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Real-Time Reconstruction and High-Speed Processing in Functional MR Imaging

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Summary: Access to fully processed activation maps in near real time during a functional MR examination enables run-to-run assessment of results. This is particularly useful in clinical studies, since the results of the functional MR examination can be ascertained before the patient leaves the MR suite, permitting interactive tailoring of the functional MR study. We describe how a real-time MR system can be customized to complete the following tasks in less than 3 minutes: obtain an 81-second acquisition of a multisection functional MR imaging time series using single-shot echo-planar imaging, perform image reconstruction, extract functional MR activation maps using cross-correlation and thresholding, and superimpose activation maps on previously acquired T1-weighted anatomic images.

Methods for performing functional MR imaging examinations have yet to be standardized, but rapid imaging techniques, such as single-shot echo-planar imaging (EPI), that generate a large number of images are often used (1). For example, for multisection 64×64 resolution data, 500 to 1000 single-shot echo-planar images are typically acquired per functional MR run over the course of a few minutes. A functional MR examination usually involves acquisition of several separate functional MR runs. Processing and then thresholding of the data for a functional MR run by one of the many available algorithms (2–5) result in an activation map, which is then commonly overlaid on 2D anatomic images and/or incorporated into 3D brain renderings. These processes may take tens of minutes to hours. It is typically only at this point that interpretation of the functional MR study becomes clinically useful.

The generation of clinical results in a "fast" manner for functional MR imaging studies involving patients is motivated by at least two specific objectives. First, as in any clinical radiologic procedure, a timely diagnostic assessment or interpretation is often needed. Thus, turnaround times on the order of hours or longer are a liability for functional MR imaging as a diagnostic tool in the clinical setting. For example, in our own clinical practice of neurosurgical treatment of tumors and epilepsy, it is common for the patient to be seen by a neurologist and neurosurgeon on the morning of the first day of a visit, followed by various tests (including functional MR imaging) for surgical planning, with surgery performed the next day. Second, with the availability of functional MR results within tens of seconds after the acquisition of the functional MR data, it is feasible to monitor the functional MR study and tailor the functional MR examination accordingly while the patient is in the MR imaging suite. This standard of adapting the examination to the specific patient is no different from that which is commonly done in conventional (nonfunctional) MR imaging examinations.

In the following section we describe the method of instrumentation that allows rapid generation of functional MR imaging results using general postprocessing algorithms.

Methods

The Reconstruction and Processing System

All image reconstruction and processing are performed on a custom-made real-time MR fluoroscopic imaging system, which is linked to a standard MR imaging unit. A detailed overview has been described previously (6). As illustrated in a simplified schematic in Figure 1, the system is a combination array processor (MC-RACE, Mercury Computer Systems, Chelmsford, MA) and Sparc 5 workstation (Sun Microsystems, Mountain View, CA). The system has direct access to raw MR imaging data immediately after digitization for image reconstruction/processing, as well as the capability for interactive pulse-sequence control. All imaging data are vectored to optimize execution of operations on the array processor. The array processor has 64 MB of on-board memory. Shared memory between the array processor and Sparc 5 workstation as well as assembly-coded library routines also contribute to efficiency and speed.

Image Acquisition

Scanning was performed on a 1.5-T GE Signa MR imager equipped with EchoSpeed gradients (23 mT/m, 184-microsecond rise times) using a standard bird-cage transmit-receive head coil. For localization, a sagittal scan through the interhemispheric fissure was obtained. T1-weighted images of nine 5-mm-thick contiguous axial sections transecting the somatotopic hand region were then acquired and automatically stored

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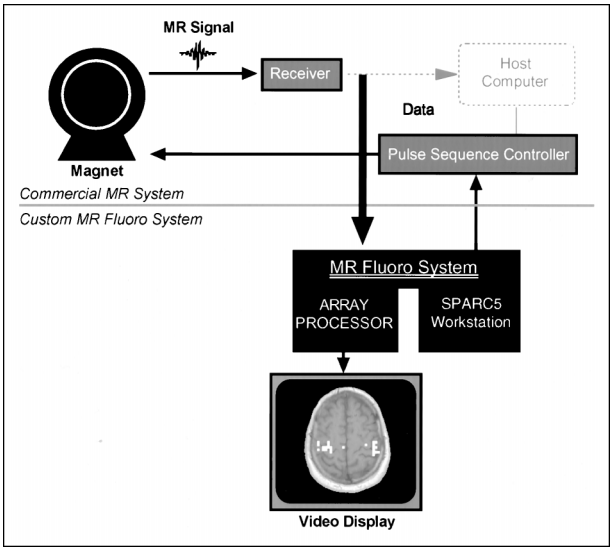

FIG 1. Simplified schematic of the real-time MR fluoroscopic system. The top part of the schematic depicts the flow of data from the receiver coil to the host computer (*dashed arrow*) in a commercial MR system. The custom MR fluoroscopic system, represented in the bottom part of the schematic, has direct access to raw MR data. With communication links to the scanner, the fluoroscopic system is able to execute pulse-sequence control, and, with array-processing capabilities, signal and image processing can return results to the video-display in near real time.

in a file accessible by the fluoroscopic system and used later as anatomic references.

