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ORIGINAL ARTICLE

Ventricular Function

Improved Accuracy of Quantitative Assessment of Left Ventricular Volume and Ejection Fraction by Geometric Models with Steady-State Free Precession

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ABSTRACT

The purpose of this study was to determine whether steady-state free precession (SSFP) could improve accuracy of geometric models for evaluation of left ventricular (LV) function in comparison to turbo gradient echo (TGrE) and thereby reduce the acquisition and post-processing times, which are commonly long by use of the Simpson's Rule. In 25 subjects, cine loops of the complete heart in short and horizontal long-axis planes were acquired using TGrE (TR/TE/flip = 5.0/1.9/25) compared with SSFP (TR/TE/flip = 3.2/1.2/60). LV volumes and EF were measured with various geometric models for TGrE and SSFP. With three-dimensional data, the LV volumes were higher and the resulting EF lower for SSFP in contrast to TGrE (51 ± 15% vs. 57 ± 15%, $p < 0.001$*). With SSFP, various geometric models yielded good to excellent correlations for LV volumes and LVEF compared to volumetric data (*$r = 0.94 - 0.98$*, mean relative difference 7.0–11.4%). In contrast, correlations were low using biplane or single-plane ellipsoid models in TGrE (*$r = 0.71 - 0.75$*, mean relative difference 15.9–30.2%). A new combined*

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geometric model, taking all three dimensions into account, yielded the highest accuracy for SSFP in comparison to volumetric data (r = *0.99*, *mean relative difference 4.7%). Geometric models for assessment of LV volumes and EF yield higher accuracy and reproducibility by use of the SSFP sequence than by standard TGrE. This may increase clinical utility of magnetic resonance by shorter acquisition and processing times.*

Key Words: *Magnetic resonance; Steady-state free precession; Left ventricular function; Left ventricular volumes; Image quality*

INTRODUCTION

The accurate and reproducible measurement of left ventricular (LV) volumes and function is important for monitoring progression, therapeutic responses,[1] timing of surgery,[2] or to discriminate prognosis in cardiac diseases.[3] Three-dimensional (3D) magnetic resonance (MR) methods have been shown to be highly accurate and reproducible[4–10] and are regarded as the reference standard for volume determination. However, a limitation to the widespread use of cardiac MR for serial assessment of LV volumes and function is the time required for acquisition of a complete 3D data set of the heart and the time-consuming procedure of manual or semiautomated tracing of endocardial contours. Automated and semiautomated contour detection programs are still not robust to replace manual drawing of up to 40 slices.[11,12] An additional problem occurs in the evaluation of the most basal image plane in volumetric data sets. Due to the through-plane motion of the basal slice, it or parts of it may belong to the LV volume at enddiastole but may need to be excluded at systole. Currently, there are multiple different approaches to circumvent this problem, but as a result volumetric data sets, although the reference standard, still carry potential inaccuracies.[13] New through-plane motion correction programs could show significant differences for end-systolic volumes (ESV) and EF in comparison to the slice omission method but are not available for routine scanning.[14] Thus, a combination of short- and long-axis views, which could cover all three dimensions and would take long-axis shortening into account would be desirable and could possibly improve inter- and intraobserver variability, as well as accuracy. However, especially in long-axis planes and in patients with impaired LV function contrast between blood and the myocardium can be low due to saturation effects in standard turbo gradient echo (TGrE) techniques, which are used for most clinical MR studies. This low contrast may introduce errors for the depiction of the endocardial border, which may be the major reason for the observation that geometric models and volumetric MR cannot be considered interchangeable for a given patient,[15,16] even though from a mathematical standpoint 3D models should differ only minimally from a volumetric data set. Recently, steady-state free precession (SSFP) was introduced in cardiac MR. The SSFP sequence gives excellent contrast between blood and myocardium, even without any inflow effects and results in an improved image quality.[17–19] This is especially useful for cardiac long-axis views or patients with impaired EF. The aim of this study was to analyze the effects of improved image quality on accuracy and reproducibility of various geometric models to determine LV function and volumes by use of the SSFP sequence in comparison to a standard segmented *k*-space TGrE technique and to assess a new geometric model, which combines a biplane and single-plane approach and provides good depiction of the mitral valve plane during systole and diastole.

METHODS

Study Population

Twenty-two patients and three healthy volunteers were enrolled in the study after written informed consent and approval of the study by the local ethics committee. Mean age was 57 ± 14.6 (range 28–77 years). Twenty-three subjects were male and two female. Subjects were excluded from the study, if they were hemodynamically instable or had contraindications for MR examination such as implanted pacemakers and metallic cerebral clips or reasons for inadequate image quality such as high-grade ventricular arrhythmias, atrial flutter, or fibrillation. The 25 subjects included 19 patients with coronary artery disease, 11 with previous myocardial infarction, 11 with LV hypertrophy due to long-standing arterial hypertension, one with dilated cardiomyopathy, one with aortic stenosis, and three with mitral regurgitation.

Magnetic Resonance Imaging

All patients were examined at rest (heart rate < 100 beats per minute) in the supine position with a whole body 1.5 T MR tomograph (Gyroscan ACS NT, PT 6000 gradients, Release 6.2 with INCA2 prototype software, Philips Medical Systems, Best, The Netherlands) using a 5-element cardiac synergy coil for signal reception. To obtain a small field of view and to avoid fold-over only the two anterior segments of the coil were used for data acquisition. All images were acquired during breath hold at end expiration. Respiratory status was checked with a strain gauge. After two rapid surveys for determination of the cardiac position and orientation, 7–15 continuous short axis planes (slice thickness 8 mm, no gap), which covered the complete left and right ventricle, were acquired. A horizontal and a vertical long-axis plane were additionally imaged in all patients.

