ORIGINAL ARTICLE

Custom-designed On-line Functional MRI Analysis

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On-line image reconstruction, image realignment for motion correction, and statistical functional analyses are required during functional MRI (fMRI) acquisition for real-time processing. An on-line processing system provides the feedback system to investigators and on-line quality control of fMRI. By adapting the program, Analysis of Functional NeuroImage (AFNI, Medical College of Wisconsin, WI, USA), custom-designed image processing demonstrated on-line evaluation of motion displacement and functional analyses of 6 normal volunteers and a patient with meningioma by applying the paradigm of a motor task.

With on-line processing during standard data acquisition at an Octane workstation, processing time was about 40 seconds after completion of image acquisition. On-line functional processing illustrates the potential applications in clinical functional studies and on-line feedback for fMRI experimental design. Easy implementation of the processing configuration can be realized in the standard clinical environment at no additional cost.

***Key words:* On-line processing; Motion correction; Pre-surgical planning; Functional MRI; Real-time MRI**

A functional MRI (fMRI) method has been verified to non-invasively identify critical cortical areas for pre-surgical mapping or engaged cortical regions for neuro-psychiatric tasks. Optimization of fMRI studies has been concerned with time efficiency and quality control. Quality control of fMRI includes (a) stability of the MR scanner (especially for echo planar image sequences), (b) physiological stability and performance of subjects, (c) motion detection or correction within 1 session of functional study, (d) motion detection or correction between functional studies, and (e) motion correction or realignment between studies of the same subject in a longitudinal approach [1, 2]. For time efficiency, real-time feedback to investigators or a MR control system is necessary for (b), (c), and (d).

For an ideal arrangement of real-time fMRI (rt-fMRI), the following requirements should be considered [3-5]: (a) monitoring the response of subjects to functional tasks, (b) recording and monitoring multiple physiological parameters (e.g., heart rate, respiration rate, end-tidal CO2, etc.) during the tasks, (c) real-time reconstruction of MR data sets and data transfer to the processing unit, (d) monitoring subject motion (e.g., translation and rotation of the head) during or between studies, (e) evaluating functional analyses for confirming the efficiency of statistics or the functional paradigm, and (f) calculating

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parameters of fMRI measurements (e.g., slice location) to correct for motion within a fixed time interval (real-time scale). Various temporal scalings for real-time measurements are defined and results and maps are displayed with fixed time intervals after the end of each run (in minutes) or after completing each image acquisition (in seconds for entire brain study), respectively [3, 8]. To our knowledge, at several sites worldwide, rt-fMRI has been developed to increase the efficiency of fMRI experiments by applying specific hardware designs for data pipeline and parallel processing [4-8]. Present fMRI research applies post-processing for motion correction with the introduction of averaging and blurring effects. Furthermore, most studies do not match the rt-fMRI requirement as mentioned previously, and many related factors (e.g., head motion, physiological change, etc.) may interfere with the final functional analyses.

In this study, we designed and implemented custom-designed on-line processing of motion-detection, motion-correction, and preliminary functional analyses in a temporal resolution of mostly 2~3 minutes. By adapting AFNI software from the public domain, the custom arrangement can be made compatible with any clinical environment at no additional cost.

MATERIALS AND METHODS

Subjects and Image Acquisition

All studies of on-line functional mapping of motor activation paradigms were performed on 6 normal subjects (M/F, 4/2; mean age, 22 years) and a patient (M, 42 years old) with a meningioma, surgically proven, in the left high parietal region. All subjects gave written informed consent in accordance with the IRB Internal review board of Taipei-VGH under regulation of the Bureau of Health for human trials. Subjects were required to perform motor responses (e.g., repetitive bilateral finger tapping) when a sensory cue was delivered in a block-design paradigm. Images were acquired with a Bruker 3T MEDSPEC S300 MR system equipped with a bird-cage quadrature coil. Images were stored on the host computer (SGI, R5000; memory, 128 MB). Imaging processing was performed using on-line SGI computers (O2 R5000; RAM, 128 MB, using IRIX.6.3, or Octane R10000; RAM, 256 MB, using IRIX.6.3) by routing data through the NFS from the host computer (100 MB by an Ethernet connection). Standard functional MR study was obtained with a BLIP echo-planar image (EPI) sequence using the following parameters: matrix, 64 x 64; slice thickness/gap, 5/1 mm; slice number, 20; flip angle, 90˚; echo time (TE), 50 milliseconds; repetition time (TR), 2 seconds; repetition number (NR), 80; and number of dummy scans, 5. The rate of data generation was about 82 kbyte/sec, well within the capacity of the present network links. The head of each subject was held using a vacuum cushion during data acquisition.

