Free-breathing, Black-blood Cardiac Imaging Using Single-shot bSSFP Sequence: A Feasibility Study

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Introduction: Cardiac MRI has been continuously challenged by complex cardiac motion, respiratory motion and pulsatile blood flow of the heart. ECG-gating and breath-holding have been commonly used to suppress the adverse effect of motion, together with black blood (BB) preparation[1,2] to minimize flow-related imaging artifacts. Segmented fast spin echo (FSE, TSE) sequence has been widely used to collect 2D images within multiple breath-holds. However, suboptimal breath-holding or heart rate variation (e.g., arrhythmia) during segmented data acquisition may impair image quality.

Development of fast imaging techniques (e.g., bSSFP) and acceleration strategies (e.g., parallel imaging, partial Fourier) in the past decade substantially reduce the imaging time required for a 2D image. Furthermore, the balanced gradient structure in bSSFP preserves magnetization across a longer readout train without image blurring associated with conventional spoiled gradient-echo or FSE sequences. The purpose of this study was therefore to: 1) investigate the feasibility of free-breathing BB cardiac imaging using a single-shot bSSFP sequence; 2) compare the efficacy of two BB methods: double inversion recovery (DIR)[1] and T2IR[2,3] for this application.

Methods: *Numerical Simulations*: To optimize the preparation time (inversion recovery time (TI) for DIR; T2prep-TI time for T2IR) for blood nulling, simulations were performed in Matlab (The MathWorks Inc., USA) based on Bloch equations. Simulation parameters included: T_1/T_{2blood} = 1250/250 msec; $T_1/T_{2myocardium}$ = 950/50 msec; flip angle = 70°; 10 linear ramp-ups before single-shot bSSFP readout.

Volunteer Study: Five healthy subjects with informed consent were scanned on a 1.5T whole body MRI (MAGNETOM Espree, Siemens AG Healthcare, Germany). Fourteen short-axis slices and two long-axis slices (four-chamber and two-chamber) were acquired from each subject to cover the entire heart. Each measurement was performed twice using DIR (TI = 800 msec) and T2IR (T2prep = 60 msec; TI = 640 msec) preparations, respectively, in random order. Typical imaging parameters included: FOV = 24 x 30 cm^2; matrix=164 x 192; voxel size = 1.5 x 1.6 x 5.0 mm^3; flip angle = 70°; TR/TE = 3.2/1.5 msec; phase partial Fourier = 6/8; parallel imaging (GRAPPA) factor of 2. Data acquisition lasted for 260 msec and was gated to diastolic cardiac phase. Fat saturation and 10 linear ramp-ups were applied before centric-reordering bSSFP readout.

Data analysis: Myocardium signal and myocardium-blood contrast were measured to compare the efficacy of the two BB methods. Since the absolute values of the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) could not be directly measured due to utilization of parallel imaging, relative values (rSNR, rCNR) were obtained by closely matching measurement regions-of-interest for 70 short-axis DIR and T2IR image pairs acquired with identical parameters and coil configuration. rSNR and rCNR from DIR and T2IR preparations were compared using paired t-test.

Results: Figure 1 shows simulated normalized imaging contrast between myocardium and blood as a function of T2prep time and TI using T2IR preparation. The combination of 60 msec T2prep and 640 msec TI yields reasonable myocardium-blood contrast (0.18) with good blood suppression as indicated by the blue blood nulling line. Blood signal after DIR preparation is a special case of T2IR (T2prep =0) and a TI value of 800 msec leads to effective blood suppression and good blood-myocardium contrast (0.53).

Figure 2 shows representative free-breathing, single-shot BB images acquired from a healthy subject. The left ventricle (LV) is well delineated using both T2IR and DIR preparations. The right ventricular (RV) free wall is better depicted with T2IR preparation (red arrows). In addition, T2IR yields consistent blood suppression including in long axis views and apical short-axis slices (green arrows) where through plane blood flow is limited. The rSNR and rCNR values are significantly higher using DIR preparation, as summarized in Table 1.