The imaging sequences have been described in detail elsewhere.[19] In brief, images were acquired with a segmented *k*-space TGrE technique (repetition time 5.0 msec, echo time 1.9 msec, flip angle 25°, spatial resolution $1.3 \times 2.6 \times 8$ mm, temporal resolution 31 msec, field of view $310–350 \times 200$ mm) using prospective ECG triggering and breath holding (6–16 heartbeats depending on heart rate and duration of breath hold) for motion suppression.

A second data set with identical geometry was acquired using SSFP (repetition time 3.2 msec, echo time 1.2 msec, flip angle 60°, spatial resolution $1.3 \times 2.6 \times 8$ mm, temporal resolution 31 msec, field of view $310–350 \times 200$ mm). Motion suppression was achieved by prospective ECG-gating and breath holding of 6–16 heartbeats. To avoid magnetic field inhomogeneities, shimming was performed for the imaged area.

Volume Calculation and Ejection Fraction Measurement

The acquired images were analyzed on an independent off-line Sparc 5 workstation (Easy Vision Release 4, Cardiac Package, Philips Medical Systems, Best, The Netherlands). Endocardial borders were traced manually using a mouse. The first phase of each slice was defined as enddiastole. Endsystole was defined as the phase with the smallest total LV volume. Papillary muscles were excluded from the LV volume (Fig. 1). The most basal slice to be included had to cover $>50\%$ of the circumference of the LV. Slices, containing solely the left atrium, were excluded.

LV enddiastolic (EDV) and ESV, stroke volume (SV = EDV − ESV) and ejection fraction (EF = SV/EDV) were calculated from short-axis views covering the complete ventricle. The volumes were calculated as the sum of the areas of the LV cavity multiplied by the slice thickness. Endocardial borders of the LV were traced the same way in the long-axis projections and papillary muscles, if present, were also excluded from the LV volume. The ventricular length was defined as the length of the LV cavity measured from the mitral valve annulus to the endocardial border of the apex.

Volumes were also calculated by use of several geometric models: the modified Simpson rule model, the hemisphere cylinder model, the biplane ellipsoid model, the single-plane ellipsoid model, and the Teichholz model (Fig. 2).[5] Additionally a new model, which combines two long-axis planes and one short-axis plane measured on the section of the papillary muscle, was used (= combined triplane model) (Fig. 2). The geometric models were grouped according the following definitions: A = models using only short-axis views for volume calculation (the modified Simpson rule model, the hemisphere cylinder model, and the Teichholz model); B = models using

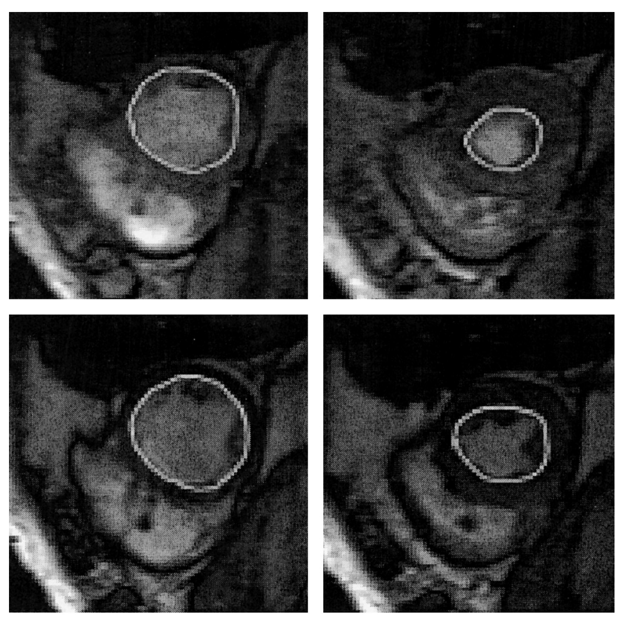

Figure 1. Tracing of endocardial border in short-axis planes during diastole (left column) and systole (right column) for TGrE (top row) and SSFP (bottom row).

long-axis views for calculation (the biplane ellipsoid model, the single-plane ellipsoid model for the horizontal and vertical long-axis plane); C = models using long- and short-axis views for calculation (the combined triplane model). The volumes and the EF obtained by the individual geometric model acquired by TGrE (SSFP) were compared to the volumetric data set as reference acquired by TGrE (SSFP). There were no comparisons between the imaging methods, apart from the comparison of the volumetric data sets between TGrE and SSFP.

For clinical purposes, subjects were classified into one of the three categories according to LVEF: 1) normal LVEF ($\geq 55\%$); 2) moderately depressed LVEF ($> 35\%$ to $< 55\%$); or 3) severely depressed LVEF ($\leq 35\%$).

