Brain Circuit Analysis with Real-Time Optogenetic Functional Magnetic Resonance Imaging (rt-ofMRI)

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INTRODUCTION

Optogenetic functional magnetic resonance imaging (ofMRI) is a novel technology, which enables systematic analysis of brain circuits by using optogenetic stimulation as input, and fMRI readout as output [1-4]. Real-time ofMRI (rt-ofMRI) aims to provide real-time brain circuit analysis capabilities using ofMRI. Our goal is to acquire, reconstruct, motion correct, and analyze ofMRI images in real-time. Development of rt-ofMRI marks an essential stage in bringing ofMRI studies to its full potential. It will enable high-throughput ofMRI studies with live activation feedback on image quality, motion characteristics, and optogenetic stimulation response. It saves researchers from long offline processing and facilitates interactive experiment parameter selection (e.g. stimulation frequency, isoflurane level, etc.).

METHODS

There are two main components in our rt-ofMRI system: a 7T Bruker small animal MRI scanner and a real-time workstation. We designed two spiral readout sequences for the real-time scanning: a 4-interleaf 750 ms TR gradient recalled echo (GRE) sequence and a 10-interleaf 9.375 ms TR passband balanced steady state precession (bSSFP) sequence [5, 6]. Both sequences are able to update a 128x128x23 GRE BOLD or a 128x128x32 bSSFP image in 3 s. During scanning, acquired data are sent interleaf by interleaf through the ethernet for real-time processing (Fig. 1). There are three streamlined CPU threads working on the real-time workstation: Thread 1 receives and pre-processes the spiral data; Thread 2 controls the GPU and performs real-time reconstruction, motion correction and analysis through massively parallel computation algorithms; Thread 3 interacts with the user and displays real-time ofMRI images. All rt-ofMRI algorithms are designed and optimized to fully utilize the GPU's computation architecture. Parallelization and efficiency is maximized. Built-in hardware features including data caching, linear interpolation are also employed to speed up the overall process. Because the processing speed of our rt-ofMRI system is much faster than the supported sampling speed, we reconstruct images with partial updates from the scanner. With this partial reconstruction, we are able to capture faster temporal dynamics of the BOLD response (Fig. 2b).

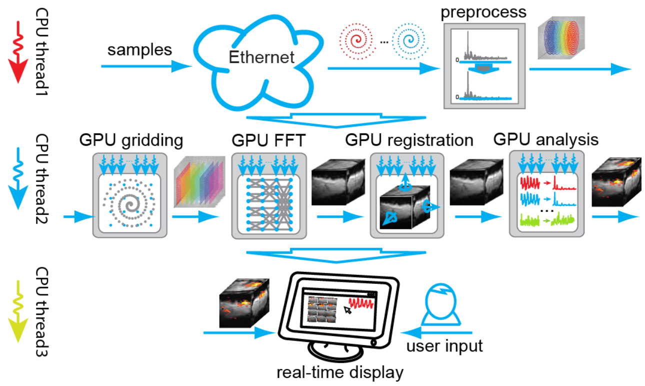

Figure 1 Parallel rt-ofMRI system structure. One of the main features of this rt-ofMRI system is the massively parallel processing in CPU thread 2. When sample is ready, thousands of GPU threads are allocated to grid, motion correct and analyze the ofMRI images.

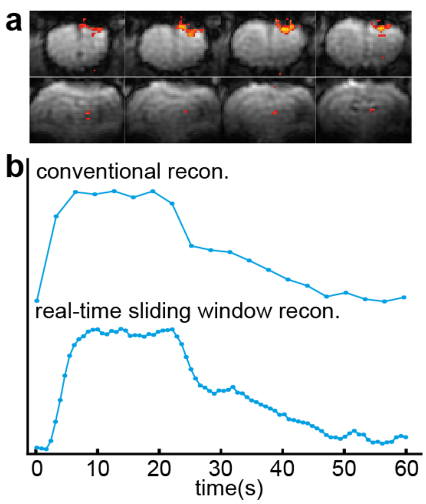

Figure 2 a. Real-time reconstructed ofMRI images showing the whole brain activity. b. Partial reconstruction time-series vs. regular reconstruction time-series. The partially reconstructed time-series keeps more details of the original scan.

RESULTS AND DISCUSSION

We first measured the speed performances of our rt-ofMRI system (Table 1). The overall speed of our rt-ofMRI system is able to reach 137 frames/s for the GRE-BOLD sequence and 126 frames/s for the passband bSSFP sequence with motion correction disabled. When the motion correction is enabled, the system is still able to process 23 GRE BOLD images and 14 passband bSSFP images in one second.

Figure 2a shows an example of the real-time display of our rt-ofMRI system. The subject's pyramidal neurons in the motor cortex is optically stimulated. With the high-speed capability, our system is able to reconstruct, motion correct, analyze, and display incoming data after acquisition of every interleaf. Figure 2b illustrates the advantage of high-temporal resolution real-time reconstruction. Details of the temporal dynamics is well captured at a high frame rate.

We also compared the robustness of our real-time motion correction algorithm with other real-time motion correction packages such as AFNI [7],offline packages such as FSL [8] and SPM [9]. With our massive parallelization approach, the comparison shows that our algorithm is both more robust and faster than other algorithms.

REFERENCES

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	GRE (ms)	bSSFP (ms)
Recon.	7.28	7.89
LSE M.C.	30.60	54.62
Analysis	0.035 /f	0.05 /f
Overall (-M.C.)	7.32 ms,137 f/s	7.94 ms, 126 f/s
Overall (+M.C.)	37.92 ms, 26 f/s	62.56 ms, 16 f/s

Table 1 Speed performance of the rt-ofMRI system. M.C. represents Motion Correction. +M.C. represents Motion Correction Enabled. -M.C. represents Motion Correction Disabled.

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