Technical Challenges and Opportunities in Studying Brain Function with Magnetic Resonance

Richard W. Briggs, Ph.D.

Department of Radiology, Division of Neuroradiology
Department of Biomedical Engineering
University of Texas Southwestern Medical Center
Dallas, Texas
MR Methods of Assessing Brain Function

- Spectroscopy (\(^1\)H, \(^{13}\)C, \(^{31}\)P)
- Perfusion and Flow Imaging
- Sodium Imaging
- BOLD fMRI
  - Connectivity mapping
  - HRF analysis of temporal information
  - Cortical columns and layers
- Diffusion Tensor Imaging (DTI)
- Magnetic Source MRI (msMRI)
- Multi-modal imaging: fMRI-MEG, fMRI-EEG/ERP
Challenges and Problems in MR Neuroimaging

• MR Data Acquisition and Image Quality
  – Susceptibility voids and distortions
  – Motion artifacts
  – Parallel imaging
  – RF and gradient coil design

• Electromagnetic Field Modeling
  – $B_1$ for RF coil design
  – SAR modeling and heating effects
  – $B_0$ for susceptibility distortions and voids
Challenges and Problems in MR Neuroimaging (continued)

• Other Engineering Challenges
  – Stimulus presentation and response monitoring
  – Acoustic noise
  – Multimodal integration
  – Data storage, transfer, and analysis infrastructure

• Physiology and Psychology Challenges
  – Neuropsychology task design
  – Physiological modeling of neuronal and vascular systems and responses
Challenges and Problems in MR Neuroimaging (continued)

• Image and Data Analysis Challenges
  – Image segmentation and registration
  – Time series analysis and statistics (spatial and temporal autocorrelations, multiple comparisons)
  – Multiple session comparisons (subject/scanner/voxel position/task performance differences)
  – DTI tractography analysis
Magnetic Field Distortions Caused by Susceptibility Gradients

K.M. Brindle, F.F. Brown, I.D. Campbell, C. Grathwohl, P.W. Kuchel
Biochem. J. 180, 37-44 (1979)
Artifact Reduction by Susceptibility Matching

Iron Oxide Suspensions (5-7), Water (8), and Mixtures of Iron Oxide and Barium Sulfate (1-4)
EPI Susceptibility Artifacts at 3 Tesla

Top - 1.3 mm 3D anatomic (TE = 8 ms)

Bottom - 6.8 mm EPI (TE = 30 ms)
Susceptibility Void Correction with RF Pulse Phasing in Gradient Echo EPI

Gradient-echo echo-planar images

No phase compensation  With phase compensation

Composite Image
Mouse Brain GESEPI at 14T

<table>
<thead>
<tr>
<th>TE</th>
<th>Std. GRE</th>
<th>GESEPI</th>
</tr>
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<tbody>
<tr>
<td>6 ms</td>
<td></td>
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<tr>
<td>12 ms</td>
<td></td>
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<tr>
<td>20 ms</td>
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Susceptibility-induced $B_0$ Gradients in Human Head


Note largest gradients are in S-I direction, therefore ....

Minimize diffusion path length (voxel dimension) in S-I direction.

Electromagnetic Field Modeling

Finite Difference Time Domain Modeling
Simulated CP $B_1$ Coronal (xz plane) Maps in a 10-cm Aqueous Saline Sphere ($\sigma = 80$) as a Function of Larmor Frequency and Sample Conductivity

Solid: $B_{1(x)}$ ($\theta = 90^\circ$)
Dash: $B_{1(z)}$ ($\theta = 0^\circ$)

Empirical (L) and Modeled (R) Images at 4T (top) and 7T (bottom)

Numbers on images are B1 values in T

Motion Effects

Local motion, often perturbing $B_0$

Global, rigid-body motion

Second-order distortions from these $B_0$ effects

Signal changes from spin history effects, caused by through-plane rigid-body motion or local $B_0$ fluctuations

Motions (global or local) can be random or periodic (cardiac or respiratory) or correlated with stimuli or responses
Subject Comfort and Head Restraint

1. Bite bars can be effective, but:
   - don’t allow speaking
   - are uncomfortable, cause salivation & swallowing
   - can introduce motion from gradient vibrations

2. Head molds, thermoplastic masks, air bags

3. Foam or towel padding effective and comfortable

4. Pads under knees to prevent back stress, under arms

5. Sheet & blanket for warmth

6. Communication is comforting! Vision combats claustrophobia!
PACE Theoretical Performance

PACE – 2.5° Through-Plane Rotation (Nodding Motion)

PACE – 0.25° Through-Plane Rotation (Nodding Motion)

3 orthogonal ONAVs (11 msec each) start sequence, followed by gradient adjustments (black). Total implementation time is about 160 msec per TR. More accuracy can be obtained by using two successive ONAVs (320 msec).