For assessment of interobserver variability in determination of LV volumes and EF by group B geometric models, the relevant data sets were analyzed

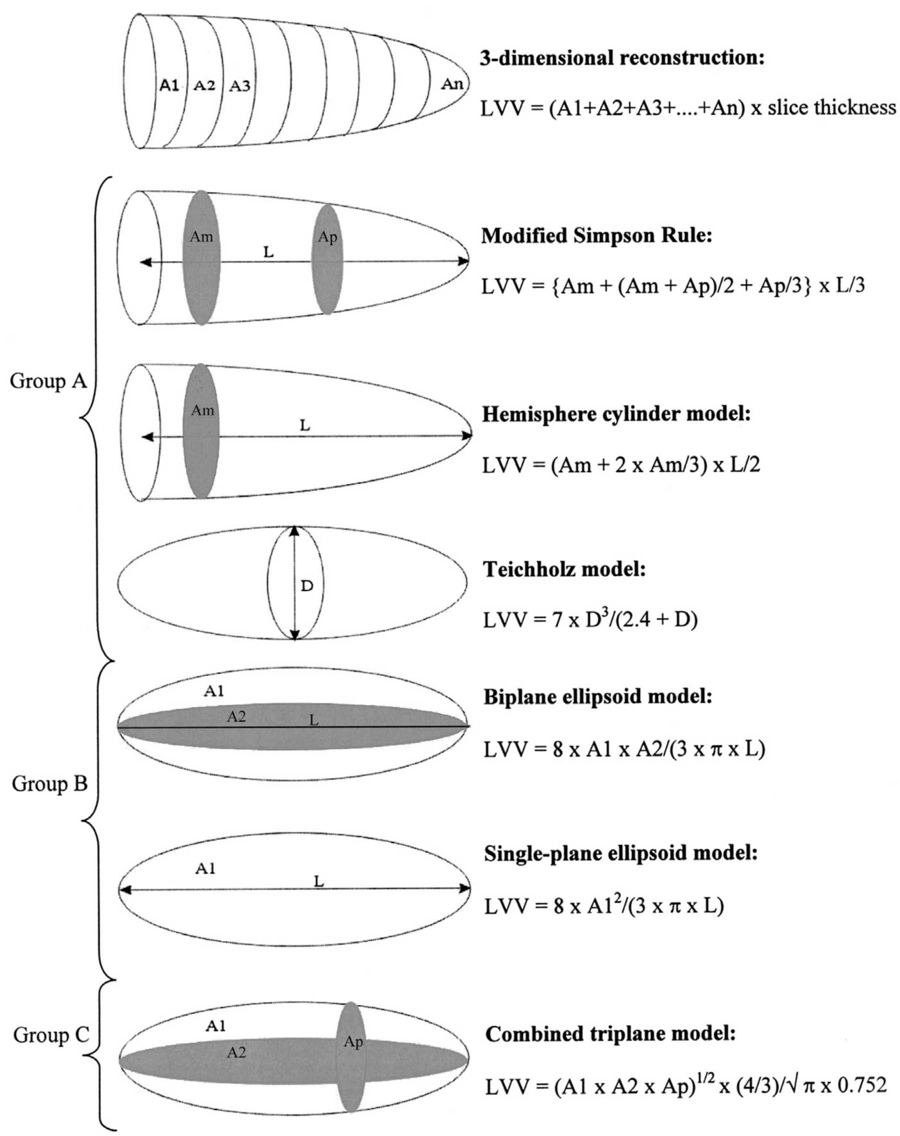

Figure 2. Algorithms and formula for geometric models and a 3D data set for determination of LV volumes (LVV = left ventricular volume; Am = short axis area of left ventricle at mitral valve level; Ap = short axis area of left ventricle at papillary muscle level; L = length of left ventricle; D = short axis diameter of left ventricle at mitral valve level).

by two independent observers. To determine intraobserver variability, analysis of all subjects was repeated after four weeks by one of the observers without reviewing the results of the first analysis.

Statistical Analysis

For all parameters mean ± standard deviation are given. Results for TGrE imaging and the SSFP technique were compared by analysis of variance for repeated measurements. The paired Student–Newman–Keuls test was performed for multiple pairwise comparisons between imaging strategies using statistical software (SigmaStat® 2.03, Version 2.0 SPSS Inc.). All tests were two-tailed and a p value < 0.05 was considered statistically significant. The results of LV volumes and EF, as measured with the various geometric models were linearly correlated with the 3D data set as reference of either SSFP or the TGrE technique. Linear correlation was performed for intra- and inter-observer variability. The degrees of agreement between two methods, different observers and repeated measurements of one observer were determined as mean absolute difference (bias), 95% confidence interval of the mean difference and mean relative difference (difference of two techniques divided by their mean value) according to the methods of Bland and Altman.[20]

RESULTS

All images obtained were sufficient for tracing of the endocardial contours (example see Fig. 3). As all patients were at rest with heart rates < 100 beats per minute, no significant flow artifacts occurred in the SSFP sequence.

Left Ventricular Volumes and Ejection Fraction by 3D Reconstruction

EDV for TGrE, as determined from the 3D data, ranged from 66 to 371 mL (186 ± 74 mL), ESV ranged from 15 to 290 mL (89 ± 67 mL), and LVEF ranged from 21 to 81% (57 ± 15%). There was a strong correlation for TGrE with the SSFP technique. However, EDV and even more ESV were significantly higher ($p < 0.001$) and LVEF was lower ($p < 0.001$) by use of the SSFP technique (Table 1).

3D Data Sets vs. Various Geometric Models

Correlations (r) for EDV and ESV determined by a volumetric data set and by geometric models were excellent for SSFP ($r = 0.94–0.99$) except for the Teichholz model ($r = 0.88–0.92$). With TGrE correlations were excellent for group A (except the Teichholz model) and C models ($r = 0.95–0.99$), although not as good as for SSFP, and mildly to substantially lower for group B models ($r = 0.87–0.94$). Analogously, for LV volumes limits of agreement were slightly wider for TGrE in comparison to SSFP for group A (except the Teichholz model) and C models. However, in those geometric models, which include long-axis planes for calculation (group B) SSFP yielded approximately two fold smaller differences than TGrE.

