Eur Radiol (2003) 13:1931–1936
DOI 10.1007/s00330-003-1982-9

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Single breath-hold real-time cine MR imaging: improved temporal resolution using generalized autocalibrating partially parallel acquisition (GRAPPA) algorithm

Received: 7 February 2003
Revised: 5 May 2003
Accepted: 8 May 2003
Published online: 29 May 2003

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Abstract The purpose of this study was to test parallel imaging techniques for improvement of temporal resolution in multislice single breath-hold real-time cine steady-state free precession (SSFP) in comparison with standard segmented single-slice SSFP techniques. Eighteen subjects were examined on a 1.5-T scanner using a multislice real-time cine SSFP technique using the GRAPPA algorithm. Global left ventricular parameters (EDV, ESV, SV, EF) were evaluated and results compared with a standard segmented single-slice SSFP technique. Results for EDV (r=0.93), ESV (r=0.99), SV (r=0.83), and EF (r=0.99) of real-time multislice SSFP imaging showed a high correlation with results of segmented SSFP acquisitions. Systematic differences between both techniques were statistically non-significant. Single breath-hold multislice techniques using GRAPPA allow for improvement of temporal resolution and for accurate assessment of global left ventricular functional parameters.

Keywords Heart · Heart volume · MR · MR cine study · MR volume measurement

Introduction

Cardiac MRI has been extensively used and validated in assessment of global and regional myocardial function. It has been established as the standard of reference because of its high accuracy, its low intra- and interobserver variability, as well as its high reproducibility.

Most commonly, assessment of cardiac function is based on a stack of double oblique short axis slices acquiring a single slice cine-loop each breath-hold. Recently developed real-time imaging techniques using steady-state free precession (SSFP) sequences allow for a single breath-hold evaluation of global cardiac function [1, 2]; however, due to the restriction to a single breath-hold, this results in low spatial and low temporal resolution that may affect accuracy of volumetric results. New data acquisition and post-processing strategies, such as parallel acquisition techniques (PAT), allow for further acceleration of data acquisition and therefore for improvement of either spatial or temporal resolution in real-time cine imaging.

Therefore, we implemented a real-time multislice SSFP cine technique for assessment of global left ventricular function using parallel acquisition techniques. Volumetric results were compared with a state-of-the-art single-slice segmented SSFP technique.

Materials and methods

Eighteen patients with suspicious/known cardiac disease (i.e., coronary artery disease with/without myocardial infarction, right ventricular dysplasia, pericardial disease) underwent cardiac MRI on a 1.5-T whole body scanner (Magnetom Sonata Maestro Class, Siemens Medical Solutions, Erlangen, Germany). All patients were referred to cardiac MRI for clinical purposes and written informed consent was obtained from all subjects. The scanner system provides eight parallel receiver channels and a gradient system with a maximum strength of 40 mT/m and a slew rate of 200 T/m s^{-1}. For signal reception, a new 12-element surface-coil array was used. Outside elements on each side were combined to fit to the limit of eight receiver channels. In addition, integrated parallel acquisition techniques (iPAT, Siemens Medical Solutions, Erlangen, Germany) were implemented on the scanner.

In all patients functional assessment of the ventricular function was performed in double-oblique short-axis orientation. Patients were examined using a recently developed real-time multislice cine TrueFISP (TR 2.0 ms, TE 0.8 ms, flip angle 50°) technique [3]. The sequence acquires a single slice every other heartbeat initiated by ECG triggering [1]. For improvement of temporal resolution a generalized autocalibrating partially parallel acquisition (GRAPPA) algorithm with an acceleration factor of 2 was used [4]. GRAPPA is an autoSMASH-like parallel acquisition technique that allows for considerable reduction of measured phase-encoding steps and therefore reducing data sampling time. Missing lines are then retrospectively reconstructed based on spatial coil sensitivities. For improved assessment of coil sensitivity profiles, six additional lines (auto-calibration signal=ACS) were acquired within the center of k-space. With an overall matrix size of 60×128 a temporal resolution of 48 ms was achieved using echo sharing. At a constant field of view (FOV) of 400 mm (rectangular FOV: 62.5%) the resulting spatial resolution was 4.2×3.1 mm^2. Left ventricular (LV) volume assessment was performed using a stack of short axis slices with a slice thickness of 8 mm and an interslice gap of 2 mm (Table 1). Coverage of the whole left ventricle was therefore provided with 9–11 slices in a single breath-hold corresponding to an acquisition time of 18–22 heartbeats.

