Original Article

Diagnostic efficacy of 2-shot compressed sensing cine sequence cardiovascular magnetic resonance imaging for left ventricular function

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Background: Cardiac magnetic resonance cine images are conventionally acquired in breath-hold with a segmented balanced steady-state free precession (bSSFP) sequence, which requires a relatively long acquisition time and high patient cooperation. The single-shot compressed sensing (ss CS) cine sequence is a real-time sequence that has reasonable spatial and temporal resolution and can be applied during free breathing. However, the contrast between the myocardium and surrounding soft tissue is relatively reduced, and the epicardial delineation results are not as accurate with the ss CS cine sequence compared with the bSSFP sequence. In this study, we evaluated the use of a 2-shot CS cine technique in quickly acquiring high-quality images and accurately assessing cardiac function in clinical practice.

Methods: The patients enrolled in the study underwent cardiovascular magnetic resonance (CMR) on a 3T scanner from Jul. to Dec. 2018. Cine imaging was performed with 3 different methods: a standard segment cine sequence, a real-time ss CS cine sequence, and a 2-shot CS cine sequence prototype. Quantitative analysis of image quality was performed using a 0-4 scoring system, and also edge sharpness was measured, and cardiac function analysis was performed for all 3 types of cine images.

Results: Thirty-eight patients underwent imaging with the three types of cine sequences. The average scan time of the standard cine sequence was 101±20 s, the average scan time of the ss CS cine sequence was 20±4 s, and the average scan time of the 2-shot CS cine sequence was 30±6 s. The standard cine sequence image score was 3.68±0.64 and edge sharpness was (2.47±0.18) mm, the ss CS cine sequence image score was 3.13±0.35 and edge sharpness was (4.69±0.02) mm, and the 2-shot cine sequence image score was 3.54±0.51 and the edge sharpness was (2.51±0.13) mm. In terms of the quantitative study of cardiac function, the differences between the standard cine sequence and the ss CS cine sequence were not statistically significant, except for those of the imaging score and LV mass. There were no significant differences in the cardiac function parameters between the standard cine sequence and the 2-shot cine sequence. There was a strong correlation between the standard cine and ss CS cine sequences and between the standard cine and 2-shot CS cine sequences ($P<0.01$) of all the cardiac function parameters.

Conclusions: The 2-shot CS cine sequence can acquire images with a level of quality comparable to that of the standard cine sequence in a significantly shorter period of time. The functional parameters are similar between the 2-shot CS cine sequence and the standard cine sequence.

Keywords: Compressed sensing (CS); cardiovascular magnetic resonance (CMR) imaging; cine

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Introduction

It is vitally important to assess cardiac function in cardiac disease patients, as it is one of the strongest predictors of the prognosis of patients (1,2). It can guide decision making or the implantation of devices during treatment (3). Cardiovascular magnetic resonance (CMR) cine imaging can be used to assess the left ventricular (LV) volume, and it can be considered the noninvasive gold standard (4,5). The retrospective electrocardiogram (ECG)-gated, balanced steady-state free precession (bSSFP) cine sequence during breath-hold is a well-established sequence and is generally considered the standard sequence; in this sequence, segments of the entire k-space are collected for multiple cardiac cycles. However, as each slice requires multiple heartbeats, and only one or two slices can be scanned with one breath-hold. Hence, the whole CMR examination tends to take a long time. If a patient cannot tolerate multiple breath-holds or has arrhythmia, the images will have many artifacts, which lead to difficulties in the evaluation of LV function (6-9). The compressed sensing (CS) technique with sparse sampling can drastically reduce the acquisition time of CMR scans, and an iterative reconstruction algorithm can be used to prevent declines in image resolution (10,11). The CS approach can be integrated into single- or multi-shot sequences with different acceleration rates to record a complete cardiac cycle. Some studies have demonstrated the utility of single-shot (ss) CS cine CMR imaging for the evaluation of LV function (4). However, the image quality is inferior to that of standard cine CMR imaging. Because the ss CS cine sequence reduces the contrast between the myocardium and surrounding tissues due to the lower flip angle on the 3T scanner required to meet the SAR restriction, there are inaccuracies in delineating the epicardium and endocardium, which lead to some deviations (12). Multi-shot CS cine imaging reduces the acceleration rate or increases the spatial and/or temporal resolution compared to single-shot imaging. It can also increase the number of excitations, increase the image contrast and improve the image quality. In this study, we evaluated the use of a 2-shot CS cine technique in quickly acquiring high-quality images and accurately assessing cardiac function in clinical practice.

