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Free Breathing Single Navigator Gated Cine Cardiac Magnetic Resonance at 3 Tesla: Feasibility Study in Patients

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Abstract

Background—Cardiac magnetic resonance imaging (CMRI) is an important tool to assess cardiac function. However, one of the limitations of CMRI is the need for frequent breath holding steps. This may be inconvenient to some patients and limit the use of this modality in patients unable to cooperate because of cognitive reasons or, physically incapable of perform the required breath-holding steps. The purpose of this study is to overcome intrinsic timing and computation limitations of dual-navigator cine imaging and demonstrate the feasibility of free-breathing (FB) cine cardiac left ventricular function with a single respiratory navigator gating at 3T.

Results—Eight participants underwent cine CMRI with both the conventional 2D cine BH and FB navigator gated technique. Scan parameters were identical, except in the FB technique, in which a respiratory navigator and only two signal averages were used. Images were scored for quality. Left ventricular end-systolic volume (ESV) and end-diastolic volume (EDV) were calculated. The difference in the ESV and EDV assessed by the BH, and FB were not statistically significant (P -value =0.9, and 0.2) respectively. There was good agreement between LV volumes with the limits of agreement ($\pm 2SD = \pm 22.36\text{ml}$). Image quality score was not significantly different (p -value =0.76).

Conclusion—FB cine imaging utilizing a single respiratory navigator gating technique is comparable to conventional BH techniques in both qualitative and quantitative imaging measures. Therefore the FB cine technique can be used as an alternative for children and patients who are unable to hold their breath.

INTRODUCTION

Advancement in MR has allowed for its increased used in cardiac imaging, such as in the assessment of congenital heart disease, pericardial disease, ventricular and valvular dysfunctions as well as the assessment of myocardial wall motion. Cardiac Magnetic Resonance is a reliable diagnostic tool in the assessment of cardiovascular function and for proper patient management. However, the need for repeated breath-holding (BH) steps add difficulty in obtaining good quality images due to various factors including drifting of the left heart margin and irregular positioning and movement of the diaphragm^{1–3}.

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Furthermore, the repeated BH steps preclude the use of the BH cine technique in children and patients with medical conditions that prevent them from breath-holding. As such, there is a need for techniques that do not require complicated planning and demonstrate similar quality on both quantitative (end-systolic volume, end-diastolic volume, ejection fraction) and qualitative (image quality scoring) measures while permitting the patient to breathe freely within clinically reasonable scan time. A suitable free-breathing technique could also simplify various cardiac MR stress procedures like dobutamine stress test since such procedures require multiple short breath holds ^{4,5}.

Various techniques have been developed to monitor respiration and chest wall movement ⁶⁻⁸. However, they do not circumvent the problem of imaging children and patients with medical conditions that prevent breath holding. Seeger et al.⁹ demonstrated the possibility of obtaining 3D cine free breathing techniques at 1.5T without respiratory navigation in infants using up to 3 averages which was possible due the little respiratory motion in this patient group (average age 2.2 years) but would not be feasible in an older patient group with greater diaphragmatic excursion. In an older subject group, Peters et al.⁵ showed a FB cine technique at 1.5T requires sophisticated dual navigator technique and software manipulation as well as offline reconstruction while allowing for acquisition of only 16 cardiac phases. This complicated planning and manipulations that require pulse sequence programming preclude the feasibility of utilizing these techniques in routine clinical imaging and in imaging centers that do not have the technical expertise of such programming. A commonly used alternative is increasing the number of signal averages (NSA) to 4 or higher which substantially prolongs the scan time. In this work, we tested the hypothesis that free-breathing cine imaging is feasible in general patient population with a single navigator and only two NSA. We evaluated the feasibility of free breathing (FB) 2D multi-slice cine cardiac imaging with single respiratory navigator gating at 3T and its comparability in both objective and subjective measures to traditional BH technique.

METHODS

Participants

A 3T Philips Achieva equipped with a six-channel surface coil (Philips Medical Systems, Best, NL) was used to image all subjects. A healthy subject was initially imaged to determine the appropriate imaging parameters during free-breathing using various settings of incremental increase in signal averages (NSA). This initial scan was used to visually assess the best possible free breathing setting resulting in least myocardial edge blur with the shortest scan times for a single cine short axis position. Subsequently, as part of a comprehensive cardiovascular evaluation for young adults and pediatric patients with Human Immunodeficiency Virus (HIV), eight HIV-positive subjects (six females) aged 12–46 underwent cardiac MR to assess myocardial wall motion. All subjects signed informed consent for this institutional review board approved protocol and the study was HIPAA compliant.