Table 1 Imaging parameters for segmented single-slice cine TrueFISP and real-time multislice cine TrueFISP. *n.a.* not applicable

	Segmented TrueFISP[a]	Real-time TrueFISP[a,b]
TR (ms)	3.0	0.8
TE (ms)	1.5	0.9
Flip angle (°)	55	50
Lines per segment	28	n.a.
Temporal resolution (ms)	42	48
Bandwidth (Hz)	930	1395
Field of view (mm)	380×285	400×250
Acquisition matrix	256×192	128×60
Spatial resolution	1.5×1.5	3.1×4.2
Slice thickness (mm)	8	8
Interslice gap (mm)	2	2

[a] Both techniques were applied using echo sharing
[b] Using generalized autocalibrating partially parallel acquisition (GRAPPA) factor 2; 12 reference lines

As a standard of reference, segmented ECG-triggered cine TrueFISP (TR 3.0 ms, TE 1.5 ms, flip angle 55°) with echo sharing was performed in all subjects at identical slice positions in multiple breath-holds (a single slice per breath-hold) with a length of seven heartbeats each. With a matrix size of 192×256 and a constant FOV of 380 mm (rectangular FOV: 75%) this technique allowed a spatial resolution of 1.5×1.5 mm^2. Acquiring 28 lines per frame and heartbeat in conjunction with echo sharing, a temporal resolution of 42 ms was provided (Table 1). The total examination time for covering the heart with the single-slice technique ranged from 7 to 10 min including data acquisition and patients' recovery periods.

For both imaging protocols LV volume computations at end diastole and end systole were performed using commercially available semi-automatic segmentation algorithms (ARGUS; Siemens Medical Solutions, Erlangen, Germany). The first cine frame after R peak was set as the end-diastolic time point, whereas the end-systolic time point was separately assessed for both techniques by an interactive review of all frames and choosing the one with lowest LV blood-pool area.

Results of automated endocardial segmentation were confirmed and corrected by an experienced reader whenever the contour was not adequately detected by the segmentation algorithm. In all cases of real-time cine imaging manual correction was necessary. Subsequently, end-diastolic volume (EDV) and end-systolic volume (ESV) were automatically calculated by the post-processing software applying Simpson's rule. Based on these results the LV stroke volume (SV=EDV−ESV) and LV ejection fraction (EF=(SV/EDV) were calculated.

Systematic and random differences between both measurements were calculated and statistical significance assessed using

