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Compressed SENSE single-breath-hold and free-breathing cine imaging for accelerated clinical evaluation of the left ventricle

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AIM: To assess the accuracy of compressed SENSE (CS-SENSE) cine cardiac magnetic resonance imaging (CMR) with and without breath-hold in comparison to standard cine CMR with breath-hold for the assessment of left ventricular (LV) function.

MATERIALS AND METHODS: Thirty-three healthy volunteers underwent balanced turbo field-echo cine CMR with breath-hold (BTFE-BH; reference standard), single breath-hold CS-SENSE (csBTFE-BH) cine CMR, and free-breathing (FB) CS-SENSE (csBTFE-FB) cine CMR on a 3 T MRI system. All images were acquired in stacks of eight short-axis sections. Image quality was assessed and compared by the Wilcoxon matched-pairs signed-rank test. End-diastolic volume, end-systolic volume, stroke volume, ejection fraction, LV end-diastolic (LVED) mass, regional myocardial wall motion, and scan time were compared by paired *t*-test, linear regression, and Bland–Altman analyses.

RESULTS: All techniques provided acceptable image quality (score $\geq$3) for LV volumetric analysis in all participants (BTFE-BH [reference standard]: 5.00$\pm$0.00; csBTFE-BH: 4.03$\pm$0.17 [$p<0.001$]; csBTFE-FB: 3.76$\pm$0.44 [$p<0.001$]), with good agreement in LV function assessment; however, there was a slight but significant underestimation of LVED mass by csBTFE-FB (csBTFE-FB: 73.63$\pm$17.31 g versus BTFE-BH [reference standard]: 75.12$\pm$18.18 g, $p=0.037$). All methods showed a strong correlation with quantitative regional myocardial wall motion. Acquisition times for both csBTFE-BH and csBTFE-FB were significantly shorter than that for BTFE-BH (BTFE-BH [reference standard]: 89.3$\pm$5.70 seconds; csBTFE-BH: 24.42$\pm$2.18 seconds [$p<0.001$]; csBTFE-FB: 22.48$\pm$1.85 seconds [$p<0.001$]).

CONCLUSION: LV function assessment with the novel CS-SENSE cine CMR is not inferior to standard cine CMR, irrespective of BH; however, LVED mass is underestimated by csBTFE-FB.
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Introduction

Accurate and non-invasive assessment of left ventricular (LV) function is a strong predictor of outcome and plays an important role in the diagnosis and management of cardiac disease, especially coronary heart disease (CHD).[1]

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Cardiovascular magnetic resonance imaging (CMR) is generally considered the reference standard among non-invasive techniques for the measurement of resting LV function.[2,3] The standard CMR protocol for assessment of LV volume and ejection fraction (EF) is retrospective electrocardiogram (ECG)-gated cine CMR with breath-hold (BH)[4]; however, this imaging sequence requires multiple BH scans to cover the entire LV, and is thus prone to prolonged duration of the CMR examination, which becomes particularly challenging in CHD because many patients are unable perform even a short BH. A number of cardiac acceleration techniques have been developed to reduce the acquisition time for cine CMR.[5–7] Prospective ECG-triggered compressed sensing (CS) methods have recently shown considerably accelerated data acquisition,[4,8] but it remains difficult to capture the complete end-diastolic phase of the cardiac cycle with CS techniques because the acquisition window is set to a fixed length.[4,9,10] This often leads to an underestimation of end-diastolic volume (EDV) and variations in EF estimates relative to standard cine CMR.[4] Compressed SENSE (CS-SENSE) is a newly developed rapid MRI technique that combines SENSE,[11] the routine parallel imaging technique, with compressed sensing.[12] CS-SENSE can be used with retrospective ECG-gating to capture the entire end-diastole because it is less sensitive to noise breakthrough at high acceleration factors than SENSE. CS-SENSE is based on SENSE,[13] with randomly sparse, undersampled k-space data and iterative reconstruction, and it can drastically reduce MRI acquisition times. To date, no clinical trial of CS-SENSE for cine CMR for LV function has been reported. Furthermore, the feasibility and accuracy of free-breathing (FB) CS-SENSE remains an open question.

Thus, the purpose of the present study was to evaluate prospectively the accuracy of retrospective ECG-gated CS-SENSE cine CMR at 3 T with and without BH for LV assessment.

Materials and methods

Study population

This prospective study was approved by the Ethics Review Board (2018PS013J), and included 33 healthy volunteers (Table 1). All participants provided written informed consent. This study was performed according to the standards of the Health Insurance Portability and Accountability Act and the Declaration of Helsinki. All participants underwent balanced turbo field echo cine CMR with BH (BTFE-BH; reference standard), single BH CS-SENSE (csBTFE-BH) cine CMR, and FB CS-SENSE (csBTFE-FB) cine CMR. In the FB procedure, the subject performed shallow breathing, without undertaking large movements of the chest and abdomen.

Table 1
Characteristics of study population (n=33).

Characteristics	Healthy volunteers (n=33)
Sex (F/M)	18/15
Age (years)	25.61±8.24
Height (cm)	168.36±8.37
Weight (kg)	62.55±13.85
Body mass index (kg/m^2)	21.83±3.29
Body surface area (m^2)	1.79±0.22
Heart rate (beats/min)	69.55±8.39

Data are mean ± SD.

