RECENT DEVELOPMENTS IN REAL-TIME MRI

Stephen J. Riederer, Ph.D.

Magnetic Resonance Laboratory; Department of Radiology; Mayo Clinic

200 First Street SW; Rochester MN 55905 USA

Phone: 507-284-6209; Fax: 507-284-9778; email: riederer@mayo.edu

Introduction

Ever since the earliest descriptions of MRI over two decades ago investigators have been interested in "real-time" MRI. The vision at that time may well have been the ability to depict the beating heart at 30 Hz frame rates with high spatial resolution. Although this specific application has not materialized, in the interim there has been increased definition and understanding of the role and limitations of MRI in general, and of the specific applications of real-time techniques in particular. The purpose of this work is to attempt to review the current status and potential future developments and usage of real-time techniques in MRI.

The Motivation for Real-Time MRI

Although the above-mentioned goal of direct acquisition of images of the beating heart is still valid, the rationale for real-time MRI techniques has expanded. Table 1 summarizes potential, general motivating factors for performing MRI in a real-time manner. Four such factors are listed.

The first, direct acquisition of diagnostic images, would include the 30 Hz cardiac imaging method alluded to previously. However, given the tradeoff of MR image quality and acquisition time, in some cases one is willing to accept a reduction in the image frame rate in exchange for high spatial resolution and high immunity to artifacts. This can be the case with single-shot spin-echo imaging when operated with a TR time in the 1000 to 2000 msec range. Recently this has been used for fetal MRI (1), the real-time nature of the method enabling the operator to track the fetal motion and still obtain high quality images.

Table 1. Motivating factors and examples of real-time MRI			
Specific Motivation	*Example*	*MRI Pulse Sequence*	*Acquisition Time per Image*
1. Direct acquisition of diagnostic quality images	Fetal MRI	Single-shot fast-spin-echo (SSFSE)	1-2 sec
2. Facilitation of patient-specific acquisition	Real-time triggering of contrast-enhanced MRA	Spoiled gradient echo	0.5 sec
3. Reduction of examination time	Real-time analysis of functional neuro MRI	T2*-weighted echo-planar imaging	<100 msec
4. MRI-based control of an additional process	MRI monitoring and control of thermal ablation	Gradient-echo based phase difference imaging	>10 sec

The second motivating factor listed has its roots in classic, x-ray-based radiology, and this is the manner in which x-ray fluoroscopy is used to position the patient and establish angulation immediately prior to a high-exposure, diagnostic procedure. Real-time x-ray fluoroscopy allows fast establishment of patient-specific parameters. This same mentality applies to this motivating factor for real-time MRI. In this case a fast MRI acquisition technique, possibly without the spatial resolution or contrast necessary for diagnosis, can be used to establish patient specific parameters. One example not shown in the table is the rapid determination of oblique angulation, as may be important for cardiac imaging. The specific example which is shown is the real-time determination of the arrival time of an intravenously administered contrast bolus as used for MR angiography (2). Real-time monitoring allows fast and easy synchronization of the MR data acquisition to the patient-specific transit time of the bolus.

The third motivating factor shown is more general, reduction of overall examination time. The concept of this is to aid the operator in determining when the examination is finished, thereby permitting release of the patient. As the complexity of specific MR image formation techniques has increased, such as those involving the mathematical processing of series of reconstructed images, it may not always be obvious after image acquisition whether the acquired data are adequate. Real-time methods may be valuable to clarify this. One example is the rapid formation of activation maps from a time series of echo-planar images as for functional neuro MRI of the brain. Rapid formation of such maps during or immediately after the acquisition may be useful in guiding whether or not the specific acquisition should be repeated.

The final motivating factor shown has come about from the realization of the broad applicability of the flexible contrast properties of MRI. Specifically, these can be exploited in assisting some other process. One example is within the field of "interventional MRI." As an interventional procedure is performed within the bore of the MR scanner, MRI itself can be used to monitor the progress and control the application of the intervention. Importantly, the MRI acquisition parameters can be adapted to match the timeframe of the intervention. For example, in a number of implementations of thermal ablation the time constant of the heating is on the order of tens of seconds. This time provides a guide as to the necessary acquisition time for monitoring and often relaxes stringent requirements on high frame rate for MRI.

Technical Elements of Real-Time MRI

Real-time MRI systems can be considered as being composed of three technical elements: (i) a pulse sequence that can be applied repetitively to allow continuous image acquisition; (ii) means for rapid image reconstruction; and (iii) means for allowing the MR acquisition to be modified based on what may be observed in the reconstructed images. As such, these can be identified concisely as "acquisition," "reconstruction," and "interactive control."

In considering the performance of a real-time system and the technical specifications placed on the elements of such a system, it is important to keep in mind the specific applications for which the system is to be used. In particular, the characteristic time of the phenomenon under study may will dictate the image acquisition rate, the reconstruction time, and response time of the system to operator alteration of a scanning parameter. For example, referring to Table 1, for real-time motion compensation in functional neuro MRI it is desirable to alter the spatial frame of reference of the acquisition as quickly as possible after acquisition of navigator echoes which provide a careful measure of the subject position. In this case the acquisition, reconstruction, and coordinate alteration are all ideally performed within msec. On the other hand, the monitoring of temperature rise in an thermal ablation procedure may well allow image acquisition times of 5 to 10 seconds. This may well allow some relaxation of stringent speed requirements for the reconstruction and control technical elements.