Methods

Study population

In this study, we continuously included patients from July 2018 to December 2018. Patients were scheduled for a CMR examination and had a variety of cardiac diseases. The exclusion criteria were patients who had a cardiac implantable electronic device, had claustrophobia, or failed to complete a CMR scan. This study was approved by the Ethics Committee of Peking Union Medical College Hospital (Ethical file code JS-1499).

The sample size was estimated based on the primary difference between the EF measurements. We assumed the common SD of the mean EF measure to be 0.15, the probability of type I error to be 0.05 (with both sides), and the probability of type II error to be 0.20. We calculated the necessary sample size for this research to be 36.

Cine magnetic resonance protocol

All the CMR examinations were performed with the clinical 3T MR scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany). All patients were subjected to the same scan procedure. After the localized images were taken, the cardiac axis views were planned, including three long axes (4-chamber, 3-chamber, 2-chamber) and a stack of eight to twelve short-axis slices covering the entire LV from the mitral valve to the apex. Then, three kinds of cine sequences were performed sequentially, and all of them included the three long-axis images and all the short-axis images that were mentioned above. The standard retrospectively gated segmented bSSFP cine sequence was first performed. The prototype ECG ss CS cine sequence with adaptive triggering and the prototype retrospectively gated 2-shot CS cine sequence were performed immediately after the standard cine sequence. Both ss CS cine and 2-shot CS cine sequence used the same iterative reconstruction algorithm. All the sequences were performed with breath-holding at end-expiration and covered the complete cardiac cycle. During the scanning, when it reached the SAR restriction, we chose to reduce the flip angle to reduce the

Table 1 Key parameters for all cine sequences

	Standard segmented cine	Single-shot CS cine	2-shot CS cine
ECG gating	Retrospective	Adaptive trigger	retrospective
TE/TR (ms)	1.4/3.3	1.2/3 (2.9)	1.3/3
FOV (mm^2)	340×265	380×300	380×280
Image matrix	208×113	208×113	208×113
Spatial resolution (mm^2)	1.6×1.6	1.7×1.7	1.6×1.5
Temporal resolution (ms)	45	42	42
Slice thickness (mm)	8	8	8
Flip angle range (°)	50–70	30–45	30–45
Bandwidth (Hz/pixel)	962	893	888
Cardiac phase	25	22	25
Breath-hold	8 heart-beats/slice	2 heart-beats/slice	3 heart-beats/slice
Acceleration factor	3	9.5	6.5

CS, compressed sensing.

SAR value. The details of all the sequence parameters are listed in *Table 1*.

Qualitative image quality analysis

Two radiologists with 6 and 5 years of experience in CMR assessed all three types of cine sequences independently, focusing on the border of the myocardium and artifacts. The image quality was evaluated visually using a five-point scale: 0 = nondiagnostic quality, extensive artifacts affecting volumetric analysis, 1 = poor quality, moderate artifacts affecting volumetric analysis; 2 = adequate quality, mild artifacts affecting volumetric analysis; 3 = good quality, minimal or no artifacts affecting volumetric analysis; and 4 = excellent quality, no artifacts. The edge sharpness was evaluated by measured the maximum gradient of pixel intensities across the septal part in the middle segment of interventricular at the end of diastolic phase in 4 chamber view. The higher the gradient of the pixel intensities, the sharper of the edges were. The measure performed by one of the radiologists using ImageJ (National Institutes of Health, USA). Before the measurement, a scale bar was set to convert the pixel to the actual distance.

Quantitative analysis of the LV volume

For the quantitative measurement, all stacks of the short-axis slices of all cine CMR images were assessed using Medis Suite 3.1 (Medis Medical Imaging System, Leiden, The Netherlands). The epicardial and endocardial contours were traced manually and separately by the two radiologists. The endocardial trabeculations and papillary muscles of the left ventricle were included in the cavity volume of the LV. The most basal slice with at least 75% of the muscular ring at the end of systolic phase was considered the base, and the most apical slice that showed the LV cavity at the end of the diastolic phase was regarded as the apex. The LV volume and LV mass were calculated using the Simpson method in the software. The end of the systolic phase and end of the diastolic phase were detected manually based on the smallest and largest LV volumes over the entire cardiac cycle.

