Biomagnetism
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Magnetism in Medicine: A bad beginning
Some current “applications” of magnetism:

Franz Mesmer (1734-1815)
• “discoverer” of “animal magnetism”

Current Medical Applications of Magnetism
Magnetic resonance imaging (MRI)
Transcranial magnetic stimulation (TMS)
Magnetoencephalography (MEG)

Nerve and muscle cells act like tiny batteries that drive ionic currents:
• current dipole, Q (current source)
• volume current, JV

Ionic currents produce electric and magnetic signals:
• electrocardiogram (ECG) and magnetocardiogram (MCG)
• electroencephalogram (EEG) and magnetoencephalogram (MEG)
**MEG provides improved source localization

Origin of Surface Electric vs. Magnetic Signals
Extracellular current (volume current) \(\rightarrow\) surface electric potentials
• topography is distorted by inhomogenous conductivity
Intracellular current (primary current) \(\rightarrow\) surface magnetic fields
• topography of magnetic signals is distorted much less, allowing accurate source localization

Neuromagnetism
• Focal activity produces dipolar spatial pattern
• Source lies below phase inversion

• Dendritic activity gives rise to EEG/MEG
• Neurons organized in columnar arrangement
• Need >1000 neurons to get detectable signal
• geofield
• typical urban magnetic noise
• magnetic field of magnetic contaminants in lung
• magnetocardiogram
• fetal magnetocardiogram
• spontaneous magnetoencephalogram
• evoked magnetic brain responses

**Instrumentation Requirements**

1. extremely sensitivity detector: SQUID
   (superconducting quantum interference device)
2. noise rejection: magnetically shielded room
   (high-magnetic permeability alloy, aluminum)

**Whole-head system**
- 148 channels

**Dual-system system**
- 74 channels

**SQUID (Superconducting Quantum Interference Device)**

- Superconducting loop interrupted by two “weak-links” (Josephson tunnel junctions)
- Current-voltage characteristic
  - current at zero voltage (supercurrent, Ic)

**Modulation of I-V Characteristic by Magnetic Signal**

- supercurrent show interference pattern

**Ehrenberg-Siday-Aharonov-Bohm Effect**

1. particle beam divides
2. paths enclose region of flux
3. vector potential, A, alters phase
   \( B = \nabla \times A \)

4. phase advances
5. phase retards
Current-Biased SQUID: Periodic $V \text{ vs. } \Phi$

Magnetic source imaging (MSI) = MEG + MRI

Inverse Problem

Statement of problem: To compute the distribution of brain currents based on measurement of external magnetic field

**Has no unique solution**

Modeling Assumptions

- **Dipole approximation**: signal due to collection of current dipoles—localized current elements—that lie on convoluted cortical surface
- **Homogeneous sphere model**: model head as homogenous conducting sphere

Functional brain imaging techniques

<table>
<thead>
<tr>
<th>Modality</th>
<th>Spatial Resolution</th>
<th>Temporal Resolution</th>
<th>Brain Region</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. positron emission tomography (PET)</td>
<td>1 cm</td>
<td>minutes</td>
<td>whole brain</td>
<td>$3M</td>
</tr>
<tr>
<td>2. functional magnetic resonance imaging (fMRI)</td>
<td>1 cm</td>
<td>seconds</td>
<td>whole brain</td>
<td>$3M</td>
</tr>
<tr>
<td>3. electric source imaging</td>
<td>&gt;1 cm</td>
<td>msec</td>
<td>cortex</td>
<td>$100k</td>
</tr>
<tr>
<td>4. magnetic source imaging (MEG + MRI)</td>
<td>1 cm</td>
<td>msec</td>
<td>cortex</td>
<td>$2M</td>
</tr>
</tbody>
</table>

MSI: records cortical activity directly and with high temporal resolution, but suffers from an ill-posed inverse problem
Clinical applications

• presurgical functional mapping
  – somatosensory, auditory
  – language
• epilepsy
  – localization of epileptogenic foci
  – most useful for neocortical epilepsy

approved for clinical use in 2002

Magnetic Localization of Somatosensory Cortex

sites of mechanical stimulation
sites of cortical response


Presurgical mapping of central sulcus

Central sulcus, containing somatosensory cortex, was at A, not B, allowing surgical resection of tumor


Language Mapping: Response to Visually Presented Words

Sensory and language responses are temporally distinct
Validated via intraoperative mapping

Simos et al., J Clin Exp Neuropsych 1998; 5:706

Language Lateralization

\[ LI = \frac{NL - NR}{NL + NR} \]

Magnetoencephalographic mapping of the language-specific cortex.


