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Triggered Real-Time MRI and Cardiac Applications

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Real-time interactive MRI is becoming the method of choice for many cardiac applications. One current limitation of real-time techniques is inaccurate slice registration during free-breathing. A simple "triggered real-time" imaging approach is proposed which enables the acquisition of synchronized and accurately registered real-time movie loops during short breathholds. Initial in vivo results demonstrate application to complete 4D ventricular function assessment and fully resolved flow imaging. Magn Reson Med 49:188–192, 2003. © 2003 Wiley-Liss, Inc.

Key words: real-time MRI; triggering; breathhold; spirals

In cardiac MRI, CINE (gated and breathheld) scanning techniques can achieve high temporal and spatial resolution, but are often complicated by arrhythmia and patient difficulty with long or multiple breathholds. Real-time imaging, which is typically performed independent of respiratory and cardiac motion, is robust to both arrhythmia and patient shift.

For many applications, recent MR hardware improvements and novel pulse sequences have enabled the acquisition of diagnostic quality images (with sufficient resolution and contrast) during real-time interactive scanning. The rapid imaging capability allows for fast acquisition of many different physiologic data with volumetric coverage. One limitation, however, is potential slice misregistration during these "4D" acquisitions, when multiple real-time movie loops are acquired at different respiratory positions during a free-breathing exam. Normal respiration causes diaphragm shifts on the order of 2 cm and cardiac shifts of up to 1 cm, depending on the imaging plane (1,2). Several approaches have recently been proposed to help register and combine real-time data based on the images themselves (3) or based on trigger signals (4).

In this article we present an automated trigger-based registration method in which cardiac trigger signals are monitored during continuous real-time scanning and scan parameters are automatically modified in response to each beat. Synchronized real-time movie loops can therefore be acquired—one per heartbeat. In conjunction with a breathhold, this allows N accurately registered movie loops to be acquired in N R-R intervals, thus combining accurate slice placement with many of the robust features of real-time imaging. These synchronized and registered movie loops can contain complementary data, such as different scan planes, different image contrast, or different flow encoding. We demonstrate the application of this technique to complete 4D imaging of ventricular function and fully resolved flow/motion imaging.

MATERIALS AND METHODS

Sequence and Timing

The proposed method is demonstrated by an extension to two existing single slice real-time sequences (5,6). During continuous scanning, a cardiac trigger signal (such as EKG or plethysmograph) is monitored regularly by the pulse sequence. In our implementation, the scanner's trigger state register is checked once per TR. On operator command or during a breathhold, the sequence switches to a "triggered" real-time mode, where various pulse sequence parameters are modified in response to each detected trigger. No time is ever spent waiting for a trigger. As such, N different real-time loops are acquired in N consecutive R-R intervals. Figure 1 illustrates the sequence timing.

In response to trigger signals, a variety of scan parameters may be adjusted by the pulse sequence. These include but are not limited to: slice location, type of excitation or readout, image contrast (by adjusting prepulses or acquisition timing), and flow or spectral encoding (if using flow or spectrally sensitive sequences). For example, in multislice studies the scan plane is shifted to a new slice location with each cardiac trigger. The order and placement of slices may be arbitrarily defined. As soon as the scan plane is shifted, new field maps are acquired and scanning continues. This is repeated until all N real-time loops are acquired.

A trigger delay is used when scanning with either ECG or plethysmograph (illustrated in Fig. 1). In our studies, plethysmograph gating was used with a trigger delay of 300 ms. To prevent premature switching in case of arrhythmia, a minimum trigger spacing of 400 ms is enforced before the sequence is allowed to respond to a trigger. Data acquired between extrasystoles may then be excluded; however, the physiologic changes that follow an extrasystole may necessitate reacquisition of some loops. We are able to notice these cases immediately due to the real-time reconstruction and, if necessary, repeat the breathhold.

Experimental Methods

All studies were performed on a GE Signa 1.5 T CV/i scanner (GE Medical Systems, Milwaukee, WI) using the Stanford real-time interactive (RTI) imaging platform (7). The scanner was equipped with gradients capable of 40 mT/m magnitude and 150 T/m/s slew rate and a receiver capable of 4 μs sampling (±125 kHz). In all studies a body coil was used for RF transmission and a 5-inch surface coil was used for signal reception.

