Cardiac function and morphology provide vital information in the diagnosis, treatment and prognosis of cardiovascular disease. Although numerous imaging modalities are available, echocardiography is the current noninvasive standard. Echocardiography is portable, interactive and provides real-time visualization of the wall segments was obtained 38% of the time using ECHO and 97% of the time using CMRI (p < 0.0001). When grouped into coronary segments, adequate visualization of at least one segment occurred in 18 of 30 patients (60%) with ECHO and in all 30 patients (100%) with CMRI (p < 0.0001). In group C, adequate visualization of the wall segments was obtained in 58% (CI 0.53–0.62) of the time using echocardiography and 99.7% (CI 0.99–1.0) of the time using CMRI (p < 0.0001).

Conclusions. The new CMRI system provides clinically reliable evaluation of LV function and complements suboptimal echocardiography. In comparison with the conventional CMRI, the new CMRI system significantly reduces scan time, patient discomfort and associated cost.

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tomographic views leads to long scan time (8). Finally, the images are not displayed in real-time (9,10). Therefore, dynamic adjustments of the imaging plane are not possible. The resultant potentially off-axis images create well-known diagnostic problems. All these factors contribute to high cost, reduced clinical versatility and patient discomfort.

The real-time interactive CMRI system has been developed specifically to address the limitations of the CMRI system today. The system accomplishes the following: 1) ultrafast image acquisition, which eliminates the need for cardiac or respiratory gating; 2) interactive selection of scan plane, which allows immediate control of the desired view plane and 3) real-time image reconstruction and display, which provides instant image-based feedback. These features are achieved with only a modest increase in system cost. To test the system, we studied 85 patients to determine whether we could obtain reliable and clinically useful real-time images of their LV function.

**Methods**

**Real-time, interactive CMRI system.** The real-time interactive CMRI system requires a modest upgrade to a conventional 1.5T Signa MRI Scanner (GE, Milwaukee, Wisconsin). The upgrade, consisting of a workstation and a bus adapter (11), constitutes the hardware platform of our system. No other modification to the hardware is necessary.

The system performs four major real-time functions: 1) data acquisition, 2) data transfer, 3) image reconstruction and 4) interactive control and display. A simple overview of the system architecture is illustrated on a block diagram in Figure 1. A detailed description of our CMRI system has been reported by Kerr et al. (11). A brief description of the system follows.

**Data acquisition.** The pulse sequence utilizes a 7.68-ms spectral spatial pulse, which excites water and suppresses fat (12). A short repetition time (30 ms), low flip angle (20–40 degrees) and gradient-recalled ECHO sequence using a short spiral read-out is implemented as shown in Figure 2. The raw data are collected on a spiral interleaf k-space trajectory as shown in Figure 3 (13). Each interleaf is acquired every repetition time (TR) of 30 ms with an echocardiography time (TE) of 4.6 ms. A complete image is obtained every six interleaves, requiring 180 ms as illustrated in Figure 3. Our current spiral gradient waveform is designed to provide a field of view (FOV) of 20 cm with a resolution of 2.25 mm, subject to the hardware constraints of a maximum gradient amplitude of 1 Gauss/cm and maximum slew rate of 2 Gauss/cm/ms (14).

A 5-in diameter surface coil is used for signal reception.

**Data transfer.** A workstation 20/7; Sun Sparc, Mountain View, California, bypasses the host computer and directly interfaces with the transceiver processor and storage (TPS) cabinet, which controls the magnet and its associated hardware. A bus adapter (model 943; Bit 3 Computer Corporation, St. Paul, Minnesota) links the workstation to the bulk access memory of the TPS where the raw data is stored, allowing rapid access of the data by the workstation. The workstation and the bus adapter function together as the primary user interface for the real-time interactive system.