Data acquisition

All imaging was performed with a clinical 3 T MRI system (Ingenia CX, Philips Healthcare, Best, The Netherlands) using a 32-channel phased-array body coil. Short-axis multiple BH standard cine images were acquired in stacks of eight sections with adequate section gaps to cover the entire LV, using a segmented two-dimensional BTFE sequence with a SENSE acceleration factor of two, which is described in detail elsewhere,[14] and these images (BTFE-BH) served as the reference standard. BTFE-BH cine CMR, csBTFE-BH, and csBTFE-FB sequences were all acquired using retrospective ECG-gating, with segmented imaging data obtained during the total cardiac cycle. The CS-SENSE method is a real-time segmented technique, which was implemented for cine CMR with retrospective ECG to capture full cardiac cycle phase data. Both csBTFE-BH and csBTFE-FB sequences required three cardiac cycles per layer; two heartbeats were used for data acquisition, and one heartbeat was employed to reach the "magnetisation steady state". Identical spatial resolution and section orientation were maintained for all three protocols. Imaging parameters are summarised in Table 2.

Table 2
Summary of imaging parameters.

Parameter	Standard of reference	csBTFE-BH	csBTFE-FB
ECG mode	Retrospective	Retrospective	Retrospective
Repetition time (ms)	2.7	2.7	2.7
Echo time (ms)	1.3	1.3	1.3
FOV (mm)	350×350	350×350	350×350
Image matrix	124×250	124×250	124×250
Reconstructed spatial resolution (mm)	1.7×1.7	1.2×1.2	1.2×1.2
Temporal resolution (ms)	41	<41	<41
Section thickness (mm)	8	8	8
No. sections	8	8	8
Intersection gap (mm)	1–2	1–2	1–2
Flip angle (°)	45	45	45
Bandwidth (Hz/pixel)	2967	3360	3360
Cardiac cycles	4	2	2
No. BH	4	1	0
Acceleration factor	2	4	4
Scan duration(s)	89.3±5.70	24.42±2.18	22.48±1.85

BH, breath-hold; FB, free-breathing; cs, compressed SENSE; BTFE, balanced-turbo field echo; ECG, electrocardiogram; FOV, field of view; CMR, cardiovascular magnetic resonance imaging.

Image analysis

Entire LV short-axis film sequences (the whole stack) were evaluated independently and in random order by two radiologists with 5 and 10 years of experience in CMR, respectively.

Image quality was assessed visually with focus on the adequacy of contour detection for LV by the two readers and scored using a five-point scale[15,16] with 1=non-diagnostic; 2=poor; 3=adequate; 4=good; and 5=excellent. Data were presented as median and inter-quartile ranges. Images scored ≥3 were considered to be acceptable for LV volume analysis.

Quantitative LV assessments, consisting of end-diastolic volume (EDV), end-systolic volume (ESV), stroke volume (SV), ejection fraction (EF), LV end-diastolic (LVED) mass, and regional myocardial wall motion, were performed offline using the Cvi42 software (Circle Cardiovascular Imaging, Calgary, Canada). For the measurement of LV volume, stacks of eight short-axis cine MR images were assessed via a semi-automated method to draw endocardial and epicardial contours. Papillary muscles and trabeculations of the LV were included in the LV chamber volume.[17,18] For regional myocardial wall motion, 50 equidistant chords were fitted automatically within each section and changes in the centreline between end-systole and end-diastole were represented using the standard American Heart Association (AHA) 16-segment model.

Inter- and intra-observer variability for the two CS-SENSE sequences were tested in 10 randomly selected participants.[16,19] Variability was quantified for LV EDV, ESV, SV, EF, and mass.

Statistical analysis

All statistical analyses were performed with dedicated software (MedCalc 12.7.7; MedCalc Software, Ostend, Belgium, and SPSS 20.0; SPSS Software, Chicago, IL, USA). Continuous data were expressed as mean ± standard deviation (SD). Paired *t*-tests were used to compare scan times, EDV, ESV, SV, EF, LVED mass, and regional myocardial wall motion between the reference images (BTFE-BH) and the two CS-SENSE methods (csBTFE-BH, csBTFE-FB). The Wilcoxon matched-pairs signed-rank test was applied to compare image quality between reference images and the two CS-SENSE datasets, respectively. Kappa statistic was used to assess interobserver reliability in image-quality assessment. Linear regression and Bland–Altman analyses were performed to assess the correlation and agreement between LV measurements and to evaluate inter- and intra-observer variabilities in the two csBTFE sequences. $p<0.05$ was considered statistically significant.

Results

All three imaging sequences were performed successfully in all 33 volunteers. BTFE-BH standard cine CMR images were used as the reference standard. The total acquisition time for the full LV short-axis series was significantly shorter for both csBTFE sequences compared to the reference standard (89.3±5.70 versus 24.42±2.18 [csBTFE-BH] and 22.48±1.85 seconds [csBTFE-FB], both $p<0.001$).

Image quality scores were ≥3, which was sufficient for contour detection, in all images by all sequences in all 33 study participants (see Fig 1 and Electronic Supplementary Material, Movies S1–3 for examples of average image quality). Image quality of both csBTFE sequences was slightly inferior to that of the standard BTFE-BH sequence (scores of 5 [5, 5], standard, versus 4 [4, 4], csBTFE-BH, and 4 [3.5, 4], csBTFE-FB; both $p<0.001$). There was good interobserver agreement for image quality for all sequences (BTFE-BH, $\kappa=0.74$; csBTFE-BH, $\kappa=0.75$; csBTFE-FB, $\kappa=0.73$).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.crad.2018.12.012.

