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Rapid Ventricular Assessment Using Real-Time Interactive Multislice MRI

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A multislice real-time imaging technique is described which can provide continuous visualization of the entire left ventricle under resting and stress conditions. Three dynamically adjustable slices containing apical, mid, and base short axis views are imaged 16 times/sec (48 images/sec), with each image providing 3.12 mm resolution over a 20 cm field of view. Initial studies indicate that this technique is useful for the assessment of LV function by providing simultaneous real-time visualization of all 16 wall segments. This technique may also be used for stress LV function and, when used in conjunction with contrast agents, myocardial perfusion imaging. Magn Reson Med 45: 371–375, 2001. © 2001 Wiley-Liss, Inc.

Key words: real-time interactive MRI; ventricular assessment; perfusion; multislice

The detection of myocardial perfusion deficits and contractile dysfunction is the most frequent clinical assessment made in ischemic heart disease. Annually, more than 3 million stress nuclear and echocardiography studies are performed in the United States alone (1). Magnetic resonance determination of stress-induced wall motion changes and perfusion have been demonstrated (2–4). However, there exist significant limitations related to total scan time, scan plane prescription, arrhythmia, and image registration. Recent studies suggest that, for wall motion assessment, imaging time may be as long as 1 hr using current techniques (2), with good quality images obtained in only 80% of patients (3). Furthermore, up to 35% of patients develop significant ventricular (>5/min) or atrial extrasystoles during pharmacologic stress (5). This clinically tolerable rate of arrhythmia significantly complicates sequences that require gating.

Myocardial perfusion imaging has been investigated using several MR techniques. Early studies used T_1 or T_2^* agents and gradient recalled sequences to demonstrate the ability to detect myocardial perfusion defects in humans (6–8). Recently, using echo-planar imaging (EPI) acquisitions, multiphase multilevel perfusion imaging has also been reported (9). Initial studies providing quantitation of myocardial perfusion using the ventricular input function and a temporal resolution of 160–235 ms have been performed (8,10). However, these clinical perfusion studies are not done under true stress conditions and may be infeasible given the prolonged image acquisition and contrast bolus timing.

Current perfusion protocols rely on vasodilation rather than true ischemic stress. While these established techniques can acquire images in about 100 ms/slice, they are suitable only at rest. Under the conditions of true stress and induced ischemia, where the diastolic window can be less than 180 ms, faster volumetric and we believe real-time techniques are necessary.

Real-time wall-motion imaging using single-slice techniques have already shown that rapid acquisitions can provide accurate wall-motion information and quantitative measures of function during free breathing (11,12). Using slice interleaving, real-time images of up to two slices have also been demonstrated with limited interactive control (13,14).

An ideal cardiac wall motion and perfusion study would combine the high spatial resolution, image quality, and variable scan plane features of MR imaging with the real-time temporal resolution and control of echo cardiography. Multislice coverage is extremely important for the thorough evaluation of myocardial ischemia. The current standard requires imaging 16 myocardial segments as defined by the American Society of Echocardiography (ASE) (15,16), which must be done quickly and accurately during stress and must correspond to the segments imaged at rest. Current real-time imaging systems are able to evaluate left ventricular (LV) function and wall motion in single slices, but multislice coverage and imaging under stress would be useful additions to such a system.

In summary, the limitations of current methods include: 1) suboptimal temporal resolution preventing volumetric perfusion studies under conditions of true induced ischemia (tachycardia); 2) dependence on cardiac gating, which excludes patients with arrhythmia at rest or induced by stress; 3) multiple breath-holds, which requires patient cooperation and cannot be expected of patients experiencing true ischemia; 4) lengthy examinations due to the need for multiple scout images and static planning scans; and 5) the lack of simultaneous volumetric coverage, requiring registration of multiple slices during stress function studies.

To address these issues, we have developed a real-time interactive (RTI) multislice MR imaging system that is capable of volumetric LV evaluation under resting and stress conditions. Three parallel slices are continuously imaged in an interleaved fashion. By choosing these slices to contain apical, mid, and base short axis views, all 16 myocardial segments (as defined by the ASE; 15,16) can be visualized simultaneously. Initial studies using this system indicate that in healthy subjects resting and stress LV function can be evaluated in examinations requiring about 5 min each (including prescan calibration) and

