Banding Artifact Reduction in 2D CINE Balanced SSFP at 3.0 T Using Phase-Cycling and *k-t* BLAST

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Introduction

Balanced steady-state free precession (bSSFP) offers excellent signal-to-noise ratio (SNR) and consistent blood/myocardium contrast which renders 2D CINE bSSFP an ideal clinical choice for LV function assessment [1] at 1.5 T. bSSFP imaging remains challenging at 3.0 T due to its sensitivity to adverse off-resonance effects induced by strong field inhomogeneities at the heart-lung interface which might cause severe dark bands and hence bear the risk to impede the detection and tracking of endocardial and epicardial borders. Various approaches have been proposed to eliminate/lessen banding artifacts, such as target anatomy selective shimming, frequency scouting, alternating repetition time (wideband) bSSFP, and multiple-acquisition bSSFP [2-4]. Unlike wideband bSSFP, which suffers from severe SNR reduction, multiple-acquisition bSSFP provides enhanced SNR. Admittedly multiple-acquisition bSSFP goes along with an inherent scan time penalty which might be prohibitive for single breath-hold scans. To overcome the scan time constraints while still improving 2D CINE bSSFP's resilience to off-resonance effect induced banding artifacts this work proposes to combine phase-cycled bSSFP with accelerated imaging and *k-t* BLAST reconstruction [5].

Materials and Methods

Simulations for three different phase-cycling strategies were performed with Matlab (The Mathworks, Natick, USA) to examine the passband plateau for each of these strategies. 2D CINE imaging was conducted in healthy adult volunteers using a 6-element cardiac coil array at 3.0 T (Philips Achieva, Best, The Netherlands). Phase-cycled 2D CINE bSSFP acquisitions (TE=1.48 ms, TR=2.95 ms, α=37°, FOV=320x320 mm^2, matrix size=192x192, cardiac phases=24) were obtained using four-fold accelerated *k-t* BLAST. Aliasing in the undersampled *k-t* data was resolved using signal correlations obtained from integrated low resolution, full k-space training acquired in the same breath-hold. Accelerated breath-held (end-expiration) multiple-acquisition CINE imaging was conducted using a fixed phase increment $\Delta\phi=\pi/2$, $\Delta\phi=\pi$, and $\Delta\phi=3\pi/2$, respectively. Sum-of-squares combination of the individual acquisitions was employed using Matlab. For comparison conventional 2D CINE bSSFP was carried out. Endocardial border sharpness assessment was performed to examine cardiac motion artifacts induced by mis-synchronization. For this purpose, the transitional border zone between myocardium and ventricular blood was defined as: $SI_{myo}+1/3*(SI_{blood}-SI_{myo})$.

Results

Standard bSSFP employs a fixed phase increment $\Delta\phi=\pi$ from excitation to excitation to center the passband on $\theta=0$, where θ is the phase-offset within TR as illustrated in Figure 1a). Multiple-acquisition bSSFP combines a series of N bSSFP acquisitions, each with a specific phase increment $\Delta\phi=2\pi n/N$ (n=0..N-1)[4]. Usually four different phase-cycles are used for banding removal as shown in Figure 1b), but the images acquired with $\Delta\phi=0$ suffer from severe artifacts as a result of the stopband at $\theta=0$. Omitting this phase-cycle disturbs the plateau of the resulting off-resonance profile as demonstrated in Figure 1c). Alternatively, the use of a series of three bSSFP acquisitions with $\Delta\phi=[\pi/3, \pi, 5\pi/3]$ is conceptually appealing to smooth the plateau of the off-resonance spectra. The feasibility and applicability of phase-cycled, accelerated 2D CINE bSSFP imaging is been demonstrated in Figure 2. To achieve high accelerations for balancing the inherent increase in scan time of multiple acquisitions without prohibitive noise amplification associated with coil sensitivity encoding (SENSE) based parallel imaging spatio-temporal correlations in dynamic CINE imaging are exploited using *k-t* BLAST. In contrast to the predictions given by the theory, omitting $\Delta\phi=0$ from the conventional phase-cycling scheme used for *in vivo* imaging yielded only mild disturbances in the off-resonance profile but excellent banding artifact reduction as shown in Figure 2. Banding artifact reduction improved the mean endocardial border sharpness in the inferolateral segment from 1.9 pixels to 1.2 pixels and hence helps to facilitate an enhanced detection of the endo- and epicardial border.

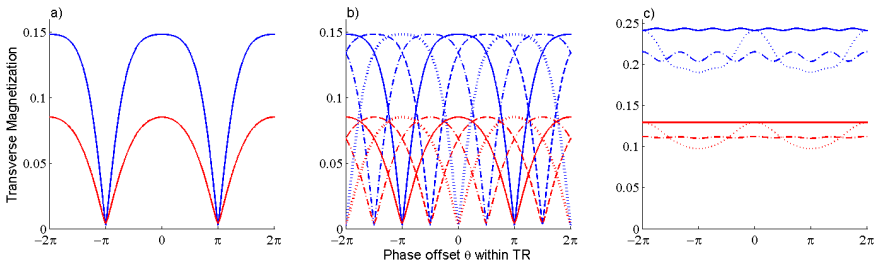

Figure 1: bSSFP off-resonance profiles for myocardium (blue) and blood (red): a) Standard bSSFP, b) Multiple acquisition bSSFP with fixed phase increment $\Delta\phi=2\pi n/4$ (n=0..3), c) Sum-of-squares combination for $\Delta\phi=[0, \pi/2, \pi, 3\pi/2]$ (solid line), $\Delta\phi=[\pi/2, \pi, 3\pi/2]$ (dotted line), and $\Delta\phi=[\pi/3, \pi, 5\pi/3]$ (dash-dotted line).

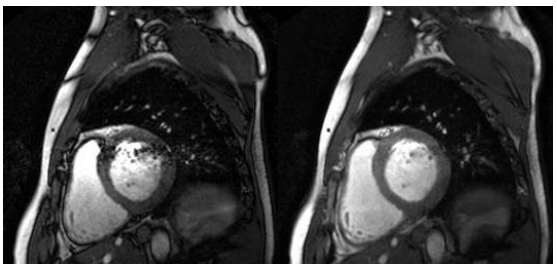

Figure 2: Standard bSSFP and phase-cycled, multiple acquisition bSSFP using $\Delta\phi=[\pi/2, \pi, 3\pi/2]$ in conjunction with four-fold *k-t* BLAST acceleration.

Discussion and Conclusions

The accelerated, phase-cycled 2D bSSFP imaging paradigm presented here promises to extend the capabilities of routine CINE imaging at (ultra)high field strengths. The proposed approach reduces the demands for time consuming shimming or systems calibration while improving both operator convenience and patient comfort. 2D CINE bSSFP free of banding artifacts holds the promise to make the interim solution of spoiled gradient echo CINE imaging obsolete and hence obviates the need for exogenous contrast agent application to enhance the poor native blood/myocardium contrast. A recognized limitation of this study is its assessment in a limited number of subjects. Therefore, efficacy of the described accelerated, phase-cycling methods in the clinical routine environment awaits further study.

References:

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