Statistical analysis

If the data showed a normal distribution, the data were expressed as the mean ± standard deviation (SD). If the data showed an abnormal distribution, the data were expressed as the median (first quartile, third quartile). The image quality was determined using the Wilcoxon matched-pairs signed-rank test. The edge sharpness was determined using paired *t*-test. The results of the LVEDV, left-ventricle end-systolic volume (LVESV), left-ventricle stroke volume (LVSV), LV mass, and left ventricular ejection fraction (LVEF) for each cine sequence were compared by the Wilcoxon matched-pairs signed-rank test. Linear regression and Bland–Altman

Table 2 Study population

Data	
General information	
Age (years)	48.6±13.9
Sex (male/female)	19/19
Height (cm)	164.9±7.5
Weight (kg)	59.9±11.6
HR (beats/min)	73.7±14.3
Clinical diagnosis	
Hemopathy	17
Connective tissue disease	9
Cardiomyopathy	5
Pericardial inflammatory disease	3
Arrhythmia	2
Acromegaly	2

analysis were used to evaluate the correlation and agreement between these LV measurements. The interobserver and intraobserver reliability were assessed using the intraclass coefficient correlation (ICC). A P value of less than 0.05 was considered statistically significant. All statistical analyses were performed by the commercially available software MedCalc Statistical Software, version 18.2.1 (MedCalc Software bvba, Ostend, Belgium; http://www.medcalc.org; 2018).

Results

Thirty-eight patients successfully completed imaging scans with the three types of cine sequences. The detailed characteristics of the study population are summarized in *Table 2*. The mean heart rate was 74±14 bpm (range, 55–106 bpm) during the CMR scans. Among all patients, there were 2 patients encountered arrythmia and all of them were atrial fibrillation, while none of patients in this study encountered poor breath hold capacity.

Examination time

The total examination time was 101±20 s (range, 67–146 s) for the standard cine sequence, 20±4 s (range, 14-29 s) for the ss CS cine sequence, and 30±6 s (range, 21–44 s) for the 2-shot CS cine sequence. The ss CS cine and 2-shot CS cine sequences had significantly shorter durations than did the standard cine sequence.

Image quality

The standard cine sequence image score was 3.68±0.64, the ss CS cine sequence image score was 3.13±0.35, and the 2-shot cine sequence image score was 3.54±0.51. There was a significant difference in the image quality between the standard cine sequence and the ss CS cine sequence (Z=−2.858, P=0.004), while there was no significant difference between the standard cine sequence and the 2-shot CS cine sequence (Z=−0.832, P=0.405). There was good interobserver agreement in image quality for all types of cine sequence images. The *kappa* score was 0.871 for the standard cine sequence, 0.939 for the ss CS cine sequence, and 0.897 for the 2-shot CS cine sequence. The standard cine sequence edge sharpness was (2.47±0.18) mm, the ss CS cine sequence edge sharpness was (4.69±0.02) mm, and the 2-shot cine sequence edge sharpness was (2.51±0.13) mm. There was a significant difference in the edge sharpness between the standard cine sequence and the ss CS cine sequence (P<0.001), and between the standard cine sequence and the 2-shot CS cine sequence (P=0.037). *Figures 1,2* show typical images for all the different types of the three cine sequences of a dilated cardiomyopathy patient with regular rhythm at diastole phase (*Figure 1*), and an atrial fibrillation patient at systolic phase (*Figure 2*).

LV function

All 38 patients underwent quantitative analysis of the LV volume measurements. The standard cine images were used as the standard reference for the LV function measurement. *Table 3* shows the cardiac function parameters for all three types of cardiac cine sequences. *Table 4* show that according to the linear regression, there was good agreement between the standard cine and single-shot CS cine sequences and between the standard cine and 2-shot CS cine sequences, while for each LV volume measurement, the coefficient of determination (R^2) between the standard cine and 2-shot CS cine sequences was better than the R^2 between the standard cine and single-shot CS cine sequences. *Table 5* and *Figure 3* show the mean difference with the 95% confidence interval (CI) between the standard cine and the single-shot CS cine sequences and between the standard cine and 2-shot CS cine sequences according to the Bland-Altman analysis results. All the mean differences between the standard cine and 2-shot CS cine sequences are closer to zero than the