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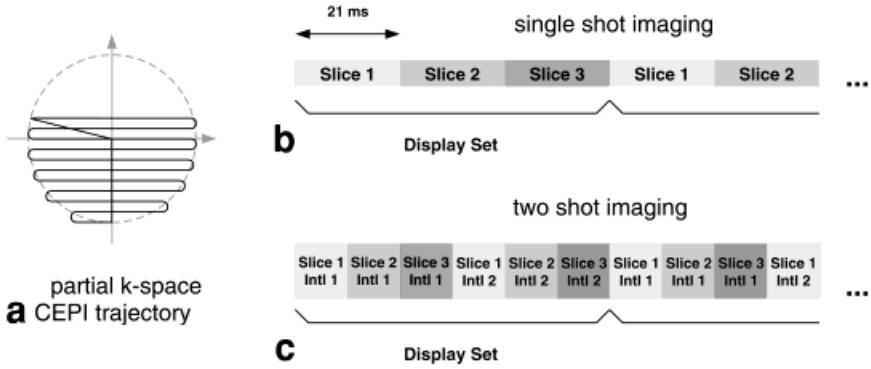

FIG. 1. Acquisition and display timing. Three slices are imaged using (**a**) partial *k*-space circular echo planar trajectories. Depending on the application, images are acquired using a single-shot or two-shots. Acquisition ordering is shown for (**b**) single-shot and (**c**) two-shot imaging with two interleaved acquisitions. All three slices are imaged continuously and are displayed together.

when used with contrast agents can provide perfusion information in all slices.

METHOD

Our RTI multislice sequence was implemented within the Stanford RTI system (17), which provides the framework for real-time reconstruction and interactive adjustment of imaging parameters. In this system, the operator is provided with interactive control over the scan plane for the rapid localization of desired views, and over scan parameters such as field of view, slice thickness, and flip angle.

The pulse sequence consists of a slice-selective excitation followed by a readout and a crusher in the slice-select direction. Slice-selective excitations were designed using the Shinnar-LeRoux algorithm (18,19). Our initial studies used a 2 ms excitation with a sharp profile and minimum slice thickness of 3 mm. For studies requiring shorter TRs, we used a 640 μs excitation with minimum slice thickness of 5 mm.

Readouts used the partial *k*-space circular EPI (CEPI) trajectory (20) shown in Fig. 1a, and were designed to achieve 3.12 mm resolution over a 20 cm field of view (FOV). CEPI is a variation of the EPI trajectory that has a circular *k*-space footprint and therefore a circular image FOV. Utilizing a partial *k*-space approach (21,22), only 34 of 64 *k*-space lines are acquired for each 64 × 64 image (53% coverage). Each slice is imaged using one or two excitations. In the single-shot case, the readout duration is 14.8 ms, while the two-shot case has a readout duration of 7.6 ms. Real frame rates of 48–50 complete images/sec could thus be acquired. With the same hardware and acquisition method, one could also tradeoff spatial resolution for temporal resolution to achieve 3.64 mm resolution at 72 images/sec or 5 mm resolution at 100 images/sec.

Specific parameters from each of our studies are summarized in Table 1. We initially used single-shot CEPI in a resting wall-motion study, but found that two-shot CEPI resulted in reduced image artifacts. During stress and perfusion studies, we used two-shot CEPI and a shorter excitation pulse to maintain the same frame rate. Using the shorter excitation, all but 2 ms of each TR was occupied by readout. Under these conditions, the resolution vs. image time tradeoff is shown in Fig. 2 for different numbers of interleaves. In general, dividing the acquisition into more interleaves increases the imaging time, but shortens readouts, resulting in reduced flow and off-resonance artifacts (23,24).

The ordering of acquisitions is summarized in Fig. 1b,c. All three slices are imaged continuously and are reconstructed and displayed asynchronously at the highest rate possible. In the two-shot case, each CEPI readout is acquired for all slices before moving to the next readout. This maintains a constant TR for each slice, and therefore consistent steady-state signal levels in each slice over all excitations. Note that while three slices provide adequate coverage for the left ventricle, the method is general to any number of slices.