Discussion and Conclusions: DIR relies on inflow of inverted blood and works well in short-axis views with high rSNR and rCNR values. However, mismatch of slice position between selective inversion and imaging may lead to myocardial signal loss, as illustrated in figure 2a and 2b. T2IR explores the relaxation difference between blood and myocardium and can potentially be extended to 3D sequences to compensate for the signal loss from preparation. Furthermore, T2IR performs consistently well regardless of imaging orientation. It is particularly suitable for cases with limited through plane blood flow (e.g., hypokinetic heart; long axis views). In conclusion, free-breathing BB cardiac imaging is feasible using single-shot bSSFP sequence. While both DIR and T2IR provide effective blood nulling in the short-axis view, T2IR provides more effective blood suppression in apical short-axis slices and long-axis views at the cost of lower myocardium signal than that from DIR preparation.

	T2IR	DIR	p-value
rSNR	19.4±8.9	31.8±15.3	<0.001
rCNR	15.1±7.5	24.8±10.9	<0.001

Table 1. Relative SNR and CNR measured from 70 BB short-axis image pairs using T2IR and DIR preparations. DIR images show 63.9% and 64.2% improvement in rSNR and rCNR, respectively, as compared to corresponding values from T2IR preparation.

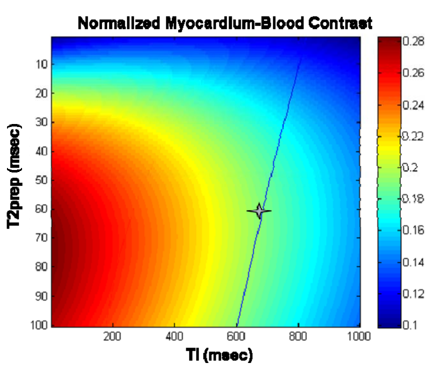

Figure 1. Normalized contrast as a function of T2prep-TI time using T2IR preparation. The blue line indicated optimal combination of T2prep and TI for blood nulling. 60 msec T2prep and 640 msec TI (star in the figure) were selected, resulting in a normalized contrast of 0.18. Using DIR, blood was nulled at TI of 800 msec as indicated by data point with 0 msec T2prep time.

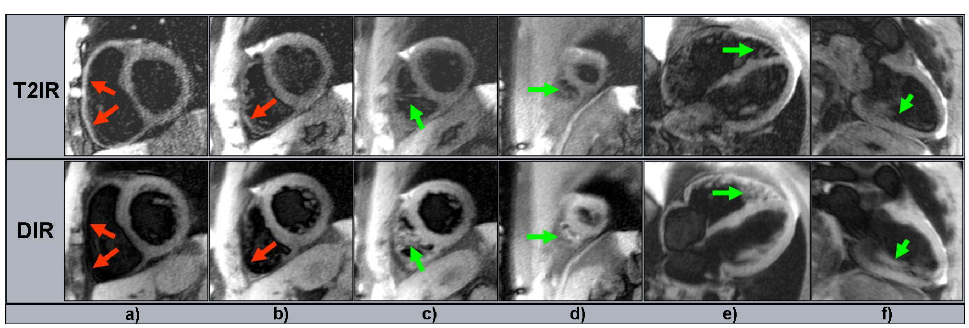

Figure 2. Representative images from a volunteer acquired with single-shot bSSFP sequence under free breathing, with T2IR (top row) and DIR (bottom row) preparations. DIR images show higher rSNR and rCNR. T2IR images have better delineation of the right ventricular wall (red arrows) and consistent blood suppression including apical short-axis slices and long axis views (green arrows).

References:

[1] Simonetti OP et al, Radiology 199: 1996
[2] Liu CY et al, ISMRM 2008: 3079
[3] Nguyen TD et al, ISMRM 2009: 607