Triggering was demonstrated in conjunction with two previously described sequences: a real-time spiral gradient

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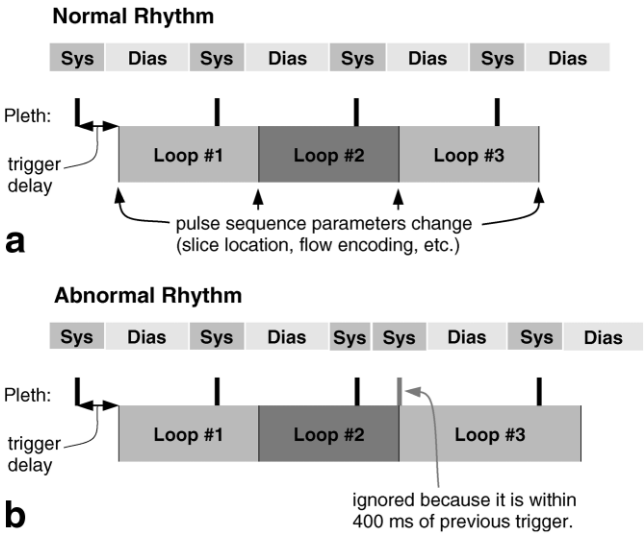


FIG. 1. Illustrations of acquisition timing for the **(a)** normal case, and **(b)** arrhythmia case. Each loop represents a real-time movie acquisition spanning one cardiac cycle. Pulse sequence parameters are modified between successive loop acquisitions and the transitions are initiated by cardiac triggers. When using ECG gating or plethysmograph gating, different trigger delays should be used. In our studies, plethysmograph gating was used with a trigger delay of 300 ms, such that end diastole to end systole contraction was captured in each slice loop. Arrhythmia or spurious trigger signals are handled by enforcing a minimum trigger spacing (of about 400 ms).

echo sequence (5) and a real-time spiral phase contrast (color flow) sequence (6). Both sequences used a 6-ms spectral-spatial excitation and interleaved 12.3 ms spiral readouts. A sliding window reconstruction (8) was used to reconstruct and display in real time at up to 30 frames/sec. Additional scan parameters are summarized in Table 1.

Table 1
Sequence Parameters for LV, Color Flow, and Strain Rate Studies

Quantity	LV function	Color flow	Strain rate
Resolution	1.88 mm	2.7 mm	1.93 mm
FOV	20 cm	20 cm	20 cm
Velocity encoding	none	±1.2 m/s	±10 cm/s
No. of interleaves	4	2 + 2	2 + 2
TR	24 ms	30 ms	28 ms
Image acquisition time	96 ms	120 ms	112 ms
Recon. frame rate	30 fps	16 fps	12 fps

RESULTS AND DISCUSSION

The triggered real-time methodology can be used to achieve many types of synchronized real-time data. Initial studies were performed to gain experience applying this methodology, as well as to establish feasibility in a few applications. In particular, we used triggering to: 1) achieve multislice (volumetric) coverage in real-time LV assessment studies, and 2) achieve multiple directions of flow encoding in real-time cardiac blood flow studies and myocardial motion studies.

Triggered Multislice LV Function

Recent clinical studies have shown real-time imaging to be accurate and effective (9–11), yet multislice coverage is