Due to the broad range of applications of real-time MRI techniques, the ideal system is one which allows essentially any pulse sequence to be operated in a continuous manner with real-time image reconstruction. This can range from fast, low spatial resolution spiral or echo-planar acquisition to longer, higher resolution spin-echo-based methods. A variety of hardware implementations have been studied by groups at academic institutions for performing real-time MRI (3,4). However, unless a dedicated technical research team is available, perhaps the best approach for obtaining real-time capability is through contact with the MRI vendor.

Applications of Real-Time MRI

Fluoroscopic Imaging. One of early identified applications of real-time imaging was for "fluoroscopy." As is practiced in conventional x-ray imaging, fluoroscopy is used for localization and establishment of angulation prior to a higher exposure sequence used for the actual diagnosis. In the x-ray case image quality, typically SNR, is sacrificed to obtain the advantages of high frame rate. For MRI the rationale is much the same, but typically contrast and spatial resolution are sacrificed for high frame rate.

For fluoroscopic MRI it can be especially important to have flexible, responsive control of the sequence parameters. Because there are many more imaging variables to adjust in MRI vs. x-ray imaging, and because a single section is imaged rather than a projection, there are potentially many more variables to control and tune. For this reason it can be sensible to develop "tools" which link a sequence of these control operations into one easy task. One example is the "three-point tool" (5) for facilitating selection of an arbitrary oblique plane of section.

Fluoroscopic Triggering of Contrast-Enhanced MRA Studies. A very specific application of real-time MRI techniques is the accurate triggering of high resolution 3D acquisitions for arterial phase contrast-enhanced angiograms. Although there is a continuing trend for acquisition times to be diminished for fixed spatial resolution, the acquisition times for high resolution 3D studies continue to be in the 10 to 40 second range, depending upon various parameters. These extended times per 3D image set make it difficult to acquire a series of such sets and be guaranteed that one of them will occur at the peak arterial phase. To match the triggering of the acquisition to the arterial phase of the contrast bolus, real-time 2D "fluoroscopic" imaging can be done to simply monitor contrast arrival in a large proximal artery (2). Upon detection of contrast arrival, the 3D acquisition can be initiated by the operator or automatically. This technique has been shown to be highly reliable for a variety of vascular areas.

Real-Time Navigator Echoes. An application of real-time methods that has evolved in the last decade is the use of special purpose MR signals to provide real-time guidance of a high resolution MR acquisition. In doing this, it was essential to realize that the guiding signals need not be an image in the traditional form in which the entire section or volume of interest is interrogated. Rather, it could be sufficient to be sensitized to a much more limited, specific phenomenon, such as the degree of motion along a specific direction. To this end real-time navigator echoes have been developed. These can limited in their spatial extent, such as column excitations for monitoring diaphragmatic motion, or limited to specific trajectories in k-space, such as orbital navigator echoes for monitoring rotational motion (6). Recently these have been implemented for real-time motion correction in functional neuro MRI.

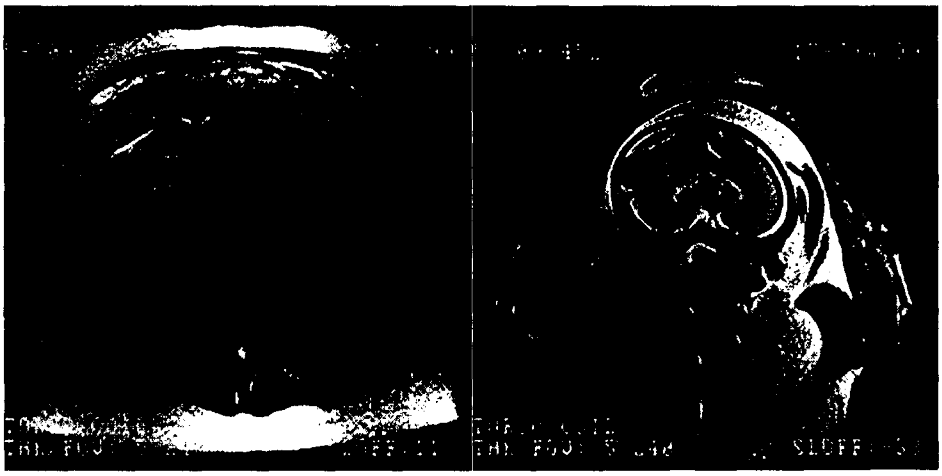

Figure 1. Example of real-time SSFSE images of the fetus, illustrating imaging of a mass in axial and coronal views.

Interactive SSFSE. Another real-time technique recently studied has been the implementation of interactive fast-spin-echo (SSFSE) imaging. The motivation is to attempt to exploit the high immunity to artifact and high spatial resolution of spin-echo imaging while allowing some modest decrease in the acquisition to rates of one image every several seconds. The technique of choice in this case is a single-shot FSE method (1), with some flexibility in the effective echo time based on the phase encode view order used. This technique has recently been used in imaging of the fetus, the interactivity allowing tracking of fetal motion during the examination. An example is shown in Figure 1.

Summary

Real-time techniques are motivated by a number of factors including the potential for direct acquisition of diagnostic quality images, facilitation of patient-specific imaging parameters, and reduced examination time. Real-time MRI includes not only a rapid pulse sequence but also high speed image reconstruction and easy interactivity. The frame rate of the real-time technique used should be matched to the physiological timeframes under study. Principal applications thusfar have been in localization, fluoroscopic triggering, guidance of other processes, and potentially in the generation of diagnostic images of moving structures.

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