Similarly, correlations for LVEF determined from the 3D data were higher for SSFP ($r = 0.88–0.99$) than for TGrE ($r = 0.71–0.98$) in comparison with various geometric models. The limits of agreement shown by Bland–Altman plots (Fig. 4a) in TGrE yielded a small systematic difference and small 95% intervals (± 7.6 to ± 10.0 EF units) for group A (except the Teichholz model) and C models in comparison to the volumetric method, but the mean bias and 95% confidence intervals were large for group B models and the Teichholz model (± 19.4 to ± 23.0 EF units). Using the SSFP technique, mean bias and 95% confidence intervals were modestly lower in comparison with the TGrE technique for group A (Teichholz model excluded) and C models (± 5.1 and ± 7.4 EF units). In contrast, the mean relative difference for LVEF was much smaller for group B models when compared to TGrE (± 8.0 to ± 11.8 EF units) (Fig. 4b). The obtained EF in TGrE [SSFP] was significantly different in comparison to the 3D data set for the biplane ($p = 0.01$) [$p = 0.02$], single plane 4-chamber ($p = 0.0004$) [$p = 0.02$], single plane 2-chamber ($p = 0.04$) [$p = 0.18$] and the Teichholz model ($p < 0.001$) [$p = 0.004$].

Accuracy of Geometric Models in Patients with Regional Dysfunction

Subgroup analysis of patients with regional dysfunction ($n = 13$) showed lower correlations and a wider limit of agreement for LVEF by use of all geometric models compared to patients with global normal LV ($n = 12$) for both imaging techniques (Table 2), although in group C models correlation and mean relative difference were still excellent. Again, group B models with SSFP yielded a more accurate estimation of LV function and volumes in comparison to TGrE.

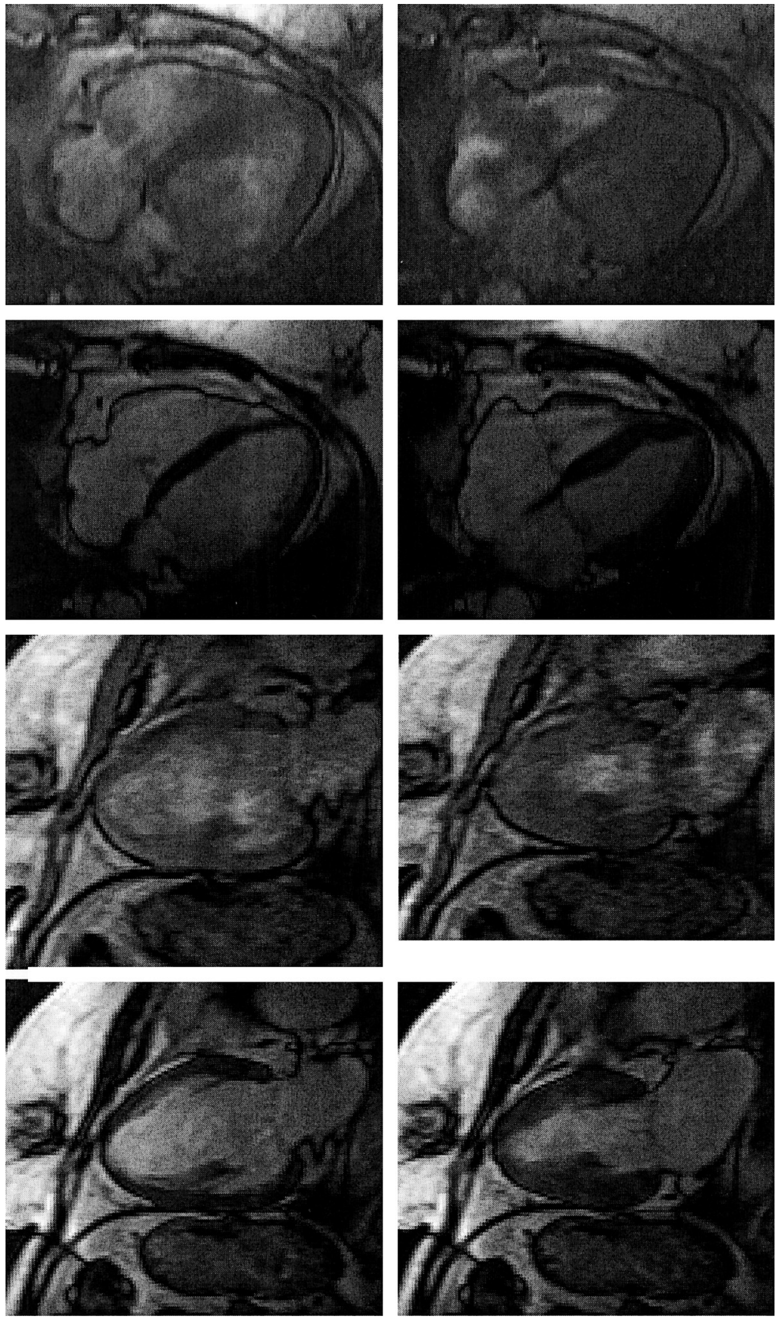

Figure 3. Enddiastolic (left column) and endsystolic four-chamber view images (right column) in TGrE (top row) and SSFP (2nd row) as well as two-chamber-plane images in TGrE (3rd row) and SSFP (4th row).

