Performance of Compressed Sensing Cardiac Cine Imaging in Children: Initial Experience

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Abstract

The aim of our study was to compare conventional segmented balanced steady-state free precession (bSSFP) and real-time Compressed Sensing (CS) cardiac cine imaging in a small group of pediatric patients[1]. 20 subjects with either cardiomyopathy or congenital heart disease treated with biventricular repair were included. Examinations were carried out on our MAGNETOM Aera 1.5T (Siemens Healthcare, Erlangen, Germany) using both retrospectively cardiac-gated Cartesian conventional bSSFP and real-time CS cardiac cine sequences with whole coverage of the ventricles in the short-axis plane. Quantification of ventricular volumes was performed in all cases by two clinical cardiac MRI specialists in consensus. They were blinded to patient diagnosis and type of sequence, and correlated values with phase-contrast flow measurements. CS cardiac cine imaging showed good diagnostic quality and performance. It had slightly lower spatial and temporal resolution but there were no significant differences between ventricular volumes compared to conventional bSSFP sequences. We believe that real-time CS cardiac cine definitely has potential for the pediatric population. However, more work is needed to assess its performance and overcome its current limitations.

Parameters	bSSFP	CS
TR/TE (ms)	2.92/1.21	2.66/1.1
Temporal resolution (ms)	37.44	39.90
FOV (mm)	340	360
Rectangular FOV (%)	75	75
Matrix	256 x 192	208 x 156
Spatial resolution (mm)	1.5 x 1.5 x 7	1.7 x 1.7 x 7
Flip angle (°)	73	55
Bandwidth (Hz/pixel)	930	962
GRAPPA	x2	–
CS	–	x9.9
Cardiac gating	Retrospective	ECG-triggered
Trajectory	Cartesian	Cartesian
Reconstructed cardiac phases	25	20
Number of slices	~15 (12–18)	~15 (12–18)
Breath-hold time (s)	~10 (6.8–13.5) / 2 slices	~20 (17–25)
Total SAX acquisition time (s)	~160 (130–190)	~20 (17–25)
Total reconstruction time (s)	~immediate	~120 (100–150)

Table 1: Sequence parameters.
bSSFP = balanced steady-state free precession; CS = Compressed Sensing; FOV = field of view; GRAPPA = generalized autocalibrating partially parallel acquisition; SAX = short axis; TE = echo time; TR = repetition time

Introduction

Compressed Sensing (CS) is a relatively novel magnetic resonance imaging (MRI) technique based on *k*-space incoherent subsampling paired with a noise-reduction algorithm employing sparse representation in a nonlinear iterative reconstruction process. The aim is to drastically speed up acquisition without significantly degrading image quality [1]. In recent years, CS has become increasingly popular in cardiac MRI. This is especially true for cine imaging in adults, where CS has shown itself to be accurate and reproducible, allowing for fast and reliable scanning even in difficult patients [2, 3]. Compared to conventional segmented balanced steady-state free precession (bSSFP) cine sequences, the major advantages of real-time CS cardiac cine are the decreased scan duration and the relative insensitivity to motion such as irregular heart rhythms and breathing [4]. These features account for most of its appeal in pediatric cases, where patient cooperation is often limited. Moreover, in contrast with classic real-time cine imaging using parallel imaging, CS cardiac cine yields higher spatial and temporal resolution, closer to that of conventional segmented bSSFP [5]. Nevertheless, the smaller anatomical structures and higher heart rates typically found in children can still be a concern. Additionally, congenital heart disease (CHD) can significantly subvert the usual cardiac anatomy and multiple lesions can exist simultaneously. This leads to complex ventricular geometry and flow-volume calculations, and therefore requires a high degree of definition and accuracy. A disadvantage of CS is the relatively long reconstruction times [3], which could impact exam planning and limit clinical implementation. However, recent experiences investigating CS in children and CHD are encouraging, showing feasibility and good agreement with conventional cine imaging [6]. In this context, we present results from our initial experience of how real-time CS cardiac cine performs in comparison with conventional segmented bSSFP cine in a small group of pediatric patients.

Methods

Between January and March 2019, we studied 20 patients who had either cardiomyopathy or CHD treated with biventricular repair and who were referred for cardiac MRI. Informed written consent for additional research scans was obtained from all individuals/guardians. All procedures were in accordance with the ethical standards of the responsible committee on human experimentation and with the Declaration of Helsinki and its later amendments.