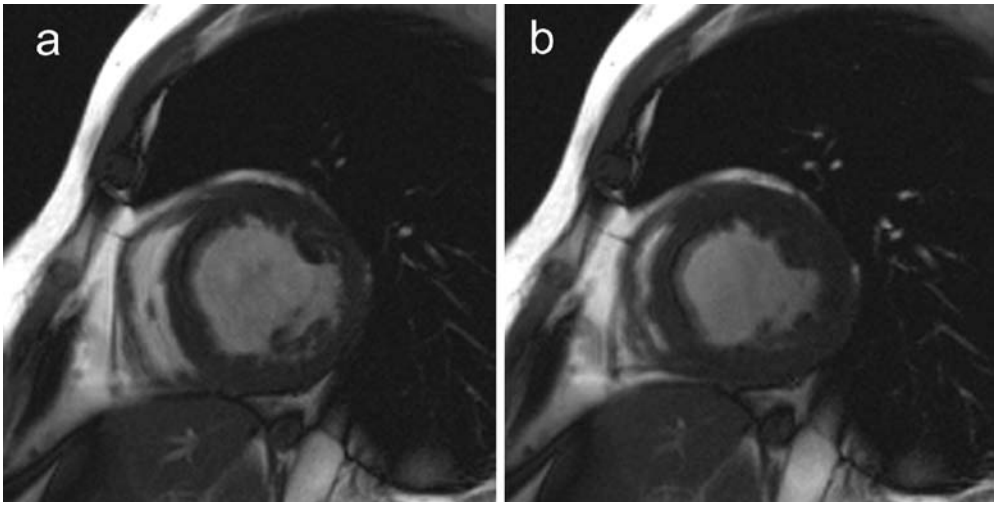

Fig. 1a, b Segmented TrueFISP. Midventricular **a** end-diastolic and **b** end-systolic short-axis views in a patient with dilatative cardiomyopathy (DCM) and marked reduction of ejection faction

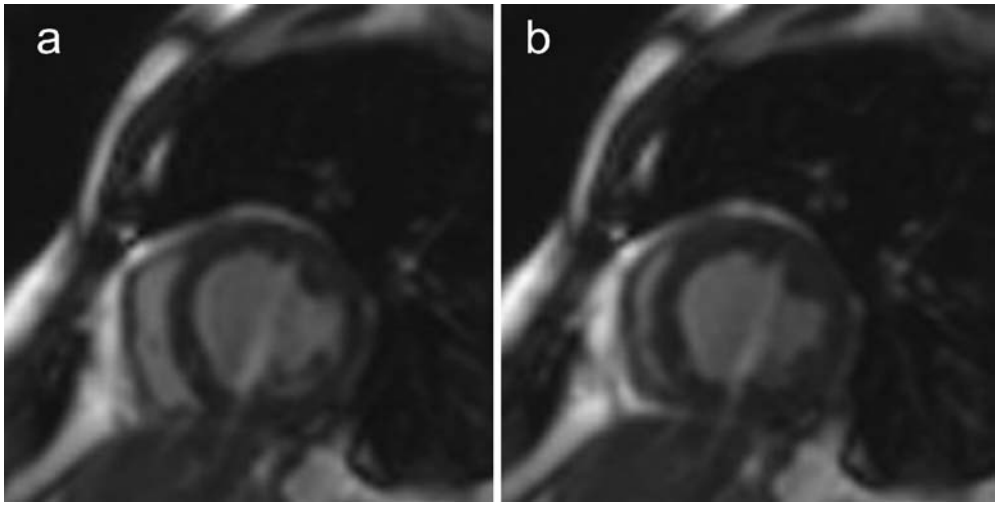

Fig. 2a, b Real-time TrueFISP with generalized autocalibrating partially parallel acquisition: corresponding views to Fig. 1. **a** End-diastolic and **b** end-systolic short-axis views in the same patient with DCM