**Image reconstruction.** As the raw data are accessed, the workstation distributes the data to one of the multiple reconstruction servers running on local computers connected via a local Ethernet (15). As illustrated in Figure 3, a sliding window made of the most recently acquired six spiral interleaves is used to reconstruct an image. The subsequent new image is reconstructed from a window made of six interleaves updated by one

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**Abbreviations and Acronyms**

- CMRI = cardiac magnetic resonance imaging
- ECHO = echocardiography
- EPI = ECHO planar imaging
- FOV = field of view
- LV = left ventricular
- TE = ECHO time
- TPS = transceiver processor and storage
- TR = repetition time

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**Figure 1.** Block diagram of system architecture. A GE 1.5T Signa scanner components: console, TPS and magnet. The bus adaptor links the workstation to the TPS for rapid access to the raw data. The local Ethernet connects the workstation to the console and to the reconstruction servers.

**Figure 2.** The pulse sequence used for data acquisition: a 7.68-ms spectral spatial pulse, a short repetition time (30 ms), low flip angle (20–40 degrees), and gradient-recalled ECHO sequence is shown. The spiral read-out results from the time-varying gradients, Gx and Gz and constant gradient spoiler Gz.
or two interleaves (9,10). The distributive computing approach consists of a client workstation (20/71; Sun Sparc) and five reconstruction computers (770; Hewlett Packard, Palo Alto, California; 170; Sun Ultra, Mountain View, California and three SPARC 10's, Mountain View, California). Recently, the workstation has been upgraded with four Hypersparc (Ross, Austin, Texas) processors, allowing image reconstruction on the same workstation.

Interactive control and display. The real-time control and display are designed using the X-window protocol. The application enables graphical manipulation of the interactive control suite and off-resonance control. As illustrated in Figure 4,

there are three major interface windows on the workstation: the imaging scan control window, the image display window and the image display control window.

Patient selection. A total of 85 patients were enrolled in the study. Patients were randomly selected based on the echocardiographic and clinical criteria of each patient group. The study protocol was approved by the Human Subjects Committee at Stanford University. The patients were recruited from both Stanford and Palo Alto VA Medical Centers. All participants were informed of the study and gave written informed consent. Patients were ineligible if they had any contraindication to undergo MRI scan as listed on the written consent.

The study was divided into three groups (A, B and C) based on the official clinical echocardiography reports that were reviewed. Six patients in group B with severe pulmonary disease were also enrolled in group C.

The subjects in group A (31 patients) consisted of those who had acceptable quality echocardiography study with echo-

![Figure 3. The six spiral interleaf kappa space trajectories. The six interleaves constitute one complete image. Each interfleaf shifts 60 degrees, completing a full cycle for each image. A sliding window reconstruction of an image using the most recently acquired six spiral interleaves is shown. Each subsequent image is updated by one or two spiral interleaves.](image)

![Figure 4. Four X-windows. The graphical user interface windows are imaging scan control window, image display window, imaging extra control window and imaging display control.](image)
cardiographic evidence of wall motion abnormalities. The patients were selected to undergo CMRI to compare wall motion and image quality between CMRI and echocardiography. This comparison was performed to validate the diagnostic accuracy of CMRI system in evaluating LV function and regional wall motion abnormality.

The subjects in group B (31 patients) consisted of those who had suboptimal quality echocardiography study. The patients were selected to undergo CMRI to determine whether the interpretation of LV function of suboptimal echocardiographic images could be improved by CMRI.

The subjects in group C (29 patients) consisted of the following: 1) severe pulmonary disease including chronic obstructive pulmonary disease, cystic fibrosis, primary pulmonary hypertension and alpha-1 antitrypsin deficiency; and 2) adult congenital heart disease including transposition of great arteries, tricuspid atresia, single ventricle, tetralogy of Fallot and ventricular septal defect. The patients were selected to undergo CMRI to test the hypothesis that CMRI will improve the evaluation of LV function in select groups of patients who frequently have suboptimal echocardiography.

Study protocol. Standard echocardiographic imaging was performed consisting of parasternal long and short axes as well as long axis four- (left and right ventricles and atria), three- (left ventricle, left atrium and aorta) and two- (left ventricle and atrium) chamber views in each patient. In all cases, images were recorded on super VHS videotapes.