Comparison of EDV, ESV, SV, LVED mass, and EF measurements is shown in Table 3. There were no significant differences in EDV, ESV, SV, or EF measurements among the three datasets. Relative to the reference standard, however, a small but significant underestimation of LVED mass was noted with the csBTFE-FB sequences. Nevertheless, linear regression analysis and Bland–Altman analysis showed good agreement between the reference images and both csBTFE sequences for all measurements (Table 4, Figs 2 and 3).

The *t*-test revealed a small but significant underestimation in quantitative regional myocardial wall motion analysis by csBTFE-BH compared to the reference dataset ($n=523$ segments; BTFE-BH [reference]=8.30±2.60 mm, csBTFE-BH=8.16±2.75 mm, $p=0.025$), while there was no significant difference between the reference images and csBTFE-FB ($n=523$ segments; reference=8.30±2.60 mm, csBTFE-FB=8.24±2.61 mm, $p=0.341$); however, linear regression analysis and Bland–Altman analysis demonstrated strong correlation and small mean difference between the reference sequence and the csBTFE-BH and csBTFE-FB sequences in assessing myocardial systolic wall motion ($n=523$ segments; csBTFE-BH, R=0.86, $p<0.001$; mean difference=0.1, 95% confidence interval [CI] = −2.7–2.9 mm; csBTFE-FB, R=0.83, $p<0.001$; mean difference=0.1, 95% CI = −2.9–3 mm; Fig 4).

Inter- and intra-observer variability for LV measurements was excellent for both csBTFE datasets in a subset of 10 subjects (intra-observer: 0.78 to 0.43%, csBTFE-BH; −6.49–3.85%, csBTFE-FB; interobserver, −4.32–1.63%, csBTFE-BH; −7.15–2.58%, csBTFE-FB; Table 5).

Discussion

This prospective study demonstrated similar accuracy in the quantification of LV function between csBTFE cine CMR with either single BH or FB and the multi-BH BTFE cine CMR reference sequences. In addition, a systematic underestimation of LVED mass and regional myocardial wall motion by the csBTFE sequences was found irrespective of BH. Otherwise, CS-SENSE sequences, irrespective of BH during image acquisition, were not inferior to the reference

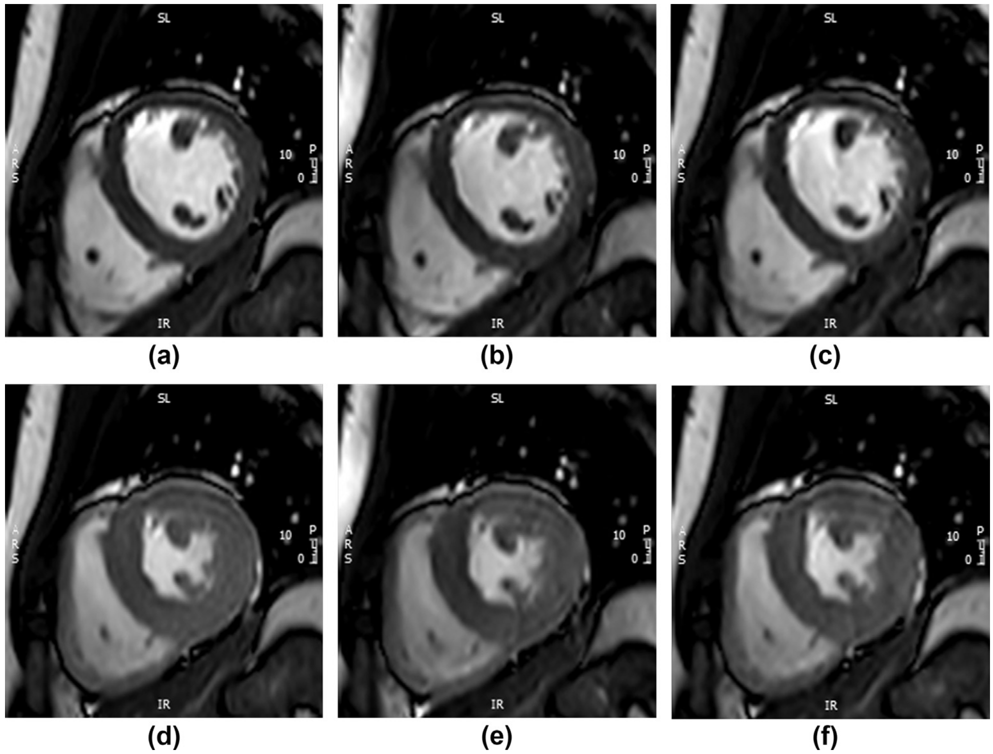


Figure 1 Mid-ventricular short-axial images of a 26-year-old female participant. Images by the BTFE-BH standard (a,d), csBTFE-BH (b,e) and csBTFE-FB (c,f) sequences, at end-diastole (a,b,c) and end-systole (d,e,f). Both observers rated BTFE-BH standard (a,d) and csBTFE-BH (b,d) cine CMR quality as excellent (i.e., score of 5) and csBTFE-FB (c,f) cine CMR quality as good (i.e., score of 4).

Table 3
Measurements of LV volumetry with reference standard, csBTFE-BH, and csBTFE-FB sequences (n=33).