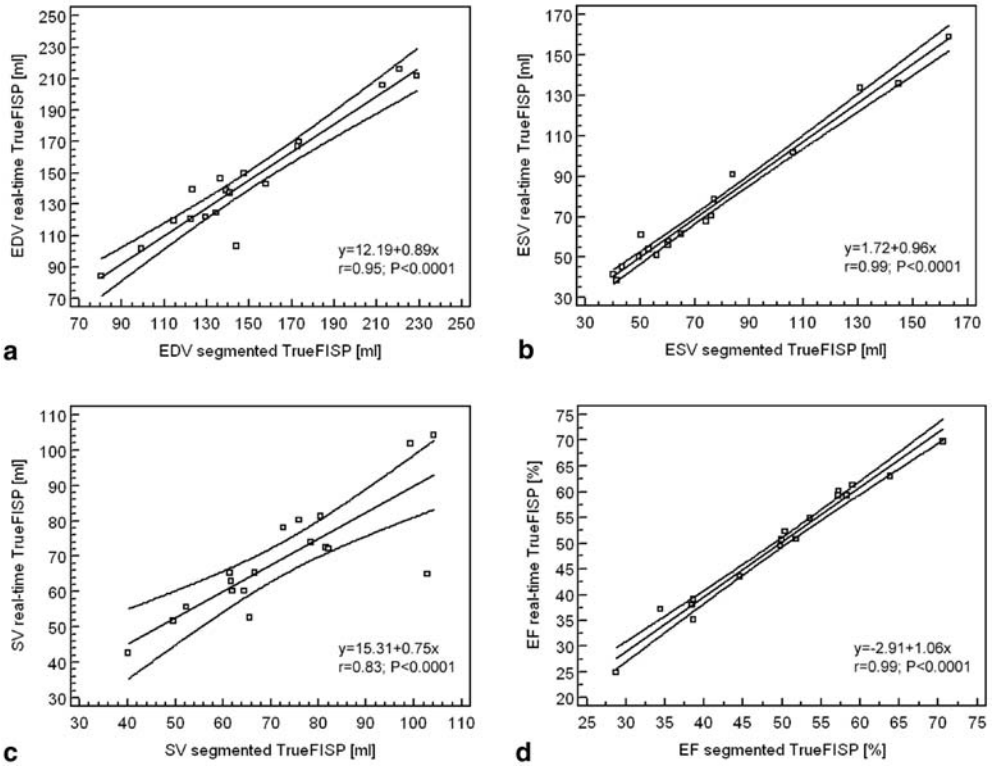

Fig. 3a–d Correlation and regression (including 95% confidence intervals) for real-time TrueFISP in comparison with segmented TrueFISP: results are shown for **a** end-diastolic volume, **b** end-systolic volume, **c** stroke volume, and **d** ejection fraction

Student's two-tailed *t* test for paired samples. In addition, linear regression analysis was performed. Limits of agreement between both techniques were estimated by the Bland-Altman method [5]. A level of $p<0.05$ was considered as statistically significant.

Results

The endocardial contour, representing the border in between the ventricular blood pool and the myocardium, could be delineated and semi-automatically drawn in all subjects, although the reduced spatial resolution of the real-time multislice TrueFISP technique resulted in increased image blurring compared with segmented TrueFISP (Figs. 1, 2). All data sets were eligible for volumetric analysis; however, for real-time multislice data sets considerably more user interaction was necessary using the semi-automated post-processing software.

Results of real-time TrueFISP imaging showed excellent correlation to those of segmented TrueFISP imaging for EDV ($r=0.95$; $p<0.0001$), ESV ($r=0.99$; $p<0.0001$) volumes as well as for EF ($r=0.99$; $p<0.0001$; Fig. 3;

