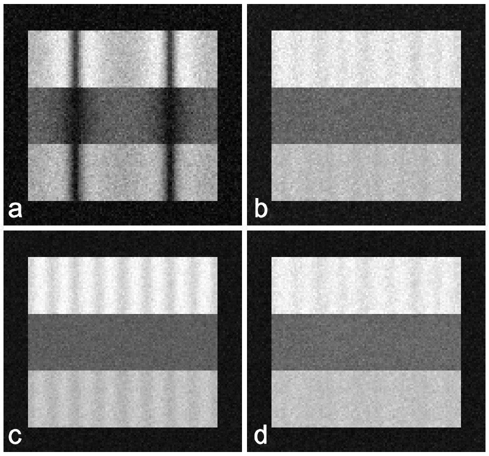

Figure 1. a: Field homogeneity simulated SSFP phantom (tissues from top to bottom: fat, muscle and blood). **b:** The initial reference MW-CS (p = 50) image. Images reconstructed with **c:** the SOS combination, and **d:** the proposed method.

In this work, accurate estimates of the SSFP sensitivities are obtained from full-resolution images using the magnitude-weighted complex-sum (MW-CS) method [6] for initialization. SSFP data can then be combined to yield robust banding artifact suppression and near-optimal SNR.

Methods: Because the MW-CS method yields better banding artifact reduction than the MI combination [5], the sensitivity estimates are more accurate. Given N measurements $\mathbf{m_i}$, and a reference image –assumed to represent the center-of-the-pass-band SSFP contrast- $\mathbf{M_{ref}} = |\sum|\mathbf{m_i}|^{\mathbf{p}}\mathbf{m_i}|^{\mathbf{1/(1+p)}}$ (MW-CS image), the sensitivity for each acquisition ($\mathbf{S_i}$) is obtained by solving: $\mathbf{argmin_S}\ ||\mathbf{M_{ref}.S_i - m_i}||^2 + \boldsymbol{\lambda}\mathbf{R(S_i)}$. Because the inverse problem is ill-conditioned, a finite-difference regularization term -$\mathbf{R(S_i)}$- is introduced to exploit the smoothness of the estimates and denoise them. It should be noted that the estimates will have some image structure due to the T1 and T2 dependence. The estimates determine the weights of the optimal linear combination $\mathbf{M} = \sum\mathbf{m_i w_i}$, where the weights are: $\mathbf{w_i} = \mathbf{S^*_i}/\sum|\mathbf{S_i}|^2$.

Results: SSFP images simulating off-resonance were generated. The simulation parameters were: $\alpha = 30^o$, TR/TE = 10/5 ms, T1/T2 = 270/85 (fat), 870/47 (muscle), 1000/200 (blood) ms. Bivariate Gaussian noise was added to the data. The results for the sum-of-squares combination and the proposed method are shown in Fig.1. The initial MW-CS reference image reduces banding artifacts, but has less SNR than the sum-of-squares (SOS) combination. The optimal linear combination preserves the banding reduction performance of the initial reference image and the high SNR of the SOS method.

Phase-cycled SSFP images (N=4) of three $MnCl_2$-doped water phantoms were acquired. $\alpha = 30^o$, 16 cm FOV, $0.5\times0.5\times2\ mm^3$ resolution, TR/TE = 20/10 ms, and 30 kHz bandwidth were prescribed. The sensitivity estimate for a single acquisition is displayed in Fig.2 along with the images from the proposed method and the SOS combination. The proposed method effectively suppresses banding artifacts while achieving high SNR efficiency.

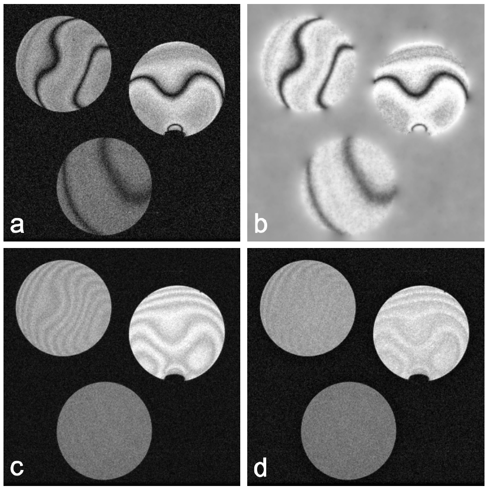

Figure 2. An SSFP acquisition **(a)** and the corresponding sensitivity estimate **(b)** are shown. T1/T2 = 1300/900 (upper-right), 800/375 (upper-left), 250/50 (lower) ms. Four acquisitions were combined with SOS **(c)** and our method **(d)**.

3DFT brain images were acquired at 1.5 T with the following parameters: $\alpha = 30^o$, TR/TE = 15/7.2 ms, $0.67\times1.3\times4\ mm^3$ resolution, 384×192×16 encoding, 31.25 kHz bandwidth, N = 2 and a scan time of 1:32. Figure 3 shows the results of the SOS combination and the proposed reconstruction. The proposed method achieves more robust banding artifact reduction than the SOS reconstruction.

Conclusion: Accurate estimates of the SSFP sensitivities can be obtained from phase-cycled acquisitions. The degree of banding reduction in the initial reference image is crucial at this stage and the MW-CS method performs well in this respect. SSFP images with near-optimal SNR and reduced banding artifacts are reconstructed.

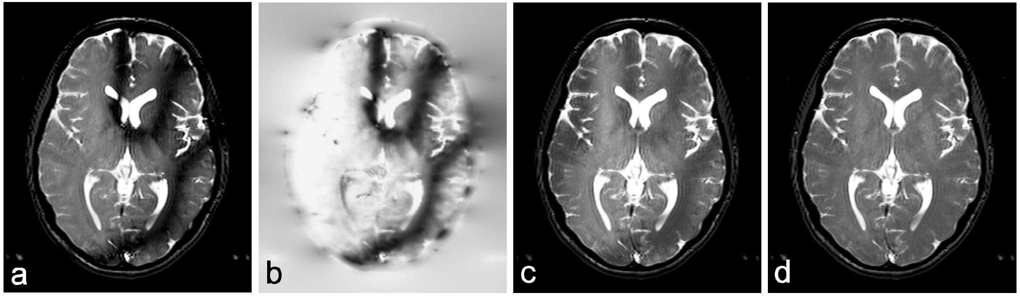

Figure 3. An axial slice of a single SSFP acquisition **(a)** and the corresponding sensitivity **(b).** Two acquisitions were combined with SOS **(c)** and our method **(d)**. The dark bands in **c** are not noticeable in **d**.

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