Dual Acquisition Cardiac Cine BOLD Imaging with Flow Compensation at 3T: Early Findings

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Purpose: Both preclinical and clinical studies have shown that balanced steady-state free precession (bSSFP) based Blood-oxygen-Level-Dependent (BOLD) MRI may be valuable for detecting myocardial oxygenation changes associated with ischemic heart disease [1,2]. In particular, previous studies have shown that the oxygen-sensitive contrast in bSSFP images is directly related to repetition time (TR)[3]. However, in the presence of static field inhomogeneities, image artifacts scale with TR; in the form of band artifacts or intense signal heterogeneity due to spin motion in a field variation. Although recent studies at 1.5T have shown that the motion artifacts can be reduced with first-order motion compensation [4], it cannot mitigate the band artifacts in long TR bSSFP acquisitions. Through simulations and experimental studies in human, here we demonstrate that a dual-acquisition strategy with flow compensation may provide enhanced immunity to band artifacts for bSSFP-based cine BOLD MRI at 3T.

Theory: Multiple bSSFP acquisition strategies have been proposed for minimizing banding artifacts [5]. However, to date, such an approach has not been adopted for cardiac applications. To effectively translate the multiple acquisition strategy for cardiac cine BOLD imaging, it is imperative to (a) ensure that the independent acquisitions do not lead to off-resonance dark bands within the left ventricular (LV) cavity; and (b) that the signal intensity variations within the myocardium are significantly smaller than the signal variations observed within conventional (short TR) bSSFP acquisitions (<5%). In the most time-efficient version of the multiple acquisition strategy, dual acquisition, such a restriction may be accommodated by carefully controlling the phase rotation angle (β) of phase-cycled RF excitation pulses. Simulation of the resulting off-resonance spectrum from combined (maximum intensity projection, MIP) bSSFP signals with different Δβ that permits a 5% tolerance, hereinafter referred to as *Spectral Tolerance*, can be achieved with Δβ of approximately 100° for a range of excitation flip angles (Fig. 1). Off-resonance spectral profiles of two phase-cycled bSSFP acquisitions (one at β = 0° and the other at β = 100°), along with the MIP of the bSSFP profiles are shown in Fig. 2. Note that the *Spectral Tolerance* achieved with Δβ of 100° from the dual acquisition doubles the *Spectral Tolerance* of a single bSSFP acquisition. This provides significantly increased immunity to off-resonance (approximately 2/3TR) and limit the dark bands from either of the two acquisitions from being placed within the LV chambers.

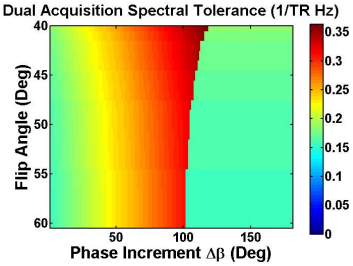

Fig. 1 *Spectral Tolerance* (color bar) as a function of Δβ and flip angles in the pragmatic range at 3T. Simulations assume T_1/T_2 = 900/200ms.

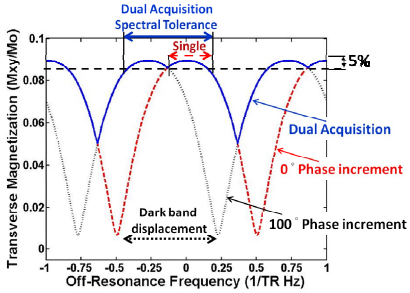

Fig. 2 Off-resonance profile of individual (red (β = 0°) and black (β= 100°) lines) and MIP of the two bSSFP profiles (blue) with Δβ = 100° (T_1/T_2 = 900/200 ms).