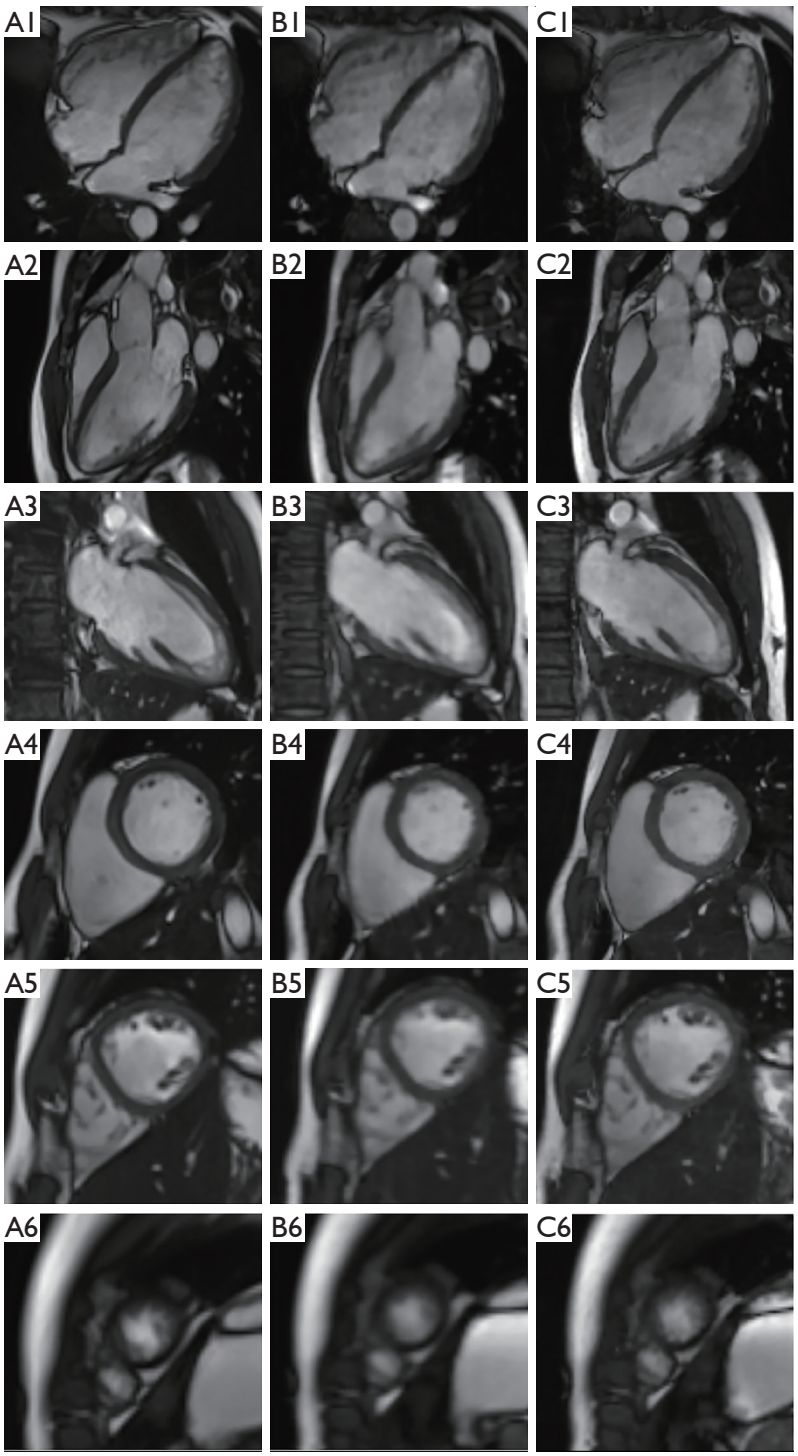

Figure 1 Images of each cardiac magnetic resonance cine sequence of a dilated cardiomyopathy patient with regular rhythm. A 27-year-old male with dilated cardiomyopathy, with the average heart rate 58 beats per minute. Compared with the single-shot CS cine images, the 2-shot CS cine images have a sharper delineation in the myocardial margin, have better contrast in the myocardium blood pool, have fewer artifacts, and are more similar to the standard cine images. A1–A6: standard cine; B1–B6: single-shot compressed sensing cine; C1–C6: 2-shot compressed sensing cine. A1, B1, C1: 4-chamber long-axis view; A2, B2, C2: 3-chamber long-axis view; A3, B3, C3: 2-chamber long-axis view; A4, B4, C4: basal segment of the short-axis view; A5, B5, C5: middle segment of the short-axis view; A6, B6, C6: apex segment of the short-axis view.