Imaging

The eight subjects were imaged using gradient-recalled-echo (GRE) 2D cine BH with one average and FB respiratory navigator gated technique with 2 averages on the same 3T scanner. NSA=2 was employed to further suppress motion artifacts. Patients with standard contraindications to MR (cardiac pacemakers, cerebrovascular clips, cochlear implants) were excluded.

In the FB technique with navigator, a pencil- beam respiratory navigator was positioned on the right hemi-diaphragm with an acceptance window of 3mm and slice-tracking ¹⁰. The

navigator pulse was 11 ms long and utilized in a leading position directly after the R-wave. Scanning covered 30 cardiac phases with temporal resolution = 24 ms with 50% view-sharing interpolation, corresponding to 720 ms of coverage. Acquisition of a breath-old single-average dataset of a one slice was accomplished in 21 cardiac cycles. An NSA of 2 was used for the free breathing technique. Otherwise, the BH and FB scan parameters were identical: TR/TE/ θ = 5.93ms/3.57ms/15°, number of echoes=8 acquiring 30 phases of the cardiac cycle with a temporal resolution equal 24 ms. The acquired FOV was 300×286 mm² and the spatial resolution was 1.8 × 2.4× 5mm³. Inter-slice spacing was set at an average of 4mm ± 1mm to insure volume coverage of the entire left ventricle. The increase of scan duration due to the tight navigator window is compensated for by using parallel imaging at high field strength (3T). Therefore, images were obtained using parallel image technique (SENSE factor of 2) and 10 slices were acquired in the short axis orientation to cover the entire left ventricle.

Analysis

Images derived from both techniques were anonymized, randomized, and scored for image quality by an experienced cardiologist blinded to the techniques. A four-level scoring system developed by Seeger et al.⁹ was employed (1= poor, ventricular borders are markedly blurred; 2= good, ventricular borders are moderately blurred; 3= very good, borders are mildly blurred; 4= excellent, sharply defined borders).

The left ventricular end-systolic and end-diastolic volumes (ESV and EDV) were measured by a single observer in the short axis orientation using with commercially available image analysis software (Virtual Place Advance; Aze, Tokyo, Japan). The end-diastolic and end-systolic cine images were identified, and the endocardial and epicardial borders were manually traced. Left ventricular ejection fraction was also calculated with the same software for both the BH and the FB cine images.

No patient was excluded because of inadequate views or inability to obtain diagnostic images. Results from the FB and BH techniques were compared. A two-tailed Student paired t-test was used with *p-value* < 0.05 considered as significant. Bland-Altman analysis assessed the limit of agreement between the two techniques.

RESULTS

All navigator-guided free-breathing scans were completed successfully. In the preparatory phase of the protocol, FB with NSA=2 and 3 mm respiratory navigator (NAV) window showed excellent visual resemblance to BH during both systole and diastole, while FB without NAV showed noticeable motion and blurring artifacts (Figure 1). Without NAV, these artifacts were not reasonably reduced until the number of averages was increased to NSA= 5; however acquisition time increased and the substantial edge blurring persisted (Figure 1). In this preliminary scan performed in a healthy subject the scan times was 16 seconds per slice for the BH, and 74 seconds per slice for the FB with NSA=2 and NAV. For the FB without NAV the scan time per slice for NSA= 2, 3, 4 and 5 were 32 seconds, 47 seconds, 63 seconds and 79 seconds respectively. The preparatory scan showed increasing the averages to 4 and 5 required as much time as the FB with NSA=2 and NAV but did not reduce the blurring of endocardial edges.

All eight patients were successfully imaged. Difference in ESV and EDV from FB and BH techniques, did not reach statistical significance (*p-value*=0.9 and 0.2, respectively). Average 3mm navigator window efficiency (accepted navigator positions/total navigator positions collected) was 20%. The Bland-Altman bias (−1.1% for EF, 0.5ml for ESV, and

–5.5ml for EDV) was less than a standard deviation for each parameter. FB and BH cine techniques showed good agreement in measurement of LV volumes as depicted in Figure 2.

The total acquisition time for the 10 slices, was longer for the FB technique (12.8 minutes) than using the standard BH technique (7.8 minutes) ($p\text{-value} = 0.004$). For the BH technique this total scan time includes the resting intervals required between breath-holds. Figure 3 depicts the short axis slices, in different cardiac phases, with the BH and the FB cine techniques showing similar image quality. The FB technique scored an average of 2.15 on image quality assessment while the BH cine images scored an average of 2 (table 1). Four sets of images were of poor quality (one FB and three BH), but all images could be analyzed. There was no statistically significant difference ($p\text{-value} = 0.76$) in image quality between the two techniques.