	Reference standard	csBTFE-BH	csBTFE-FB	*p*-Value	
				Standard versus csBTFE-BH	Standard versus csBTFE-FB
LVEDV (ml)	111.50±19.27	111.27±18.88	112.84±18.22	0.726	0.178
LVESV (ml)	41.08±10.58	41.47±10.74	41.76±10.57	0.184	0.054
LVSV (ml)	70.42±10.62	69.80±10.20	71.08±10.12	0.251	0.384
LVED mass (g)	75.12±18.18	74.61±18.52	73.63±17.31	0.503	0.037[a]
LVEF (%)	63.50±4.47	63.10±4.70	63.36±4.89	0.079	0.524

Data are median±SD.
[a]$P<0.05$.
EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; LV, left ventricular; LVED, left ventricular end-diastole; SV, stroke volume. Other abbreviations as in Table 2.

Table 4
Results of Bland–Altman analysis comparing both csBTFE sequences with the reference standard (n=33).

		Difference	Variability (%)	Limits of agreement	Limits of agreement (%)
LVEDV (ml)	Standard versus csBTFE-BH	0.23±3.76	0.21±3.47	-7.14 to 7.60	-6.60 to 7.00
	Standard versus csBTFE-FBrowhead	-1.34±5.60	-1.30±4.84	-12.31 to 9.64	-10.78 to 8.17
LVESV (ml)	Standard versus csBTFE-BH	-0.39±1.64	-0.81±4.39	-3.60 to 2.82	-9.42 to 7.79
	Standard versus csBTFE-FBrowhead	-0.68±1.95	-1.55±5.02	-4.50 to 3.14	-11.39 to 8.29
LVSV (ml)	Standard versus csBTFE-BH	0.62±3.04	0.86±4.27	-5.34 to 6.57	-7.51 to 9.23
	Standard versus csBTFE-FBrowhead	-0.66±4.31	-1.03±5.79	-9.11 to 7.78	-12.38 to 10.31
LVED mass (g)	Standard versus csBTFE-BH	0.51±4.28	0.78±4.98	-7.89 to 8.90	-8.98 to 10.54
	Standard versus csBTFE-FBrowhead	1.49±3.93	1.88±5.55	-6.22 to 9.19	-8.99 to 12.75
LVEF (%)	Standard versus csBTFE-BH	0.40±1.25	0.66±1.98	-2.06 to 2.85	-3.22 to 4.53
	Standard versus csBTFE-FBrowhead	0.14±1.25	0.27±1.94	-2.31 to 2.59	-3.53 to 4.07

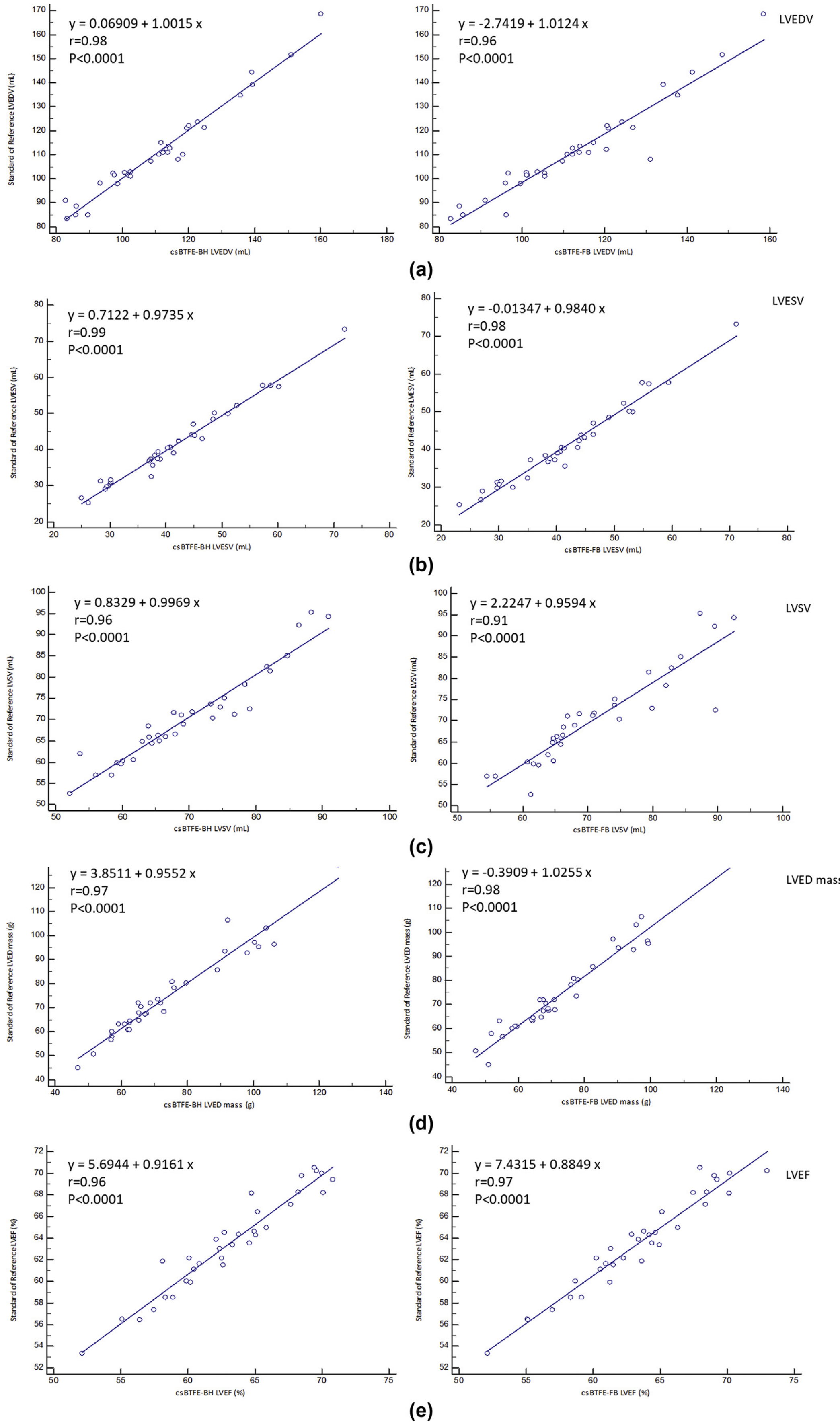
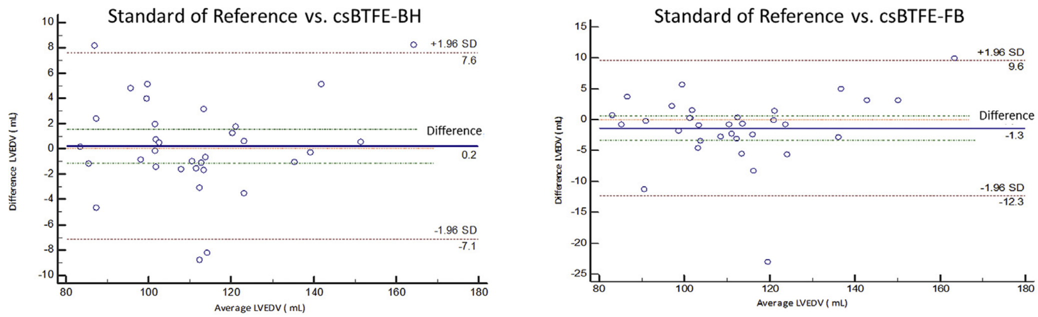
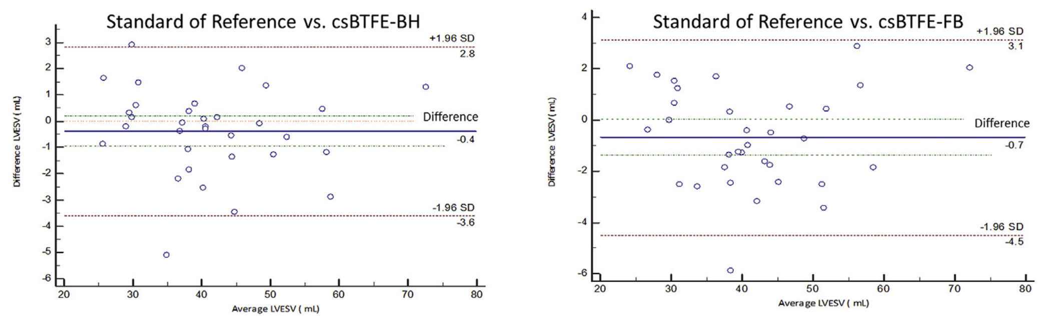