All imaging was performed on a 1.5-Tesla MRI scanner (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany). We used the Body 18 matrix coil and the spine coil incorporated into the scan table. A vector electrocardiographic system was used for cardiac-gating. Ventricular volume assessment was performed with both conventional bSSFP and real-time CS cardiac cine sequences in the ventricular short-axis (SAX) plane using sufficient contiguous slices for gapless imaging to ensure whole coverage of both ventricles. Conventional bSSFP cine imaging involved a multi-slice retrospectively cardiac-gated Cartesian sequence, with two slices acquired during every breath-hold. Spatial resolution was 1.5 x 1.5 x 7 mm and temporal resolution was ~37 ms. Real-time CS cardiac cine imaging employed a multi-slice cardiac-gated Cartesian sequence, with the whole volume obtained during a single breath-hold or during free-breathing if breath-holding was not feasible. The acquisition duration was two R-R intervals per slice; the first heartbeat was a non-imaging "dummy" used to reach the steady state, and the second heartbeat was used for data acquisition. Spatial resolution was 1.7 x 1.7 x 7 mm (8 mm in two cases) and temporal resolution was ~40 ms. Full sequence parameters are shown in Table 1.

Quantification of ventricular volumes was performed in all cases by two clinical cardiac MRI specialists in consensus (FD with 6 months and CD with 5 years of experience, respectively), blinded to patient diagnosis and type of sequence, in a random order, and using a commercially available software (cvi[42], Circle Cardiovascular Imaging Inc., Calgary, Canada). The end-diastolic and end-systolic phases were identified for each ventricle through simultaneous visual inspection of all SAX cine images. The endocardial borders of all slices at end-diastole and end-systole were traced manually and included papillary muscles and trabeculation in the blood pool volume. End-diastolic volume (EDV), end-systolic volume (ESV), stroke volume (SV = EDV − ESV), and ejection fraction (EF = SV/EDV × 100) were calculated, correlating SV with aortic and pulmonary valve phase-contrast flow measurements.

Normally distributed continuous data were reported as mean ± standard deviation. Categorical variables were reported as numbers and percentages. Student's independent t-test was used to compare continuous variables. A p-value of less than 0.05 indicated a significant difference.

[1]MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures. Note: This disclaimer does not represent the opinion of the authors.

Results

The mean patient age was 14.57 ± 4.92 years (range: 7–21). 10 patients (50%) were male. 11 had CHD, while the rest had suspected or known cardiomyopathy. The mean heart rate was 80.89 ± 14.48 bpm (range: 55–110 bpm). Demographic details and diagnoses are provided in Table 2.

Our preliminary results showed that there were no statistically significant differences ($p > 0.05$) in EDV, ESV, SV, or EF for left ventricular and right ventricular measurements using either bSSFP or CS sequences. Although not significant, for CS there was a small tendency toward underestimation of all volumes (which was more evident for the RV), and toward overestimation of EF. Ventricular measurements obtained with both sequences are summarized in Table 3. Notably, mean reconstruction time was quite long for CS, with an approximate mean time of 120 ± 15 seconds (range: 100–150) to complete the whole volume.

Characteristics	Mean ± SD (range)
Male/Female	10/10
Age (years)	14.57 ± 4.92 (7–21)
Height (cm)	147.76 ± 17.21 (110–178)
Weight (kg)	48.4 ± 17.09 (26–72)
BSA (m^2)	1.46 ± 0.33 (0.9–2)
Heart rate (bpm)	80.89 ± 14.48 (55–110)
Cardiomyopathy	8
Aortic coarctation	3
Aortic stenosis	2
Tetralogy of Fallot (repaired)	2
Transposition of the great arteries (repaired)	2
Aortopathy	1
Congenitally corrected transposition of the great arteries	1
Myopericarditis	1

Table 2: Patient demographics and diagnoses.
BSA = body surface area; SD = standard deviation

