Introduction to Magnetoencephalography

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Biomagnetism is the study of magnetic fields produced by living organisms

- Brain activity (currents in neurons)
- Electrical activity of the heart
- Muscle activity
- Ferromagnetic and paramagnetic materials in the body (e.g., protein bound iron in liver)
- Introduction of magnetic material (lung, GI tract)
Biomagnetism

- Biomagnetic fields are generating by electrical currents according to the right-hand rule.
- In comparison to electrical currents, magnetic fields pass through many materials (e.g., skin, bone) undistorted.
Magnetoencephalography (MEG)

MEG is the measurement of magnetic fields generated by electrical currents in the brain.

These fields exit and enter the scalp surface and can be measured using highly sensitive pickup coils.

MEG fields at the scalp surface have strength and direction (right-hand rule).
MEG Technology – early development


MEG Instrumentation – Signal to Noise

Biomagnetic fields are more than 1 million times smaller than the earth’s magnetic field (≈ 50 µTesla) and require high sensitivity instrumentation.

1 Tesla = $10^4$ Gauss
Modern MEG systems use Superconducting Quantum Interference Devices (SQUIDS) which are flux-to-voltage converters with sensitivity of less than 1 femtoTesla.

SQUID-based systems require low-noise RF shielded cryogenic containers (dewars) for operation at Liquid Helium temperatures of 4.2 °K (-269 °C).

- Magnetic fields from brain induce currents in pickup coils arranged as helmet shaped array.
- Environmental magnetic fields measured simultaneously for noise cancellation.
- Superconducting currents from detectors are applied inductively to SQUIDs which transform them into normal conducting currents.
Whole-head MEG systems

First whole-head systems became available in 1993

CTF (VSM/MISL) (BC Canada)

4D Neuroimaging (San Diego)

Elekta-Neuromag (Finland)
Gradient coil designs are often used to reduce pickup of environmental noise fields.

This results in two different field patterns:

- Bipolar with source below point of reversal (axial magnetometers and gradiometers)

- Monopolar with source below maximum gradient over scalp surface (planar gradiometers) -- requires two directions!
Magnetic Shielding

MEG systems are usually placed in a magnetically shielded rooms (MSR)

- Shielding factor is modest for low frequencies (-30dB)
- MSRs are expensive ($\approx$500,000 US)
Noise Reduction methods in MEG

Additional noise reduction may be needed for noisy environments (e.g., urban environments). This is typically achieved by subtracting noise measured at “reference” detectors not near the head.

There are two methods:

• adaptive noise cancellation (must re-compute weights if environment changes)

• synthetic higher order gradients (fixed weights independent of changing noise environment)
MEG Instrumentation – Sickkids 151 channel CTF System

There are two installed MEG systems at the Hospital for Sick Children
  • clinical system (installed in 2000)
  • research dedicated system (installed May, 2010)

  • 151 1st-order axial gradiometers
  • sitting or supine recording positions
  • located in 3-layer (1 layer Al, 2 layers muMetal) magnetically shielded rooms
  • synthetic 3rd-gradient noise reduction (noisy environment)
Advances in MEG Technology

CTF 151 MEG Sensor array

Blue = Coils of first-order axial gradiometers (5 cm baseline)

Gray = outer helmet surface

Yellow = cortical surface mesh from adult male subject

Mean distance to cortical surface ≈ 6.5 – 8.5 cm
Pediatric MEG systems

4 year old in Child MEG system (Kanazawa Institute of Technology, Japan)

Macquarie University, Sydney, Australia

14 month old in “Artemis123” (Tristan Technologies, San Diego)

Children’s Hospital of Philadelphia
Biophysics of the MEG signal

What generates neuromagnetic fields?
- dendritic currents due to PSPs in pyramidal cells
- organized in functional columns (≈100,000 neurons / mm²)
- summation of many neurons generates ≈ 10 - 30 nA-m
- a single neuron would not generate a measurable field

How large is the MEG signal?

Evoked responses
- typical amplitudes ≈ 100 – 400 femtoTesla
- requires averaging of 100+ responses
- smallest measurable evoked response ≈ 5 fT

Epileptic spikes
- amplitudes > 1000 femtoTesla
- single spikes visible in background MEG
Biophysics of the MEG signal

MEG versus EEG:

1. MEG is *mainly* sensitive to intracellular (impressed) currents
2. EEG is *only* sensitive to extracellular (volume) currents
3. Intracellular and extracellular generated fields cancel for radial sources in a spherical conductor

This means MEG is more sensitive to tangentially oriented currents in the folds (sulcus) of the cortex
Magnetic Source Imaging

Temporal waveforms

Spatial patterns

latency = 40 ms

MEG appears similar to EEG, but is more focal and undistorted by the overlying skull/scalp.

