Variable Flip Angle balanced SSFP for Low SAR Cardiac Cine Imaging

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Introduction: Cardiac cine imaging is performed clinically using balanced SSFP[1] (bSSFP) due to its high blood-myocardial contrast and SNR efficiency. Higher flip angles (FA) generate higher blood-myocardium contrast[2], but can result in substantially increased SAR, which may result in exceeding SAR limitations. Low SAR imaging is needed for imaging at field strengths >1.5T and for imaging patients with implanted devices. The ***objective*** of this work was to lower the SAR of cardiac cine bSSFP using a variable FA[2-3] (VFA) scheme while maintaining blood-myocardium contrast similar to conventional segmented constant FA (sCFA) bSSFP.

Methods: The proposed VFA scheme (Fig.1A) consists of a symmetric trapezoidal FA profile synchronized to a linear top-down (non-segmented) *k*-space acquisition. The outer *k*-space lines are acquired with a lower FA (α_{low}) to reduce SAR, followed by ramp pulses to smooth the transition into the dynamic steady-state of the higher FA (α_{high}) echoes acquired near the center of *k*-space to achieve the desired SNR and CNR. To reconstruct cardiac cine VFA images we acquire single shot images continuously (cVFA) and asynchronous to the cardiac cycle (Fig. 1C) so that each k_y-line is acquired for each cardiac phase with the appropriate contrast. The data is retrospectively rebinned based on the ECG signal. *Simulation:* Bloch equation simulations were performed in MATLAB to help design the VFA scheme to achieve blood-myocardial contrast similar to CFA. Simulations were performed for stationary myocardium (T_1/T_2: 867/57ms), flowing blood (T_1/T_2: 1200/20ms) with percent spin replacement per TR (Δs) of 50%, imperfect slice profile, TR/TE=3.1/1.5ms, #measurements=23, and #ky=204. *Volunteer imaging:* Five volunteers (N=5) were imaged on 1.5T (Siemens, Erlangen, Germany) with imaging parameters similar to the simulation (cardiac phases: 25, resolution: 1.5x1.5x5 mm, TE/TR=3.1/1.5ms, BW: 1502 Hz/px). Five different experiments were conducted with the following FA schemes: 1) sCFA 70˚ 2) cCFA 70˚ 3) cVFA (α_{low}:30˚, α_{high}:70˚, #ramp:20 and #high:80) 4) cCFA 78˚ 5) cVFA (α_{low}:50˚, α_{high}:98˚, #ramp:40 and #high:40) . *Image analysis:* The cVFA and cCFA reconstructions were performed offline. Each k_y-line was then retrospectively time-normalized based on the RR interval from the ECG data and linearly interpolated into 25 cardiac phases. *Data analysis:* ROIs were drawn in blood, myocardium, and the background noise in diastolic images to compare the blood-myocardial CNR for the sCFA, cCFA, and cVFA schemes.

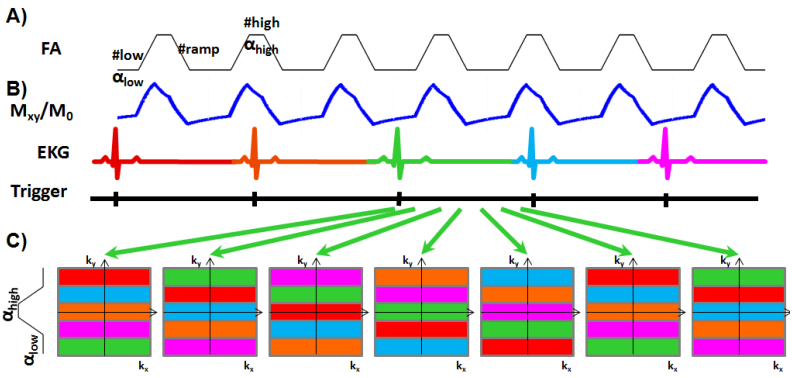

Figure 1: Diagram of the VFA cardiac cine acquisition for the acquisition of 7 cardiac phases with 5 shots in 5 RR intervals. The k-space is acquired continuously over each RR interval (i.e) 1st shot of the 1st cardiac phase, followed by the 2nd shot of the 2nd cardiac phase and so on to maintain similar contrast over all the cardiac phases. The FA is varied from α_{low} to α_{high} along the linear k-space to reduce the SAR (bottom left).

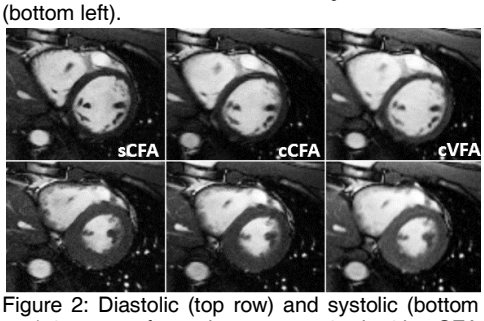

Figure 2: Diastolic (top row) and systolic (bottom row) images of a volunteer acquired with sCFA (left), cCFA (middle) of 70˚ and cVFA acquisition (α_{low}:30˚, α_{high}:70˚, #ramp:20 and #high:80).

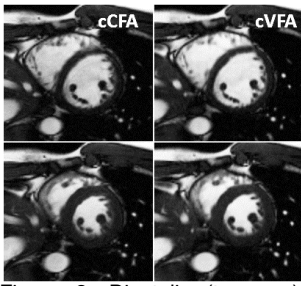

Figure 3: Diastolic (top row) and systolic (bottom row) images of a volunteer acquired with cCFA (left) 78˚, and cVFA acquisition (α_{low}:50˚, α_{high}:98˚, #ramp:40 and #high:40).

Results: Fig. 1B shows the simulated dynamic steady state signal (M_{xy}/M_0) for myocardium using the cVFA scheme. Fig. 2 shows the volunteer images acquired using sCFA, cCFA and cVFA schemes at end-diastole and end-systole. SAR decreased by 45% for cVFA compared to sCFA (1.6±0.1 vs. 2.9±0.2 W/kg) with an insignificant decrease in CNR (39±10 vs. 37±7). Simulation results showed that the VFA scheme used in Fig. 2 increased the FWHM from 1 to 1.34. Fig. 3 shows the images acquired in another volunteer with maximum SAR using cCFA and cVFA schemes. Blood-myocardial CNR increased by 29% for VFA compared to CFA (55±9 vs. 43±8) with similar SAR (3.3±0.5 vs. 3.3±0.5 W/kg).

Discussion and Conclusion: The low SAR cVFA scheme enables cardiac cine imaging with image contrast similar to conventional sCFA and only a modest decrease in resolution. The low SAR cVFA technique will be useful for imaging at ≥3T with higher effective FA than current SAR limits permit and for safer imaging of patients with implantable devices.

References: 1. Finn JP *et al.*, *Radiology* 2006;241(2):p338. 2. Hennig J *et al.*, *MRM* 2003;49(3):p527. 3. Paul D *et al.*, *MRI* 2009;27(7):p933. **Acknowledgement**: The authors are grateful for research support from Siemens Medical Systems.