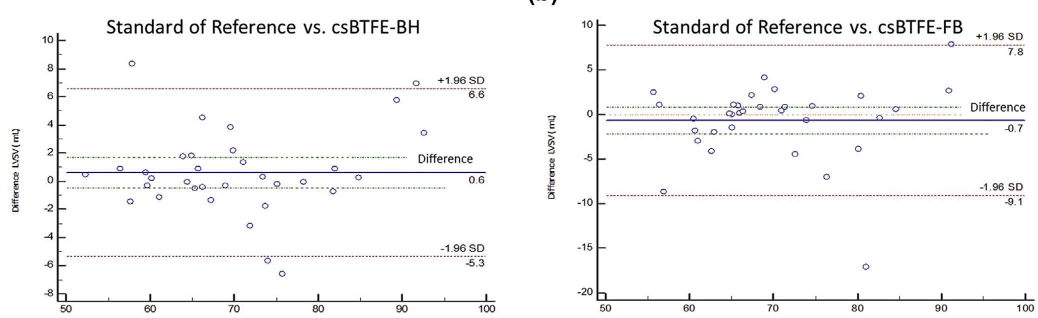
Figure 2 Correlation between BH standard and csBTFE cine CMR for parameters in the measurement of LV volume. Left, csBTFE-BH cine CMR; right, csBTFE-FB cine CMR. (a) EDV; (b) ESV; (c) SV; (d) LVED mass; and (e) EF.


Standard of Reference vs. csBTFE-BH
+1.96 SD
7.6
Difference
0.2
-1.96 SD
-7.1
Difference LVEDV (mL)
Average LVEDV (mL)
Standard of Reference vs. csBTFE-FB
+1.96 SD
9.6
Difference
-1.3
-1.96 SD
-12.3
Difference LVEDV (mL)
Average LVEDV (mL)

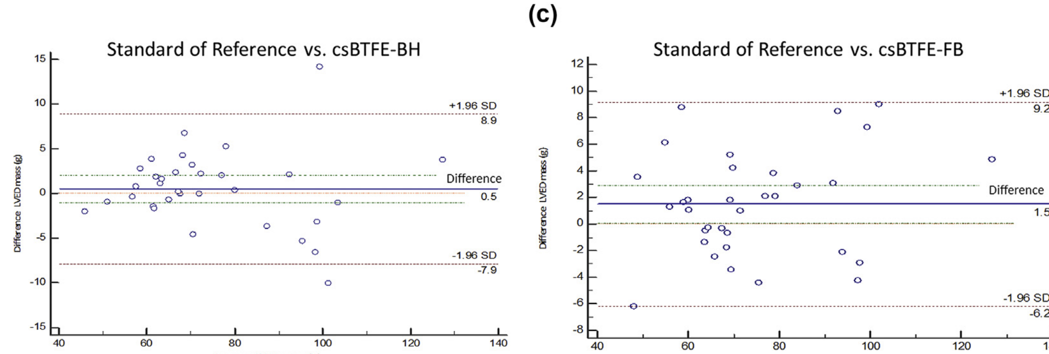
(a)