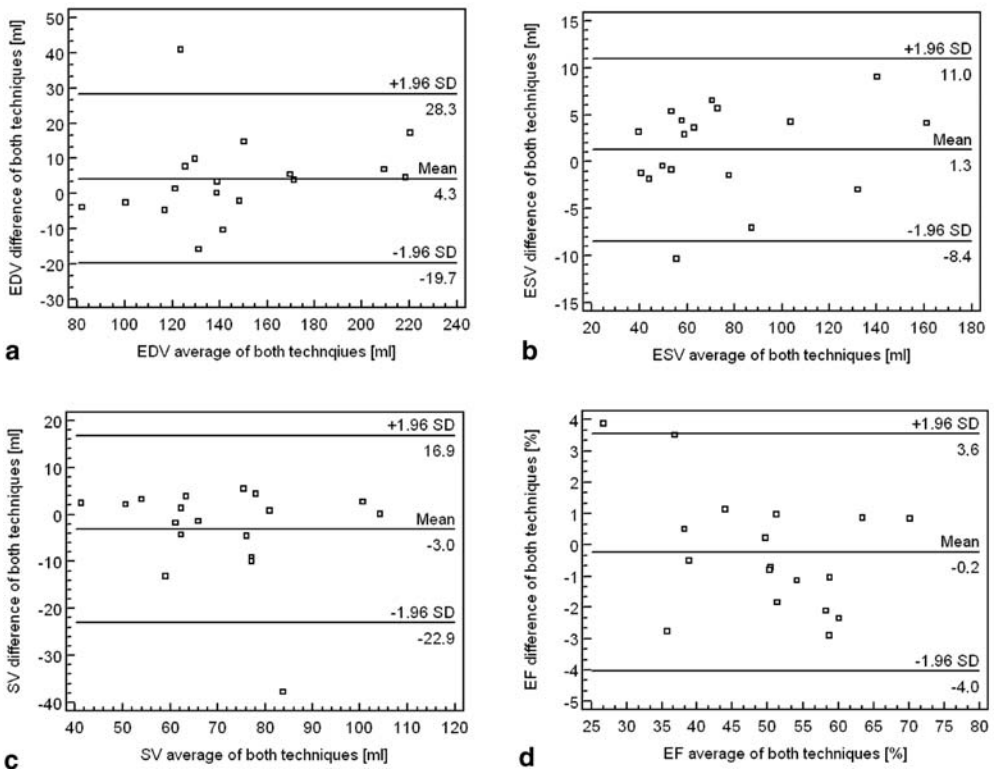

Fig. 4a–d Method comparison with systematic and random differences for **a** end-diastolic volume, **b** end-systolic volume, **c** stroke volume, and **d** ejection fraction between real-time TrueFISP and segmented TrueFISP using Bland-Altman plots

Table 2 Systematic and random differences between results of real-time TrueFISP and segmented TrueFISP

Parameter	Absolute difference	Correlation coefficient (*r*)
End-diastolic volume (ml)	–4.4±12.2	0.95
End-systolic volume (ml)	–1.3±4.9	0.99
Stroke volume (ml)	–3.1±10.2	0.83
Ejection fraction (%)	0.2±1.9	0.99

Table 3 Overall results of real-time TrueFISP and segmented TrueFISP in assessment of left ventricular volumes and function

Parameter	Real-time TrueFISP	Segmented TrueFISP	*P* value
End-diastolic volume (ml)	144.4±37.5	148.8±40.2	0.15
End-systolic volume (ml)	75.1±35.4	76.4±36.5	0.28
Stroke volume (ml)	69.3±16.1	72.3±17.8	0.22
Ejection fraction (%)	50.0±11.7	49.7±10.9	0.61

Student's *t* test (paired samples)

Table 2). The SV correlation was somewhat lower (r=0.83; p<0.0001).

Values of EDV did not show significant differences between segmented TrueFISP (148.6±40.2 ml) and multislice TrueFISP (144.4±37.5 ml; p=0.15). Also for ESV, no significant differences were found for multislice TrueFISP (75.1 ±36.5 ml) compared with segmented TrueFISP (76.4±35.4 ml; p=0.28). Regarding the derived values the following results were found: left ventricular SV was 69.3±16.11 ml for the real-time approach and 72.3±17.8 ml for the segmented technique (p=0.22). Quantitative results for EF were 50.0±11.7 and 49.7± 10.9% for real-time TrueFISP and segmented TrueFISP, respectively (p=0.61; Table 3).

Systematic and random differences between both techniques were –4.3±12.2 ml for EDV, –1.3±4.9 ml for ESV, –3.1±10.2 ml for SV, and 0.2±1.9% for EF (Fig. 4; Table 2).

Discussion

Accuracy of cine MR imaging has been shown in numerous studies throughout the past decade. Data acquisition in cine imaging has been accomplished during free breathing using data averaging until development of fast gradient techniques allowed for segmented data acquisition and therefore introduction of breath-hold cine imaging [6, 7, 8]. A comparison of both techniques showed accurate results for the breath-hold approach, although differences in the patients' breath-hold level might occur [7, 8].

Recently, with improvements of scanner and gradient hardware, SSFP techniques have been introduced into

functional cardiac imaging allowing for improved contrast-to-noise ratios (CNR) and therefore for a better delineation of the endocardial border [9, 10]. Although SSFP techniques have shown high reproducibility similar to fast low-angle shot technique, they lead to higher EDV and ESV based on a better delineation of the endocardial border in areas of trabeculation [9, 10]. In addition to the improved CNR, the data acquisition is accelerated resulting in shorter breath-hold periods per slice; however, SSFP techniques still require multiple breath-holds (~8–12) for short-axis coverage resulting in imaging times of ~10 min including data acquisition, image reconstruction, and patients' recovery periods. The use of real-time multislice techniques allow for acquisitions of volume data sets within a single breath-hold period; however, temporal as well as spatial resolution of these techniques is limited. Barkhausen and co-workers recently showed that a temporal resolution of approximately 75 ms leads to an overestimation of ESV and underestimation of EF when compared with segmented single slice TrueFISP techniques [1]. Controversially, a study by Lee and co-workers showed comparable results using both techniques, although only a temporal resolution of 90 ms was implemented for the real-time technique [2].

