Original Article | Cardiovascular Imaging

eISSN 2005-8330
https://doi.org/10.3348/kjr.2020.1296
Korean J Radiol 2021;22(7):1044-1053

Korean Journal of Radiology
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Free-Breathing Motion-Corrected Single-Shot Phase-Sensitive Inversion Recovery Late-Gadolinium-Enhancement Imaging: A Prospective Study of Image Quality in Patients with Hypertrophic Cardiomyopathy

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Objective: Motion-corrected averaging with a single-shot technique was introduced for faster acquisition of late-gadolinium-enhancement (LGE) cardiovascular magnetic resonance (CMR) imaging while free-breathing. We aimed to evaluate the image quality (IQ) of free-breathing motion-corrected single-shot LGE (moco-ss-LGE) in patients with hypertrophic cardiomyopathy (HCM).

Materials and Methods: Between April and December 2019, 30 patients (23 men; median age, 48.5; interquartile range [IQR], 36.5–61.3) with HCM were prospectively enrolled. Breath-held single-shot LGE (bh-ss-LGE) and free-breathing moco-ss-LGE images were acquired in random order on a 3T MR system. Semi-quantitative IQ scores, contrast-to-noise ratios (CNRs), and quantitative size of myocardial scar were assessed on pairs of bh-ss-LGE and moco-ss-LGE. The mean ± standard deviation of the parameters was obtained. The results were compared using the Wilcoxon signed-rank test.

Results: The moco-ss-LGE images had better IQ scores than the bh-ss-LGE images (4.55 ± 0.55 vs. 3.68 ± 0.45, $p < 0.001$). The CNR of the scar to the remote myocardium (34.46 ± 11.85 vs. 26.13 ± 10.04, $p < 0.001$), scar to left ventricle (LV) cavity (13.09 ± 7.95 vs. 9.84 ± 6.65, $p = 0.030$), and LV cavity to remote myocardium (33.12 ± 15.53 vs. 22.69 ± 11.27, $p < 0.001$) were consistently greater for moco-ss-LGE images than for bh-ss-LGE images. Measurements of scar size did not differ significantly between LGE pairs using the following three different quantification methods: 1) full width at half-maximum method; 23.84 ± 12.88% vs. 24.05 ± 12.81% ($p = 0.820$), 2) 6-standard deviation method, 15.14 ± 10.78% vs. 15.99 ± 10.99% ($p = 0.186$), and 3) 3-standard deviation method; 36.51 ± 17.60% vs. 37.50 ± 17.90% ($p = 0.785$).

Conclusion: Motion-corrected averaging may allow for superior IQ and CNRs with free-breathing in single-shot LGE imaging, with a herald of free-breathing moco-ss-LGE as the scar imaging technique of choice for clinical practice.

Keywords: *Hypertrophic cardiomyopathy; Late gadolinium enhancement; Free-breathing; Single-shot; Motion-correction*

Received: June 30, 2020 **Revised:** December 7, 2020 **Accepted:** December 9, 2020
TAEJOON PHARM Co., Ltd, Korea provided the funding for this study.

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INTRODUCTION

The introduction of late-gadolinium-enhancement (LGE) images on cardiovascular magnetic resonance (CMR) allows for the assessment of myocardial replacement fibrosis and scarring [1,2]. With a growing body of evidence indicating that the presence and extent of LGE are associated with poor prognosis in various diseases, LGE on CMR has been applied to a wide variety of indications in clinical cardiology [3,4]. In terms of hypertrophic cardiomyopathy (HCM), LGE was listed as a potential risk modifier for sudden cardiac death and a predictor of cardiovascular mortality in professional guidelines [5-9].

The standard technique for LGE acquisition is a segmented phase-sensitive inversion recovery (PSIR) sequence with breath-holding. Segmented PSIR LGE generally provides satisfactory image quality, based on good patient cooperation and a stable heartbeat as prerequisites [10]. With the widespread use of CMR in clinical practice, however, the need for LGE acquisition in patients with arrhythmias or an inability to maintain adequate breath-holding has increased. In these patients, breathing and an irregular heartbeat may lead to modulation of signal and ghosting artifacts, thus hindering the precise interpretation of myocardial fibrosis [11]. Furthermore, reducing the scan time is another critical issue for CMR.

To overcome these issues, single-shot LGE was introduced. Given that one LGE slice can be acquired within one cardiac cycle, this technique is highly useful in patients with arrhythmias and difficulty in multiple breath-holding and also increases the patient throughput of the MR system. However, this scan-time reduction comes at the cost of a lower signal-to-noise ratio (SNR) and decreased spatial resolution. Fortunately, parallel imaging reconstruction has enabled single-shot LGE without compromising spatial resolution. Further, multiple images may be registered and averaged to enhance the SNR without discernible respiration-related motion blurring, which is known as motion-corrected averaging [12,13].

In this prospective study, we aimed to evaluate the image quality of free-breathing motion-corrected single-shot LGE (moco-ss-LGE) in comparison with breath-held single-shot LGE (bh-ss-LGE) in patients with HCM. We hypothesized that image quality and diagnostic confidence of moco-ss-LGE would be superior to that of bh-ss-LGE without a discernible difference in quantitative scar size measurement.

MATERIALS AND METHODS

The Institutional Review Board of Chung-Ang university hospital approved this prospective study, and written informed consent was obtained from all participants before CMR acquisition (IRB No. 1801-011-346).