Table 1
Scan Parameters for RTI Multislice Studies

	Rest study	Stress study	Perfusion study
Field of view (FOV)	20 cm	20 cm	20 cm
Resolution	3.12 mm	3.12 mm	3.12 mm
Slice thickness	3 mm	5 mm	5 mm
Flip angle	30°	30°	80°
Number of interleaves	1	2	2
Excitation duration	2.048 ms	640 μs	640 μs
Readout duration	14.8 ms	7.6 ms	7.6 ms
Repetition time (TR)	21 ms	10 ms	10 ms
Image rate (triples)	15.87 fps	16.7 fps	16.7 fps

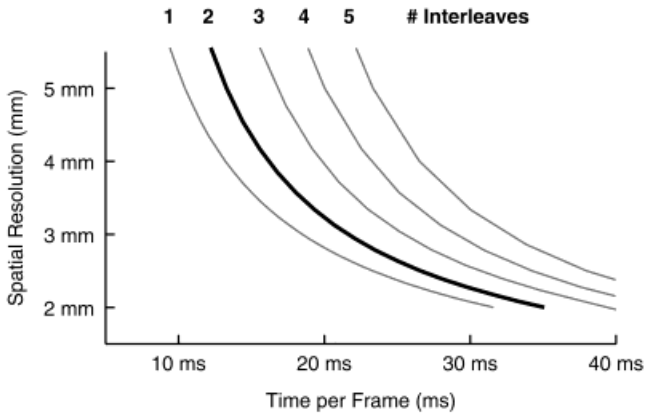

FIG. 2. Resolution tradeoff for high frame rate real-time imaging using the partial *k*-space CEPI trajectory. The resolution curves for one to five interleave CEPI acquisitions are shown based on a 20 cm FOV and 2 ms per TR for the excitation and crusher.

Real-time reconstruction and display is managed by an external workstation (17). For each display set, the three slices are reconstructed and displayed for immediate feedback. Image triplets are reconstructed and displayed at the rate of 16 frames/sec with a display latency of less than 1 sec. If desired, in the multishot case higher frame rates could be achieved by using a sliding window reconstruction (25). Homodyne reconstruction was used to reconstruct partial *k*-space data (21,22).

Our MR studies were conducted on a 1.5 T GE Signa CV/i scanner (General Electric, Milwaukee, WI). The scanner was equipped with gradients supporting 40 mT/m magnitude and 150 mT/m/ms slew rate and a receiver supporting 4 μs sampling (±125 kHz). A body coil was used for transmission of RF, with a 5-inch surface coil used for signal reception. The multislice sequence was designed for three slices, with imaging parameters summarized in Table 1.

RESULTS

Ventricular Function

Our initial multislice real-time system was validated in a study of healthy volunteers. Twenty healthy subjects were scanned to evaluate the visibility of LV wall segments at rest and during free breathing. For each subject, apical, mid, and base short axis views were localized and 10–15 sec of video was stored. Each exam took no longer than 5 min (including prescan calibration, interactive localization, and video acquisition). Figure 3 contains a representative image sequence acquired during one such study (with every fourth frame shown). In this subject, 17 frames of each slice were acquired within one cardiac cycle at a heart rate of 54 bpm. Six of 17 frames occurred during the systolic period. LV wall segments are clearly visualized, while LV blood volume experiences some signal voids due to the movement of saturated spins (from the other slices). In the 20 subjects studied, all 16 wall segments were adequately visualized. Five of the studies showed reduced signal in the posterior lateral wall segments due to coil falloff, and three studies showed some susceptibility artifacts. However, neither artifact prohibited the evaluation of wall motion.

Due to the high temporal resolution of this sequence, it may also be used to assess wall motion during stress. Figure 4 contains systolic and diastolic images of a normal subject studied at rest and under physiological stress. In this study, physiological stress was induced by having the subject run for 10 min immediately before scanning. This subject had a resting heart rate of 86 bpm and a stress heart rate of 176 bpm. We observe that even under highly stressed conditions, wall motion is well resolved in all three slices.

Myocardial Perfusion

When used in conjunction with contrast agents, multislice fluoroscopy provides perfusion as well as wall motion information. The course of a bolus contrast can be tracked in real-time with effectively volumetric LV coverage. Figure 5 illustrates the blood and myocardium signal enhancement observed after a bolus injection of Gadolinium-DTPA (10 ml Magnevist, Berlex Laboratories, Wayne, NJ). Figure 6 illustrates the signal levels in the right ventricle, left ventricle, and myocardium for 45 sec following the introduction of contrast. In this healthy subject at rest (heart rate 83 bpm), enhancement is seen in the right ventricle, left ventricle, and finally in the myocardium. Due to the volumetric coverage and real-time nature of this sequence, only a single contrast injection without the need for careful bolus timing is needed to study perfusion throughout the left ventricular wall. Note that a nulling prepulse was not used in this acquisition, but can be included at a small cost in imaging time.

