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# Function

# Magnetic Resonance Real-Time Imaging for the Evaluation of Left Ventricular Function

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### ABSTRACT

New ultrafast gradient systems and hybrid imaging sequences make it possible to acquire a complete image in real time, without the need for breathholding or electrocardiogram (ECG) triggering. In 21 patients, left ventricular function was assessed by the use of a turbo-gradient echo technique, an echoplanar imaging (EPI) technique, and a new real-time imaging technique. End-diastolic and endsystolic volumes, left ventricular muscle mass, and ejection fraction of the ultrafast techniques were compared with the turbo-gradient echo technique. Inter- and intraobserver variability was determined for each technique. Image quality was sufficient for automated contour detection in all but two patients in whom foldover occurred in the real-time images. Results of the ultrafast imaging techniques were comparable with conventional turbo-gradient echo techniques. There was a tendency to overestimate the end-diastolic volume by 3.9 and 1.3 ml with EPI real-time imaging, the end-systolic volume by 0.9 and 5.0 ml, and the left ventricular mass by 2.6 and 23.8 g. Ejection fraction showed a tendency to be overestimated by 1.1% with EPI and underestimated by 4.5% with real-time imaging. Correlation between EPI real-time imaging and turbo-gradient echo were 0.94 and 0.95, respectively, for enddiastolic volumes, 0.98 and 0.96, respectively, for end-systolic volumes, and 0.96 and 0.89, respectively, for left ventricular mass. Inter- and intraobserver variability was low with all three techniques. Real-time imaging allows an accurate determination of left ventricular function without ECG triggering. Scan times can be reduced significantly with this new technique. Further studies will have to assess the value of real-time imaging for the detection of wall motion abnormalities and the imaging of patients with atrial fibrillation.

**KEY WORDS:** Left ventricular function; Magnetic resonance; Real-time imaging.

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### INTRODUCTION

Magnetic resonance (MR) imaging of the heart has been shown to be highly accurate and reproducible for the evaluation of left ventricular (LV) function and muscle mass (LVM) (1-5). In contrast to angiography or scintigraphy, no geometric assumptions for the determination of volumes are needed because three-dimensional data sets are available. The feasibility and accuracy of turbo-gradient echo (6) breathhold imaging for evaluation of LV volume and mass with low interstudy variability have been demonstrated (7-9). Recently, it has been shown that good accuracy can also be attained with rectilinear echo-planar imaging (EPI) (10) and spiral echoplanar imaging (11-14). However, even with these ultrafast breathhold techniques, a major limitation of MR tomography when compared with echocardiography is the acquisition of images during several heart beats. Realtime planning or adapting of imaging planes is impossible, and breathholding is required to suppress breathing motion artifacts. In addition, the assessment of the complete left ventricle during stress examiantions may not be possible because the acquisition duration may exceed the longest acceptable duration of the stress test. This may be of special importance because high-dose dobutamine stress MR imaging has been shown to be highly superior to dobutamine stress echocardiography for the noninvasive detection of myocardial ischemia (15).

The development of high-performance gradient systems and optimized hybrid sequences, which combine turbo-gradient echo and EPI (16,17), today enables the acquisition of complete cardiac images in real time with high temporal resolution. This tremendous speed has several advantages when compared with conventional acquisition techniques. For example, electrocardiogram (ECG) triggering will become obsolete because the complete data set is acquired during a single measurement interval and not during several heart beats as with older techniques. In combination with interactive planning tools, real-time planning and adaptation of imaging planes can be performed (18). The reduction of measurement time to one or two heart beats per slice makes the imaging of the complete left ventricle feasible within a single breathhold. However, to reach this acquisition speed, spatial resolution needs to be reduced and high EPI factors have to be accepted, which may lead to image distortion and reduce accuracy. Recently, it was reported that image quality of real-time scans is sufficient for an assessment of LV function (18), and a close correlation between realtime and EPI was reported in a preliminary study (19).

The aim of this study was to analyze the accuracy and

reproducibility of real-time imaging and EPI techniques for the evaluation of LV function, including end-diastolic volume (EDV), end-systolic volume (ESV), and left ventricular ejection fraction (EF), and LVM when compared with ultrafast turbo-gradient echo techniques.