Table 1. Performance of on-line functional analyses

Analytical procedure	CPU time at O2 (s, mean ± 1 SD)	CPU time at Octane (s, mean ± 1 SD)
Reconstruction with phase correction	101 ± 18	59 ± 12
Format transformation	20 ± 4	10 ± 1
Realignment* (Fourier interpolation)	48 ± 8	15 ± 3
Realignment* (heptic interpolation)	34 ± 4	9 ± 1
Realignment* (quintic interpolation)	30 ± 3	8 ± 1
Realignment* (cubic interpolation)	27 ± 3	7 ± 1
Functional analyses	17 ± 3	12 ± 6
Total time (using Fourier interpolation)	186 ± 32#	88 ± 22#

* Image realignment applied 1 algorithm during functional analyses.

\# Significantly different, *n* = 6 (normal subject) for each group.

Functional Analyses

On-line image reconstruction with phase correction was performed using Bruker software (ParaVision). On-line image realignment using various algorithms (Fourier interpolation, heptic interpolation, quintic interpolation, or cubic interpolation) and functional analyses using the algorithm of cross-correlation were obtained using the Analysis of Functional NeuroImage (AFNI, Medical College Wisconsin, Milwaukee, WI, USA). Additional format transformation was needed for AFNI processing, and a prior known template of block-designed ideal response was fixed for analysis by cross-correlation before the functional study. Automation within ParaVision GUI was conducted with output of motion parameters (3 translations and 3 angulations) and functional maps. The macro program code is provided in an appendix.

With off-line processing, data from patients were analyzed with Statistical Parametric Mapping (SPM99, Welcome Department of Cognitive Neurology, London, UK) implemented in MATLAB (Mathworks, Sherborn, MA, USA). Scans of each subject were realigned with each other to correct for interscan movement artifacts. The functional images were coregistered on the anatomical data sets after manually defining the anterior commissure reference point and then smoothed with a Gaussian spatial kernel of 4-mm FWHM (full-width half-volume). Statistical analysis was tested with a *t*-value (SPM {*t*}) at each voxel using a box-car reference waveform. Each SPM {*t*} was transformed to a unit normal distribution to give the SPM {Z} statistic. Regional activations significant at $P < 0.01$, uncorrected for multiple comparisons ($Z > 2.33$, in standard normal distribution) and cluster size > 0 voxels, were considered.

Performance Testing

For the 6 normal subjects, the efficiency of the on-line processing was measured by timing central processing unit (CPU) execution of individual data analyses, including image reconstruction, format transformation, image realignment with various algorithms, and functional analysis using cross-correlation. The latency measurement of individual analysis components was performed when the main console was fully loaded by fMRI data acquisition, simulating the condition of on-line processing. In the main console, no additional memory was available from Bruker instruments (e.g., ADC).

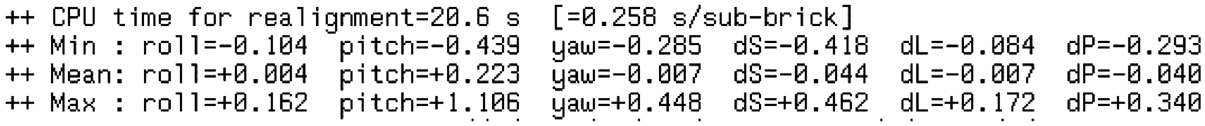
RESULTS

Performance of On-line Functional Analyses

For the EPI studies (NR, 80; number of dummy scans, 5; TR, 2 seconds; examination time, 170 seconds), on-line reconstruction with phase correction could be completed within 101 ± 18 (mean ± 1 standard deviation) and 59 ± 12 seconds using on-line processing by O2 and Octane, respectively. The functional analyses included image reconstruction with phase correction, format transformation of AFNI, motion detection and realignment, and functional analyses by cross-correlation. For processing of functional data with small motion (average translation < 2 mm, and average rotation < 2°) using Fourier interpolation, the on-line functional analyses were completed within 186 ± 32 and 88 ± 22 seconds by O2 and Octane, respectively. Realignment of small head motion required processing times of 48 ± 8 and 15 ± 3 seconds for O2 and Octane, respectively. CPU times needed for every step in the functional analyses are summarized in Table 1. Image reconstruction with phase correction was the most time-consuming step. But parallel processing of image reconstruction can be performed during image acquisition. Basically, functional results could be obtained before accomplishing the following session.