High temporal resolution is of paramount importance for adequate and accurate evaluation of cardiac volumes. Especially end-systole represents a very short time period of least left ventricular volume in between aortic valve closure and mitral valve opening known as the isovolumetric relaxation. This period is flanked by rapid cardiac output in systole and the rapid filling in early diastole. The length of the isovolumetric end-systolic period has been reported to be as short as ~40 ms [11]. A study conducted by Setser and co-workers compared theoretically necessary data sampling frequencies (based on Nyquist criteria) to findings in a volunteer study and suggested a sampling frequency of 20–25 Hz which corresponds to a temporal resolution of 50–40 ms at a heart rate of 60 bpm [12]. In addition, Miller and co-workers conducted a volunteer study using a single slice technique with different temporal and spatial resolutions. They found that ESV and EF are affected mainly by changes in temporal resolution, rather than by changes in spatial resolution [13]. Consistent with the theoretical considerations and calculations by Setser and co-workers [12], they did show that with a temporal resolution of less than 45 ms values of ESV changes, whereas EDV remains constant [13].

The sequence technique used in the current study does meet the requirements of a high temporal resolution in order to accurately assess global cardiac function throughout a wide range of heart rates within a single breath-hold. Compared with the results of Barkhausen and co-workers, there were no significant differences found between a multislice single breath-hold cine technique and a standard segmented cine technique (Tables 2, 3) [1]. The improvement in temporal resolution had become possible using an auto-SMASH-like parallel acquisition technique called GRAPPA that allows for a significant reduction in acquired phase-encoding steps followed by reconstruction of missing lines based on coil-sensitivity profiles [4]; however, to keep breath-hold periods within a reasonable range, there still has to be a trade-off in spatial resolution which also may influence results of ventricular volumes [12]. Although parallel imaging algorithms allow for even higher acceleration factors, depending on the algorithm used, higher acceleration factors go along with increasing image artifacts and a decreasing signal-to-noise ratio (SNR).

Besides parallel imaging techniques, other implementations and strategies allow for improvement of temporal resolution in multislice cardiac cine imaging. Schalla and co-workers reported accurate volumetric results using a multislice real-time echo-planar imaging (EPI) approach with a temporal resolution of 62 ms [14]. Improvement of temporal resolution has recently also been reported using undersampled projection reconstruction that can also be applied to cardiac cine imaging [15, 16, 17].

In addition to an adequate temporal resolution, spatial resolution of cine imaging as well is of importance especially in assessment of regional myocardial function. Although visual interpretation of wall motion at rest as well as during stress has been reported to be accurate using real-time EPI technique [14, 18], Plein and co-workers found an underestimation in wall thickening compared with standard cine techniques that is most likely to be based on the reduced spatial resolution [18].

However, this study was carried out in order to assess the accuracy of this new technique for evaluation of global functional parameters. Its accuracy concerning regional wall motion analysis has yet to be determined.

Although the spatial resolution is lower than with segmented cine SSFP techniques, it has been shown to be a promising tool to cut down overall examination time. This might be particularly attractive for a comprehensive imaging approach of the whole cardiovascular system in combination with other techniques such as MR angiography or cardiac perfusion imaging. The use of the GRAPPA technique for other cardiac applications, e.g., myocardial perfusion, imaging has to be evaluated. The combination of the GRAPPA technique in combination with dynamic MR angiography data acquisition has already been reported by Nikolaou and co-workers [19].

Conclusion

This study shows that multislice real-time cine imaging using GRAPPA provides a sufficient temporal resolution for accurate evaluation of global left ventricular volumes. Concerning regional wall motion assessment, further investigations have to be performed.

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