Study Population

Between April and December 2019, 35 patients initially recorded as having HCM on echocardiography underwent gadolinium-enhanced CMR for the evaluation of HCM at our institution. Among the 35 patients, those who agreed to the additional acquisition of moco-ss-LGE during CMR acquisition were enrolled in this study. Patients were required to be ≥ 18 years of age, with no contraindications to gadolinium contrast agents, inclusive of an estimated glomerular filtration rate of > 60 mL/min/1.73 m^2. Patients with a history of percutaneous coronary intervention and implantable cardiac devices were excluded during screening. Finally, 32 patients with HCM underwent CMR, including both moco-ss-LGE and bh-ss-LGE, while two patients were excluded because one had an unrecognized myocardial infarction (MI) and the other was confirmed not to have HCM (maximal myocardial thickness less than 15 mm) on CMR. Finally, 30 patients (23 men; median age, 48.5; interquartile range [IQR], 36.5–61.3) were included in our study (Fig. 1).

Acquisition of CMR

All patients underwent CMR at 3T (MAGNETOM Skyra,

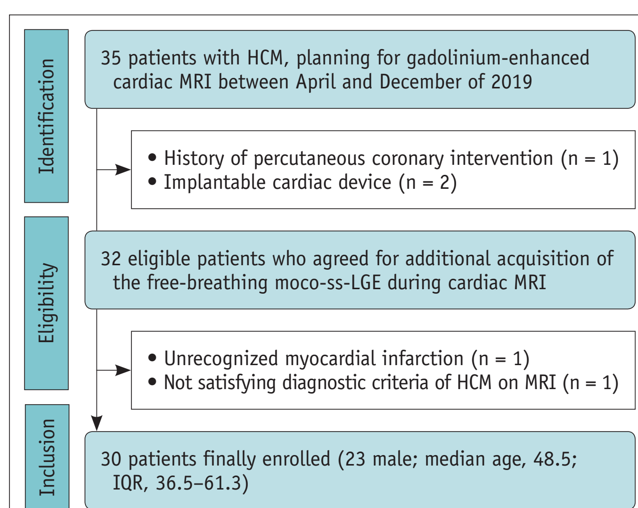

Fig. 1. Patient enrollment. HCM = hypertrophic cardiomyopathy, IQR = interquartile range, moco-ss-LGE = motion-corrected single-shot late-gadolinium-enhancement, MRI = magnetic resonance imaging

 https://doi.org/10.3348/kjr.2020.1296

Siemens Healthineers), and a detailed CMR protocol is listed in the Supplementary Materials.

The bh-ss-LGE and free-breathing moco-ss-LGE sequences were performed in random order to avoid systematic bias caused by differences in contrast washout. LGE acquisition was initiated 10 minutes after contrast administration by short-axis slices covering the full left ventricle (LV). Each LGE image was obtained after obtaining scout images using an inversion recovery turbo fast low-angle shot sequence, and reconstructions were performed using PSIR. The detailed parameters for the two LGE sequences were as follows: 1) bh-ss-LGE: field of view (FOV) of 363 x 272 mm, 8 mm slice thickness with 2 mm slice gap, image matrix of 256 x 144, repetition time (TR)/echo time (TE) of 2.5/1.06 ms, pixel bandwidth of 1184 Hz, acceleration factor (GRAPPA) of 2, number of excitations (NEX) of 1, 72 lines per segment, and a flip angle of 40°; and 2) free-breathing moco-ss-LGE: FOV of 363 x 272 mm, 8 mm slice thickness with 2 mm slice gap, image matrix of 256 x 144, TR/TE of 2.8/1.18 msec, pixel bandwidth of 1085 Hz, acceleration factor (GRAPPA) of 2, NEX of 1, and a flip angle of 40°. bh-ss-LGE sequences were acquired during breath-holding during end-expiration, and two or three breath-holds were required for the entire slice acquisition. For free-breathing moco-ss-LGE, each acquisition involved eight repeated measurements per slice with measurements performed at every second RR interval for a duration of 16 heartbeats [12]. Fully automated in-plane respiratory motion compensation was achieved by performing independent non-rigid registration processes to a reference frame with respect to all other frames in the complete set of acquired images. Each independent registration step implemented an optimization procedure that minimizes a similarity measure of the two images to identify the best transformation that maps a given frame into the frame of reference described previously, which represents an image-based navigator scheme [14].

Quantitative Image Quality Analysis

The quantitative analysis was independently performed by two observers (a board-certified radiologist and cardiologist with 6 and 12 years of cardiac multimodality imaging experience, respectively). Regions of interest (ROIs) were drawn in the LV blood pool, a remote area of the normal myocardium, and the area of hyperenhancement to obtain signals from the respective tissues. Image noise was defined as the standard deviation (SD) of the signal intensity in the normal-appearing remote myocardium. The contrast-to-noise ratio (CNR) was calculated as the ratio of the difference in the mean signal intensity between ROIs and the image noise. The CNR was calculated for the difference between the scar and the blood pool ($CNR_{scar\text{-}blood}$), between the scar and the myocardium ($CNR_{scar\text{-}myo}$), and between the blood and the remote myocardium ($CNR_{blood\text{-}myo}$). As PSIR reconstruction fundamentally implements the process of spatial smoothing to reduce the noise of reference images, the background noise measured on PSIR images does not indicate the true value. Thus, we did not perform an SNR assessment.