#### **METHODS**

# Patients

Twenty-one patients (15 men, 6 women, aged  $60 \pm$  9 yr, heart rate 75  $\pm$  19 beats/min) were included in the study after informed consent, of which 3 patients had LV hypertrophy due to long-standing arterial hypertension, 4 patients had myocardial infarction, and 1 patient had dilative cardiomyopathy. Patients with contraindications for MR examinations or high-grade ventricular arrhythmias or atrial flutter/fibrillation were excluded from the study.

### **MR** Imaging

All patients were examined in the supine position with a 1.5-T whole body MR scanner (ACS NT, Philips, Best, The Netherlands, CPR6), which was equipped with ultrafast gradients (21 mT m<sup>-1</sup> amplitude, 100 T m<sup>-1</sup> sec<sup>-1</sup> slew rate) that used a five-element phased array cardiac coil that was placed around the thorax of the patient. To avoid foldover, only the two anterior segments of the coil were used for data acquisition. All images were acquired during breathholding at end expiration. Respiration was checked with a strain gauge, and ECG triggering was used for the turbo-gradient and EPI image acquisition. After two rapid surveys to determine the exact axis of the left ventricle, 7–12 continuous short-axis planes (slice thickness 8 mm, no gap), which covered the complete left ventricle, were planned.

Turbo-field echo imaging (TFE = T1-weighted turbogradient echo) was performed with a segmented k-space technique over 16 heart beats (Fig. 1). The details of the sequence are shown in Table 1.

EPI was performed with the identical geometry that used a segmented k-space technique over 16 heart beats (Fig. 1). For details see Table 1. In two patients, no EPI measurements were performed to shorten the duration of the session.

Real-time imaging was performed with a hybrid turbo-gradient echo-EPI sequence (Fig. 1) (16,17). A temporal resolution of 62 msec (=16 images per second) was achieved by reducing spatial resolution to  $2.2 \times 4.4$ mm (Table 1). Forty consecutive images were acquired

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Figure 1. End-diastolic and end-systolic equatorial short-axis views of a turbo-gradient echo image (top row), echo-planar image (middle row), and real-time image (bottom row) of the same patient.

to cover at least two complete heart beats. To ensure a similar geometry when compared with the other two imaging techniques, real-time imaging was also performed during breathholding at end expiration, even though this was not required to preserve image quality.

#### **Image Analysis**

In the end-diastolic and end-systolic images, the endoand epicardial borders were traced by the use of a commercially available software with automated contour detection and manual correction, if necessary, on a Sparc 5 work station (EasyVision 4, Cardiac Package, Philips). For the TFE and EPI image series, end-diastolic images were chosen as the first phase after triggering of the Rwave, for the real-time scans the frame with the largest LV cavity area. End-systolic images were defined as the images with the smallest cavity area (Fig. 1). The most basal slice to be included had to cover >50% of the circumference. The volume of each slice was determined from the area within the endocardial tracing (excluding both papillary muscles) multiplied by the slice thickness. EDV and ESV were calculated by summing the volumes of all short-axis slices (Simpson's method). EF was calculated as (ESV - EDV)/EDV and LVM at end-diastole by subtracting the EDV from the end-diastolic epicardial volume multiple by 1.05 g/cm<sup>3</sup> (specific myocardial gravity) and adding the mass of the papillary muscles. All scans were analyzed by two independent observers (U.S. and T.I.). Analysis of 10 patients was repeated after 4 weeks by one of the examiners (U.S.) without reviewing the first analysis to determine intraobserver variability.

#### **Statistical Analysis**

For all parameters, means  $\pm$ SD are given. An AN-OVA for repeated measurements was performed for all measured parameters for the comparison of different imaging techniques. If significant differences occurred (*p* 

Scan Parameters				
	TFE	EPI	Real Time	
TE, msec	2.1	5.6	6.8	
TR, msec	5.9	20	15.5	
Flip angle, degree	25	30	20	
K-lines per shot	4	7	36	
EPI factor	_	7	9	
Matrix	121 × 256*	96 × 128*	64 × 128*	
Temporal resolution, msec	50	20	62	
Spatial resolution, mm	$1.3 \times 2.6$	$2.6 \times 3.4$	$2.2 \times 4.4$	

Table 1

All measurements were performed with flow compensation.

\*Raw data were filtered and zero filled to 256 points.