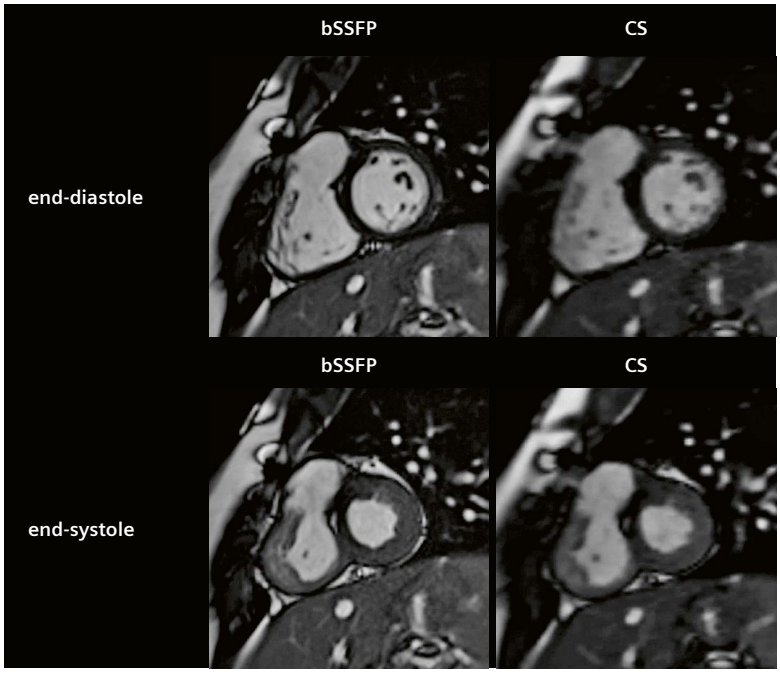
Discussion

In our study, real-time CS cardiac cine imaging showed good diagnostic quality and performance, with slightly lower spatial and temporal resolution (Figs. 1, 2) but no significant differences between calculated ventricular volumes compared to conventional segmented bSSFP sequences. In some cases where irregular heart rhythm or difficulties in breath-holding caused mild motion artifacts on bSSFP images, free-breathing CS cardiac cine provided visually more robust images for volume quantification (Fig. 3). From a clinical point of view, reproducible ventricular quantification is paramount, irrespective of differences in image quality, as significant biases may impact clinical decision making [6, 7]. However, poorer edge definition and myocardial blood pool contrast still posed a major challenge for accurate ventricular segmentation with CS. This aspect might also vary depending on the type of CS sequence employed, with spiral *k*-space trajectories showing better reported results compared to Cartesian acquisition [3, 6]. However, we believe that this difficulty was substantially mitigated by the use of phase-contrast imaging to obtain stroke volume reference values. Although not specifically evaluated, our impression was that the straightforward analysis of CS images without phase-contrast correlation might not yield the same results, as minor but frequent adjustments were required to achieve values that were in accordance with flow measurements. End-diastolic volumes would probably be slightly underestimated and end-systolic volumes would

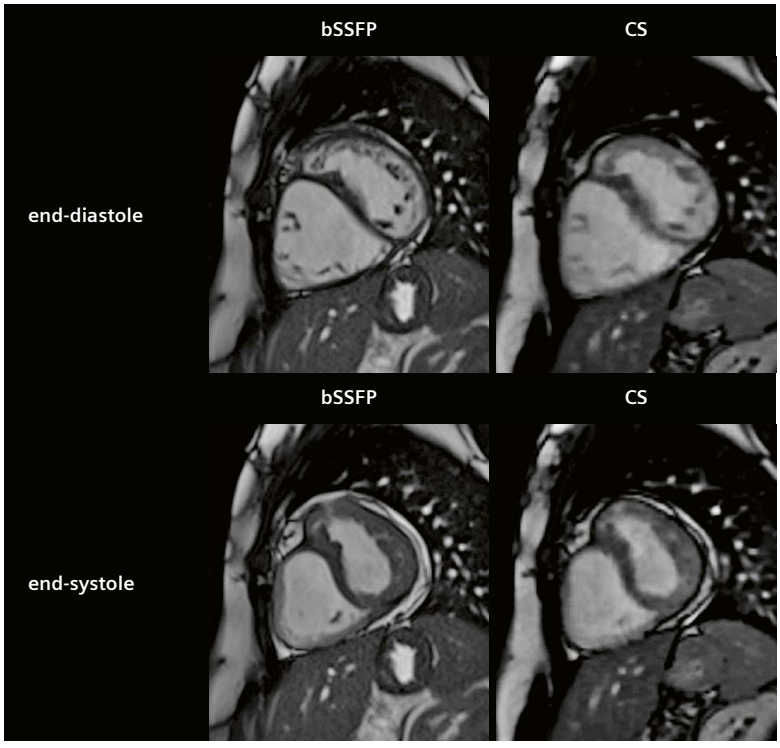
Measurements	bSSFP	CS	p
LV EDV (mL)	135.8 ± 48.1	133.2 ± 50.2	0.87
LV ESV (mL)	53.5 ± 24.9	52.7 ± 27.6	0.91
LV SV (mL)	82.5 ± 25.5	80.7 ± 25.3	0.82
LV EF (%)	61.6 ± 7.0	61.9 ± 7.4	0.9
RV EDV (mL)	140.2 ± 39.9	134.6 ± 37.3	0.6
RV ESV (mL)	59.5 ± 21.6	55.9 ± 19.6	0.58
RV SV (mL)	80.9 ± 21.2	74.3 ± 24.2	0.36
RV EF (%)	58.5 ± 6.4	59.1 ± 6.7	0.79

Table 3: Ventricular measurements obtained with bSSFP and CS cine imaging.
bSSFP = balanced steady-state free precession; CS = Compressed Sensing; EDV = end-diastolic volume; EF = ejection fraction; ESV = end-systolic volume; LV = left ventricular; RV = right ventricular; SV = stroke volume
Ventricular measurements are expressed as mean ± standard deviation.