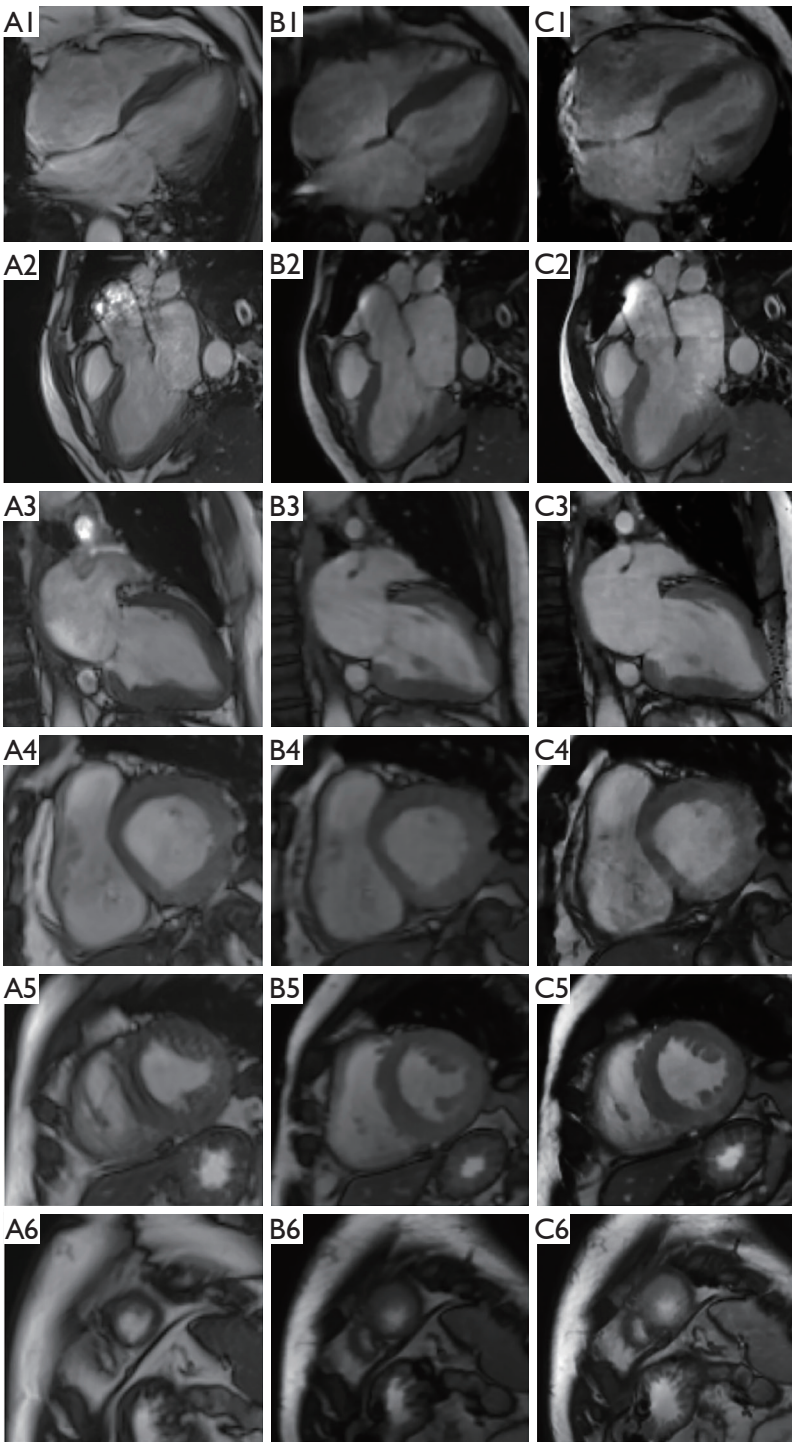

Figure 2 Images of each cardiac magnetic resonance cine sequence of an atrial fibrillation patient. A 67-year-old male with atrial fibrillation at systolic phase, with the average heart rate 67 beats per minute. All images have some of the artifacts especially of the standard cine images. The 2-shot CS cine images have a sharper myocardial margin and better contrast, especially of the short-axis view images. A1–A6: standard cine; B1–B6: single-shot compressed sensing cine; C1–C6: 2-shot compressed sensing cine. A1, B1, C1: 4-chamber long-axis view; A2, B2, C2: 3-chamber long-axis view; A3, B3, C3: 2-chamber long-axis view; A4, B4, C4: basal segment of the short-axis view; A5, B5, C5: middle segment of the short-axis view; A6, B6, C6: apex segment of the short-axis view.