< 0.05), a Scheffé procedure was applied for post-hoc testing of individual groups. The results from the realtime and EPI technique were linearly correlated with the turbo-gradient echo technique. Linear correlation was also performed for interobserver and intraobserver variability. Absolute and relative differences between the different techniques (difference of two techniques divided by their mean value), different observers, and repeated measurements of one observer were calculated (20).

#### RESULTS

Image quality was sufficient for automated contour detection with all techniques in all but two patients (Fig. 2). In these patients, foldover occurred in the real-time images due to the small field of view chosen; these patients were excluded from the analysis. Only minimal user interference was needed in any image. Contrast be-



Figure 2. Real-time image series in an equatorial short-axis view. ES, end-systolic; ED, end-diastole.



Figure 3. Correlation between the EPI and real-time (RT) techniques when compared with the turbo-gradient echo technique.

tween blood and endocardium was good with all scan techniques.

There was a correlation of EPI and real-time with the turbo-gradient echo technique for EDV, ESV, and EF (Figs. 3 and 4). The correlation factor for the determination of LVM with real-time or turbo-gradient echo techniques was only 0.88. The absolute and relative differences between EPI, real-time, and turbo-gradient echo

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**Figure 4.** Bland-Altman plot for EDV (A), ESV (B), and LVM (C). The difference between the fast technique (EPI respectively real-time [RT]) is plotted against the standard technique (TFE). Means and one SD are given.

techniques for EDV, ESV, LVM, and EF are summarized in Table 2. With the EPI technique, the mean differences from the turbo-gradient echo technique for ESV, EDV, LVM, and EF were small and showed no systematic over- or underestimation. There was a tendency to overestimate ESV and LVM with the real-time technique when compared with the turbo-gradient echo technique and to underestimate EF. The relative differences in EF were  $1.1 \pm 5.8\%$  for EPI versus turbo-gradient echo measurements and  $-4.5 \pm 4.7\%$  for real-time versus turbogradient echo measurements. The highest relative differences were found between real-time and turbo-gradient echo measurements for ESV (14.8%) and LVM (15.9%). Intraobserver variability and interobserver variability was low for all three techniques (Table 3).

# DISCUSSION

With ultrafast MR techniques, it was possible to acquire non-ECG triggered high-quality images of the beat-



#### Table 2

Mean and Relative Differences According to Bland and Altman (in parentheses) Between the Ultrafast Techniques (EPI and Real Time) when Compared With the Standard Technique (Turbo-Gradient Echo)

	EPI	Real Time
EDV; ml	$3.9 \pm 12.5 (10.3 \pm 11.6\%)$	$13.3 \pm 12.2 \ (11.3 \pm 8.8\%)$
ESV, ml	$0.9 \pm 6.2 (14.4 \pm 15.0\%)$	$5.0 \pm 5.5 \ (14.8 \pm 10.6\%)$
LVM, g	$2.6 \pm 19.3 (9.7 \pm 11.0\%)$	$23.8 \pm 35.7 (15.9 \pm 14.1\%)$
EF; %	1.1 ± 5.8 (6.0 ± 4.7%)	$-4.5 \pm 4.7 (10.3 \pm 5.3\%)$

Inter- and Intraobserver Variability					
	TFE	EPI	Real Time		
EDV			u		
Difference, ml	-1.1 (2.61)	-7.2 (-2.6)	0.8(-2.3)		
r	0.96 (0.98)	0.94 (0.96)	0.95 (0.98)		
ESV					
Difference, ml	-3.4 (0.38)	-2.6 (-1.57)	-7.1 (-1.4)		
r	0.98 (0.99)	0.98 (0.99)	0.97 (0.99)		
LVM	. ,	. ,	,		
Difference, g	-7.2 (-2.9)	-2.9 (-1.7)	-10.6(3.7)		
r	0.94 (0.99)	0.97 (0.99)	0.91 (0.94)		
EF		· · ·			
Difference, %	4.8 (1.1)	1.8 (0.2)	6.2 (0.9)		
r	0.93 (0.97)	0.97 (0.99)	0.94 (0.97)		

The difference and correlation factor between the two observers (two measurements) are given.

ing heart in real time with a temporal resolution of 62 msec. Two patients had to be excluded due to insufficient image quality caused by foldover. Spatial resolution and contrast between intracavitary blood and endocardium were sufficient to allow a quantitative image analysis. With real-time imaging, a tendency to overestimate LV mass and ESVs was found, which resulted in a tendency to underestimate EF. All techniques were highly reproducible with a low intra- and interobserver variability.

