Optimal balanced SSFP image recombination technique for suppression of banding artifacts surrounding surgical implants

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Introduction

Fully balanced steady-state free precession (b-SSFP) has become an established sequence with both clinical and research applications including joint imaging, cardiovascular imaging and angiography, fMRI, and contrast enhanced cellular micro imaging. This sequence boasts high SNR, and unique T_2/T_1 contrast. However, b-SSFP is highly sensitive to magnetic field inhomogeneity and displays periodic banding artifacts with reduced signal intensity in regions of specific off-resonance separated by 1/TR. One common artifact suppression strategy involves the reduction of TR to maximize the off-resonance value where banding artifacts form, an approach limited by hardware considerations and field strength. A more robust approach involves the acquisition of multiple images with deliberately varied RF modulation frequency over the TR interval (multiple acquisition technique) [1]. Images formed through this approach displace the banding artifacts to different spatial locations, and so image recombination techniques may be used to produce a single artifact suppressed image.

The multiple acquisition technique has proven to be robust at correcting large-scale inhomogeneities where the spacing between adjacent bands is much greater than the image resolution. The efficacy of this method to reduce banding over small spatial scales where the separation between bands approaches the image resolution remains unknown. This scenario occurs in regions of rapidly varying off-resonance caused by inclusions having strong susceptibility difference from tissue, as with metallic implants (Figure 1) and air-tissue interfaces. Through analytic calculation and numerical modeling, this work determines the minimum distance from a strong point susceptibility inclusion that multiple acquisition b-SSFP will effectively correct banding artifacts. This allows for optimization of the image resolution, number of signal averages and off-resonant acquisitions, as well as selection of the recombination method best suited to artifact suppression around the inclusion.

Theory

The b-SSFP periodic banding artifacts are separated by spatial locations corresponding to off-resonant frequency offsets defined by 1/TR, however, the actual spatial location of the bands can be shifted through modulation of the RF phase offset between sequential pulses. A series of *N* images collected with RF phase increments can be combined, on a pixel-by-pixel basis, through numerous approaches. The most promising for SNR optimization is the sum of squares (SS) approach while artifact suppression is ideally handled by maximum intensity projection (MP) recombination [1].

We model a susceptibility inclusion as an object of radius R_0 and susceptibility difference from tissue of $\Delta\chi$ and calculate the off-resonance dipolar field pattern extending into the surrounding media [2]. Assuming a linear field variation over the voxel width *dx*, we equate the dipolar frequency spread across the voxel with a numerically determined acceptable frequency spread, *F(p)* (expressed in terms of #pixels/band). The number of pixels *n* from the center of the susceptibility inclusion in the *Bo* direction is related to the imaging parameters, inclusion magnitude, and acceptable banding level as follows:

$$\frac{1}{(n+1/2)^3}-\frac{1}{(n-1/2)^3}=\left(\frac{dx_0}{R_0}\right)^3\frac{3\pi}{\gamma\Delta\chi B_0 TR}\frac{1}{F(p)}\,.$$

The artifact intensity function *F(p)* provides the number of pixels spanning each band required for either MP or SS to provide artifact suppression to within a tolerance of *p* percent as defined by $p = (max-min)/max\cdot 100\%$, where *max* and *min* are the maximum and minimum pixel intensities in the final image respectively.

Methods

The artifact intensity functions *F(p)* are computed using the b-SSFP signal equations, numerically integrated over 1D voxels, assuming the susceptibility inclusion produces a linear field variation over the pixel dimension. We assume a 10% banding threshold to represent adequate artifact suppression for these calculations (ie. *F*(10%)). Valid comparison of images obtained using different image resolution and recombination methods requires normalization for scan time and SNR. Scan time was normalized by scaling SNR as the square root of the number of signal averages (avg). SNR was scaled with changes in image resolution through a simplified scaling of SNR with voxel volume. The SS and MP combination methods were evaluated through measurement of the combined image SNR for four source images that were generated synthetically with Gaussian noise addition.

Results and Discussion

Fig. 2 displays the percent signal modulation due to the banding artifact after MP and SS recombination as a function of the number of pixels spanning each band. For a fixed resolution and banding spatial frequency, MP is found to outperform SS under all circumstances, but for *N*=2 in particular. The relative SNR efficiency using different image acquisition and recombination strategies are shown in Table 1, in addition to the resolution enhancement permissible to maintain SNR normalization. Under these conditions, Fig. 3 shows that each image combination method offers artifact suppression to a similar distance, however SS achieves this using improved image resolution over the MP techniques.

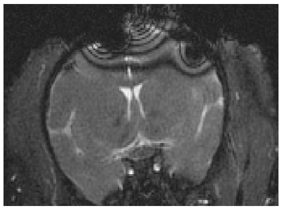

Figure 1: Single b-SSFP acquisition of a primate brain with titanium skull implants. This image could be improved, to some extent, with multiple acquisitions.

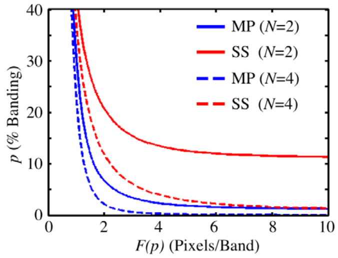

Figure 2: Percent artifact burden versus band spacing

	SNR	
	N=2; avg=2	*N*=4; avg=1
MP	1.131	1
SS	1.233	1.238
	dx (dx$_0$)	
	N=2; avg=2	*N*=4; avg=1
MP	0.9598	1
SS	0.9325	0.9313

Table 1: SNR relative to *N*=4 MP and subsequent resolution reduction factors in terms of dx$_0$

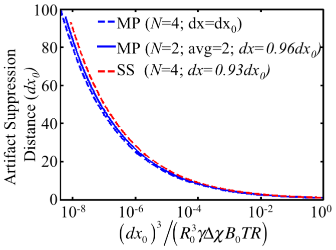

Figure 3: Artifact radius as a function of the voxel volume to perturber strength ratio

Conclusions

For RF phase incremented acquisitions at a given resolution, MP offers superior artifact reduction as compared to SS. However, the 24% gain in SNR efficiency provided by SS relative to MP permits isotropic resolution reduction for SS images by the factor 0.93. Under these circumstances, SS image recombination permits imaging near susceptibility inclusions to the same absolute distance, but with the added benefit of higher resolution images having the same SNR. Normalizing for scan time and SNR, we predict a four RF phase modulated acquisition with SS recombination provides the greatest available image resolution with minimal artifact burden. These results can be applied to tailor the scan parameters for artifact reduced imaging in numerous clinical and research areas such as anatomical imaging of patients with high susceptibility implants, and contrast enhanced cellular imaging near air/tissue interfaces.

References

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