Free Breathing Variable Flip Angle Balanced SSFP Cardiac Cine Imaging with Reduced SAR at 3T

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PURPOSE: Breath-hold, segmented, balanced steady state free precession (bSSFP) for cardiac cine imaging is challenging at 3T, more so in patients with poor breath holding capacity. Poor breath holding results in motion artifacts and compromises evaluation of cardiac function. These motion artifacts can be reduced by free-breathing, real-time imaging with retrospective data binning and image reconstruction [1,2], but this is SAR intensive at 3T. Recently, breath-hold, variable flip angle (VFA) cardiac cine imaging technique [3] was used to reduce the SAR at 1.5T. The ***objective*** of this study was to develop and evaluate a free breathing VFA (FB-VFA) cardiac cine imaging technique with reduced SAR at 3T.

METHODS: Bloch equation simulations were performed to define the trapezoidal VFA scheme [2] with the least deposited RF energy, point spread function (PSF) ≤ 1.2, and blood-myocardium contrast similar to the constant SAR-limited flip angle (α) of 40° at 3T. The deposited RF energy was estimated as the sum of squares of individual flip angles of the VFA scheme. The optimized VFA scheme used: α_{high}=50°, α_{low}=25°, number of α_{low} pulses (N_{low})=25, N_{ramp}=20 and number of α_{high} (N_{high})=3 for N_{ky}=93. The simulated VFA scheme reduced deposited RF energy by 35% compared to constant FA (CFA)=40° with PSF=1.18 and blood-myocardium contrast of 0.11 identical to CFA=40°. Note that the optimized VFA scheme has α_{high}=50°>CFA=40° which results in increased blood [4] and myocardium signal but with similar contrast.

FB-VFA and segmented, breath-hold CFA (BH-CFA) cardiac cine images were acquired in both short-axis and four chamber imaging planes in healthy subjects (N=10) and one patient with Duchenne Muscular Dystrophy (DMD) with limited breath hold capacity. The imaging parameters were: FOV= 360×303 mm, slice thickness=6mm, slice gap=4mm, 10 to 12 slices, resolution=1.9×1.9 mm, TR/TE=2.8/1.4 ms, bandwidth=1371 Hz/px and GRAPPA factor=2. The real-time, FB-VFA images had a temporal footprint of 263ms and were acquired for 60 seconds. The ECG timestamp and the bellows signal were recorded for each k_y line. The k_y lines below the bellows threshold were discarded and the remaining lines were binned based on the ECG timestamp, normalized for RR-interval changes, linearly interpolated to 20 cardiac phases (~50ms), and GRAPPA reconstructed [5].

The BH-CFA and the reconstructed FB-VFA cardiac cine images were scored by two cardiac MRI experts using a 5-point scale in increments of 0.5 with 5 being excellent. SNR was measured in the LV-blood, RV-blood, and myocardial septum at end-diastole. Quantitative measurements of ejection fraction (LVEF), end diastolic volume (LVEDV), end systolic volume (LVESV), stroke volume (LVSV), and end diastolic myocardial mass (LVEDM) were measured using manual contour analysis.

RESULTS: *Image Quality* – Fig. 1 shows a diastolic phase of the four-chamber view acquired in a healthy subject with BH-CFA and FB-VFA. The line profile through the mitral valve along the time dimension clearly delineates the mitral valve in both reconstructions. Fig. 2 shows end-diastolic and end-systolic short-axis cardiac cine images acquired in the DMD patient. Myocardial motion artifacts due to poor breath hold capacity are seen in the in BH-CFA (arrowheads) and are absent in the FB-VFA images, which clearly depict the myocardial wall and papillary muscles.

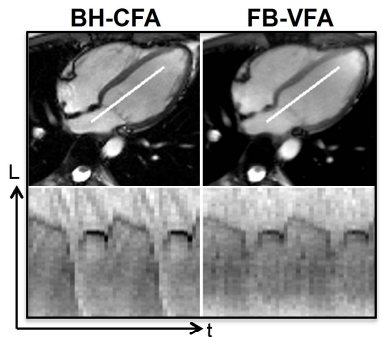

Fig.1 BH-CFA and FB-VFA images acquired in a healthy subject (top row) and the corresponding line profile through the mitral valve (white line) along the time dimension (bottom row) clearly delineates the mitral valve in both the reconstructions.

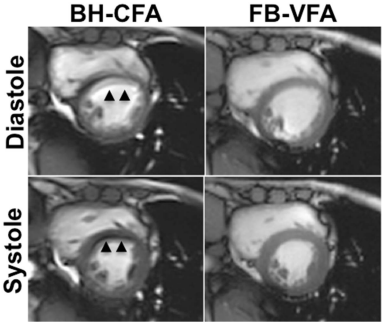

Fig.2 BH-CFA and FB-VFA images acquired in a DMD patient. Motion artifacts are visible in the septal wall due to poor breath holding (arrows) during BH-CFA and are eliminated in the FB-VFA reconstruction.

Image Analysis – Table 1 shows the SAR, image quality scores, quantitative LV measurements, SNR and CNR measured in BH-CFA and FB-VFA in healthy subjects (N=10). The SAR was reduced by 25% in FB-VFA exams compared to BH-CFA. The qualitative scores for the FB-VFA images indicated that the image quality was sufficient (>3) to perform global and regional cardiac functional analysis. FB-VFA estimates of LVEDV and LVSV were significantly different compared to BH-CFA, with FB-VFA reporting an average of 5% increase in LVEDV and a 12% increase in LVSV. Lastly, the SNR of the LV-blood and myocardium were increased in FB-VFA compared to BH-CFA, as shown in the simulations.

		BH-CFA	FB-VFA
	SAR (W/kg)	2.8±0.7	2.1±0.5*
Score	Short-axis	4.3±0.8	3.1±0.5*
	Four-Chamber	4.6±0.6	3.4±0.4*
LV Measurements	LVEF (%)	60±6	63±4
	LVEDV (ml)	128±23	134±21*
	LVESV (ml)	51±9	49±7
	LVSV (ml)	77±19	86±17*
	LVEDM (g)	95±23	93±23
SNR	LV-blood	94±28	121±43*
	RV-blood	84±23	98±51
	Myocardium	34±8	60±22*
	CNR	60±22	61±23

*Table 1: SAR, image quality score, quantitative LV measurements, SNR, and CNR comparison of BH-CFA and FB-VFA cardiac cine images in healthy subjects. * indicates P<0.01*

DISCUSSION: The FB-VFA technique will likely be especially useful in patients with poor breath-hold capacity. Note, as expected, the reported ventricular volumes are different between FB-VFA and BH-CFA, which are likely due to differences in loading conditions during breath-hold and free-breathing. The clinical evaluation of FB-VFA technique in DMD patients with poor respiratory function is an ongoing study at our Institution and further clinical studies are needed to evaluate its robustness in these and similar patients.

CONCLUSION: FB-VFA can be used to reduce SAR by 25% for free-breathing, cardiac cine imaging at 3T, with image quality sufficient to perform global and regional cardiac functional analysis.

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