Left Ventricular Ejection Fraction Classification

Classification of patients into normal, moderately depressed, or severely depressed resulted in the following for TGrE [SSFP] in comparison with the 3D evaluation: modified Simpson rule 0 [0] misclassifications, hemisphere cylinder model 3 [2], Teichholz model 9 [4], biplane ellipsoid model 10 [3], horizontal single-plane ellipsoid model 10 [4], vertical single-plane

Table 1

Left Ventricular Volumes (EDV, ESV, SV) and EF, Correlations, and Absolute Differences by 3D Reconstruction Between TGrE and SSFP

	TGrE	SSFP	Correlation (r)	Absolute Difference	p
3D EDV (mL)	186 ± 75	200 ± 82	0.99	− 13.7 ± 12.4	<0.001
3D ESV (mL)	89 ± 67	107 ± 76	0.99	− 18.1 ± 12.1	<0.001
3D SV (mL)	97 ± 23	92 ± 23	0.93	4.4 ± 8.8	= 0.021
3D EF (%)	57 ± 15	51 ± 15	0.97	5.8 ± 3.9	<0.001

TGrE = turbo gradient echo; EDV = enddiastolic volume; ESV = endsystolic volume; SV = stroke volume; EF = ejection fraction.

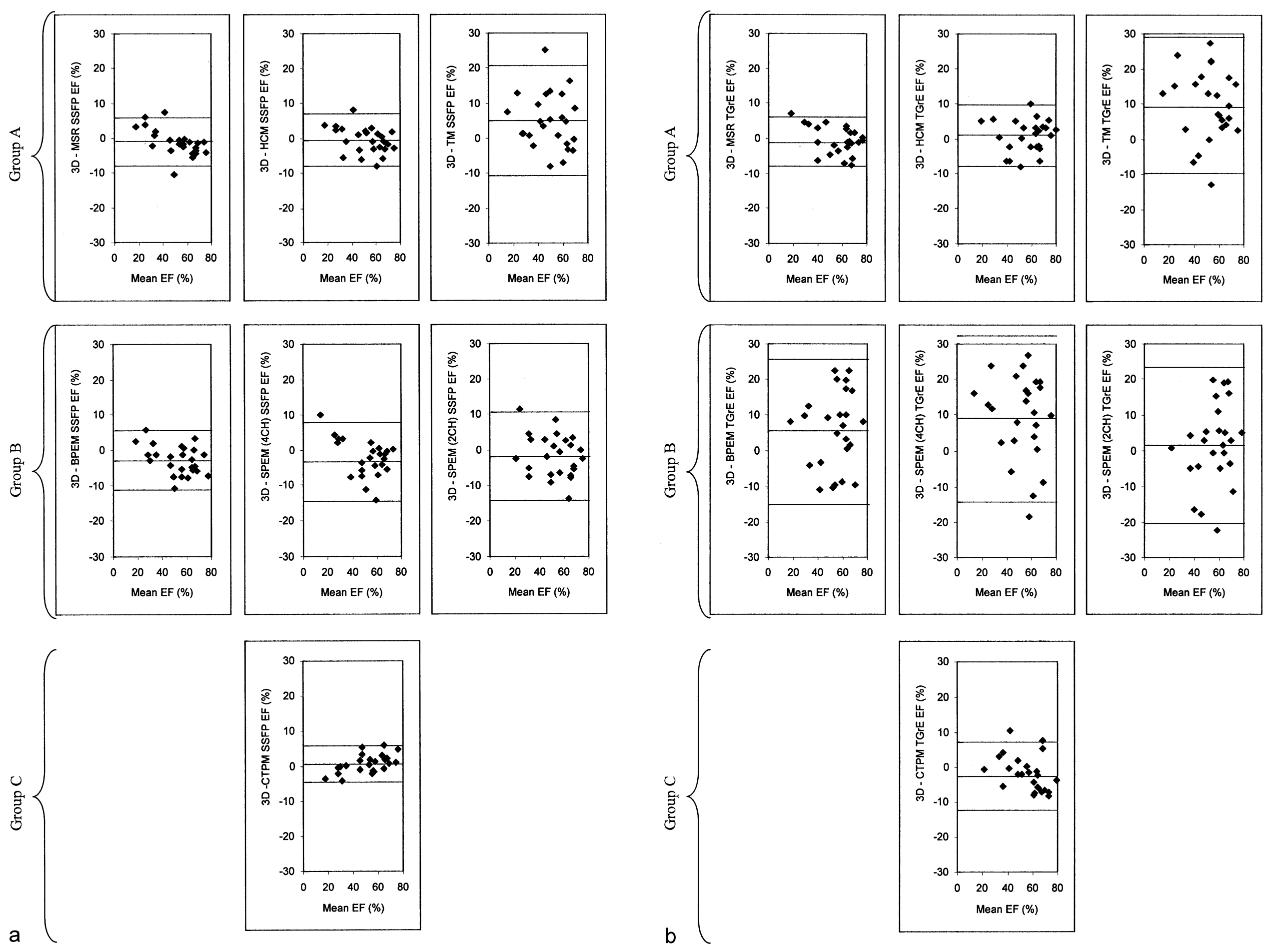

Figure 4. Bland–Altman-Plots for LVEF between a 3D data set acquired by TGrE a) or SSFP b) and group A models (MSR = modified Simpson rule; HCM = hemisphere cylinder model, TM = Teichholz model), group B models [BPEM = biplane ellipsoid model, SPEM = single-plane ellipsoid model of the four- (4CH) and two-chamber view (2CH)], and group C models (CTPM = combined triplane model). In each plot, the central horizontal line indicates the mean absolute difference or bias, upper and lower lines represent 95% confidence intervals.

