Non-Invasive Brain Imaging

- Magnetic Resonance Imaging (MRI)
  - Good spatial resolution, poor temporal resolution

- Functional MRI

- Electroencephalography (EEG)
  - Good temporal resolution, poor spatial resolution

- Magnetoencephalography (MEG)

&
Figure adapted from Cohen and Bookheimer (1994)
Bioelectric signals are spatially blurred as they pass through the csf, brain, skull, & scalp.

To understand the reason for the blurring, need to understand biophysics of EEG/MEG

Large spatial blurring at scalp
Small neural source at cortex
What are EEG and MEG Signals?

EEG measures the electric potential differences across scalp arising from current flow within the head & brain.

\[ V = IR \]

\( V = \) electric potential ("voltage") analogous to water pressure

\( I = \) electric current (analogous to rate of water flow)

\( R = \) resistance to flow of electricity (size of pipes)

\( \sigma \sim 1/R = \) conductance of flow of electricity

Figure from Halliday, Resnick, & Krane, 1992)
MEG measures the magnetic fields produced by current flow within the head & brain.

An electric current (flow of electrons) produces a magnetic field around it.

Images from Wikipedia
EEG and MEG signals arise primarily from synaptic activity

Figures from Speckman and Elger (1999)
EEG/MEG signals represent the summed activity of large populations of synchronously firing neurons.
EEG/MEG sources are well approximated as current dipoles/dipole layers

Neural dipoles => electromagnetic field changes throughout the head
=> current flow through head and scalp.

Figure adapted from Spehlman, 1981

Image Adapted from Wikipedia
Dipolar nature of neural sources implies:

1) Primarily cortical EEG & MEG signals observable at scalp

2) EEG ~ Gyrus sources
   MEG ~ Sulci sources

EEG signal spatial distortion arises from differences in head tissue electrical resistance ($R$) /conductance ($\sigma$).
High R (low sigma):
=> More collisions of electrons with tissue molecules & thus greater deviation from trajectories determined by electric fields of neural sources.

Skull & scalp have lower $\sigma$ (high R) than brain and CSF
=> most spatial blurring of electric current due to skull & scalp.

Blurring of scalp potentials is even greater.

MEG signals are less affected by conductance/resistance (signal falls off rapidly from source $\sim 1/r^2$ & magnetic fields of impressed currents are very small), & thus have better spatial resolution than EEG.

Figure from Halliday, Resnick, & Krane, 1992)
It is possible to improve the resolution of scalp EEG signals by transforming the signals into measures of electric current. (Nunez & Srinivasan, 2005)
Laplacian Current Source Density (CSD) Transform

\[
\nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial^2 x} + \frac{\partial^2 \Phi}{\partial^2 y} + \frac{\partial^2 \Phi}{\partial^2 z} = \frac{\nabla J}{\sigma} = 0
\]

Laplace’s Eq.

\[
\nabla J = 0
\]

=> no net current through spherical scalp “shell”.

\[
J \sim \text{I/m}^2
\]
\[
\frac{\partial^2 \Phi}{\partial^2 x} + \frac{\partial^2 \Phi}{\partial^2 y} + \frac{\partial^2 \Phi}{\partial^2 z} = 0
\]

**Scalp Laplacian**

\[L(x, y) = \frac{\partial^2 \Phi}{\partial^2 z} = -\left(\frac{\partial^2 \Phi}{\partial^2 x} + \frac{\partial^2 \Phi}{\partial^2 y}\right)\]

\[\sim \text{ radial electric current through scalp}\]
Model Source Distribution

Isopotential Map

Laplacian Map

Law, Nunez, and Wijesinghe, R.S. (1993)
EEG/MEG Source Reconstruction

- estimating cortical source distribution of scalp recorded electromagnetic signals

Source reconstruction principles are the same for EEG & MEG; only differ in the mathematical details.

Usually performed on ERPs in order to reduce effects of noise on source solutions.
The Inverse Problem:

Any measured scalp electromagnetic distribution may be described by an infinite number of possible source distributions.

Must use functional–anatomical criteria to constrain the number of possible source distributions.

1) 2) or 3)
Two steps to EEG/MEG Source Reconstruction:

1) Create a model of brain, skull, and scalp.