DISCUSSION

To the best of our knowledge this study is the first report of the feasibility and accuracy of cardiac magnetic resonance using a free breathing, single respiratory navigator gated technique at 3T. Earlier studies reported free breathing imaging at 1.5T with 3-D cine SSFP sequence using 3 averages tested in young children (mean age 2.2 ± 2.1 years) and was shown to provide sufficient functional and anatomical information with adequate resolution⁹. However, that study was done in young children with little respiratory motion and cannot be extrapolated to adult patients. Other previous studies have assessed single breath-hold with triggered, real-time SSFP; and respiratory self-gated techniques at 1.5 T^{11–13}. At 3T, SSFP requires complicated shimming requirements and suffers from large magnetic (B_0 and B_1) inhomogeneities and absorption rate related limitations that preclude the use of minimal TR¹⁴. Our data suggest FB single-navigator gated cine technique can be used as an alternative technique to conventional BH technique especially in children and patients who are unable to hold their breath or follow instructions. Feasibility of a single leading navigator is achievable with optimization of imaging time and quality via the utilization of parallel imaging, GRE instead of SSFP, and a narrow navigator acceptance window. This study is not particularly for HIV patients; however, it is intended for patients from general population with risk cardiovascular diseases and cannot hold their breath or cooperate adequately during scanning. Pediatric patients and those with cognitive limitations are ideal candidates to test the utility of the proposed method in a clinical setup.

In principle, using single navigator with the regular 5 mm acceptance window for cine imaging directly after the R-wave preserves the quality of only the imaged cardiac phases in the systole directly after the navigator, where the drift of the imaged slice due to breathing is either still within the navigator window or did not deviate significantly outside the window. Imaged phases during diastole can potentially have significant deviation outside the navigator acceptance window, resulting in blurring. A typical approach to correct this is by utilizing dual navigators; one for systolic and one for diastolic images^{5,15}. Using dual navigators for cine imaging mandates additional real-time computations during scanning, limits the temporal window available for data acquisition, and increases scanning time as two gating signals must meet acceptance criteria. In this study, we investigated the feasibility of utilizing a single end-diastolic navigator with a tight 3 mm acceptance window. The strict window permitted systole images with a breathing diaphragm drift of less than 3 mm. Moreover, images acquired using 3mm navigator acceptance window during diastole only endured a little diaphragm drift, which was shown to be tolerable and has insignificant effect on image quality given that a 5mm acceptance window is typically used in literature. Tighter navigator windows typically result in potentially unacceptably long scan times. In our protocol, this was mitigated by the use of parallel imaging, which is tolerable at higher field strength (3T) due to the intrinsically high signal to noise ratio (SNR). Although actual

temporal coverage in the study was 720 ms, the only uncoverable period is the duration of the navigator and its postprocessing (20ms after R-wave). The duration of 720ms was sufficient to cover the entire systolic and a large part of the diastolic phases of the cardiac cycle. This adequate coverage allowed for correct identification of the end-diastole and end-systole time points in all the subjects for successful ESV and EDV measurements. In practice, this sequence permits the modification of this temporal coverage to accommodate the patient's heart rate, thereby, encompassing the whole cycle without restriction except the short duration of the NAV pulse, NAV processing, and any other preparation pulses.

The ESV and EDV limits of agreement are comparable to other studies measuring ESV and EDV using other MRI imaging sequences¹⁶. Our FB cine technique demonstrated comparability to the traditional BH technique on quantitative (ESV, EDV, and EF) and qualitative measurements (image quality scoring) without statistical significance between the two (FB vs. BH) methods. The data shows that the FB technique can be used as a reproducible alternative to the conventional BH technique in CMRI. Furthermore, because of the higher SNR at 3T, we were able to use SENSE and to acquire single-navigator gated FB cardiac cine images with up to 30 cardiac phases using techniques that do not require special software programming or offline reconstruction on the commercial system used in the study and could potentially be easily implemented on other vendor platforms as it is a simple extension of a traditional navigator echo technique and does not require adaptive sampling schemes. This would allow this method to be used routinely without the need for special expertise in pulse programming.

The signal-to-noise (SNR) and contrast-to-noise (CNR) ratios were not determined on purpose since noise statistics are not easily obtained on SENSE images. However, on image quality assessment, the FB technique slightly outperformed the traditional BH approach (2.15 versus 2), although not statistically significant. This may be due to cardiac and diaphragm drifting during the breath holding. Our study is consistent with other studies that show better MR images with respiratory gating^{13,17}. In our study, four images were scored as poor quality; three BH and one FB. However, the difference in the image quality scores were not statistically significant ($P=0.76$). This demonstrates that the FB cine technique does not diminish image quality with a trend towards better image quality.