Table 2

Correlations, Mean Relative Differences, and Limits of Agreement of Left Ventricular EF Between Various Geometric Models and a 3D Data Set for TGrE and SSFP in Patients with and without Regional Dysfunction

	Group A			Group B			
	3D vs. MSR	3D vs. HCM	3D vs. TM	3D vs. BPEM	3D vs. SPEM (4CH)	3D vs. SPEM (2CH)	Group C, 3D vs. CTPM
TGrE							
No regional dysfunction ($n = 12$)							
Correlation (r)	0.97	0.93	0.72	0.74	0.77	0.58	0.94
Mean relative difference (%)	3.6	4.9	18.4	18.1	24.5	13.3	7.9
95% confidence interval (EF units)	± 6.2	± 6.9	± 15.5	± 18.6	± 18.0	± 19.2	± 3.1
p value	0.53	0.92	0.03	0.47	0.12	0.09	0.42
Regional dysfunction ($n = 13$)							
Correlation (r)	0.88	0.84	0.62	0.22	0.48	0.09	0.87
Mean relative difference (%)	10.5	10.7	34.1	22.9	35.5	18.3	7.8
95% confidence interval (EF units)	± 8.1	± 10.4	± 22.1	± 20.4	± 24.9	± 22.8	± 6.8
p value	0.08	0.19	0.0006	0.004	0.004	0.02	0.11
SSFP							
No regional dysfunction ($n = 12$)							
Correlation (r)	0.98	0.96	0.78	0.97	0.96	0.96	0.98
Mean relative difference (%)	4.3	3.1	13.0	5.5	4.8	6.2	3.7
95% confidence interval (EF units)	± 3.0	± 4.0	± 15.2	± 6.2	± 7.9	± 8.4	± 2.3
p value	0.88	0.93	0.05	0.06	0.18	0.53	0.72
Regional dysfunction ($n = 13$)							
Correlation (r)	0.96	0.94	0.56	0.90	0.90	0.80	0.96
Mean relative difference (%)	9.8	9.9	16.2	9.7	18.1	13.4	6.1
95% confidence interval (EF units)	± 9.1	± 8.7	± 15.5	± 8.2	± 13.5	± 12.5	± 5.7
p value	0.11	0.09	0.03	0.01	0.03	0.14	0.13

TGrE = turbo gradient echo; SSFP = steady-state free precession; 3D = three-dimensional data set; MSR = modified Simpson rule; HCM = hemisphere–cylinder model; TM = Teichholz model; BPEM = biplane ellipsoid model; SPEM = single-plane ellipsoid model; 4CH = four-chamber; 2CH = two-chamber; CTPM = combined triplane model; EF = ejection fraction.

ellipsoid model 8 [4], and combined triplane ellipsoid model 2 [1] (Fig. 5a and b).

Inter- and Intraobserver Variability

Inter- and intraobserver variability for LV volumes and EF were lower for SSFP than for TGrE for group B models. The results are shown in Table 3.

DISCUSSION

With the SSFP technique, it was possible to acquire nearly inflow independent high quality cine images of the heart. The improved image quality resulted in higher accuracy for LVEF and LV volumes assessed by all geometric models but especially in those, which include long-axis projections, in comparison to volumetric data sets. Classification to a functional category was also more consistent with SSFP in contrast to TGrE.

Previous Use of Geometric Models in Comparison with 3D Data Sets

All geometric models used in the present study were previously developed for use with angiography and echocardiography[21–26] and have already been trans-