Qualitative Image Quality Analysis

Two experienced observers (board-certified radiologists with 6 and 12 years of CMR experience, respectively) reviewed the images independently. We used subjective image quality ratings as follows: 1 = very poor and not analyzable; 2 = poor; 3 = acceptable; 4 = good; and 5 = very good. We also rated the degree of observer confidence with regard to the presence or absence of myocardial scarring as 1 = low confidence, 2 = some confidence, and 3 = high confidence [11,15].

Myocardial Scar Size Measurement

LGE quantification was performed using dedicated software (Circle Cardiovascular Imaging 4.2, Circle Cardiovascular Imaging) by a radiologist (with 6 years of experience in CMR) blinded to the image acquisition technique. The hyperenhanced myocardium was automatically segmented using three different methods: 1) the full width at half-maximum (FWHM; threshold of 50% of the maximum intensity within the scar), 2) the 3-SD and 3) the 6-SD methods, which define LGE as the myocardial signal intensity plus 3 or 6 SDs above that of the normal-appearing myocardium, respectively [16,17]. The percentage of fibrous tissue mass to the total myocardial LV mass was calculated.

Statistical Analysis

For sample size calculation, preliminary images were obtained from six volunteers who were not included in the final study population. The average image quality scores ± SD by two independent readers for two sets of LGE images were 4.42 ± 0.66 and 3.58 ± 0.49, respectively. We found that at least 30 subjects were required in order to obtain a power of 80% and a two-sided α-level of 0.05, with an effect size of 0.58, considering a dropout rate of 10%.

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Semi-quantitative image quality scores and CNRs, diagnostic confidence scores, scan times, and scar tissue percentages were compared using the Wilcoxon signed-rank test. Bland-Altman analysis and Spearman correlation analysis were used to evaluate the agreement of LGE size assessed by both techniques. The kappa statistic was used for interobserver agreement of the qualitative image quality and confidence scores. The agreement was categorized as slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (0.81–1.00) [18,19]. The intraclass correlation coefficient (ICC) was obtained for interobserver agreement of the CNR measurements. A p value of < 0.05 was considered statistically significant. All statistical analyses were performed using SPSS statistics for windows version 20.0 (IBM Corp.) and software dedicated to statistical power analysis (G*Power version 3.1.9.6).

RESULTS

Baseline Characteristics and Acquisition Time

All 30 patients were examined successfully. Sixteen patients underwent bh-ss-LGE first followed by moco-ss-LGE, and the remaining 14 patients underwent imaging in the opposite order. The qualitative image quality and diagnostic confidence did not differ significantly according to the scan order of the LGEs (Supplementary Table 1).

Table 1. Clinical Characteristics of the Study Population

Characteristics	Values
Age, years*	48.5 (36.5–61.3)
Sex, male:female	23:7
HCM subtypes	
Apical HCM	14 (46.7)
Asymmetric septal HCM	11 (36.7)
Mixed HCM	5 (16.6)
Atrial fibrillation	7 (23.3)
CMR findings*	
Maximal ED wall thickness, mm	18 (15.8–20.3)
LV mass index, g/m^2	89.7 (78.8–116.5)
LVEDVi, mL/m^2	71.5 (60.9–83.4)
LVESVi, mL/m^2	27.3 (18.9–32.0)
LV ejection fraction, %	64.8 (58.5–69.0)

Data are number of patients with corresponding percentage in the parentheses, unless specified otherwise. *Median (interquartile range). CMR = cardiac magnetic resonance, ED = end-diastolic, HCM = hypertrophic cardiomyopathy, LV = left ventricle, LVEDVi = left ventricular end-diastolic volume index, LVESVi = left ventricular end-systolic volume index

Patient characteristics are shown in Table 1. The median patient body surface area was 1.80 (IQR, 1.66–1.97), and the median heart rate during CMR acquisition was 59 bpm (IQR, 57–67). Seven patients (23.3%) experienced atrial fibrillation (four persistent and three paroxysmal atrial fibrillation). The mean acquisition time ± SD for moco-ss-LGE was 180.8 ± 38.7 seconds. For bh-ss-LGE, it was 57.9 ± 17.8 seconds, together with breath-hold voice commands and breathing cycles between the image acquisition periods. The number and level of slices for both LGE pairs were identical, ranging from 9 to 15, according to the LV chamber size.

Quantitative Image Quality

There were no significant differences in CNR values between the measurements obtained by the two observers, and the interobserver agreement was as follows: ICC for $CNR_{blood\text{-}myo}$ = 0.797 (95% confidence interval [CI], 0.547–0.909; p < 0.001), ICC for $CNR_{scar\text{-}blood}$ = 0.885 (95% CI, 0.733–0.950; p < 0.001), and ICC for $CNR_{scar\text{-}myo}$ = 0.877 (95% CI, 0.716–0.927; p < 0.001). Thus, the mean values of both observers' measurements were used for further calculations. Table 2 illustrates that the CNRs were significantly higher in moco-ss-LGE images than in bh-ss-LGE images. The CNR of the scar to the remote myocardium (mean ± SD, 34.46 ± 11.85 vs. 26.13 ± 10.04, p < 0.001), scar to LV cavity (13.09 ± 7.95 vs. 9.84 ± 6.65, p = 0.030), and LV cavity to remote myocardium (33.12 ± 15.53 vs. 22.69 ± 11.27, p < 0.001) were consistently greater for moco-ss-LGE than for bh-ss-LGE. When we performed subgroup analysis in seven patients with atrial fibrillation, $CNR_{blood\text{-}myo}$ (31.89 ± 9.76 vs. 24.76 ± 7.60, p = 0.043) and $CNR_{scar\text{-}myo}$ (26.05 ± 8.79 vs. 19.99 ± 5.02, p = 0.018) were significantly higher in moco-ss-LGE images than in bh-ss-LGE images (Supplementary Table 2). The CNR measurements in both LGE images were lower in patients with atrial fibrillation than in those without; however, this difference was not statistically significant (Supplementary Table 3).