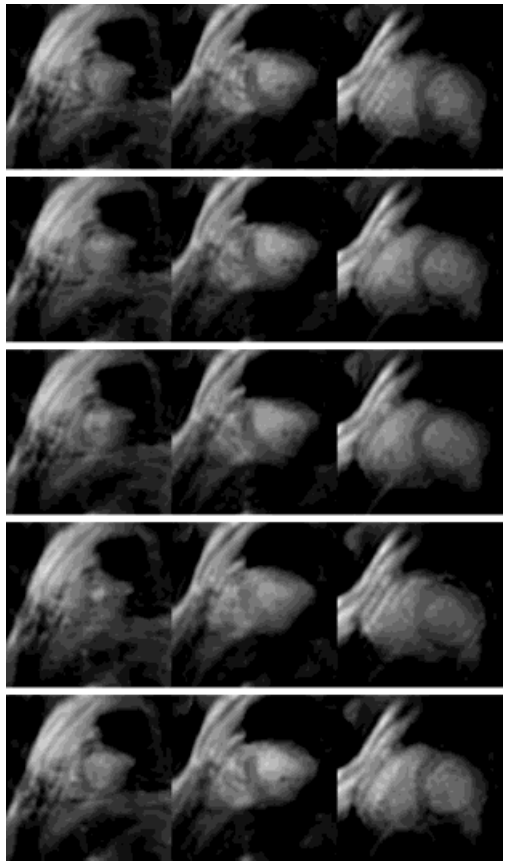

FIG. 3. Multislice image sequence from a normal volunteer. Real-time imaging of three slices allows visualization of the entire LV during systole and diastole. In this subject, 17 frames of each slice were acquired within one cardiac cycle at a heart rate of 57 bpm (every fourth frame is shown). Six of 17 frames occurred during the systolic period.

Left ventricular contractile function and blood flow is simultaneously obtained. Furthermore, the arterial input function is sampled evenly throughout the cardiac cycle compared to current multiple slice acquisitions (10). This avoids the need for further image registration prior to interpretation and should improve quantitative analysis.

DISCUSSION

Real-time interactive multislice MRI is a practical tool for evaluating LV function. It can provide volumetric coverage of 16 wall segments in real-time and at frame rates suffi-

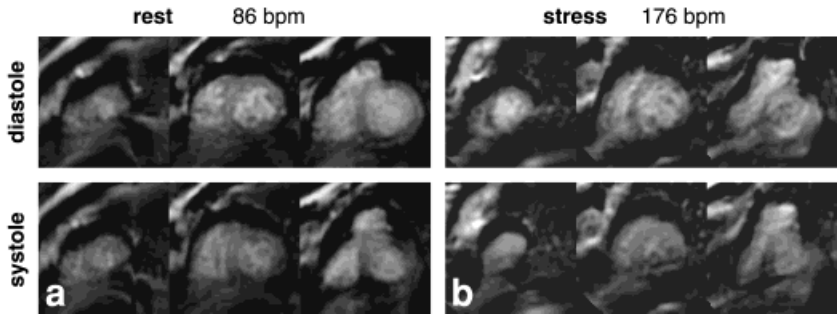

FIG. 4. Resting vs. stress. Three-level images from a normal volunteer scanned under (**a**) resting conditions (heart rate of 86 bpm), and under (**b**) physiological stress (heart rate of 176 bpm). Physiological stress in the subject was induced by running for 10 min immediately before the scan.

cient for combined stress wall-motion and perfusion study. The interactive nature enables rapid localization and real-time scan plane adjustment, while rapid acquisitions eliminate the need for gating or breath-holding. Our initial studies indicate that an LV wall-motion study can be completed in roughly 5 min, while stress and perfusion studies are also possible with similar scan times.

Changes in cardiac position during stress studies are common due to changes in hemodynamics and patient motion, especially when patient discomfort is present when true ischemia is induced. An extremely important component of stress imaging is the ability for the operator to compensate for these changes. Current MR stress studies do not address this issue of registration since the current process of slice prescription is time-consuming and not amenable to rapid adjustment. The same limitation applies to perfusion imaging.