Table 3 Comparison of the cardiac function parameters for each sequence

Parameter	Standard cine	ss CS cine	2-shot CS cine
LVEDV (V/mL)	113.15 (55.9–272.6)	113.75 (57.6–274.0)	113.45 (56.2–272.0)
LVESV (V/mL)	46.55 (17.5–205.9)	47.01 (15.0–209.4)	45.96 (15.2–206.5)
LVEF (%)	59.15 (23.5–82.8)	59.39 (22.0–85.0)	60.78 (22.6–84.8)
LVCO (L/min)	4.58 (1.9–7.6)	4.61 (2.0–7.8)	4.57 (1.9–7.8)
LV mass (m/g)	100.82 (32.8–151.2)	102.10 (35.9–150.4)	101.40 (32.20–151.6)

ss, single-shot; CS, compressed sensing; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction; LVCO, left ventricular cardiac output; LV mass, left ventricular mass.

Table 4 Linear regression of the cardiac function parameters for each sequence

Parameter	R^2 of Standard cine *vs.* ss CS cine*	R^2 of Standard cine *vs.* 2-shot CS cine*
LVEDV (mL)	0.9980	0.9989
LVESV (mL)	0.9984	0.9987
LVEF (%)	0.9886	0.9951
LVCO (L/min)	0.9743	0.9980
LV mass (g)	0.9819	0.9906

*, P<0.001 compared with each other. ss: single-shot; CS, compressed sensing; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction; LVCO, left ventricular cardiac output; LV mass, left ventricular mass.

Table 5 Bland-Altman analysis of the cardiac function parameters for each sequence

Parameter	Standard cine *vs.* ss CS cine		Standard cine *vs.* 2-shot CS cine	
	Mean difference	95% CI	Mean difference	95% CI
LVEDV (mL)	–1.0	–6.0–4.0	–0.7	–4.4–3.1
LVESV (mL)	–0.9	–4.9–3.1	–0.1	–3.7–3.5
LVEF (%)	0.4	–2.8–3.6	–0.1	–2.2–2.0
LVCO (L/min)	–0.02	–0.39–0.35	–0.02	–0.12–0.09
LV mass (g)	–0.9	–8.8–7.0	–0.8	–6.5–5.0

ss, single-shot; CS, compressed sensing; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction; LVCO, left ventricular cardiac output; LV mass, left ventricular mass.

mean differences between the standard cine and single-shot CS cine sequences. The interobserver and intraobserver reliability show very good agreement, as shown in *Tables 6*,7.

Discussion

Cardiac function is an important part of CMR examinations. The occurrence, development, treatment and prognosis of many diseases are closely related to cardiac function. CMR imaging can be used to quantify cardiac function noninvasively. Unlike other methods for which a mathematical model of the cardiac cavity is assumed, such as echocardiography, CMR imaging can accurately assess the entire cardiac cavity by direct calculations, so the results are more accurate, and CMR imaging can be considered the non-invasive gold standard.

The traditional bSSFP sequence is currently used to achieve sufficient image resolution in the evaluation of