Methods: Following informed consent, imaging studies were performed in human volunteers (n=5) on a 3T Siemens Verio MRI system (Siemens Medical Solutions, Germany). After localization scans, whole-heart shimming, and scouting to determine the appropriate center frequency, breath-held, flow-compensated bSSFP acquisitions were prescribed in multiple planes along short-axis orientation with following scan parameters: TR = 6 ms, flip angle = 50°, imaging resolution = 1.9 x 2.5 x 6 mm^3, temporal resolution = 35 ms, readout bandwidth = 550 Hz; β = 0°, and β = 100°. For comparison, conventional bSSFP images (minimum TR, TR=3ms) were also obtained. Subsequently, the images acquired with TR = 6 ms at the two different β were combined as MIPs. Endo- and epi-cardial contours were drawn on end-systolic (ES) and end-diastolic (ED) frames from the cine data set and the coefficient of variance (COV) was derived from all the pixels in the myocardium for each acquisition and MIP and averaged across all imaging slices and volunteers. One-way ANOVAs were performed to test whether the mean myocardial signal deviation is different between TR = 3 ms, single acquisitions with TR = 6 ms at the different β, and MIPs. This was performed independently for ES and ED data sets. Statistical significance was established at $p<0.05$.

Results: Representative ES and ED images from flow-compensated dual bSSFP acquisitions and the MIP of the corresponding images, along with short TR bSSFP (matched to the cardiac phase and imaging plane) are shown in Fig. 3. Note that the banding artifacts observed in acquisitions at β = 0° and β = 100° (green arrows) with TR = 6 ms are significantly reduced in the MIP images. The MIP images appear to have comparable image quality to images acquired with TR = 3 ms. Mean COVs derived from images acquired under different conditions are shown in Table 1. The mean COVs of ES and ED images acquired with TR = 6 ms at the two different β were significantly greater than that measured from the corresponding MIP (ED: $p<0.01$; ES: $p<0.01$) and short TR bSSFP (ES: $p<0.01$; ED: $p<0.02$) images. Results also showed that the mean COV values derived from MIPs and short TR bSSFP images were not statistically different.

Discussion and Conclusions: Reliable detection of myocardial oxygen changes on the basis bSSFP-based BOLD MRI at 3T requires minimization of image artifacts. In this work we demonstrated that an optimal dual acquisition strategy, combined with flow compensation, may be a viable means for achieving robust image quality for cine BOLD MRI at 3T. Although the total acquisition time is increased with the proposed dual acquisition method, given the increased SNR at 3T (relative to 1.5T), it is expected that imaging acceleration methods can be used to shorten acquisition time. Further studies are required to evaluate the utility of the approach for detecting myocardial oxygen defects in the setting of coronary artery disease.

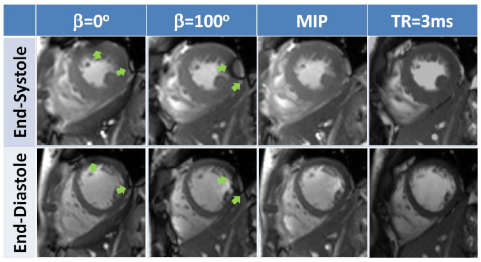

Fig.3 End-systolic (ES) and end-diastole (ED) images acquired with β = 0°, β = 100°, MIP at TR = 6 ms at 3T. For comparison, corresponding short TR images are also shown.

Coefficient of Variation (COV)	TR = 6 ms Single Acquisition	TR = 6 ms Dual Acquisition	TR = 3 ms
End systole	0.39 ± 0.14	0.21 ± 0.09	0.23 ± 0.03
End diastole	0.43 ± 0.04	0.31 ± 0.04	0.36 ± 0.01

Table 1. Mean coefficient of variation (COV) of myocardial signal intensities

Ref. : [1] Dharmakumar Invest Radio 2007; 42(3):180-8. [2] Dharmakumar JMRI 2008; 27(5):1037-45 [3] Arumana MRM 2008; 59(3):561-70 [4] Zhou JMRI 2010; 31(4): 863–871. [5] Bangerter MRM 2004; 51:1038–1047