We found that patients undergoing CMRI with the FB cine technique required more time in the scanner, averaging 5 minutes longer with FB. However, the scan time is comparable to that previously reported (10–12 minutes) for whole-heart coronary MR imaging at 3T using a respiratory navigator with a wider acceptance window of 5mm¹⁸. While a potential drawback to the FB cine technique, the effect of longer scan time on patient's comfort and cooperation may be offset by the absence of need for multiple breath holds. The ability to forgo breath holding altogether may make CMRI feasible in patients who would otherwise not undergo the procedure due to the inability to comply with breath holds. As dyspnea is exceedingly common in patients with heart failure or other cardiac indications for MR imaging, this adds substantial clinical utility. In this study, a free-breathing multi-slice 2D method was chosen mainly to demonstrate the feasibility of single-navigator (with a narrow acceptance window of 3mm) cine imaging compared to the typical used breathhold 2D cine technique. However, there is a clear potential for reducing total scan duration by applying 3D instead of multi-slice 2D imaging as is used for coronary MR imaging¹⁸. These modifications in addition to using, the now more available, 32-channel coils may result in higher SNR, which would permit a more than factor of 2 multi-dimension parallel imaging acceleration, thereby shortening scan time. The higher SNR of 3T in conjunction with parallel imaging (SENSE) have allowed for acquisitions of a whole heart cine images within reasonable time while not compromising on the cardiac phases obtained. In our preparatory scan, we demonstrated that increasing the averages to five requires as much time as our FB

with NSA=2 and NAV images but still produces images with blurry endocardial margins. It is noteworthy that although higher NSA reduces noise effect, the associated longer scan time increases the probability for introducing more motion artifacts. These motion artifacts are due to higher potential for subject motion, breathing and heart rate variability. This is demonstrated in Figure 1 with more motion seen on image corresponding to NSA=3 compared to NSA=2.

CONCLUSION

This study demonstrated the feasibility of acquiring FB cardiac cine images using a single respiratory navigator gated technique at 3T alleviating the need for extra tailing navigator and thus overcoming the inherent time and calculations restrictions associated with using respirator navigator. This was possible by utilizing the high SNR available at 3T to apply parallel imaging methods allowing the acquisition of up to 30 cardiac phases within clinically acceptable imaging time. Furthermore, the FB and BH techniques were comparable in the quantitative (ESV, EDV and wall mass) and qualitative (image quality) measures. Although the FB acquisitions are longer, the durations were clinically reasonable, tolerated and successfully completed in all the patients. The FB 2D multi-slice cardiac cine imaging may be used as an alternative technique to the conventional BH technique especially in children and patients who are unable to hold their breath or follow instructions.

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Figure 1.

(A) Left: Breath-hold. Middle: FB with Navigator. Right: FB without Navigator is blurred and has motion artifacts (indicated by arrows). (B) FB without Navigator with different number of averages. From left to right, NSA=3, 4, and 5. Motion artifacts decreases with increasing NSA but blurring endocardial margins persist

Figure 2.

(a) Bland-Altman Chart showing bias and $\pm 2SD$ for left ventricular ESV and EDV. (b) Bland-Altman Chart showing bias and $\pm 2SD$ for EF

Figure 3.

(a) FB cine images at different cardiac phases from end-systole to end-diastole in a participant HIV patient. Images were acquired with NSA=2 and NAV. (b) BH cine images at different cardiac phases from end-systole to end-diastole in the same patient as in (a). Note the comparable image quality between BH and FB sequences. We found no statistical significance in the image quality scores between these two techniques.

Table 1

(a) Patients, scan time and Image quality scores. (b) Bland-Altman showing bias and $\pm 2SD$ for left ventricular ESV, EDV, wall mass, and EF for FB and BH techniques

A.						
Patient No.	GENDER	AGE	Scan time (sec.)	HR	Image Quality Scores	
1BH	F	12	371	71		3
1FB			1040	72		2
2BH	F	13	472	69		2
2FB			772	63		3
3BH	F	15	822	78		1
3FB			1028	78		2
4BH	M	18	424	84		3
4FB			784	83		1
5 BH	F	13	497	65		3
5FB			471	70		3
6BH	M	17	452	54		1
6FB			900	57		2
7BH	F	31	311	81		1
7FB			521	80		2
8BH	F	46	398	67		2
8FB			664	64		2

B.					
	FB	BH	Bias	2SD	p-value
ESV(ml)	33.2	33.6	-0.5	24.1	0.9
EDV(ml)	93.2	98.5	-5.4	20.9	0.2
Wall Mass(g)	122.3	125.9	-3.6	33.6	0.6
EF (%)	65.1	66.3	-1.1	19.7	0.8