Study patients underwent real-time interactive MRI scan in supine position. By palpating the point of maximal impulse of the heart when each patient lay supine, a landmark was determined for the placement of the circular 5-in diameter surface coil. No cardiac gating or respiratory compensation was used. The scan was initiated in an axial view. Intermittent field maps were acquired during the study for off-resonance correction. Once the view of the heart was interactively centered on the display window, a long-axis view was prescribed by obtaining a single oblique plane from the initial axial view. The first apical short-axis view was then obtained using double-oblique prescription. Eight views of the heart were routinely obtained. Initially, five short-axis views equally spaced from the apex to the base of the heart, were obtained along the z-axis. The subsequent long-axis views consisting of the four-, three- and two-chamber views corresponding to the echocardiography studies were obtained by prescribing double oblique plane of the preceding image. A 20-s recording from each view was saved to disk.

CMRI and echocardiography interpretation. Four investigators using the standard 16-segment model scored wall motion and image quality (16,17). Each analysis of wall motion and image quality was performed by at least two independent readers. The readers were blinded to the interpretation of other MRI and echocardiography studies.

In addition to the 16-wall segments, the segments were also grouped according to the three major coronary distributions and designated as coronary segments. Wall motion was ranked using the guidelines published by the American Society of Echocardiography: 1 = normal; 2 = hypokinetic; 3 = akinetic; 4 = dyskinetic (26).

Image quality was scored using a five-point scale adapted from Hoffman’s work (17), where image quality was principally judged by the amount of endocardial visualization: 5 = complete visualization of the endocardial border and the remaining wall thickness; 4 = complete visualization of the endocardial border but incomplete visualization of the remaining wall thickness; 3 = incomplete visualization of the endocardium and the remaining wall thickness; 2 = no visualization of the endocardial border but visualization of the remaining wall thickness; 1 = visualization of the epicardium only; and 0 = no visualization. Adequate visualization was defined as image quality of 4 or better.

Statistical analysis. Agreement between echocardiography and MRI on the detection of wall motion abnormality was determined by rank order analysis and kappa statistics. Interobserver agreement was calculated using Spearman Rank Correlation. Image quality scores were averaged for the observers. Specifically, image quality was considered inadequate if the average score of either an individual segment or a coronary distribution score was 3 or less on our image quality scale. Significance between two groups (echocardiography and CMRI images) was established with t statistic. p values of less than 0.05 were considered significant.

Results

Scan time. A complete study consisting of eight views of the heart was performed in less than 15 min for each patient. The interactivity of the system enabled quick prescription of any scan plane in a minimally operator-dependent manner, reducing unnecessary scan time. Scan time included the acquisition of field maps for off-resonance correction. Image reconstruction and display at 16 images/s enabled a real-time imaging of the heart, allowing an immediate display of the cardiac function and morphology. A lagtime of less than 1 s existed when adjusting image parameters.

Patient comfort. Two of the 85 patients could not tolerate the study, complaining of claustrophobia immediately after being placed inside the magnet before starting the scan.

Patient data. The study population consisted of 85 patients with the following demographic characteristics: 64 men and 21 women, range of age from 16 to 90 years old with average age of 49 ± 30 years, and weight range from 110 to 270 lb with average weight of 208 ± 58 lb. The average time between MRI and echocardiography study was 45 ± 30 days (range 0 to 80 days).

Agreement of wall motion analysis between CMRI and echocardiography. Thirty patients in group A with echocardiographic evidence of wall motion abnormalities and acceptable quality echocardiographic study underwent CMRI scan. The wall motion of 16 wall segments was analyzed and compared by two independent observers. The interobserver analysis of the wall motion of each segment showed no significant difference when comparing the wall motion of the
corresponding segments obtained by CMRI and echocardiography (p = NS). The percent agreement between the two expert readers in the three categories of comparison, as shown in Figure 5, was the following: 1) echocardiography versus echocardiography, 94% (CI 0.91–0.95), 2) echocardiography versus CMRI, 92% (CI 0.89–0.93); and 3) CMRI versus CMRI, 93% (CI 0.90–0.94). The high agreement between echocardiography and CMRI is demonstrated by the kappa value of 0.79.