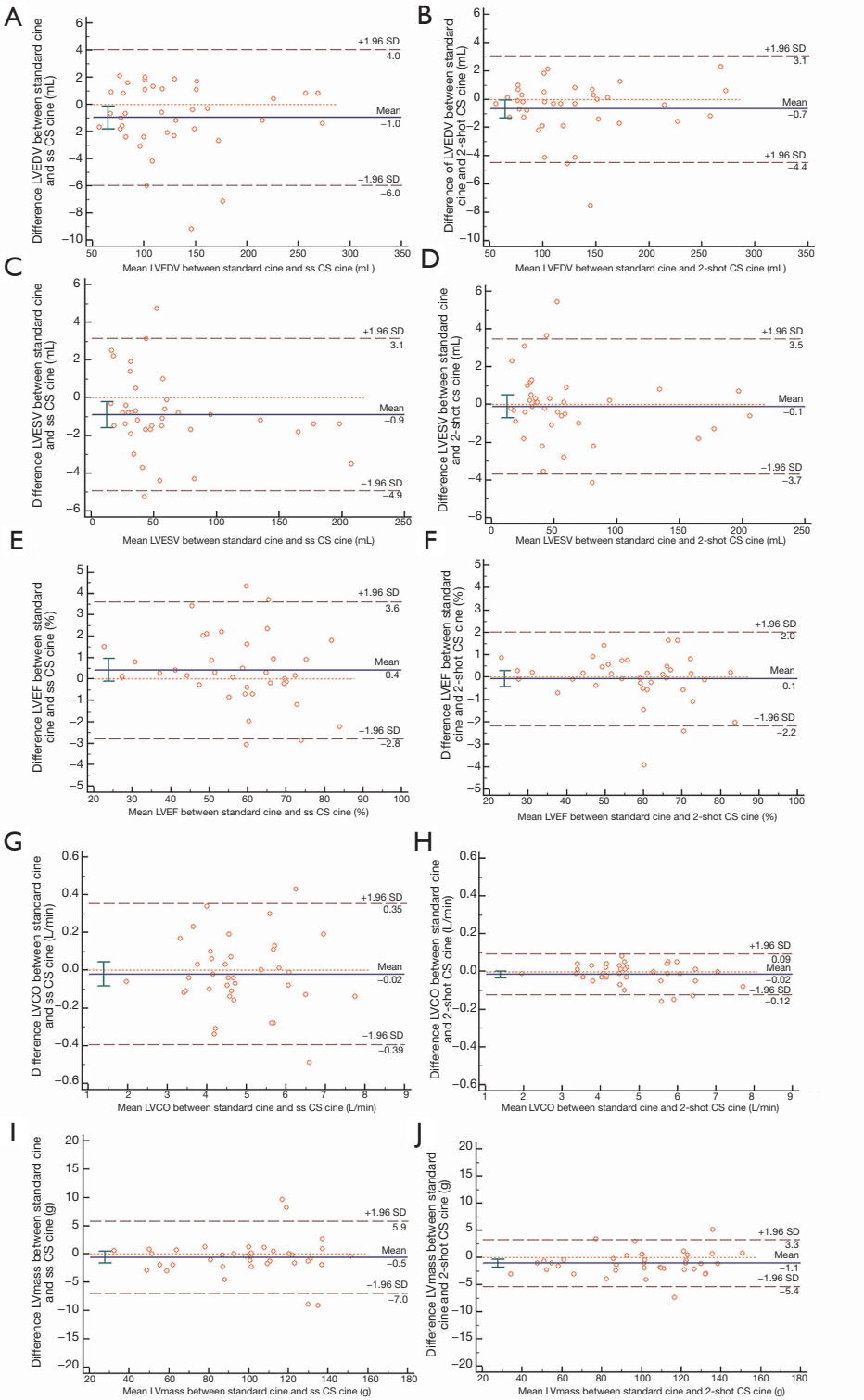

Figure 3 Bland-Altman plot of the results for each cardiac magnetic resonance cine sequence. Bland-Altman plot for the comparison of the cardiac function measurements between the standard cine and single-shot CS cine sequences (A,C,E,G,I) and between the standard cine and 2-shot CS cine sequences (B,D,F,H,J). The solid line indicates the difference between the two sequences; the lines with long dashes indicate the 95% limit agreement interval.

Table 6 Inter-observer reliability of the cardiac function parameters for each sequence

Parameter	Standard cine		ss CS cine		2-shot CS cine	
	ICC estimate	ICC 95% CI	ICC estimate	ICC 95% CI	ICC estimate	ICC 95% CI
LVEDV (mL)	0.9849	0.9712–0.9921	0.9872	0.9755–0.9933	0.9887	0.9875–0.9941
LVESV (mL)	0.9990	0.9980–0.9995	0.9980	0.9962–0.9989	0.9984	0.9970–0.9992
LVEF (%)	0.9904	0.9821–0.9949	0.9832	0.9681–0.9912	0.9873	0.9757–0.9934
LVCO (L/min)	0.9912	0.9831–0.9912	0.9887	0.9795–0.9938	0.9880	0.9973–0.9936
LV mass (g)	0.9765	0.9556–0.9876	0.9825	0.9669–0.9908	0.9831	0.9681–0.9911

ICC, intraclass correlation efficient; CI, confidence interval; ss, single-shot; CS, compressed sensing; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction; LVCO, left ventricular cardiac output; LV mass, left ventricular mass.

Table 7 Intra-observer reliability of the cardiac function parameters for each sequence

Parameter	Standard cine		ss CS cine		2-shot CS cine	
	ICC estimate	ICC 95% CI	ICC estimate	ICC 95% CI	ICC estimate	ICC 95% CI
LVEDV (mL)	0.9860	0.9730–0.9928	0.9878	0.9765–0.9937	0.9892	0.9792–0.9944
LVESV (mL)	0.9991	0.9982–0.9995	0.9986	0.9973–0.9993	0.9986	0.9973–0.9993
LVEF (%)	0.9925	0.9856–0.9961	0.9859	0.9729–0.9927	0.9876	0.9761–0.9936
LVCO (L/min)	0.9912	0.9830–0.9955	0.9906	0.9819–0.9951	0.9903	0.9814–0.9950
LV mass (g)	0.9810	0.9634–0.9901	0.9845	0.9701–0.9920	0.9831	0.9681–0.9911