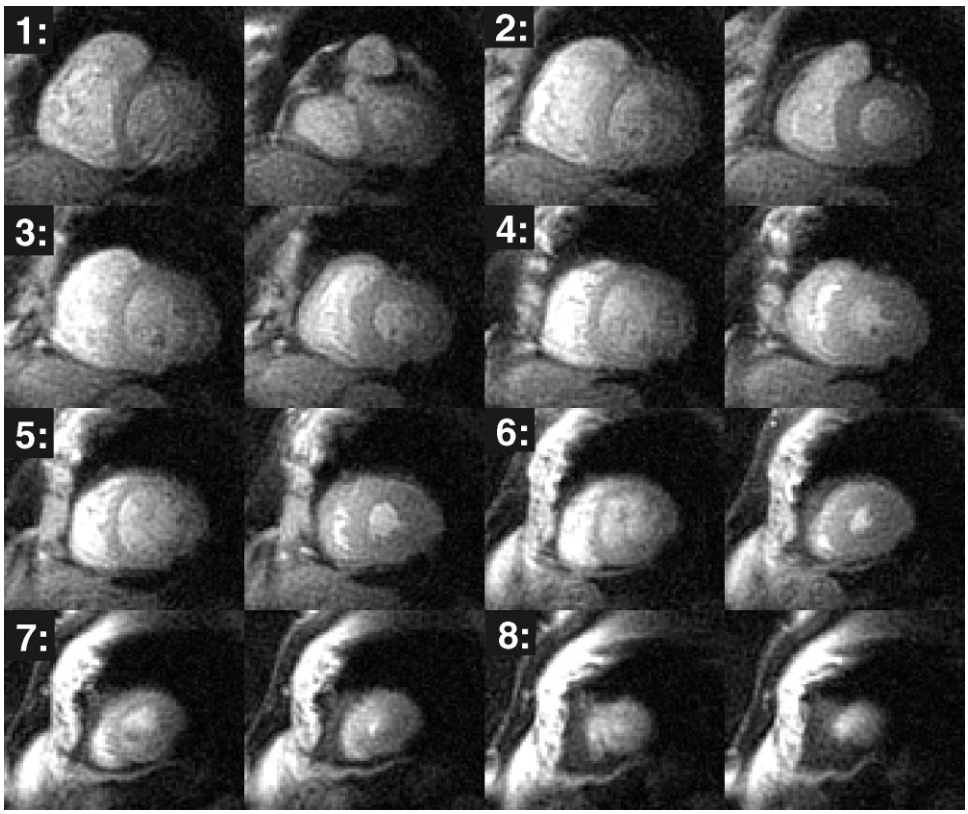


FIG. 2. LV function study in a healthy volunteer. Synchronized movie loops of eight slices were acquired in a single 7-sec breath-hold. Here (left) end-diastolic and (right) end-systolic frames are shown for all eight slices. In addition to volumetric wall-motion assessment, the following data were quantified: EDV = 72.6 ml, ESV = 26.0 ml, EF = 64.2%, Mass = 113.8 g.

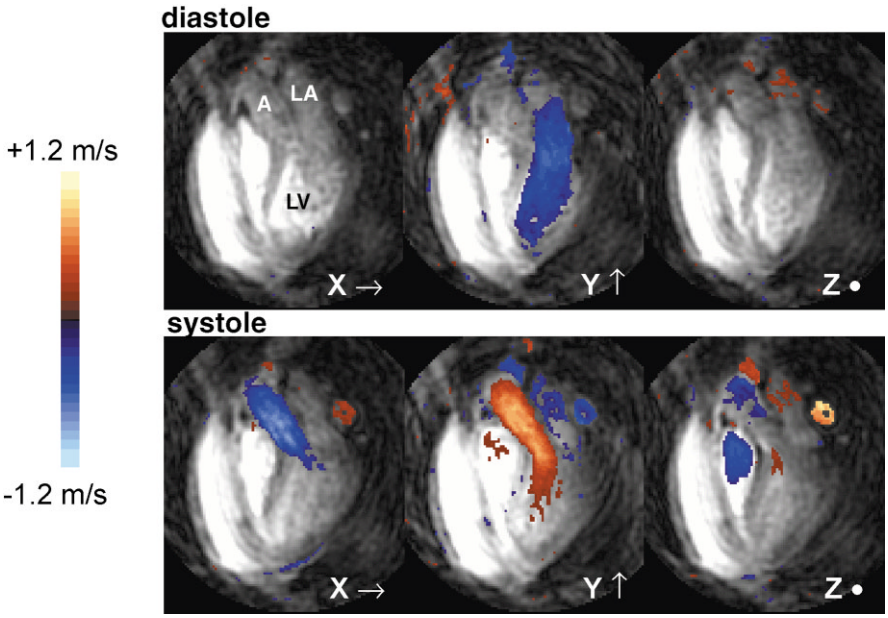


FIG. 3. Synchronized real-time color flow movie loops with flow encoding in X, Y, and Z were acquired in a 4-sec breathhold. Individual frames from mid-diastole and mid-systole are shown, with the aorta (A), left ventricle (LV), and left atrium (LA) labeled in the upper left frame. Normal mitral inflow and aortic outflow are clearly visualized in this healthy volunteer.