Clinical Application of On-line fMRI Processing

Functional MRI analysis of the patient who executed the motor task of bilateral finger tapping demonstrated the activation of bilateral motor-related areas. Head rotational and translational motion was evaluated by image realignment using the algorithm of Fourier interpolation (Fig. 1). The motor-related regions of the left cerebral hemisphere were lateral to the large tumor, with mild displacement by a tumor mass effect (Fig. 2). Similar pre-surgical mapping can be obtained by SPM after 8-hour data processing on a double-CPU UltraSprac workstation (Fig. 3). The functional analysis of on-line processing was completed within 40 seconds after image acquisition.



```
++ CPU time for realignment=20.6 s  [=0.258 s/sub-brick]
++ Min : roll=-0.104  pitch=-0.439  yaw=-0.285  dS=-0.418  dL=-0.084  dP=-0.293
++ Mean: roll=+0.004  pitch=+0.223  yaw=-0.007  dS=-0.044  dL=-0.007  dP=-0.040
++ Max : roll=+0.162  pitch=+1.106  yaw=+0.448  dS=+0.462  dL=+0.172  dP=+0.340
```

Figure 1. Display of on-line image realignment evaluating head rotational and translational motion by using the algorithm of Fourier interpolation. Parameters of 3-dimensional rotations (roll, pitch, and yaw in degrees) and translations (dS, dL, and dP in millimeters) can be obtained.

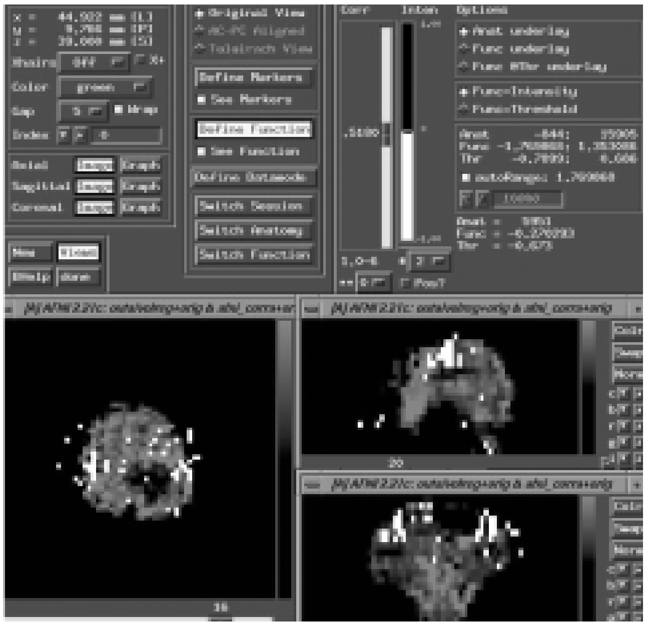


Figure 2. On-line functional analysis using AFNI demonstrating activated spatial patterns (white pixels) with correlation algorithm (Z > 0.518) after motion correction by Fourier interpolation. Image orientation follows radiological convention (right side of image is left side of subject). The subject has executed the motor task of bilateral finger tapping under a block-design paradigm, and the functional analysis was completed within 40 seconds after image acquisition.

DISCUSSION

A custom-designed data processing system provides the on-line capability for analyses of fMRI. By routing data through an NFS, parallel image reconstruction and functional processing can be performed during image acquisition. Using an Octane station, performance is optimized to obtain functional information about 40 seconds after completing image acquisition, and 6 motion parameters are utilized to examine the quality of the functional study. By verifying quality control during the study, the efficiency of the fMRI study can be improved by minimizing the number of re-examinations. However, image realignment of large motion (e.g., translation of more than 10 mm) will interfere with the regular fMRI study, because processing is time consuming (6~10 minutes, data not shown).

Optimal real-time analysis needs statistical analysis and displays results in a refreshingly faster rate than TR [8]. Also, the real-time feedback to the hardware control may enhance the efficiency and accuracy of fMRI studies with respect to activation area and motion confounding factor [4, 9]. The on-line processing design demonstrated in this study does not support (a) “true” real-time temporal resolution, (b) sophisticated motion registration, (c) complicated hardware feedback, or (d) multi-regression models [8, 9]. But useful screening and surveying of fMRI studies can be obtained using on-line processing.