Table 2. Comparison of CNRs on Pairs of LGE Images

	bh-ss-LGE	moco-ss-LGE	*P*
$CNR_{blood\text{-}myo}$	26.13 ± 10.04	34.46 ± 11.85	< 0.001
$CNR_{scar\text{-}blood}$	9.85 ± 6.65	13.09 ± 7.94	0.030
$CNR_{scar\text{-}myo}$	22.69 ± 11.27	33.12 ± 15.53	< 0.001

Data are mean ± standard deviation. bh-ss-LGE = breath-held single-shot LGE, CNR = contrast-to-noise ratio, LGE = late-gadolinium-enhancement, moco-ss-LGE = motion-corrected single-shot LGE, myo = myocardium

Qualitative Image Quality

Examples of image quality for bh-ss-LGE and moco-ss-LGE acquisitions are presented in Figure 2. Figure 3 shows representative LGE images from patients with atrial fibrillation. Table 3 summarizes the results of the image quality scoring by both readers. The image quality scores differed significantly between the moco-ss-LGE and bh-ss-LGE images. The moco-ss-LGE images received higher image quality scores than the bh-ss-LGE images (average scores of two readers ± SD, 4.55 ± 0.55 vs. 3.68 ± 0.45, respectively, $p < 0.001$). LGE was detected in 28 of 30 patients on both LGE images, with 100% agreement between the two readers. In terms of diagnostic confidence for LGE detection, there was no significant difference between LGE image pairs (average scores of two readers ± SD, 2.85 ± 0.48 vs. 2.82 ± 0.50, $p = 0.710$). The interobserver agreement for qualitative image quality assessment was substantial to almost perfect (κ = 0.683 for overall image quality and κ = 0.844 for diagnostic confidence). Subgroup analysis of seven patients with atrial fibrillation revealed consistent findings in the image quality and diagnostic confidence scores for LGE pairs, as demonstrated in Supplementary Table 4.