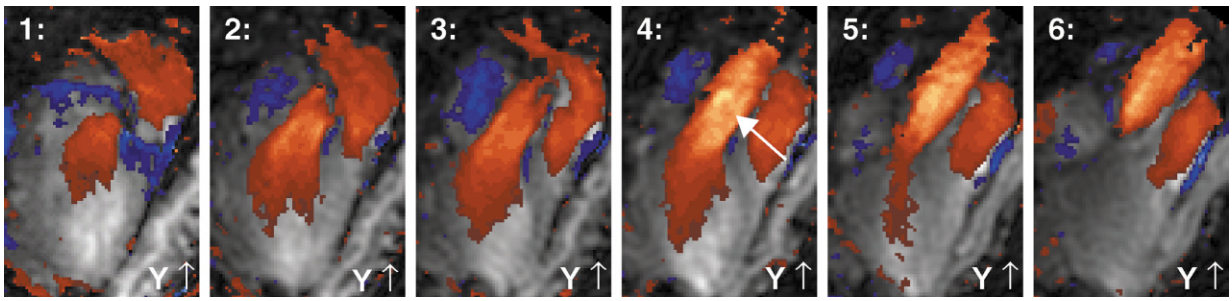
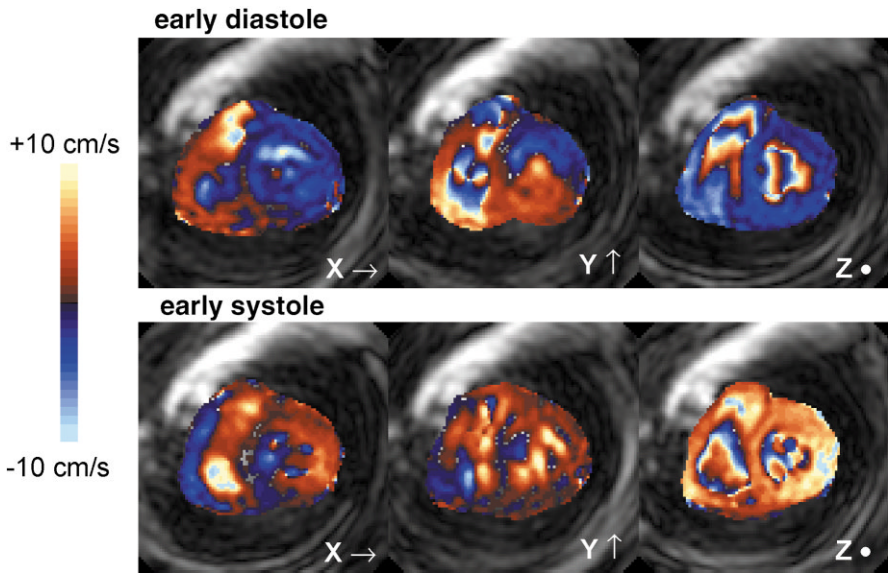


FIG. 4. Synchronized real-time color flow movie loops of six parallel slices spanning the aortic valve were acquired in a 7-sec breathhold. Frames during peak aortic outflow are shown for all six slices.