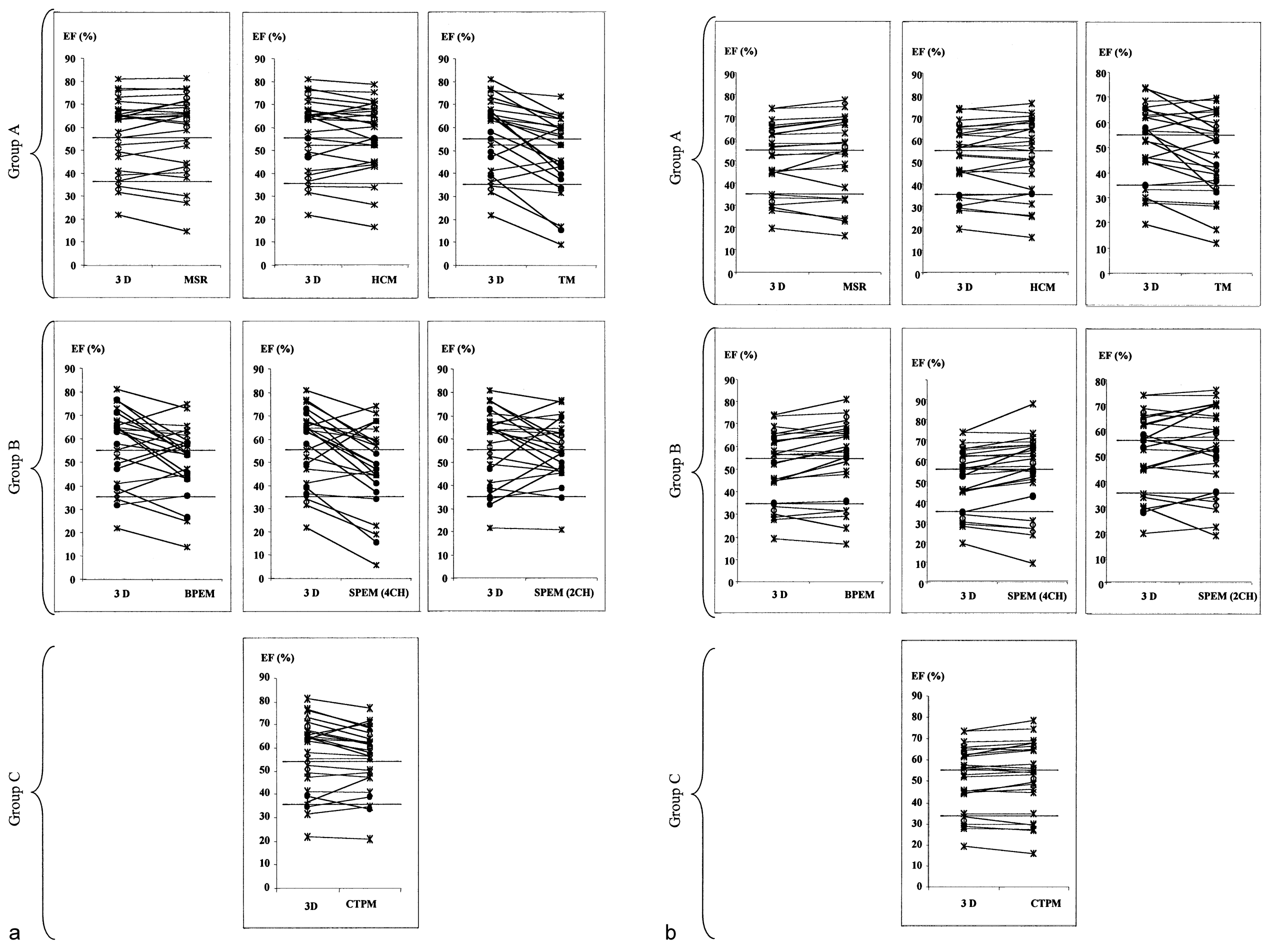

Figure 5. Comparisons of individual EF measures between a 3D data set acquired by TGrE a) or SSFP b) and group A models (MSR = modified Simpson rule; HCM = hemisphere cylinder model, TM = Teichholz model), group B models [BPEM = biplane ellipsoid model, SPEM = single-plane ellipsoid model of the four- (4CH) and two-chamber view (2CH)], and group C models (CTPM = combined triplane model). Closed points indicate patients whose EF classification defined as normal (A; LVEF ≥ 55%), moderately depressed (B, LVEF > 35%– < 55%) or severely depressed (C, LVEF ≤ 35%) changed by the methods.

Table 3

Inter- and Intraobserver Variability for Group B Models

		TGrE			SSFP		
		EDV	ESV	EF	EDV	ESV	EF
BPEM	*r*	0.97 (0.97)	0.97 (0.98)	0.84 (0.84)	0.99 (0.99)	0.99 (0.99)	0.97 (0.98)
	AD (mL or %)	8.5 (7.1)	0.3 (−3.0)	2.8 (5.2)	6.5 (3.9)	3.4 (−0.4)	0.3 (0.7)
	MD (%)	11.6 (8.7)	16.1 (13.2)	14.7 (13.9)	4.1 (5.2)	7.9 (6.3)	6.5 (6.4)
SPEM (4CH)	*r*	0.95 (0.96)	0.96 (0.96)	0.69 (0.73)	0.99 (0.98)	0.99 (0.99)	0.91 (0.96)
	AD (mL or %)	5.0 (6.7)	5.0 (1.5)	−0.7 (3.2)	5.4 (4.0)	2.9 (−0.4)	0.4 (0.8)
	MD (%)	14.9 (11.7)	18.5 (15.5)	26.1 (24.6)	4.8 (6.6)	13.5 (9.0)	10.0 (8.7)
SPEM (2CH)	*r*	0.95 (0.97)	0.95 (0.97)	0.71 (0.79)	0.99 (0.99)	0.99 (0.99)	0.97 (0.97)
	AD (mL or %)	19.0 (7.1)	−4.6 (−8.4)	7.4 (6.6)	9.4 (2.8)	3.7 (−0.2)	0.5 (0.5)
	MD (%)	13.3 (8.6)	21.0 (18.1)	24.9 (19.7)	5.0 (6.3)	8.2 (7.0)	6.5 (6.8)

Inter- and intraobserver (in parentheses) variability for geometric models involving long-axis planes. The absolute difference, mean relative difference and correlation factor are given.
TGrE = turbo gradient echo; SSFP = steady-state free precession; EDV = enddiastolic volume; ESV = endsystolic volume; EF = ejection fraction; BPEM = biplane ellipsoid model; SPEM = single-plane ellipsoid model; 4CH = four-chamber; 2CH = two-chamber; AD = absolute difference; MD = mean relative difference.

ferred for use in cardiac MR[5,15] except the combined triplane model, which has been newly developed for the current study.