Myocardial Scar Size Measurement

There was no significant difference in relative scar size

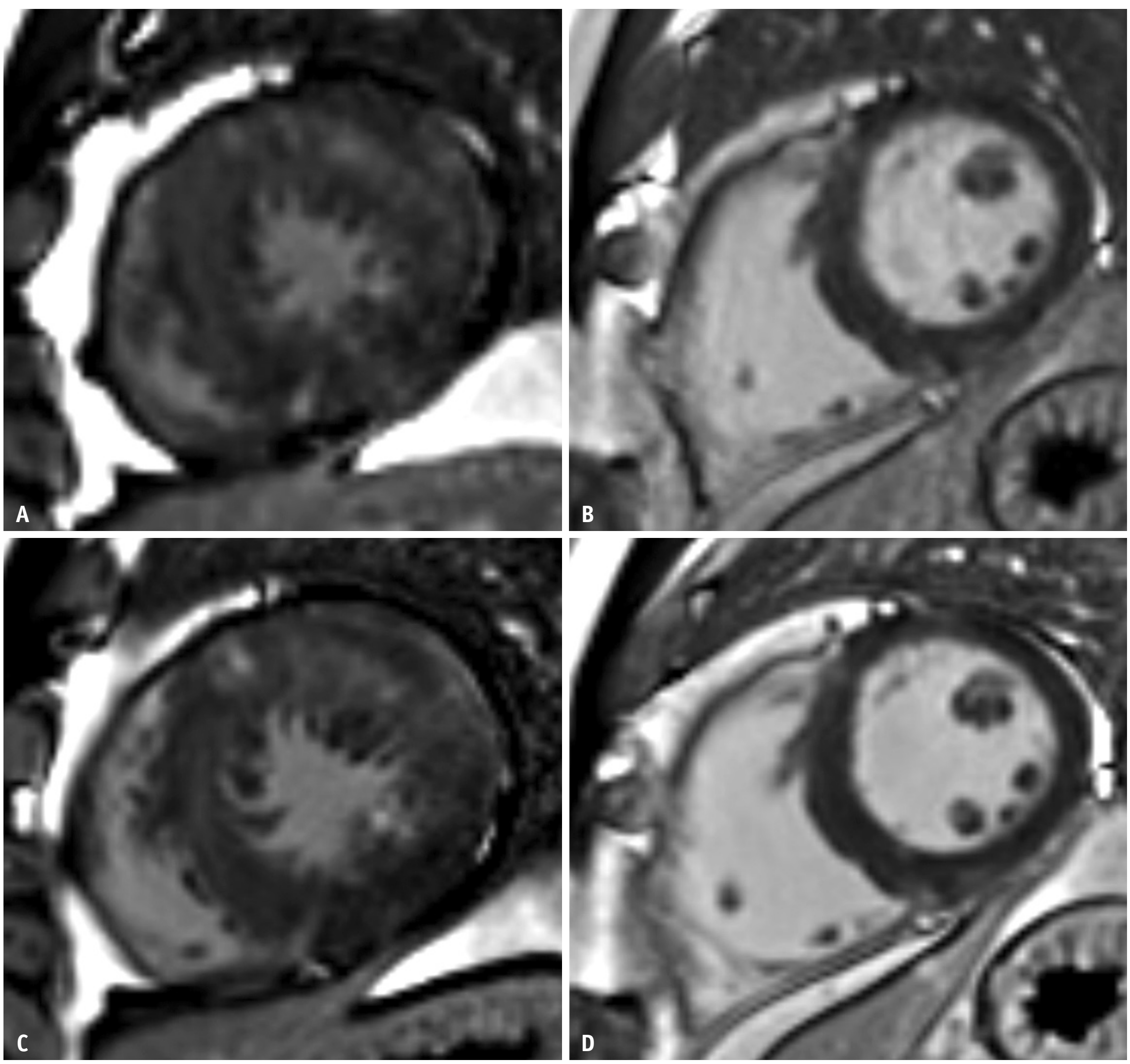

Fig. 2. Representative image pairs of bh-ss-LGE and moco-ss-LGE.
A-D. bh-ss-LGE images **(A, B)** and free-breathing moco-ss-LGE **(C, D)** images in **(A, C)** a 49-year-old male patient and **(B, D)** a 64-year-old male patient with hypertrophic cardiomyopathy, respectively. Homogenous signal intensity of the blood and the remote myocardium, resulting in better visualization of LGE, is noted on moco-ss-LGE, compared to bh-ss-LGE. The papillary muscles and trabeculae are also more clearly demarcated from the left ventricle cavity and endocardial border on moco-ss-LGE than on bh-ss-LGE. bh-ss-LGE = breath-held single-shot LGE, LGE = late-gadolinium-enhancement, moco-ss-LGE = motion-corrected single-shot LGE

https://doi.org/10.3348/kjr.2020.1296

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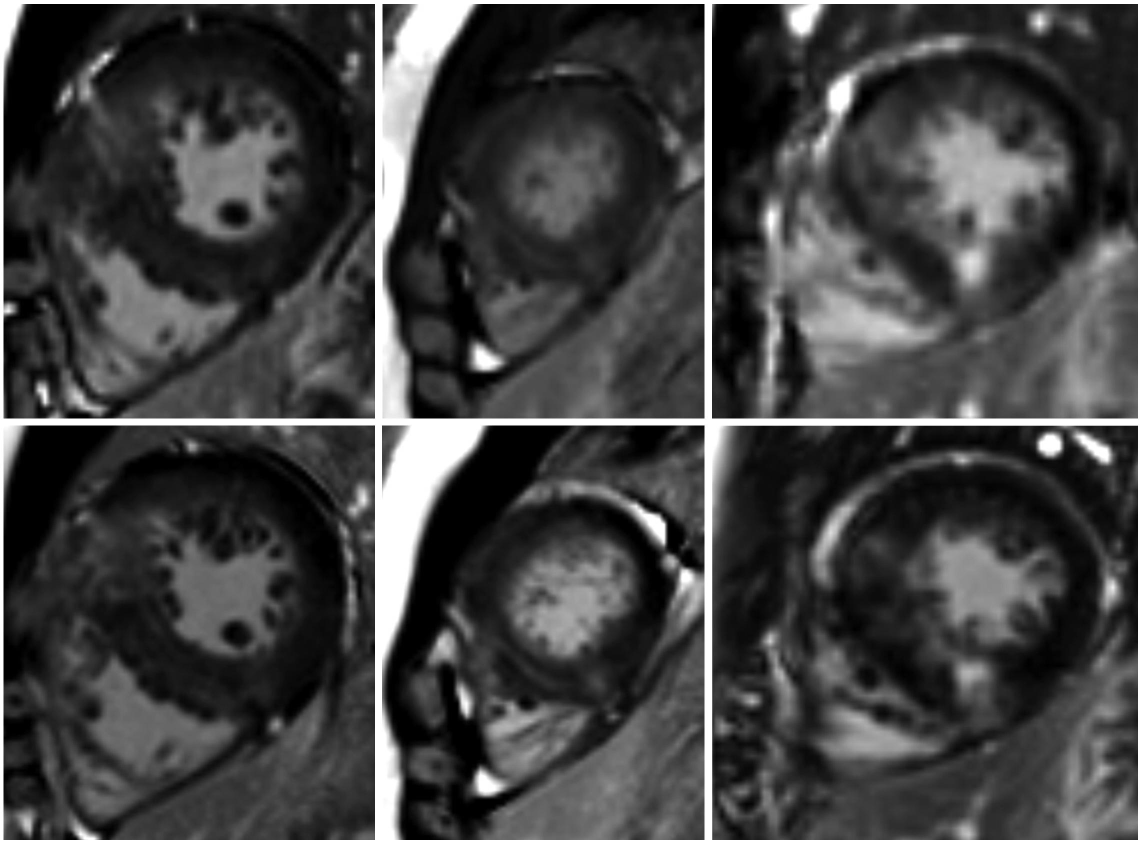