Functional MR studies were performed at the same nine 5-mm-thick, contiguous, axial sections using a gradient echo–based multisection single-shot EPI pulse sequence with an echo spacing of 720 microseconds. The acquisition matrix size was 64 × 64, the bandwidth was ±64 kHz, and the field of view (FOV) was 24 cm. The TR/TE was 1080/45, and the flip angle was 72°. The sections were acquired in interleaved scan order (odd-numbered sections followed by even-numbered sections) to minimize partial excitation of contiguous sections. For sensorimotor activation studies, visual cues that were synchronized with the pulse sequence were provided to patients to indicate correct timing of right-handed and left-handed activation tasks (sponge squeezing). The stimulus paradigm used six half-cycles (12 seconds per half-cycle) in which the right hand was stimulated for one half-cycle and the left hand was stimulated for the alternate half-cycle. Acquisition of the 648 images in a functional MR run took 81 seconds.

A flow chart illustrating the sequence and timing of events for an individual functional MR run is shown in Figure 2. For each image acquisition, the raw MR imaging data were transferred directly from the receiver coil into memory buffers in the array processor (Fig 1), whereupon conversion of integer data to real data, row flips, 2D inverse fast Fourier transforms, magnitude operations, and displays to a video monitor were accomplished within 9 milliseconds. Upon completion of the 81-second functional MR acquisition, multisection cross-correlation maps were then generated by the array processor, thresholded at $r = .50$, and displayed. This process took 35 seconds. These activation maps were generated by using a library routine that correlated the functional MR signal adjusted for baseline drift (7) on a pixel-by-pixel basis with a sine wave having the same frequency as the stimulus. Finally, composite images of the activation maps and the previously acquired T1-weighted anatomic references were made and displayed, also using the array processor. The entire process, starting with initiation of the functional MR run to completion of the presentation of the composite images, took less than 3 minutes.

Step	Process	Elapsed Time	
1	T1-weighted sagittal scout scan		
2	T1-weighted axial imaging scan (for anatomic references)		
3	Preparation for fMRI scans		
4	**FMRI data acquisition and real-time image reconstruction**	1:21	FMRI Run
5	**Cross-correlation of image time-series with sinusoid**	0:35	
6	**Formation and display of composite fMRI activation and T1-weighted images (assessment by radiologist)**	0:45	<3:00

FIG 2. Interactive loop. Steps 1 through 6 describe the sequence of events during a functional MR imaging examination. A functional MR run is defined by steps 4 through 6, which may be repeated and interactively tailored several times during the course of an examination.

Results

We performed functional MR examinations in 18 patients with this real-time system. In each examination, at least one and usually several of the individual functional MR runs were corrupted owing to global head motion, rendering the results (activation maps) unusable. We initially used cine-display loops to identify interimage global head motion in a time series, but the ultimate effect of a particular motion on the final activation map, based on viewing such loops, was generally unpredictable. Therefore, a more reliable method to determine whether any given functional MR time series had produced an interpretable result was to actually inspect the final activation map. The activation stimulus paradigm was modified one or more times in six (30%) of the 18 patient examinations based on the near real time results provided by the MR fluoroscopic system. These modifications included changing the stimulus from sponge squeezing to finger tapping; discontinuing active participatory tasks because of motion artifacts; altering brushing intensity, location, and frequency for passive sensory stimuli; and changing stimuli to activate different portions of the somatosensory homunculus (Fig 3).

Discussion

The tolerance of even the most cooperative patients for a functional MR study is limited to 30 to 60 minutes. A clinical functional MR examination must therefore be approached with the objective of obtaining the maximum amount of information within a 30- to 60-minute time frame. This often entails compromise and requires that the radiologist who will interpret the study exercise his or her judgment while the examination is in progress. For example, active sensorimotor tasks typically produce a more robust functional MR response, but are also more often corrupted by motion artifacts than are passive sensory stimuli. With real-time functional MR imaging, the type of stimulus may be chosen on the basis of a review of the results as the examination progresses.