FIG. 5. Synchronized real-time color flow movie loops with flow encoding in X, Y, and Z were acquired in a 4-sec breathhold. With a VENC of ± 10 cm/s and 1.9 mm spatial resolution, myocardial motion can be resolved and wall strain rate may be computed. Individual frames from early diastole and early systole are shown. Myocardial motion vector fields can be assembled for each temporal frame.



required. Our LV assessment scanning protocol involved localizing apical and base short axis views, requesting a single breathhold, and during that breathhold acquiring 8–10 slice loops (with a spacing of 1 cm) spanning the LV. Manual segmentation and measurement of LV end-diastolic volume (EDV), end-systolic volume (ESV), ejection fraction (EF), and mass was completed off-line (9). In addition, each study dataset was reviewed by two experienced cardiologists to verify the ability to evaluate wall motion in all segments.

Total exam time in our initial study of seven healthy volunteers (five male, two female, ages 26–32) was 5.5 ± 1 min (including prescan calibration and localization). Heart rates in the volunteers were 48–83 beats per minute, resulting in breathhold durations of 8 ± 2 sec for 8–10 slices (10 slices for the volunteers with higher heart rates). Figure 2 contains typical end-systolic and end-diastolic images from one such study. Synchronized videos were read by two cardiologists experienced in cardiac MRI and who were also readers in the recent study by Kaji et at. (9). In all studies satisfactory end-diastolic and end-systolic frames were captured at each slice location for semiautomated segmentation and volume calculation. Measurements of EF were 51–66%, and LV mass were 126–195 g, which were within the expected range for normals (12,13). In addition, using 8–10 slice coverage easily enabled regional wall motion assessment for all 16–17 myocardial segments (as defined by the ASE) (14).

Upon each slice shift, there was a noticeable transient period while the new slice reached a steady state. In initial studies the duration of this transient period was consistently between 150 and 180 ms. The scan trigger delay was purposely set to 300 ms so that the transient would occur during diastole and would not disrupt visualization of contraction in each slice.

Field map acquisition, which was performed after each slice shift, made use of a portion of this transient period. Note that the transient period may be reduced using methods proposed by Busse and Riederer (15).

Triggered Color Flow Imaging

In real-time color flow studies, we used triggering to acquire synchronized loops with different directions of flow encoding. Our original sequence (6) is capable of capturing flow along one axis with reasonable temporal resolution (~8 images/sec). Using triggering, we resolve flow in the two in-plane directions as well as the through plane direction in 3 R-R intervals. As such, a full flow/motion vector field can be assembled for each temporal frame.

Such acquisition may be used to better visualize cardiac flow. Images from a three-chamber view in a normal volunteer are shown in Fig. 3. In this healthy volunteer, aortic outflow, mitral inflow, and right ventricular outflow are nicely visualized. Note that while individual frames are shown, full movies (reconstructed at 16 frames/sec) are acquired. As shown in Fig. 4, multislice coverage also may be used with the color flow sequence in order to acquire volumetric flow information. In this example, color flow loops were acquired at six parallel slices through the aorta during a 7-sec breathhold.

Additionally, triggered color flow may be used to image myocardial motion in real time. Images from a short-axis view in a normal volunteer are shown in Fig. 5 (acquired with a VENC of ± 10 cm/sec). Such real-time techniques may be used to compute myocardial strain from data acquired in a 4-sec breathhold. In this study, we chose a long acquisition (112 ms/image) to achieve high spatial resolution (<2 mm); however, this can be flexibly reduced with correspondingly lower spatial resolution.

CONCLUSIONS

In summary, triggered real-time imaging is a useful method for acquiring synchronized real-time movie loops at the same respiratory position. This could potentially reduce the operator dependence of a standard cardiac examination. Initial studies have demonstrated the potential of this technique to support volumetric LV assessment and fully resolved velocity imaging in short breathholds.

One potential issue is the responsiveness to triggers during continuous scanning. Since the trigger signal is checked once per TR, slice loops are synchronized to within 1 TR. This may become an issue under stress conditions or with longer TRs, but was not substantial in initial resting studies with a TR ≤ 30 ms.

Another issue is patient difficulty with even short breathholds. Since this method can be implemented as a simple extension to conventional real-time interactive sequences, patients incapable of any breathhold can simply be examined without entering the triggered mode. One natural extension of this work would be to also monitor respiratory position (using bellows, navigators, etc.) (4), potentially eliminating the need for a breathhold altogether.

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