Fig. 3. Representative LGE imges of patients with hypertrophic cardiomyopathy with atrial fibrillation. bh-ss-LGE images (upper row) and free-breathing moco-ss-LGE images (lower row) obtained from hypertrophic cardiomyopathy patients with atrial fibrillation. The papillary muscles, trabeculae, and endocardial border are more clearly distinguished from the left ventricle cavity, and the myocardial scar (enhanced area) is more obviously demarcated from the remote myocardium on moco-ss-LGE than on bh-ss-LGE. bh-ss-LGE = breath-held single-shot late-gadolinium-enhancement, moco-ss-LGE = motion-corrected single-shot late-gadolinium-enhancement

Table 3. Semi-Quantitative Analysis of the Image Quality of Pairs of LGE Images

Parameter	Scoring					Mean ± SD	Kappa* (*P*)	*P*
	1	2	3	4	5			
Overall image quality								
bh-ss-LGE								
Reader 1	0	0	12	17	1	3.63 ± 0.56	0.683 (< 0.001)	< 0.001
Reader 2	0	0	8	22	0	3.73 ± 0.45		
moco-ss-LGE								
Reader 1	0	0	0	3	24	4.47 ± 0.68		
Reader 2	0	0	1	9	20	4.63 ± 0.56		

Parameter	Scoring			Mean ± SD	Kappa* (*P*)	*P*
	1	2	3			
Diagnostic confidence						
bh-ss-LGE						
Reader 1	1	3	26	2.83 ± 0.46	0.844 (< 0.001)	0.326
Reader 2	2	2	26	2.80 ± 0.55		
moco-ss-LGE						
Reader 1	1	2	27	2.87 ± 0.43		
Reader 2	2	1	27	2.83 ± 0.53		

*Interobserver variability between two readers for each parameter. bh-ss-LGE = breath-held single-shot LGE, LGE = late-gadolinium-enhancement, moco-ss-LGE = motion-corrected single-shot LGE, SD = standard deviation between the pairs of LGE images by the FWHM method (mean ± SD, 23.84 ± 12.88% vs. 24.05 ± 12.81%; p = 0.820), the 6-SD method (15.14 ± 10.78% vs. 15.99 ± 10.99%; p = 0.186), or the 3-SD method (36.51 ± 17.60% vs. 37.50 ± 17.90%; p = 0.785) (Table 4, Fig. 4). Spearman correlation analyses revealed an excellent correlation of the relative scar size between the LGE pairs using the FWHM technique (rho = 0.946, p < 0.001), 6-SD method (rho = 0.945, p < 0.001), and 3-SD method (rho = 0.916, p < 0.001). In the Bland-Altman plot analysis, none of the cases were outside the 95% limits of agreement with the use of the FWHM method. For the 6-SD and 3-SD methods, 2 (2/30; 6.7%) and 1 (1/30; 3.3%) of 30 cases were outside the limits of agreement, respectively (Fig. 5). In the subgroup analysis of patients with atrial fibrillation, a good correlation of the relative scar size between the LGE pairs was still observed using the FWHM method (rho = 0.919, p = 0.003), 6-SD method (rho = 0.893, p = 0.007), and 3-SD method (rho = 0.857, p = 0.014).

Table 4. Quantitative Assessment of Relative Myocardial Scar Size (%)

	bh-ss-LGE	moco-ss-LGE	*P*
FWHM	23.84 ± 12.88	24.05 ± 12.81	0.820
3-SD	36.51 ± 17.60	37.50 ± 17.90	0.285
6-SD	15.14 ± 10.78	15.99 ± 10.99	0.186

Data are mean ± SD. bh-ss-LGE = breath-held single-shot late-gadolinium-enhancement, FWHM = full width half-maximum, moco-ss-LGE = motion-corrected single-shot late-gadolinium-enhancement, SD = standard deviation

DISCUSSION

This prospective study demonstrated the superiority of the free-breathing moco-ss-LGE sequence over the bh-ss-LGE sequence in HCM patients referred for clinical CMR. The main finding of our study was that free-breathing moco-ss-LGE outperformed bh-ss-LGE in terms of qualitative and quantitative image quality. The scar size did not differ significantly between moco-ss-LGE and bh-ss-LGE based on three different quantification methods (FWHM, 3-SD, 6-SD). In addition, these findings were consistently observed in patients with arrhythmia (7/30; 23.3%).

Theoretically, the CNR for the images with eight averages is improved by $\sqrt{8}$ [12]. Our real-world data also demonstrated that the CNR values obtained from moco-ss-LGE images were significantly and persistently higher than those from bh-ss-LGE images. This improved contrast between the scar and the normal myocardium may enable intuitive visualization and analysis of myocardial fibrosis, even for inexperienced clinicians. In addition, improved