ICC, intraclass correlation efficient; CI, confidence interval; ss, single-shot; CS, compressed sensing; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction; LVCO, left ventricular cardiac output; LV mass, left ventricular mass.

cardiac function; only one slice is scanned at one time. CS cine imaging can acquire images much faster and can even acquire one slice in a single heartbeat. Some previous studies have shown that CS cine and traditional imaging have similar image quality and LV measurements. Some research studies have shown that EDV, SV and LVEF were underestimated with CS cine imaging because prospective ECG triggering may miss the very first and the last phase of the cardiac cycle (13). We used adaptive ECG triggering and retrospective gating and therefore always acquired the full cardiac cycle to overcome this limitation. Other substantial image quality problems may occur because the spatial and temporal resolution is lower with CS imaging than with standard CMR imaging (14). In our study, the 2-shot CS cine prototype was designed to have better spatial resolution (1.6 mm × 1.6 mm) and temporal resolution (42 mm) than the standard CMR cine sequence. Although the single-shot CS cine sequence we used in this study has a similar spatial and temporal resolution as the standard cine sequence, the 2-shot CS cine prototype has good image quality and high agreement in the LV measurements with the standard cine sequence. It is reasonable that the edge sharpness of standard cine was superior to single-shot CS cine and 2-shot cine CS cine, but as for clinical use, the 2-shot CS cine images were able to get accurate measurements. These results indicate that the 2-shot CS cine prototype has better image quality and can obtain more accurate LV measurements than the single-shot CS cine sequence. Moreover, as it can shorten the total CMR examination time, the 2-shot CS cine prototype is more cost effective than the standard cine sequence during multiple breath-holds.

As we show in *Table 1*, for single-shot CS cine sequence, it scans one slice needs two heart-beats, and 2-shot CS cine needs three heart-beats. Single-shot CS acquired all k-space lines required for reconstructing an image in one readout train in a single heart-beat, while 2-shot CS were assembling k-space lines acquire from two heart-beats then

reconstructing one image. The reason we got an extra one heart-beat is because for all CS sequence, we used the first heart-beat for steady state preparation, and the follow one or two heart-beats to acquire the data. That is why the name of the sequence is single-shot or 2-shot. For one slice, the 2-shot CS cine sequence increases the acquisition time by one heart-beat time compare with single-shot CS cine.

Moreover, the quality of retrospective standard cine images is often poor for patients with arrhythmia or a poor breath-hold capacity. Previous studies have shown that single-shot cine imaging can be inherently insensitive to arrhythmia or respiratory motions because of the single-shot acquisition technique (15). In this study, we found that the 2-shot CS cine prototype has a similar image score to the single-shot CS cine sequence, and those of both sequences were better than that of the standard cine sequence. Some of the CS cine sequences can be acquired during free breathing (16); in the future, a free-breathing CS cine sequence with better image quality should be investigated for patients with arrhythmia and a poor breath-hold capacity.

Limitations

There are some limitations to this study. Firstly, as for ss CS cine sequence, one of the major benefits is that it is insensitive to arrhythmia, theoretically 2-shot CS cine sequence may lose this benefit. In our study, we met 2 arrhythmia case, which were all atrial fibrillation. To our surprise, we did not meet very heavy artifacts, and did not affect the evaluation for cardiac parameters. But we think if the patient has some malignant arrhythmia, for 2-shot CS cine sequence will encounter heavy artifacts as the standard cine sequence, which need further study. Secondly, the sample size was relatively small, and all the participants included in the study were patients. However, because the sequence is mainly used in patients who cannot undergo the traditional examination process, the study results with patients are convincing. And lastly, he right-heart function was not evaluated, and we can compare this measure in future studies.

Conclusions

The 2-shot compressed sensing cine sequence can acquire images that are closer to the quality of the standard cine sequence, has a higher scanning speed, and has an acceptable level of accuracy in the functional parameter assessment compared with the single-shot cine sequence.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at: http://dx.doi.org/10.21037/cdt-20-135). The authors have no conflicts of interest to declare.

Ethical Statement: the authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This study was approved by the Ethics Committee of Peking Union Medical College Hospital (Ethical file code JS-1499). Written informed consent was obtained from the patient for publication of this study and any accompanying images. A copy of the written consent is available for review by the Editor-in-Chief of this journal.

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