Standard of Reference vs. csBTFE-BH
+1.96 SD
2.8
Difference
-0.4
-1.96 SD
-3.6
Difference LVESV (mL)
Average LVESV (mL)
Standard of Reference vs. csBTFE-FB
+1.96 SD
3.1
Difference
-0.7
-1.96 SD
-4.5
Difference LVESV (mL)
Average LVESV (mL)

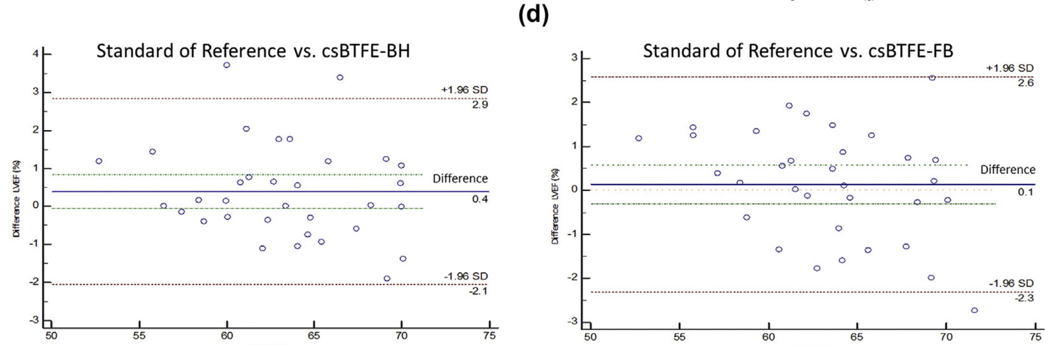
(b)


Standard of Reference vs. csBTFE-BH
+1.96 SD
6.6
Difference
0.6
-1.96 SD
-5.3
Difference LVSV (mL)
Average LVSV (mL)
Standard of Reference vs. csBTFE-FB
+1.96 SD
7.8
Difference
-0.7
-1.96 SD
-9.1
Difference LVSV (mL)
Average LVSV (mL)

(c)


Standard of Reference vs. csBTFE-BH
+1.96 SD
8.9
Difference
0.5
-1.96 SD
-7.9
Difference LVED mass (g)
Average LVED mass (g)
Standard of Reference vs. csBTFE-FB
+1.96 SD
9.2
Difference
1.5
-1.96 SD
-6.2
Difference LVED mass (g)
Average LVED mass (g)

(d)


Standard of Reference vs. csBTFE-BH
+1.96 SD
2.9
Difference
0.4
-1.96 SD
-2.1
Difference LVEF (%)
Average LVEF (%)
Standard of Reference vs. csBTFE-FB
+1.96 SD
2.6
Difference
0.1
-1.96 SD
-2.3
Difference LVEF (%)
Average LVEF (%)

(e)