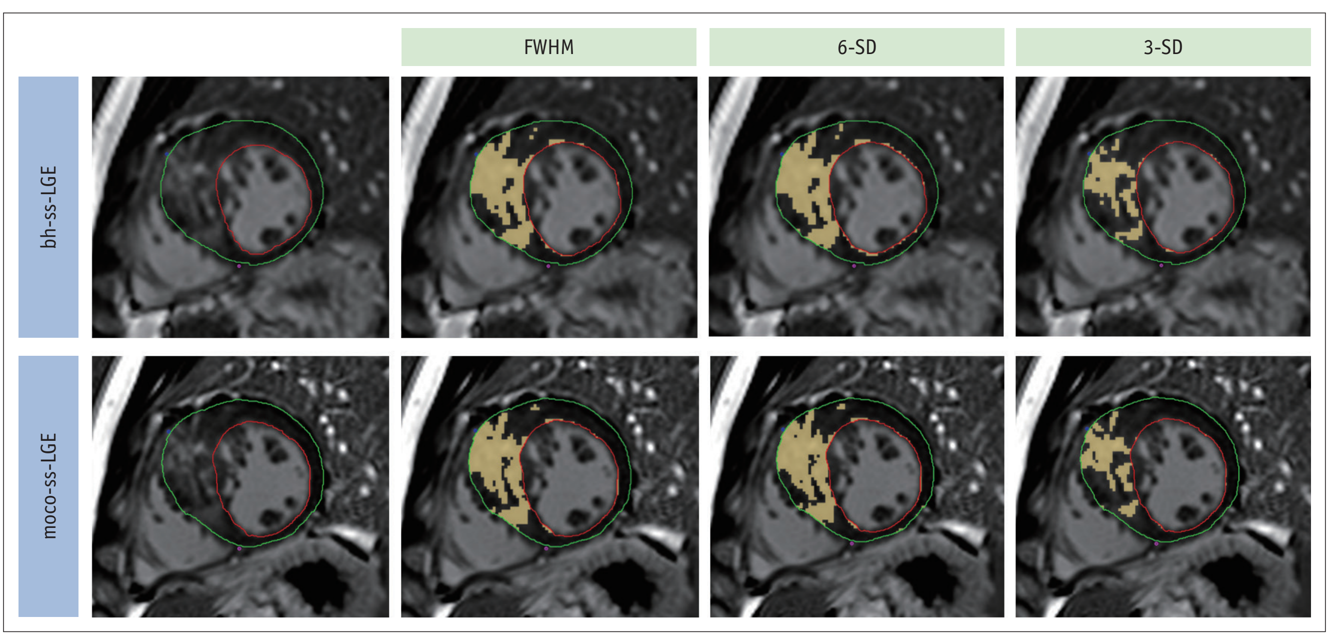

Fig. 4. Comparison between the methods of LGE quantification in a 21-year-old male with asymmetric septal hypertrophic cardiomyopathy. Relative infarct size was quantified by identifying myocardial area with LGE, overlaid with yellow, using the FWHM, 6-SD, or 3-SD method. Infarct size measures on bh-ss-LGE and moco-ss-LGE were 36.1% and 38.6% with the FWHM method, 19.2% and 21.1% with the 6-SD method, and 39.1% and 39.8% with the 3-SD method, respectively. bh-ss-LGE = breath-hold single-shot LGE, FWHM = full width at half-maximum, LGE = late-gadolinium-enhancement, moco-ss-LGE = motion-corrected single-shot LGE, SD = standard deviation

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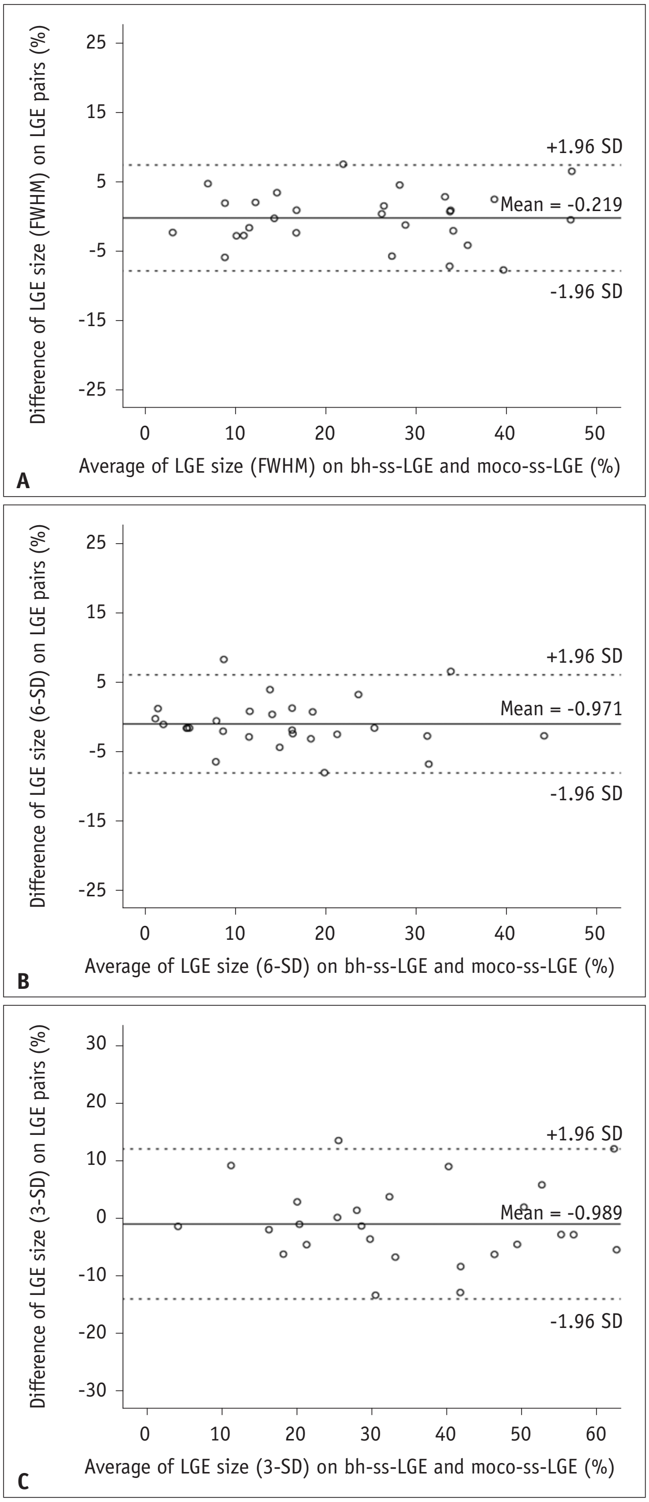