ONAV – Simultaneous 6° Through-Plane (Sagittal, Nodding Motion) and 4° In-Plane (Axial, Shaking Motion)

ONAV-corrected fMRI

Motion-Induced Changes in $B_0$

Real-time Autoshimming Method

Phase accumulated in each of 3 orthogonal dual echo NAV measures \( B_0 \) in RO direction. NAV TR = 20 msec, so 3D shim NAV takes 60 msec.

Shim-compensated EPI Sequence

ONAV Prospective Motion Correction & Dynamic Shimming

Localized SCM Artifact Reduction

- FMRI of overt word generation tasks: Noise due to stimulus correlated motion (SCM) is a problem
- Probable causes of SCM noise
  - Misregistration and/or misinterpolation of voxels
  - Magnetic field disturbances during response
- Noise due to SCM shows up as false positive activation in high contrast boundaries
- Can mask real activation
Rationale for Nonselective Detrending

- Our method reduces SCM noise in event-related word generation paradigms.

- We use the idea that the system’s impulse response to SCM is temporally resolved from task-related hemodynamic response. (Birn et al; HBM 1999;5:106-114)
The four 150-image functional runs were concatenated to give a 600-image time-series.

Linear time-invariant system model:

\[ y(t) = s(t) \times h(t) + \mathcal{E}(t) \]

- \( y(t) \) = voxel signal
- \( s(t) \) = stimulus vector
- \( h(t) \) = impulse response function
- \( \mathcal{E}(t) \) = gaussian white noise

The estimated IRF convolved with the stimulus vector to obtain the fitted voxel time series, \( y_c(t) = s(t) \times h_c(t) \).
Estimation of Motion Impulse Response

Estimated IRF for SCM by looking at voxels on high contrast boundaries in the brain with similar activation levels as word generation areas.

Red: $F(11,578) > 9$
Yellow: $F(11,578) > 11$
Estimation of IRF of SCM

- Estimated IRF due to the SCM convolved with stimulus vector to obtain SCM time-series vector
… SCM Noise Reduction..

- Stimulus correlated motion vector components detrended from FMRI time series.

- Deconvolution analysis repeated on the detrended FMRI time series to obtain a noise-reduced activation map.
Results

Before Detrending

After Detrending

Red: $F(11,578) > 9$
Yellow: $F(11,578) > 11$
MRA

Veinous Activation
The estimated hemodynamic response due to cortical activation is not significantly affected by the detrending of the FMRI time-series vector.
Selective Detrending

• If SCM and BOLD IRFs overlap, current methods (including nonselective detrending) of removing motion artifacts also reduce BOLD signal.

• Selective detrending distinguishes subtle differences in relative amounts of SCM and BOLD contributions to voxel IRFs, and reduces TCM false positives and retains BOLD true positives when both are present.

• Performance of selective detrending compared to 3 other existing methods: motion parameter regression, ignoring initial images, nonselective detrending.
Task-Correlated Motion IRFs from 3 Slices

10-15 TCM IRFs sufficient to represent TCM signal changes for whole-brain data sets
BOLD HRF Constraints

\[ h(t) = \frac{A}{2} \left[ \tanh \left( \tan \left( \frac{\pi}{2} \left( \frac{1.6(t-t_D)}{t_R} - 0.8 \right) \right) \right] + 1 \right] \quad \text{for} \quad t_D < t \leq t_D + t_R \]

\[ h(t) = \frac{A}{2} \left[ (1+U) \tanh \left( \tan \left( \frac{\pi}{2} \left( \frac{1.6(t_F+t_R+t_D-t)}{t_F} - 0.8 \right) \right) \right] - U \right] \quad \text{for} \quad t_D + t_R < t \leq t_D + t_R + t_F \]

\[ h(t) = \frac{A}{2} \left[ (-U) \tanh \left( \tan \left( \frac{\pi}{2} \left( \frac{1.6(t_F+t_R+t_D+t_{RT}-t)}{t_{RT}} - 0.8 \right) \right) \right] \right) \right] \quad \text{for} \quad t_D + t_R + t_F < t \leq t_D + t_R + t_F + t_{RT} \]

A > 0
\[ t_D + t_R + t_F > 6 \]
\[ t_D + t_R < 11 \]
\[ t_R + t_F > 4 \]
\[ t_R > 1 \]
\[ t_F > 2 \]
\[ t_D < 4 \]
\[ \max(\text{IRF}_{1-4}) > 1.2 \min(\text{IRF}_{1-4}) \]

3-4 HRFs suffice to characterize BOLD signal changes, which have less variance than SCM IRFs
(a) Representative TCM-related IRFs
(b) Representative BOLD IRFs
Selective Detrending Method Flow Chart

All voxels significantly correlated with TCM IRFs?

Y: max \(|CC_{TCM}^k|_{b-k}\) > 0.5

Separability test: Do the voxels exhibit noticeably more correlation with TCM than BOLD IRFs?