Better for modeling neural sources

Source Reconstruction
Magnetic Source Imaging

The Inverse Problem (Helmholtz, 1853)

To determine the current sources in the head from the externally measured potentials or fields

- Solutions are non-unique
- Solutions may be highly underdetermined (many more sources than sensors)

Solution: Construct models of the sources and fit models to data
Magnetic Source Imaging – Inverse Methods

- **Discrete source models (“Dipole fitting”)**
  - simple least-squares search for optimal dipole parameters
  - works best for single, highly focal sources
  - susceptible to error in presence of noise, alpha rhythm, etc

- **Distributed source models**
  - based on general linear inverse (e.g., “minimum-norm”)
  - no need to specify number of sources
  - solution is highly underdetermined
  - requires restricting source space and artifact-free data

- **Spatial filtering (e.g, “beamforming”) methods**
  - data-driven – stable inverse
  - suppresses artifacts in data automatically
  - performance degrades for highly synchronous sources
The predicted magnetic field pattern at the sensors is known as the \textit{forward model or lead field}

For focal brain activity the “source” is represented by a current dipole in a bounded medium.
Magnetic Source Imaging – Inverse Methods

\[ B(r) = \frac{\mu_0}{4\pi F^2} \left( Fq \times r' - \left[ (q \times r') \cdot r \right] \nabla F \right) \]

\[ \nabla F = \left( r^{-1} a^2 + a^{-1} a \cdot r + 2a + 2r \right) r - \left( a + 2r + a^{-1} a \cdot r \right) r' \]

\[ F = a \left( ra + r^2 - r' \cdot r \right) \quad a = |a| \quad r = |r| \quad \mu_0 = 4\pi \times 10^{-7} \text{Tm/A} \]
Magnetic Source Imaging – Inverse Methods

A bit of math:

Both primary (impressed) and volume currents contribute to the external magnetic fields.

However for a perfect sphere, some simplifications can be made:

1) If measuring the only the radial field component the volume currents can be ignored (they become mathematically, all radial currents) and the following formula applies:

\[ B(r) = \frac{\mu_0 q \times (r - r_o)}{4\pi |r - r_o|^3} \]

2) If not all detectors are radial we should include volume current contributions. For a sphere, these simplify to some additional scalar and vector terms (Sarvas, 1987).

\[ B(r) = \frac{\mu_0}{4\pi F^2} \left\{ F q \times r_o - \left[ (q \times r_o) \cdot r \right] \nabla F \right\} \]

\[ F = a (r a + r^2 - r_o \cdot r) \]
\[ \nabla F = \left( r^{-1} a^2 + a^{-1} a \cdot r + 2a + 2r \right) r - (a + 2r + a^{-1} a \cdot r) r \]

\( q = \text{dipole moment (A-m)} \)

\( \mu_0 = \text{permeability of free space} = 4\pi \times 10^{-7} \text{ Wb/A-m} \)

\( a = |a| \)
\( r = |r| \)
Improving the forward model:

• Since the head is not perfectly spherical, the sphere based forward models contain small errors.

• For non-spherical conductors, the actual volume currents (or their mathematical equivalent – the surface potentials on the boundaries) must be directly calculated using methods such as boundary or finite element modeling.

• These require physical models of the surfaces, and involve complex solutions and are not discussed here (see references for details).
Clinical Applications of MEG
Presurgical Functional Mapping using MEG

- Non-invasive localization of eloquent cortex
- Localization of early evoked brain responses in:
  - somatosensory cortex
  - auditory cortex
  - visual cortex
  - motor cortex
Application of MEG in Epilepsy

• Epilepsy is a disorder of the electrical activity of the brain resulting in seizures. It affects about 0.6% of the Canadian population.

• In 30% to 50% of patients, seizures may not be controlled by medication and are eligible for surgery.

• Non-lesional epilepsy refers to seizures that arise from unknown location in the brain, not associated with a physical abnormality.
Application of MEG in Epilepsy

• Interictal (meaning “between seizure”) epileptic discharges (IEDs, or “interictal spikes”) can help locate the epileptogenic tissue causing seizures in non-lesional epilepsy

• Due to head movement during seizures, MEG cannot usually be used to localize ictal (seizure) activity

• MEG is generally used to localize interictal activity to guide surgical planning (e.g., placement of intracranial grids)
Application of MEG in Epilepsy

interical spiking
Applications of MEG in epilepsy

Comparison of interictal spikes in EEG and MEG

Applications of MEG in epilepsy

Modeling interictal spikes as single dipoles

Co-registration of dipole “cluster” with patient’s MRI

Data courtesy of H. Otsubo, Hospital for Sick Children
Applications of beamformers in epilepsy

Combining MEG source modeling with Neuronavigation
Other clinical applications of MEG

- Language lateralization (replacement for Wada test)
- Developmental disorders (dyslexia, autism, ADHD)
- Mild head injury
- Stroke
- Assessment of neuroplasticity following brain injury
- Development of brain-machine interface
Ongoing projects in our lab…

• Neural Correlates of Movement Disorders Resulting From Childhood Stroke (Cheyne D., deVeber, G)

• Determining the Specificity of High Definition Electrical Brain Stimulation using Simultaneous MEG (Cheyne D., Master S.)

• Combining MEG and MRI to Improve Localization of Epileptic Brain Activity (Cheyne D. Lerch J., Otsubo H., Widjaja, E. Wennberg R.)

• MEG Measures of Sensorimotor Plasticity in Hemiplegic CP during Constraint Induced Movement Therapy (Cheyne D. Fehlings D.)

• Neuroimaging of Controlled and Automatic Processes in Human Motor Control (Cheyne D. Isabella S.)

• MEG investigation of the role of anticipation for speech onset in adults who stutter (De Nil L, Kroll, R. Cheyne D.)

• Somatosensory and motor mapping in patients undergoing peripheral nerve reconstruction (Borschel G., Zuker R., Donner, E. Cheyne D.)

We are looking for adult volunteers subjects!
Reviews articles on MEG


http://cheynelab.utoronto.ca/htdocs/MEG_Chapter-Cheyne&Papanicolaou.pdf