Figure 6A and B illustrate the long-axis images obtained by CMRI of two-chamber and four-chamber views, respectively. Note the clear depiction of the closed mitral valve in 6A. Figure 6C and D display the short-axis images obtained during the consecutive phases of a full cardiac cycle from (C) end-diastole to (D) end-systole, illustrating the smooth motion response of the CMRI.

Improvement of the visualization of suboptimal echocardiography images by CMRI. Thirty patients with poor, suboptimal echocardiographic study in group B underwent MRI scan. Adequate visualization of wall segments was obtained in 38% (CI 0.34–0.42) of the segments with echocardiography and in 97% (CI 0.96–0.98) of the segments with CMRI (p < 0.0001). When the wall segments were grouped into coronary segments, adequate visualization of at least one coronary segment occurred in 18 of 30 patients (60% CI 0.53–0.71) with echocardiography and in all 30 patients (100% CI 0.97–1.0) with CMRI (p < 0.0001).

Figure 7A illustrates a suboptimal quality echocardiographic image of the short-axis view due to inadequate acoustic window. As seen on the electrocardiographic (EKG) tracing on the bottom of Figure 7A, the image was obtained from a
patient who presented with multiple premature atrial contractions. The echocardiographic data could only provide equivocal evaluation of the LV function, and the conventional gated CMRI study could not be done due to multiple ectopies. Figure 7B shows the corresponding image obtained by our CMRI system. Our image demonstrates a detailed image of the myocardium with a clear contrast between the endocardium and the blood. The papillary muscles are also well depicted.

**Improvement in the evaluation of LV function in patients with severe pulmonary disease or congenital heart disease.** Twenty-nine patients in group C with either severe pulmonary disease or congenital cardiac malformation underwent MRI scan. Evaluation of their LV function improved significantly. Adequate visualization of wall segments increased from 58% (CI 0.53–0.62) of the segments with echocardiography to 99.7% (CI 0.99–1.0) of the segments with CMRI (p < 0.0001). In patients with pulmonary disorder, adequate visualization occurred in 76% (CI 0.70–0.81) of the wall segments with echocardiography and 99.5% (CI 0.99–1.0) of the wall segments with CMRI (p < 0.0001). In patients with congenital heart disease, adequate visualization occurred in 43% (CI 0.32–0.52) of the wall segments with echocardiography and 99.8% (CI 0.98–1.0) of the segments with CMRI (p < 0.0001). Table 1 illustrates the improvement in the evaluation of the LV function with CMRI.

**Discussion**

In this study, the diagnostic accuracy and clinical utility of CMRI system were tested through an investigation of the system’s ability to evaluate one of the most important parameters in cardiovascular medicine: global and regional LV function. While global function has been studied, regional wall motion has not been compared previously with established tomographic techniques such as echocardiography. Our data demonstrated that the evaluation of LV function by the real-time CMRI system correlated well with echocardiography. In the patients with suboptimal echocardiographic studies, the images obtained from the CMRI system significantly improved the assessment of LV function. Specifically, the data obtained from the patients with either severe pulmonary disease or congenital heart disease suggested that these patients should be considered routinely for CMRI examination. Second, the data demonstrated that the scan time did not exceed 15 min and that the procedure was well tolerated. In contrast to the conventional CMRI system, the new real-time CMRI system eliminated cardiac gating and respiratory breath holding, reducing scan time and patient discomfort.

Another aim in this study was to demonstrate the diagnostic importance of image quality. As early as 1985, Erbel et al. recognized that approximately 10% of echocardiographic studies were considered suboptimal (2). Crouse et al. confirmed this finding in their report that lung disease, scar tissue and body habitus create inadequate acoustic window, resulting in suboptimal study in 10% of the patients (1). Recently, Hoffman et al. reported that interinstitutional agreement in interpreting Dobutamine echocardiography studies correlated closely with image quality (17). The finding demonstrated that as the image quality of echocardiography studies deteriorated, the percent agreement declined from 100% to 43%. Along with these findings, our study confirmed the importance of image quality in interpreting image-based diagnostic data, and emphasized the clinical need of improving suboptimal echocardiographic studies.