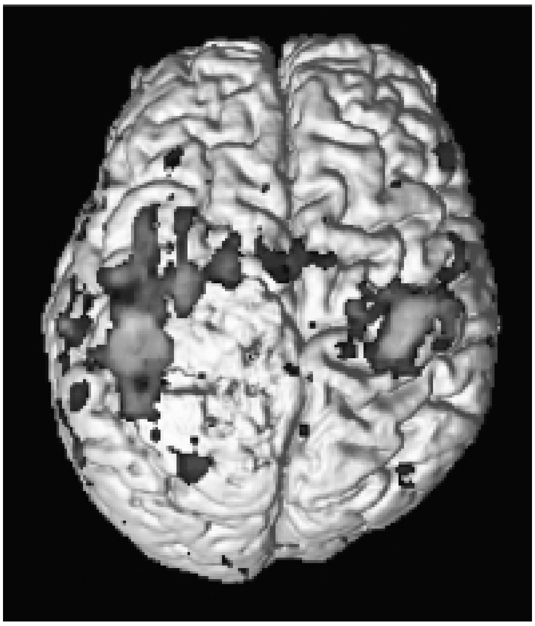


Figure 3. Off-line functional analyses using SPM demonstrating activated spatial patterns (gray) with P < 0.01, uncorrected for multiple comparisons (Z > 2.33, in standard normal distribution) and cluster size > 0 voxel. Image orientation is in the neuro-scientific fashion (right side of image is right side of subject).

In this study, custom-designed functional processing, compatible with any commercial configuration with proper system adaptation, was developed. With standard commercial specifications, the cost of this processing design is free. ◆

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APPENDIX

Automation was adapted to Bruker ParaVision software and database run on a UNIX operating system. Individual modifications were needed for custom applications. The main shell macro of the automation is as follows:

```
#! /bin/sh
# image reconstruction with regridding
$MAC/1.freco
# calculation of image parameters
tr=`pvcmd -get pvScan EPI_image_rep_time`
nr=`pvcmd -get pvScan NR`
mat=`pvcmd -get pvScan IMND_matrix_eq`
sn=`pvcmd -get pvScan IMND_n_slices`
gap_t=`pvcmd -get pvScan IMND_slicepack_gap`
gap_t=`echo $gap_t | tr -d {}`
gap=`echo "scale=1; $gap_t" | bc`
ts=`expr $sn \* $nr`
tem=`expr $nr / 2`
com=`echo "scale=1; $sn/2" | bc`
cc=`echo "$com" | grep "\.5"`
  if [ $? -eq 0 ] ; then
     result=`echo " ($sn-1) /2*$gap" | bc`
  else
     result=`echo " ($sn/2-0.5) *$gap" | bc`
  fi
I=`echo "$result""I"`
S=`echo "$result""S"`
echo "I = $I"
echo "S = $S"
# format transformation from PV to AFNI
/export/afni.install/sgi10k_6.4/to3d -epan -session `$MAC/pvcurd` -prefix afni3d -time: zt $sn $nr $tr seq+z -xFOV 125R-L -yFOV 125A-P -zSLAB $I-$S 3D: 0: 0: $mat: $mat: $ts: `$MAC/pvcurd`/2dseq
# realignment and motion correction using Fourier interpolation
/export/afni.install/sgi10k_6.4/3dvolreg -verbose -Fourier -base $tem -dfile `$MAC/pvcurd`/fourier.raw `$MAC/pvcurd`/afni3d+orig
# functional analyses using a pre-defined temporal function
cp /export/afni.install/afni_template/wave.80 `$MAC/pvcurd`/
/export/afni.install/sgi10k_6.4/3dfim -ideal `$MAC/pvcurd`/wave.80 -prefix afni_corra -input `$MAC/pvcurd`/volreg+orig
# display functional image
mkdir `$MAC/pvcurd`/outa
mv `$MAC/pvcurd`/volreg+orig* `$MAC/pvcurd`/outa/
mv `$MAC/pvcurd`/afni_corr* `$MAC/pvcurd`/outa
/export/afni.install/sgi10k_6.4/afni `$MAC/pvcurd`/outa
```

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自裝式線上功能磁振造影分析系統

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即時性功能磁振造影需要線上的影像重組、運動位移修正的影像重新排列及統計功能分析，線上處理系統可提供研究者即時的回饋及功能性磁振造影的品管控制；藉助AFNI（Analysis of Functional NeuroImage, Medical College of Wiscosin, WI, USA）影像軟體，研發自裝式線上功能磁振造影分析系統，藉手部運動工作，於六位正常自願受試者及一位硬腦膜瘤病患測試其檢查中的運動位移及功能分析。

於一般功能性磁振造影檢查下，使用Octane工作站可於40秒內獲得線上處理結果，此線上功能磁振造影分析系統可提供臨床功能性磁振檢查的應用及檢查設計的線上回饋，同時該系統無需額外經費並可應用於標準的臨床磁振造影系統。

關鍵詞：線上處理，運動位移修正，術前計畫，功能性磁振造影，即時性磁振造影