Y: max \(|CC_{TCM}^k|_{b-k} - \max |CC_{BOLD}^k|_{b-k}\) > 0.2

- Full detrending with complete TCM vector (Case 1)

N: max \(|CC_{TCM}^k|_{b-k} - \max |CC_{BOLD}^k|_{b-k}\) < 0.2

- Partial detrending with restricted TCM vector (Case 2)

Are voxels more correlated with TCM than BOLD IRFs?

Y: max \(|CC_{TCM}^k|_{b-k} > \max |CC_{BOLD}^k|_{b-k}\)

- Partial detrending with restricted TCM vector if \(\min |ranorm_{TCM}^k|_{b-k} < 0.15\) (Case 2a)

N: max \(|CC_{TCM}^k|_{b-k} < \max |CC_{BOLD}^k|_{b-k}\)

- Partial detrending with restricted TCM vector if \(\min |ranorm_{TCM}^k|_{b-k} < 0.003\) (Case 2b)

No detrending

N: max \(|CC_{TCM}^k|_{b-k} < 0.5\)
Separability Criterion for Full Detrending

True Positives

False Positives
Activation Maps
Thresholded at $R^2 > 0.2$
(control subject 4)

(a) no noise reduction
(b) selective detrending
(c) motion parameter regression
(d) ignoring 2 images
(e) non-selective detrending
(f) BOLD (green) and TCM (red) responses
Activation Maps
Thresholded at $R^2 > 0.2$
(aphasia patient 1, post-therapy)

(a) no noise reduction

(b) selective detrending

(c) motion parameter regression

(d) ignoring 2 images

(e) non-selective detrending

(f) BOLD (green) and TCM (red) responses
(a) False Positive Reduction and (b) True Positive Retention

patient 1 (post-tx)

ML0 (blue) – no correction
ML2 (black) – minlag-2
MPR (green) – motion parameter regression
dtsel (magenta) – selective detrending
dt (red) – nonselective detrending
(a) False Positive Reduction and
(b) True Positive Retention

control subject 4

ML0 (blue) – no correction
ML2 (black) – minlag-2
MPR (green) – motion parameter regression
dtsel (magenta) – selective detrending
dt (red) – nonselective detrending
False Positive Reduction (left) and True Positive Retention (right)

patient 1 (pre-tx)): top
patient 2 (pre-tx): middle
patient 2 (post-tx): bottom

ML0 (blue) – no correction
ML2 (black) – minlag-2
MPR (green) – motion parameter regression
dtsel (magenta) – selective detrending
dt (red) – nonselective detrending
False Positive Reduction (left) and True Positive Retention (right)

control 1: top
control 2: middle
control 3: bottom

ML0 (blue) – no correction
ML2 (black) – minlag-2
MPR (green) – motion parameter regression
dtsel (magenta) – selective detrending
dt (red) – nonselective detrending
Water Diffusion

Unrestricted

Water

Restricted

Water
Corpus Callosum Diffusion Tractogram at 3T

Courtesy of Roddy McColl (UTSW). Obtained May 2004 on 3T GE short-bore with 25 diffusion directions in 9 minutes (NEX = 2), using 8-channel head coil.
Corpus Callosum Diffusion Tractogram

Courtesy of Roddy McColl (UTSW). Obtained September 2004 on 1.5T Philips Intera with 25 diffusion directions (b = 1000), NEX = 3, 3 mm slice thickness, 240 mm FOV, 128x88 matrix, TR = 6000 ms, TE = 100 ms.
Hardware and Software for Stimulus Presentation and Response Monitoring
Subject Response Devices
Vibrotactile Units for Sensory Computer

Compressed Air Source

Solenoids

Timing Circuit

Tactors

PC

D25

PC / MS

F

A

10 CHANNEL TACTOR SYSTEM

FREQUENCY

COARSE

PULSE

WIDTH

FINE
Filtering and Penetration Panel and Fiber Optics
Audio-Visual Design and Editing

- Visual - wider FOV, more comfortable, lens corrections for poor eyesight, better resolution, 3D and stereo-optic, compatible with high magnetic fields, eye tracking
- Audio – better passive acoustic shielding, active noise cancellation, dichotic presentation and control, noise-canceling microphone, compatible with high magnetic fields, digital editing of recorded waveforms (Adobe Audition)
Physiological Parameter Monitoring

- Heartbeat (ECG), EEG, respiration, O$_2$ and CO$_2$, galvanic skin response, pulse oximeter, blood gas monitoring, drug infusion
- Optical detection of motion for prospective correction
- Force transducers for motor monitoring
RF Coil Engineering – Parallel Imaging

also signal processing, ADC design, data streaming and storage …
16-ch NV Coil
PHILIPS

18 elements to 16 channels
EEG/MEG/NIR/fMRI Integration

Filtering of Electrical Artifacts and Digital Signal Processing
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