Two factors may explain the differences between turbo-gradient echo, EPI, and real-time techniques. First, spatial resolution is decreased from  $1.3 \times 2.6$  mm for TFE to  $2.2 \times 4.4$  mm for real-time imaging, which decreases the accuracy for the delineation of the endo- and epicardial borders. However, zero filling of raw data by a factor of 2 was used, which reduces partial volume effects (21,22) and leads to a reduction of edge definition artifacts (23). Second, chemical shift artifacts in EPI sequences may be very pronounced and may lead to a superposition of fat signals on parts of the myocardium. These superpositions introduce an error in the determination of LVM as the epicardial border may not be visible.

Temporal resolution was maximal with EPI (20 msec), less so with turbo-gradient echo (50 msec), and minimal with real-time imaging (62 msec). Thus, temporal resolution should be sufficient with EPI and turbo-gradient echo to accurately detect EDV and ESV which remain stable during the isovolumetric phase that lasts approximately 50–80 msec at end-systole. The mild overestimation of ESVs with the real-time technique may be explained by a mildly insufficient temporal resolution. In addition, further improvements of temporal resolution are needed to assess hemodynamic parameters such as peak filling rate.

Recently, two possibilities were suggested to solve these problems: either the use of partial k-space acquisition techniques (24) for spiral imaging or coil sensitivity encoding (25). The use of ultrafast gradient systems (21 mT m<sup>-1</sup>, 100 T m<sup>-1</sup> sec<sup>-1</sup>), which shorten echo times significantly when compared with conventional systems, leads to a reduction of many problems that may otherwise occur with EPI sequences, such as blurring due to T2\* decay, displacement due to phase errors, and systolic loss of blood signal due to intravoxel dephasing. However, these effects are more pronounced with the real-time technique when compared with the other techniques used, due to higher EPI factors and longer echo times.

In previous studies (14), a dark ring between blood and myocardium at times of high flow was observed. In the current study, all measurements were performed using flow compensation to eliminate these problems.

Some errors may have occurred with all techniques due to missed slices or slice overlap caused inconsistent breathhold positions. The use of navigator echoes to determine the diaphragmatic position, combined with feedback mechanisms for reproducible and constant breathholding (26) or respiratory gating during free respiration (27), may help to solve this problem. In addition, multislice real-time imaging allows us to cover the complete heart within a single breathhold.

Another method, which is successfully used for functional cardiac imaging, is spiral k-space acquisition (14,18). The advantages of this method are a high temporal resolution and robustness against motion. However, there are known problems with magnetic field inhomogeneities and off-resonance effects.

EF was more than 70% in three patients. These patients had LV hypertrophy due to severe arterial hypertension and thus very small ESV.

Real-time imaging offers a completely new quality to cardiac MR imaging as ECG triggering becomes dispensable. This enables us to reduce the time for patient setup and scanning with low-quality ECG tracings within the magnet. Imaging is extremely fast, which can be used to reduce examination time, and costs and patient discomfort are minimized. In addition, ultrashort scan times allow the combination of different MR techniques without exceeding patient tolerance, thus making the "onestop shop'' more and more feasible. Also, it is possible to image the complete left ventricle within one breathhold, which might further improve the diagnostic accuracy of MR stress testing. No data averaging of several heart beats is needed. This makes it possible to scan patients with absolute arrhythmia or frequent premature ventricular complexes or to assess the influence of hemodynamic maneuvers. In combination with interactive planning tools, real-time planning and adaptation of imaging planes is also feasible (18) and enables us to correct for patient motion or changes of cardiac position, which may

occur during stress testing due to increased inotropy or perfusion. Breathholding is no longer required or can be reduced to a minimum (e.g., two heart beats) to ensure optimal imaging planes. Thus, recovery periods between subsequent breathholds are obsolete, which further decreases scan time.

#### CONCLUSION

Real-time imaging allows an accurate and reproducible determination of LV function and volumes without ECG triggering. Results are comparable with conventional ECG triggered turbo-gradient echo and EPI techniques. For a reliable assessment of LVM with real-time imaging, further improvements in spatial resolution are needed. Scan time can be reduced significantly with this new technique. Further studies will have to assess the value of real-time imaging for the detection of wall motion abnormalities and the imaging of patients with atrial fibrillation. In addition, the use of contrast agents has to be assessed, which will most probably enhance edge detection quality.

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