Fig. 5. Bland-Altman plots illustrate good agreement across the LGE size spectrum between bh-ss-LGE and free-breathing moco-ss-LGE images. Solid and dotted lines indicate the mean difference and ± 1.96 SD of the differences, respectively. bh-ss-LGE = breath-hold single-shot LGE, FWHM = full width at half-maximum, LGE = late-gadolinium-enhancement, moco-ss-LGE = motion-corrected single-shot LGE, SD = standard deviation

scar-to-blood pool contrast may increase subendocardial scar conspicuity, potentially improving detection of small subendocardial infarction in patients with ischemic cardiomyopathy. Regarding scan speed, the acquisition time for the moco-ss-LGE sequence was 2.91 ± 0.43 minutes, which is similar to that of previous reports using eight repeated measurements per slice [15,20,21]. Although the acquisition time for the moco-ss-LGE sequence was longer than that of the bh-ss-LGE sequence without averaging, it is still almost half of the scan time for conventional segmented LGE, which was reported to require 5–10 minutes to cover the LV [15,21,22].

Arrhythmia is a common clinical presentation in various cardiomyopathies, including HCM, in which CMR can play a role in disease evaluation and prognostication. In such cases, single-shot imaging should be recommended over conventional segmented imaging in order to avoid ghosting artifacts [23,24]. Our study contributes to the growing body of literature on the robustness of single-shot technique and motion-correction algorithm for arrhythmia by demonstrating comparable image quality and scar size measures in patients with atrial fibrillation. In addition, the motion-correction algorithm utilized in the present study suppresses artifacts caused by respiratory movements [25]. Our results suggest that free-breathing moco-ss-LGE can be utilized as the scar imaging technique of choice for various cardiac diseases in routine clinical practice, which may broaden the application of CMR.

To date, there have been several studies comparing free-breathing moco-ss-LGE with conventional segmented PSIR LGE using a 1.5T MR system. A previous study by Piehler et al. [15] was the first to report on the superiority of free-breathing moco-ss-LGE over the conventional breath-hold segmented LGE in a patient with MI. A recent study by Captur et al. [21] also demonstrated that free-breathing moco-ss-LGE provides better images and higher diagnostic performance than breath-hold segmented LGE, by performing a real-world CMR study in 400 consecutive patients. Additionally, Fan et al. [20] reported that moco-ss-LGE is a robust scar imaging technique, based on the result of a direct comparison between moco-ss-LGE and traditional breath-hold segmented LGE. Our work further validated the robustness of moco-ss-LGE using a 3T MR scanner in patients with HCM. Moreover, the current study differs from prior studies in that we focused on single-shot technique by comparing single-shot LGE images with and without motion-corrected averaging.

Our study demonstrated that there is no significant difference in scar size between single-shot LGE with and without motion-corrected averaging. We calculated LGE masses using three different quantification methods: FWHM, 3-SD, and 6-SD methods. Many previous studies have demonstrated highly correlated LGE masses between conventional segmented LGE and free-breathing moco-ss-LGE [15,20,21]. The current study also expanded the spectrum of reliable LGE imaging techniques for myocardial scar quantification.

This study has several limitations. First, it was limited by its single-center design with a single manufacturer of MR systems (Siemens Healthineers). Second, the number of patients was relatively small. Nonetheless, our study subjects were a purely clinical population with HCM and may reflect real-world practice. Further studies with patients with ischemic cardiomyopathy can have clinical implications, as detection of even small myocardial scars is prognostically important in patients with previous MI [26]. Third, we only compared short-axis slices for each LGE sequence. The robustness of the motion-correction algorithm on different orientations, such as two- or four-chamber views, should still be explored. Lastly, we did not perform conventional segmented LGE imaging as a standard reference technique for image quality evaluation and myocardial scar quantification. However, many previous studies have compared conventional segmented LGE and free-breathing moco-ss-LGE and showed that moco-ss-LGE is reliable for scar quantification with better image quality over segmented LGE. In addition, the use of single-shot LGE has been increasing, especially for those with arrhythmias or an inability to maintain adequate breath-holding.

In conclusion, the current study indicated that moco-ss-LGE is a feasible and robust sequence for LGE imaging, yielding superior image quality and similar scar size measurement compared to bh-ss-LGE in patients with HCM. We suggest that free-breathing moco-ss-LGE may be used as the scar imaging technique of choice for routine clinical practice.

Supplement

The Supplement is available with this article at https://doi.org/10.3348/kjr.2020.1296.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Acknowledgments

The authors appreciate the technical assistance of Bon Chul Ha, Min Gu Kim, Chul Lee, Sang Hoon Lee, and Hyeong Ho So for helping with MRI scans.

Author Contributions

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