**Real-time interactive CMRI.** Real-time or dynamic acquisition in MRI is a concept that dates back almost 20 years. Mansfield developed the first fast acquisition method using the echocardiography planar imaging (EPI) technique (18). This method has allowed an acquisition of a complete image within a period as short as 40 ms, yielding a rate of 25 images/s (19).
However, this acquisition method requires expensive hardware, produces poor signal-to-noise ratio and leads to limited resolution and flow motion-induced artifacts (19–22).

Real-time image reconstruction is also required for real-time MRI studies. Many methods have been proposed. In 1988, Riederer et al. introduced the sliding window reconstruction. They experimented with the possibility of off-line, real-time MRI image display on conventional scanners using fast low angle shot (FLASH) or gradient-recalled acquisition in a steady-state mode (GRASS) sequences with augmentation by new hardware (9,23,24). However, this method has been hindered by poor temporal and spatial resolution. Validation of these methods in a clinical setting has not been conducted.

To date, most of the studies to assess ventricular function using MRI are limited to quantitative analysis of global LV dimensions using computer-assisted calculation of Simpson’s rule (25–27). Recent studies assessing regional wall dysfunction using cine or EPI MR imaging have demonstrated close correlation with projection techniques such as left ventriculogram (20). However, these studies are based on similar calculation of the static images of the ventricle or the myocardium requiring long acquisition time and postacquisition image processing (20,28,29). No study has yet to report a reliable assessment of global or regional LV function based on real-time, dynamic images.

Limitations of the CMRI system. Despite the excellent clinical correlation in LV function, our system still suffers from several technical limitations that may have clinical importance. First, off-resonance related blurring may compromise detection of finer pathologies such as valvular disease or vegetation. Two methods are currently implemented in our system to improve the off-resonance artifacts: 1) linear field maps are acquired periodically during the scan, and 2) dynamic shimming of the magnet is used to maintain a homogeneous magnetic field for each scan plane orientation. Second, motion-induced artifact results from the limited temporal resolution of a complete image data set. The 180 ms required to acquire an image leads to degradation of the image. However, this problem is reduced by the current state-of-the-art gradient amplifier with maximum amplitude of 4 G/cm and slew rate of 12 G/cm/ms, enabling the reduction of acquisition time to less than 100 ms. Third, in some patients with poor ventricular function, reduced in-flow refreshment may decrease tissue contrast of the endocardium in long-axis views. We have recently minimized this limitation by reducing slice thickness from 1 to 0.5 cm. Finally, our system may be limited in the presence of tachycardia due to the currently achievable complete update rate. We expect that the currently available high-performance gradient will reduce the acquisition time necessary for complete images to 70 ms or less, allowing adequate evaluation of regional wall motion in tachycardia range.

Future direction. There is much potential for future clinical application of our CMRI system. As we have shown, the CMRI system complements suboptimal echocardiographic studies. We estimate at least 300,000 per year suboptimal echocardiographic studies are performed in the U.S. Our CMRI system should significantly improve the diagnostic yield in the assessment of LV function in these patients. Other applications include diagnosis of stress-induced functional ischemia using agents such as dobutamine. The improved detection of endocardium by our system may assist in establishing a more objective set of criteria to assess wall motion.

The system architecture is also ideal to augment the CMRI platform with traditionally important enhancements such as color flow mapping, flow velocity and high-resolution valvular imaging sequences (30–33). The real-time, interactive feature of this CMRI system has already been implemented into a coronary imaging sequence to facilitate anatomical localization of coronary arteries.

Conclusions. The intuitive graphical user interface and real-time response of the new CMRI system allow monitoring of the dynamic cardiac physiology unlike a conventional MRI system, which relies on static protocols. We have demonstrated that the CMRI system is capable of accurately assessing global and regional LV function. This imaging system complements the assessment of LV function in patients with suboptimal echocardiographic studies. The real-time interactive CMRI system should be considered for routine clinical use to evaluate LV function in patients with clinical condition that predisposes them to suboptimal echocardiographic images.

References