2) Use this model to solve for "best fitting" source distributions, where "best fit" determined by
   i) minimization of error btw model prediction & actual measurements.
   ii) Neuroanatomical constraints (e.g. expected regions of activation based on nature of stimulus & task).
Head (Volume Conductor) Models

Typical models in EEG & MEG: spherical, ellipsoidal

- Brain $\sigma_1$
- CSF $\sigma_2$
- Skull $\sigma_3$
- Scalp $\sigma_4$

Source Point $(R_0, \theta_0)$

Field Point $(R_4, \theta)$
Structural MRI-based models

Individual subject: Volumetric boundary element method

MRI informs creation of head model
Group Analyses:
Use MNI or Tailarach brain 3D templates

Requires spatial co-registration of EEG-fMRI coordinate systems

LORETA-KEY figures
Electrode coordinates may be default 10-20 International System
Electrode coordinates can be scanned in from actual scalp locations via fMRI scanner or through use of 3D scanning technology.
Dipole modeling (Scherg, 1989)

Assume a given brain response arises from brain electrical activity equivalent to a few EM dipoles.

Dipole position and moment is what gives best “fit” to scalp EEG/ERP data.
P100 (rv = 1.6)  N170 (rv = 2.17)
ERPs may reflect activation of more than one brain region.

*Independent Components Analysis (ICA)* decomposes signals into maximally temporally independent sub-signals.

P1 & N1 responses composed of early/late ICA components with different cortical locations.
Deblurring Method (Le and Gevin, 1993)

\[ \nabla^2 \Phi = \frac{\nabla J}{\sigma} \neq 0 \]

Poisson’s Eq.

\[ \frac{\nabla J}{\sigma} \neq 0 \]

\[ \Rightarrow \text{net current through volume defined by scalp and cortical surfaces} \]

Cortical surface expresses current distribution from active neural sources

Current flows through scalp surface, but does not leave it

Cortex
Lead Field Method – can estimate current sources in 3D space

*Forward solution*

\[ \Phi = KJ \] is scalp potential

K represents the “lead field”, i.e. the biophysical volumetric model of scalp, skull, & brain.

J is vector of current elements, with 1-3 elements (depending on the model) per “voxel”.

*Inverse Solution* is then

\[ J = T\Phi \] where \( T = f(K) \)

Inverse Problem \( \Rightarrow \) must choose \( T \) that gives the “best” solution.

Several different methods to choose \( T \).
Minimum Norm Solution
(Hämäläinen and Ilmoniemi, 1994)

Notice small degree of localization error. Could be due to poor head model and/or limitations of Min Norm algorithm.
Limitations of Minimum Norm:

Can sometimes exhibit large spatial error when localizing maxima of activations, especially with deep dipole sources.

Best source solutions obtained when recording EEG & MEG simultaneously & when temporal information taken into account (Dale & Sereno, 1993)
Dale & Sereno (1993)

Radial Dipole

EEG only

MEG only

EEG & MEG

MEG only
Tangential Dipole

Dale \& Sereno (1993)

EEG only

MEG only

EEG \& MEG

MEG only
Deep Radial Dipole

EEG & MEG with Information from other timepoints taken into account.
LORETA solutions have the lowest activity maxima localization error of “lead field” methods (Pascual-Marqui, 1994), but solutions are more spread out spatially, hence the term “Low Resolution”.

(Pascual-Marqui et al., 1994)
METHODOLOGICAL LIMITATIONS

1) Only as good as head model
2) Strong effect of data variance on the reconstruction algorithms
3) Inverse problem restrictions
4) Intrinsic neuroanatomical limitations of EEG (gyri) & MEG (sulci). Best results when using EEG & MEG simultaneously (Dale & Sereno, 1993)

In the end: ~ same order of temporal resolution
One - two orders of magnitude better spatial resolution then straight scalp topography
fMRI & EEG/MEG Source Localization

MRI technology can also play a role besides head model creation.

fMRI activations can be used to constrain dipole solutions, reduce source solution space created by inverse problem, & provide convergent evidence for a particular source solution.

Caveat: This role is limited in non-simultaneous combination of EEG & fMRI with task paradigms involving irreversible cognitive/perceptual changes.

This problem may be reduced by new technology allowing simultaneously recording of EEG & fMRI with task paradigms involving irreversible cognitive/perceptual changes.
Simultaneous method: fMRI signal is modeled and subtracted from raw EEG signal.

EX: Neuroscan MAGLINK system

Uncorrected/Corrected 64 Channel Spontaneous EEG
REFERENCES