Although no definitive data exist on the optimal frame rate needed for diagnostic wall motion studies, there are suggestions that frame rates beyond 24 frames/sec may not be required. At peak stress, systolic ejection is typically completed only 150–180 ms after the onset of ventricular excitation. The broad clinical experience in assessing ventricular function under stress using echo cardiography indicates the need for 4–6 frames over the systolic period (26). This translates into a temporal resolution of about 30–40 ms. The necessary high frame rate of 24 frames/sec and available imaging time at peak stress of 60–90 sec together pose stringent constraints on real-time stress wall-motion imaging sequences. Furthermore, prolonged acquisitions for perfusion (8) during diastole are not feasible during true pharmacologic stress when the entire cardiac cycle could be as short as 350 ms. Many of the available tradeoffs depend on hardware performance, software reconstruction techniques, and clinical constraints. We have demonstrated simultaneous real-time images of three slice locations at 16 complete frames/slice/sec. To further improve temporal resolution, other sampling schemes, such as partial *k*-space spirals (20) could be explored.

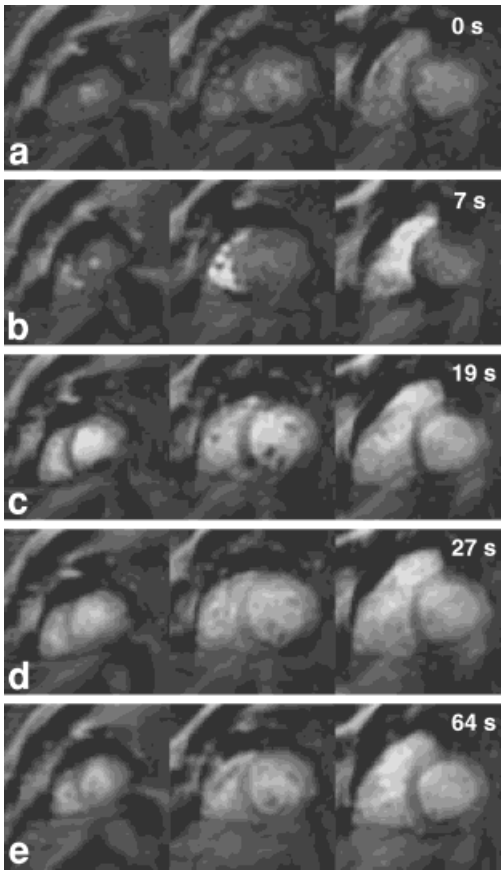

FIG. 5. First-pass perfusion images. Time series of images from a normal subject after bolus injection of Gadolinium-DTPA. Images show signal in three slices (**a**) before injection, (**b**) with RV signal elevation, (**c**) with LV signal elevation, (**d**) with myocardium signal elevation, and finally (**e**) wash out. The subject's heart rate was 83 bpm during this study.

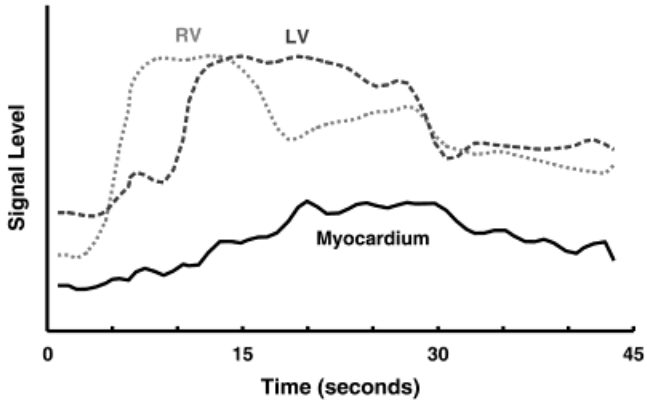

FIG. 6. First-pass perfusion signal time course. The graph shows right ventricle (RV), left ventricle (LV), and myocardium signal levels for the first 45 sec after a bolus Gadolinium-DTPA injection. Plotted quantities are signal intensities measured during late diastole, and were computed by calculating mean signal in manually selected regions of interest in the RV, LV, and anterior LV wall (myocardium).

Faster gradients will also improve both the readout and excitation performance of the multislice perfusion sequence. Readout duration can be reduced by increasing gradient area at the cost of some SNR. Increased bandwidth would also improve multislice implementations by allowing more precise slice profiles to minimize the effect of partial saturation from slice movement during the cardiac cycle.

Recently, the development of position-sensitive imaging sequences, such as SMASH (27) and SENSE (13,28), have led to significant advances in reducing the dataset needed for image reconstruction. These methods are particularly suitable for large FOV studies where greater temporal resolution is desired. In our experience, however, the 16–24 cm FOV necessary for cardiac studies can be adequately covered by a single coil or two-coil array, and currently available gradients appear capable of achieving reasonable temporal resolution. However, with improved reconstruction speed SENSE and SMASH techniques may be important for further improvements in temporal resolution with large FOV multislice imaging.

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