Myocardial BOLD Imaging using Flow Compensated 2D Cine bSSFP

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Introduction: Robust image quality is critical for reliable detection and evaluation of myocardial oxygenation changes with blood-oxygen-level-dependent (BOLD) imaging. Recently, balanced Steady-State Free Precession (bSSFP) methods have been employed to overcome image quality limitations associated with myocardial BOLD methods. However, the long TRs required for optimal BOLD contrast can lead to unwanted flow/motion artifacts, ultimately compromising image quality. In this work we evaluate the utility of 2D first-order motion compensation scheme to minimize flow/motion artifacts in cardiac phase-resolved bSSFP BOLD imaging.

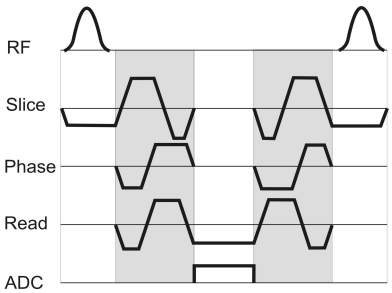

Figure 1. Timing diagram of the 2D bSSFP sequence with zeroth and first-order motion compensation. The first-order moment is compensated at both TE and TR in slice-selection and readout directions; In the phase encoding direction, the first order moment is only compensated at TR.

Methods: Animal Preparation & Imaging: Six dogs were studied in an Espree System (1.5T, Siemens Medical Solutions, Erlangen) using first-order flow/motion-compensated bSSFP method (sequence diagram shown in Figure 1) over the whole left ventricle. Basal, mid-ventricular, and apical cine images were acquired with three different approaches: (A) TR = 3.5ms (conventional cine); (B) TR = 6.2 ms (long TR without compensation); and (C) TR = 6.2 ms (long TR with flow/motion compensation). Preliminary myocardial BOLD studies were performed on animals (n=2) with controllable LCX stenosis to evaluate the benefits of flow compensation. Studies were performed under rest and adenosine stress in the absence or presence of severe stenosis (greater than 80% narrowing). Other scan parameters were: spatial resolution = 1.2x1.2x5; TE=3.1ms; and flip-angle=70°. Data Analysis: Three experts used (i) Ghost artifacts (GA), an impression of artifacts observed within the image; and (ii) myocardial inhomogeneity (MI), a measure of the signal homogeneity within the left-ventricular myocardium, to evaluate myocardial signal characteristics. One-way ANOVA was performed to ascertain whether there were any differences in the indices with various approaches. Statistical significance was set at $p<0.05$.

Results: Mean scores for the 3 approaches assessed over the various positions along the left ventricle of all animals are summarized in Figure 2. The scores for Approach (B) were significantly higher than Approaches A and C ($p<0.01$). For TR=6.2ms, GA and MI increased when moving from the apex to base. There was no statistical difference in the scores for Approaches (A) and (C). Figure 3 shows a representative set of late-systolic and late-diastolic mid-ventricular images obtained from a dog under baseline and severe LCX stenosis (SS). With stenosis, the signal loss in the LCX territories became apparent; consistent with the expectation that stenoses lead to significant reductions in myocardial oxygen reserve in the presence of adenosine stress. Results showed remarkable reduction in image artifacts, permitting the visualization of signal loss in the LCX territories over the entire cardiac cycle in the presence of LCX stenosis.

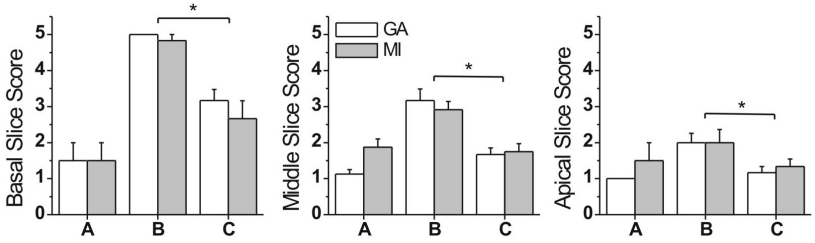

Figure 2. Expert scores (1 for best, 5 for worst) for ghost artifacts (GA) and myocardial inhomogeneity (MI) for the basal, middle (mid-ventricular), and apical slices acquired with 3 bSSFP sequences. A: TR=3.5ms, B: TR=6.2ms (A and B acquired without flow compensation); and C: TR=6.2ms (with flow compensation). Ghost artifacts and myocardial inhomogeneity in images acquired with Approach B were significantly higher than in images acquired with Approach C ($p < 0.01$) in all 3 slices. For TR=6.2ms (B, C), GA and MI increase as slice position is moved from the apex to base. Note that there is no significant difference in GA or MI for images acquired with Approach A and C in the basal, middle or apical slices.

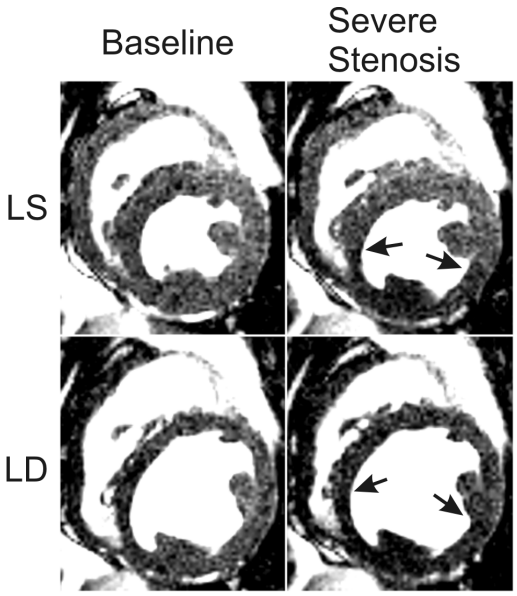

Figure 3. Representative set of cardiac phase-dependent short-axis mid-LV images [upper row: late-systole (LS); lower row: late-diastole (LD)] obtained from a canine model with no coronary artery stenosis under rest (left column), and with severe LCX stenosis under adenosine stress (right column) using flow-compensated 2D bSSFP method. The scan parameters were: TR=6.2ms, FA=70°, Temporal resolution =12ms. Note the discriminating signal loss in the LCX territories marked by arrows (short arc) in the presence adenosine stress with LCX stenosis.

Conclusions: First-order flow/motion compensation strategy employed in this study provided significant improvement in image quality compared to the standard long TR SSFP BOLD approach without flow compensation. It was also observed that the imaging artifacts observed in the flow-compensated long TR acquisitions were not significantly different when compared to the conventional (short TR) cine bSSFP imaging that is routinely employed in the assessment of cardiac function. In addition, the proposed strategy allowed for the visualization of the hypointense LCX territories in stress images with LCX stenosis throughout the cardiac cycle. We anticipate the proposed method may enable a more reliable means for detecting and evaluating BOLD signal changes due to coronary artery stenosis.