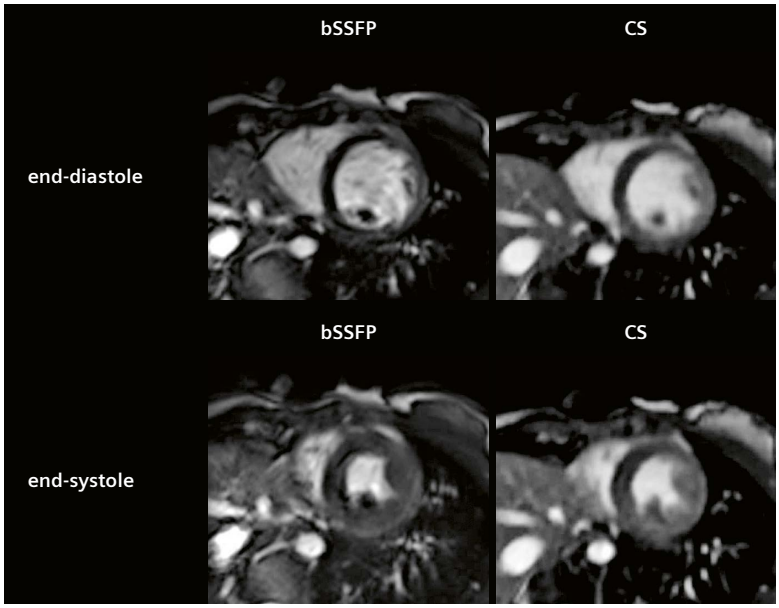
probably be slightly overestimated otherwise, due to blood pool being excluded from the contours in diastole and to myocardial mass being included in systole, particularly for the right ventricle [6]. The decision to employ phase-contrast correspondence was made because we normally use it in our everyday clinical practice and it is frequently described in children and CHD [8]. Nevertheless, it is clearly a major limitation of our study. A further drawback of CS was the long total reconstruction time [3]. In some cases, it reached several minutes, even though images of the first few slices were generally visible after about 20 seconds. Regardless, while not unacceptable, this could be a significant obstacle to adopting CS in everyday clinical practice. Another limitation of our study is the small and heterogeneous population considered. The group contained both cardiomyopathies and CHD, and there were



1 End-diastolic (top row) and end-systolic (bottom row) frames of conventional segmented balanced steady-state free precession (left column) and real-time Compressed Sensing cardiac cine sequences (right column) in a 13-year-old patient affected by tetralogy of Fallot treated with transannular patch and ventricular septal defect closure. The chemical shift artifact at the antero-basal interventricular septum corresponds to the area of ventricular septal defect repair.



2 End-diastolic (top row) and end-systolic (bottom row) frames of conventional segmented balanced steady-state free precession (left column) and real-time Compressed Sensing (right column) cardiac cine sequences in a 15-year-old patient with congenitally corrected transposition of the great arteries. The anterior chamber is the subpulmonary left ventricle, which is dilated due to the presence of an ostium secundum interatrial defect. The posterior chamber is the hypertrophied systemic right ventricle.



3 End-diastolic (top row) and end-systolic (bottom row) frames of conventional segmented balanced steady-state free precession (left column) and real-time Compressed Sensing (right column) cardiac cine sequences in a 9-year-old girl with sporadic ventricular ectopic beats and occasional difficulty performing breath-holds. Conventional bSSFP images show mild motion artifacts.

technical differences in two cases (slice thickness of 8 mm instead of 7 mm). Moreover, we did not calculate ventricular mass. Finally, the evaluation by two readers in consensus made it impossible to assess intra- and interobserver agreement. Future studies on larger and more homogeneous groups of patients could provide more robust results and evaluations of observer agreement.

In conclusion, we believe that CS definitely has potential for use in the pediatric population. However, more work is needed to assess its performance and to overcome its current limitations.

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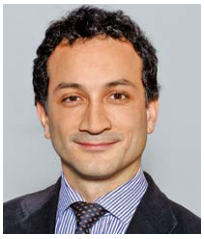
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