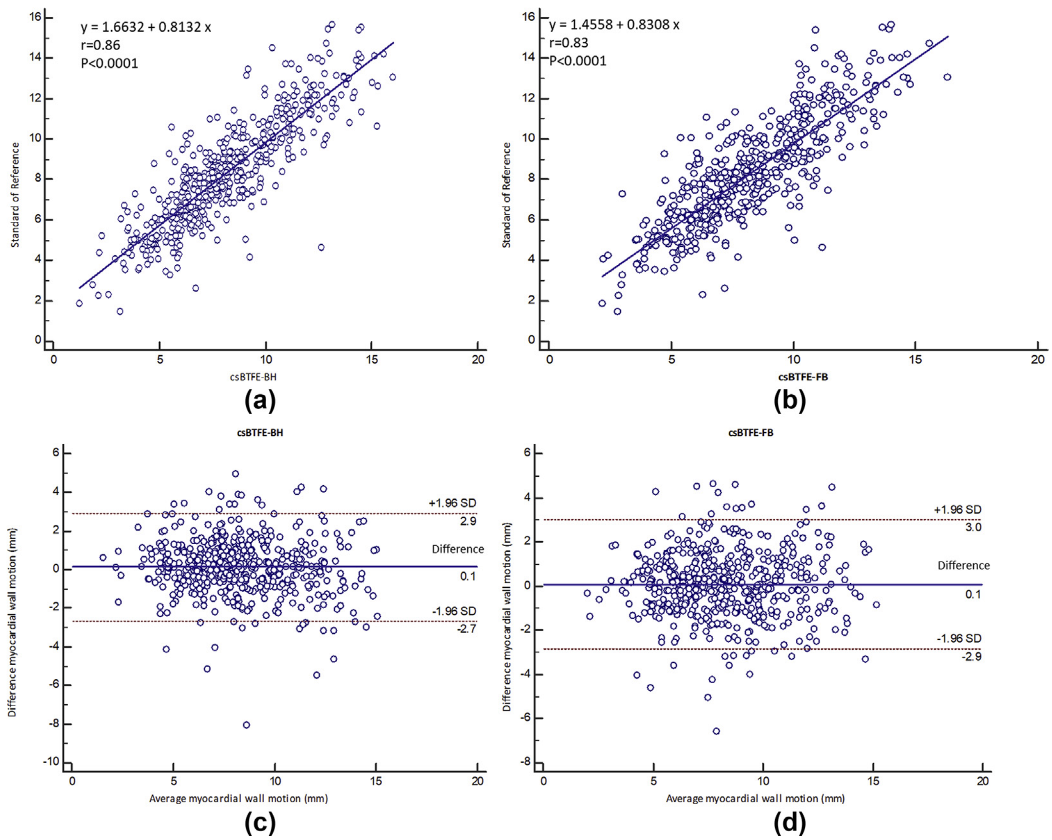


Figure 4 (a) Relationship between the csBTFE-BH technique and reference standard for quantitative regional myocardial wall motion in AHA 16-segment model (n=523; Pearson's r=0.86, p<0.001). (b) The relationship between csBTFE-FB techniques and BH standard for quantitative regional myocardial wall motion in AHA 16-segment model (n=523; Pearson's r=0.83, p<0.001. (c) Mean differences in LV regional myocardial wall motion between BH standard and csBTFE-BH cine CMR. (d) Mean differences in LV regional myocardial wall motion between BH standard and csBTFE-FB cine CMR. (——) Mean difference; (- - -) 95% CI of the mean difference; (–––) 95% limits of agreement (i.e., mean ±1.96 SD).

standard for the assessment of EDV, ESV, SV, and EF. Furthermore, inter- and intra-observer reproducibility were excellent for all assessed parameters in the csBTFE datasets, again regardless of BH.

The present results were compared after simple linear regression analysis and Bland–Altman analysis of csBTFE-BH EDV, ESV, SV, and EF measurements versus the reference standard with the results reported by Sudarski *et al.*,[16] who used a similar compressed sensing acceleration acquisition technique at 3 T. Those authors reported correlation coefficients of 0.96–0.97 for five LV measurements, with p<0.001 for all; the present results had similar correlation coefficients for all parameters (0.91–0.99, p<0.001). In terms of Bland–Altman analysis, the present csBTFE-BH results exhibited a smaller statistical variance of parameters of LV analysis, particularly EDV, than previous studies.[5–7,10,16] For example, previous studies have reported absolute mean differences of 4.9–9.9 ml for EDV, whereas the present csBTFE-BH result for EDV was 0.23 ml, which suggests that it is possible to capture the entire end-diastole by acquiring retrospective ECG-gated data and to successfully trace endocardial contours on csBTFE-BH cine CMR.

In comparison with standard cine CMR, standard real-time cine CMR with highly accelerated acquisition usually has reduced spatial resolution, and consequently, blood-filled inter-trabecular spaces might not be as well visualised, potentially resulting in a "smaller" endocardial contour (i.e., the absolute mean difference of underestimation for ESV was 2–8.4 ml in previous studies).[10,19,20] In the present study, using the CS-SENSE technique, identical spatial (1.2×1.2 mm) and temporal (<41 ms) resolution was achieved in both csBTFE cine CMR sequences, which was reflected by the good agreement for ESV compared with the reference sequence (mean difference [ESV]=−0.39 ml) and with previously reported CS cine with high spatial resolution (1.0×1.0 mm; mean difference [ESV] =1.3 ml).[21]

Furthermore, whether a single BH can be eliminated by acquiring a csBTFE sequence for LV analysis during free shallow breathing (FB) was investigated. The results showed excellent agreement of LV functional

Figure 3 Mean differences in LV measurements between BH standard and csBTFE cine CMR. Left, csBTFE-BH cine CMR; right, csBTFE-FB cine CMR. (a) EDV; (b) ESV; (c) SV; (d) LVED mass; (e) EF. (——) Mean difference; (- - -) 95% confidence interval (CI) of the mean difference; (–––) 95% limits of agreement (i.e., mean ±1.96 SD).

Table 5
Variability of csBTFE cine MRI measurement (N=10).

			Difference	Variability (%)	R^2	Slope	*p*-Value
csBTFE-BH	Intra-observer variability (1)	EDV (ml)	−0.08±1.24	−0.01±1.25	0.99	0.96	<0.001
		ESV (ml)	−0.43±1.80	−0.62±5.13	0.97	0.90	<0.001
		SV (ml)	0.35±1.07	0.43±1.53	0.99	1.06	<0.001
		LVED mass (g)	−0.51±0.93	−0.78±1.46	0.99	1.01	<0.001
		EF (%)	0.26±1.41	0.42±2.13	0.89	0.88	<0.001
	Intra-observer variability (2)	EDV (ml)	2.14±0.62	2.07±0.83	0.99	0.98	<0.001
		ESV (ml)	1.95±0.90	5.54±3.52	0.99	0.95	<0.001
		SV (ml)	0.85±0.54	1.23±0.72	0.99	1.03	<0.001
		LVED mass (g)	1.92±0.46	2.75±0.93	0.99	1.00	<0.001
		EF (%)	0.02±0.93	0.09±1.46	0.97	0.87	<0.001
	Interobserver variability	EDV (ml)	−1.54±0.62	−1.42±0.54	0.99	0.98	<0.001
		ESV (ml)	−1.72±0.90	-4.32±2.16	0.99	0.96	<0.001
		SV (ml)	0.18±0.54	0.21±0.76	0.99	1.03	<0.001
		LVED mass (g)	−1.76±0.46	−2.55±0.99	0.99	1.00	<0.001
		EF (%)	1.04±0.62	1.63±0.95	0.98	0.99	<0.001
csBTFE-FB	Intra-observer variability (1)	EDV (ml)	−2.46±1.08	−2.23±1.05	0.99	0.99	<0.001
		ESV (ml)	−2.58±1.35	−6.49±3.15	0.97	0.94	<0.001
		SV (ml)	0.12±1.13	0.20±1.80	0.99	0.99	<0.001
		LVED mass (g)	−0.73±1.16	−0.97±1.95	0.98	0.97	<0.001
		EF (%)	2.43±1.04	3.85±1.74	0.95	0.91	<0.001
	Intra-observer variability (2)	EDV (ml)	0.95±0.54	0.86±0.51	0.99	0.99	<0.001
		ESV (ml)	0.89±0.67	2.38±1.93	0.99	0.97	<0.001
		SV (ml)	0.74±0.57	1.07±0.95	0.99	0.99	<0.001
		LVED mass (g)	1.81±0.58	2.73±1.39	0.99	0.99	<0.001
		EF (%)	0.65±1.01	1.09±1.62	0.97	0.88	<0.001
	Interobserver variability	EDV (ml)	−2.73±0.54	−2.48±0.61	0.99	0.99	<0.001
		ESV (ml)	−2.79±0.67	−7.15±1.83	0.99	0.97	<0.001
		SV (ml)	0.06±0.57	0.10±0.90	0.99	0.99	<0.001
		LVED mass (g)	−1.86±0.58	−2.70±1.08	0.99	0.99	<0.001
		EF (%)	1.65±0.50	2.58±0.88	0.99	0.97	<0.001