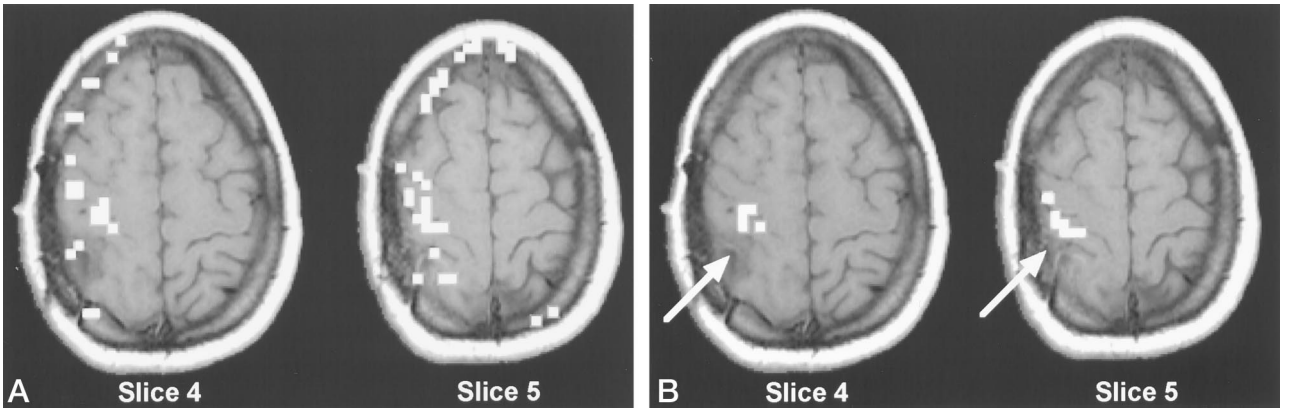

FIG 3. Interactive tailoring of a functional MR examination using real-time processing capabilities. In this example, a patient with an astrocytoma (*arrow*) performs a sponge-squeezing activation task. Results from two sections from separate 3-minute runs are shown.
A, The activation maps were corrupted by head motion, making the results uninterpretable.
B, The patient was then given additional instructions and the functional MR run was repeated, resulting in a clinically useful functional MR run. The functional hand area lies anterior to the tumor (*arrow*).

Ideally, the entire homunculus would be mapped; however, in patients with limited tolerance, the examination may be limited to a particular portion of the homunculus if this is the best option in the opinion of the radiologist monitoring the examination.

Real-time MR image reconstruction was demonstrated a number of years ago (8), and the use of specific recursive algorithms has also been implemented to reduce processing times in functional MR imaging (9). The initial real-time functional MR work reported by Cox et al (9) appears to have been done using single-section acquisition and could not accommodate an interimage acquisition time of less than 500 milliseconds because of the time required to perform one iteration of the recursive data processing algorithm after each new image. In the current work, we were able to achieve reconstruction times that can keep up with multisection single-shot EPI acquisitions (approximately 100 milliseconds' interimage time) and to perform more general-purpose functional MR processing in a timely manner using onboard processing capability. Specifically, cross-correlational results are generated within approximately 1 minute after completion of the acquisition. We acknowledge that a number of the steps of the functional MR examination described here may be specific to our own preferences and thus not necessarily applicable to the needs of others. However, it is important to recognize that the hardware used here for functional MR image reconstruction and formation can be readily adapted to individual preferences. Several technical specifications are necessary for any high-speed reconstruction system that is to be used for functional MR imaging in the general manner presented here. First, it should have the ability to accept data at high EPI-like rates, with flexible data formatting capability; for this work, the 40 MB/s capability of the input port of the array processor could readily handle the actual 125 kB/s rate of the pulse sequence. Second, it should permit high-speed reconstruction, typically at a speed that at least matches that of the data acquisition; here, nine 64×64 images per second. Third, the system should have adequate high-speed memory to store the reconstructed images for an entire run for each of the imaged sections; in this study, the 64 MB of the array processor could handle the 72 images for nine sections, or a total of 648 images. Finally, the system should be programmable to support processes beyond simple image reconstruction; for the present work, this included image subtraction, correlation of image series with a sinusoid, and formation of composite functional MR image/T1-weighted image overlays.

As mentioned, we have used the high-speed processing capabilities of the fluoroscopic system for image reconstruction, image subtraction, cross-correlation analysis, thresholding, and display. However, other operations that are useful in functional MR imaging could be performed with this system. These include image-processing steps not only for correcting artifacts, such as those due to EPI (X. Hong, M. Cohen, P. Roemer, "Functional EPI with Real Time Imaging Processing," presented at the 5th meeting of the International Society of Magnetic Resonance in Medicine, Vancouver, April 1997), physiological motion, global head motion, and B_o inhomogeneity, but also for producing other types of statistical parametric activation maps (X. Hong et al, ISMRM meeting, 1997), all of which are typically performed off-line retrospectively.

In addition to the image reconstruction and correlation processes presented, another feature of the fluoroscopic system that may prove useful in functional MR imaging is the real-time interactive pulse-sequence control capability. We have exploited this capability for real-time pulse-sequence modification to prospectively correct global interimage head motion in functional MR imaging (10, 11). We have also used real-time sequence processing to achieve a first-order correction of FOV/2 ghosts. In this latter application, non–phase-encoded data are acquired dynamically and the starting time of the data acquisition is changed interactively with microsecond resolution

to eliminate row-to-row phase offsets produced by the rapidly switching gradients.

Summary

We have described an application of instrumentation to functional MR imaging that permits rapid image reconstruction and formation of composite functional MR images/T1 activation maps. Including the 81-second data acquisition, the time needed to complete a functional MR run is under 3 minutes. We expect that such rapid processing will facilitate the more widespread use of functional MR imaging for clinical purposes.

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