In most of these previous studies those geometric models, which involve long-axis planes (= group B), failed to be interchangeable with volumetric data sets. The most likely explanation are saturation effects in long-axis planes, which may hinder functional assessment and depiction of the endocardial border especially in patients with impaired LV function, thus resulting in an inaccurate assessment of the appropriate area. Dulce et al.[5] used nonbreath hold cine MR and compared 10 healthy subjects with 10 patients with LV hypertrophy, but all with homogeneous contractility patterns. Limits of agreement analysis were not reported, but they found highest correlations for EDV and ESV ($r = 0.93-0.99$ and 0.76–0.97) for the modified Simpson rule and the biplane ellipsoid model compared with a volumetric data set in patients with and without LV hypertrophy. In their conclusion, both formulae can be used to assess LV volumes and EF. The single-plane ellipsoid model and the Teichholz model could not be recommended due to lower correlations. Cottin et al.[15] assessed all these formulae in patients with severe regional wall motion abnormalities after myocardial infarction using TGrE. Limits of agreement were reported only for the modified Simpson rule and were moderate to good. Correlations for ejection fraction between a 3D data set and the biplane and single-plane ellipsoid model were low ($r =$ 0.44–0.61) comparable to our results when TGrE was used. van Pol et al.[27] reported data of 175 MR studies, which compared 3D and biplane MR in patients with severely depressed LVEF and found a correlation for EF of only 0.88. In a different study from Chuang et al.[16] confidence intervals between biplane and volumetric MR imaging were wide. Thus, even though from a mathematical standpoint the error of the more complex models should be small, most previous studies have not demonstrated such interchangeability.

The low correlation between values obtained with the modified Teichholz model compared with values of a volumetric data set is consistent with previous findings in echocardiography[24–26] and MR, likely due to a large variety of the ratio between length and diameter of the ventricle for different patients. Similarly, low correlations were found for the single-plane ellipsoid model in MR imaging studies in comparison to angiography[28,29] or 3D data sets.[5,15]

Our data demonstrate an improvement in assessment of LV volumes and EF in comparison to a volumetric data set by use of the nearly inflow independent SSFP technique, which allows a more accurate definition of the endocardial border. Although the differences were not large in groups A and C models the slightly better accuracy resulted in a better functional classification, which is important for monitoring changes in therapy or progression of cardiac diseases. As an additional result of the improved image quality inter- and intraobserver variability was lower in SSFP in comparison to TGrE in group B models. However, mean relative differences in the single-plane ellipsoid models were still not sufficient for high accuracy and mean relative differences for the biplane ellipsoid model were rather modest. The new combined geometric model of two horizontal and one short axis plane provided highest correlations and lowest mean relative differences in comparison to a 3D data set. Main advantage is clear identification of the mitral valve plane, in contrast to a volumetric data set, in combination with an accurate assessment of long-axis planes by use of the SSFP sequence. However, the incomplete coverage of the LV with this model may introduce small errors in patients with localized contraction abnormalities. Nevertheless, this model as well as the modified Simpson rule or the hemisphere cylinder model are a solution for the unsolved problem of the through-plane motion of the basal plane in volumetric data sets, which makes determination of systolic volumes difficult.

Left Ventricular Volumes and Ejection Fraction by 3D Reconstruction

LV EDV and even more the ESV were higher by use of SSFP. One possible explanation could be the better delineation between blood and myocardium in SSFP resulting in an improved tracing of the endocardial border. In TGrE, blood pool endocardial contrast depends on inflow of unsaturated blood. This effect can be diminished in the apex and close to the endocardium, thus resulting sometimes in suboptimal visualization of blood. As a result, less individual trabeculae can be distinguished at enddiastole in comparison to SSFP. Because papillary muscles and trabeculae were defined to be excluded for volume calculations, better delineation of papillary muscles leads to an improved discrimination of the volume. That effect is more pronounced during systole, when the individual trabeculae join to form a compact compartment, which cannot be distinguished from myocardium with TGrE. With the SSFP technique, small interstices between the trabeculae can be kept apart and the trabeculae be excluded, resulting in a larger ESV (see Fig. 1). Marcus et al.[30] made similar explanations for the differences in wall thickness observed with different techniques. As a result, of a larger ESV as compared to EDV with SSFP LVEF was lower in comparison to TGrE. Previous studies comparing LV volumes by TGrE or spin-echo MR with volumes by ventricular angiography, the former reference standard, showed systematically smaller LV volumes by MR, which might also be explained by insufficient endocardial border depiction.[31,32] However, the differences in the volumes need further evaluation to assess the closest approach to the "real" volumes.

Study Limitations

The major limitation of the study is the lack of an absolute standard, since the "optimal" approach namely the complete coverage of the LV by short-axis views is hampered by the through-plane motion of the basal slice. Differences of the models to the Simpson's rule can be attributed to both, the 3D data set or the model. We believe that SSFP for the first time offers sufficient image quality to include long-axis views into the analysis. A model, which covers all segments required for wall motion analysis (16 or 17 segment model),[33] should be sufficient for adequate volumetric measurements. Thus, the newly developed combined triplane model should combine all: optimal volume determination without the problem of the basal slice with minimal measurement and evaluation time.

CONCLUSION

The inflow independent SSFP technique has excellent contrast between blood and myocardium, which leads to an unambiguous delineation of the endocardial border in both, long- and short-axis views. As a result, assessment of LV volumes and EF by all geometric models, especially those, which involve long-axis planes, is more accurate in comparison to conventional TGrE techniques, which should not be used for the assessment of LV function from such models. By use of the new combined triplane model, the best accuracy and reproducibility in comparison to a volumetric data set can be obtained even in patients with regional dysfunction. Thus, clinical utility of MR may be increased by shorter acquisition and post-processing times.

ABBREVIATIONS

3D	three-dimensional
EDV	enddiastolic volume
ESV	endsystolic volume
EF	ejection fraction
LV	left ventricular
SSFP	steady-state free precession
SV	stroke volume
TgrE	turbo gradient echo

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