Picture Naming

Application of MEG to Epilepsy

- Incidence of about 1%
- 10-20% of epilepsy is intractable to drug therapy

Presurgical evaluation
- Focal or generalized?
- Number and relative timing of foci (primary vs. secondary focus)
- Location with respect to eloquent cortex

Transmission of electric and magnetic fetal signals

- primary currents → fMCG, fMEG
- volume currents → fECG, fEEG

• fECG is attenuated strongly by the poor conductivity of vernix caseosa
• fMCG is affected much less

Fetal Magnetocardiography (fMCG)
Fetal Heart Rate (FHR) Monitoring

- Primary clinical method
- Specific for hypoxia

Reassuring FHR patterns
- Reactivity: FHR accelerations associated with movement
- Normal FHR variability

Ominous FHR patterns
- Decelerations that are late or variable with respect to uterine contractions
- Absent variability

Assessing fetal activity from the fMCG: fMCG Actocardiography

- Two pumps: left (systemic), right (pulmonary)
- Four chambers: 2 atria, 2 ventricles

The Heart

- Valves at inlet and outlet of ventricles
**Unique Electrical Properties of Cardiac Tissue**

1. Rhythmic self-excitation
   - Pacemaker tissue

2. Long refractory period
   - 250 ms (vs. 2 ms for neurons)

3. Continuous conducting surface
   - Myocardial syncytium

**Mechanisms of Arrhythmia**

1. Abnormal impulse formation
   - Ectopy
   - Altered automaticity

2. Abnormal impulse conduction
   - Accessory connection
   - Conduction block
   - Reentry

**Ventricular Fibrillation (V-fib)**

- Chaotic, ineffective beating (heart quivers)
- Most common immediate cause of sudden death
- Due to abnormal automaticity and/or “reentry” (impulse propagates through same tissue more than once)

**Fetal Arrhythmia**

- ~1-2% incidence, but most are benign
- ~10% of these are serious, sustained arrhythmias

**Drug Therapy for Fetal Arrhythmia**

- Aggressive drug therapy is used often
- Adverse side effects: toxic, proarrhythmic

**Echo/Doppler Ultrasound**

- Accurate diagnosis and follow-up are critical, especially when drug therapy is used

**Rationale for fMCG:**

- MCG/ECG is gold standard for rhythm assessment
- Ultrasound is less precise and indirect for rhythm assessment, but can also assess heart function and blood flow
Long QT Syndrome (LQTS)

- LQTS: prolonged repolarization, undetectable with ultrasound
- Polymorphic ventricular tachycardia: torsade de pointes
- Prolonged QT interval
- 2nd-degree AV block

fMCG diagnosed LQTS and torsade due to proarrhythmic drug effect

Depolarization of Heart

- Atria and ventricles are isolated except via the AV node
- P wave: atrial depolarization
- QRS complex: ventricular depolarization
- T wave: ventricular repolarization

Atrioventricular Block

- Impulse is slowed or blocked at AV node
- Second most common serious fetal arrhythmia
- 60% maternal lupus antibodies, 40% structural disease
- Congenital complete AV block
  - SA node: pacem atria
  - AV node: pacemaker at lower rate
  - Atrial and ventricular rhythms are dissociated

Supraventricular Tachycardia (SVT)

- "Accessory" pathway (extra connection) exists between atria and ventricles
- Most common serious fetal arrhythmia

Initiation and Termination of SVT: Association with Fetal Movement

- Initiation of supraventricular tachycardia:

Heart Rate Patterns in Congenital AV Block

- High ventricular rate (>60 bpm): atrial and ventricular rates are reactive and highly correlated
- Low ventricular rate (<55 bpm): ventricular tracings become flat

Subject 2: GA= 33 wks, ventricular rate= 75 bpm
Subject 3: GA= 28 wks, ventricular rate= 52 bpm
**Tachycardia in Congenital AV Block**

Subject 3: GA= 25-47 weeks; mean ventricular rate= 71 bpm

Subject 4: GA= 34 weeks; ventricular rate= 50 bpm

- 20% show tachycardia; generally not detected by ultrasound
- predictive of need for neonatal pacing