Data are mean ± SD. Abbreviations as in Tables 2 and 3.
Variability (%) is the absolute value of the difference between the two measurements divided by the mean of the two measurements.

measurements between the reference and csBTFE-FB sequences. The mean difference for EF was 0.14±1.25% (limits of agreement [LOA] −2.31 to 2.59), which was smaller than those of previous studies (1.0%±2.1 [LOA −3.2 to 5.1] and −1.1% [LOA −12% to 9%]).[16,22] A main concern in FB data acquisition is data misregistration in the craniocaudal axis; however, Hori *et al.*[23] determined that cardiac motion of apical, mid-cavity, and basal segments along the LV long axis during respiration was within 2.2 and 3.7 mm, and concluded that as long as it was less than the section interval, deterioration of image quality owing to misregistration of section position would be low. Therefore, in the present study, the section interval (9–10 mm) was much larger than the heart motion along the long axis of LV to avoid this problem.

The variability in LV volumetric results between csBTFE sequences might reflect the differences in intrathoracic pressure during BH and FB. BH cine CMR was always acquired at inspiration in the current study, and the effect of the resulting negative intrathoracic pressure on LV volume as well as the slight differences in short-axis section orientation between BH and FB sequences might have exerted an effect on LV volume.[23,24] Some image blurring due to FB may also cause slight impairment in the accuracy of determination of the endocardial contour, but the differences between the reference images and the csBTFE sequences were ultimately within the acceptable range for volumetric LV assessments.

LVED mass and regional myocardial wall motion were underestimated on csBTFE-FB and csBTFE-BH. These measurements depend mainly on defining both the endocardial and epicardial contours at end-diastole, and the epicardial contours of both sequences at end-diastole were “smaller”, mainly because of the lower contrast between the myocardium and outer surrounding structures in comparison with the contrast between the myocardium and the LV cavity. Meanwhile, there was a “larger” endocardial contour corresponding to a slight increase in EDV in the csBTFE-FB sequence versus the reference sequence because of the blur caused by FB. Together, these changes might have contributed to the significant underestimation of the LVED mass on csBTFE-FB and the significant underestimation of regional myocardial wall motion on csBTFE-BH. The difference, however, did not affect the good correlation between csBTFE techniques and the reference sequence for quantitative myocardial regional wall motion.

The present study had some limitations. First, the study population was small and included only young healthy volunteers without any known cardiovascular disease. In order to more thoroughly evaluate the clinical utility of csBTFE cine CMR sequences, additional studies in a larger cohort of patients with cardiology ailments, including those with arrhythmias and those with severely impaired BH capacity, which makes LV volume analysis challenging,[25] will be necessary, also including cases with other cardiology ailments such as cardiac amyloidosis and chronic myocardial infarction.[26,27] Secondly, shorter reconstruction times are desirable for attaining real-time images. In the present study, the reconstruction time for all short-axis sections using the MR scanner central processing unit at the end of data acquisition for the csBTFE sequences was approximately 3 min. Continued advances in reconstruction methods are expect, which will further shorten reconstruction times and overcome this limitation. Thirdly, it should be noted that both csBTFE sequences had slightly lower image quality compared with the standard BTFE-BH sequence, indicating the need for further improvement. Finally, a strong correlation between regional myocardial wall motion in the reference and csBTFE-FB sequences is tempered by the fact that there was relatively little decrease in this parameter overall. Further evaluation is required to confirm the accuracy of csBTFE-FB cine CMR for the assessment of regional myocardial wall motion abnormalities.

In conclusion, the novel CS-SENSE cine CMR method was successfully used to assess LV function, with acceptable image quality. Therefore, both csBTFE-FB and csBTFE-BH sequences could be suitable alternatives to standard BH cine CMR for LV function assessment, especially in patients with CHD who cannot tolerate multiple BH. In addition, CS-SENSE CMR is time efficient and has the potential to improve the clinical utility of CMR.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crad.2018.12.012.

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