BENG 186B: Principles of Bioinstrumentation Design

# Lecture 10

# Biopotential Sources, Recording, and Signal Processing

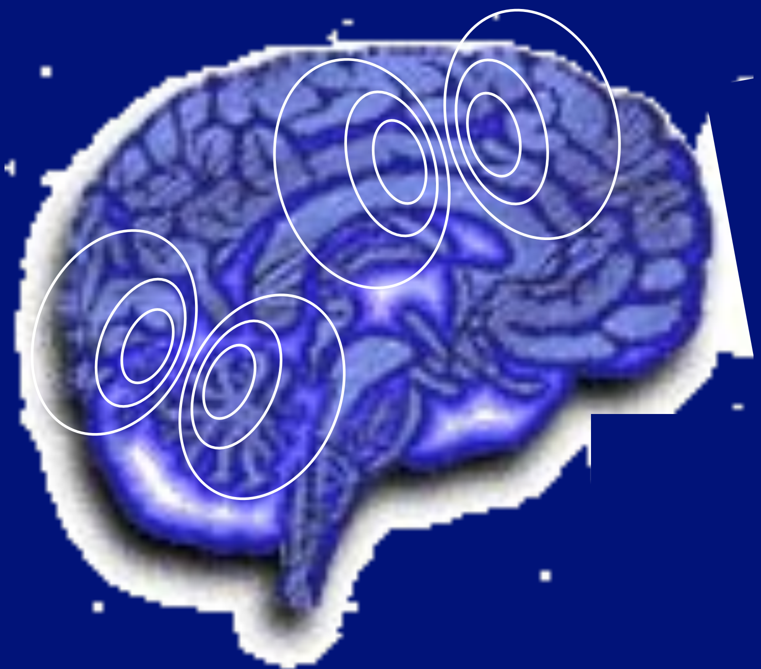
## References

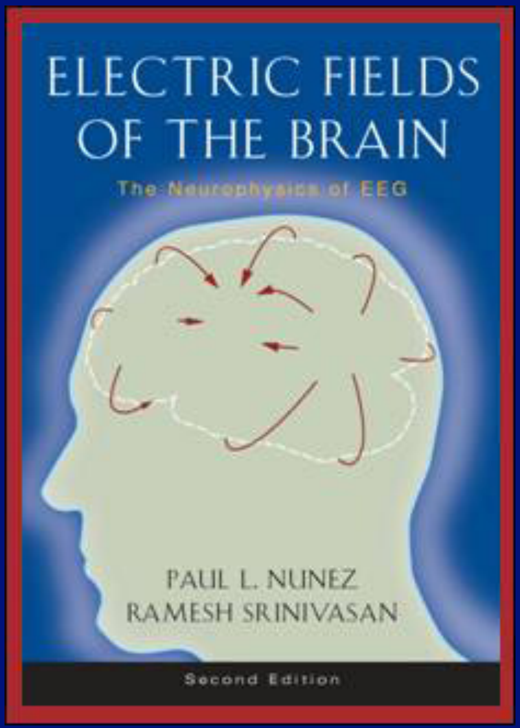
Webster, Ch. 5 (Sec. 5.6-5.11) and Ch. 4 (Sec. 4.4-4.8 Review).

Y.M. Chi, P. Ng, E. Kang, J. Kang, J. Fang, and G. Cauwenberghs, "Wireless Non-Contact Cardiac and Brain Monitoring," *Proc. ACM Wireless Health Conf. (WH 2010)*, San Diego, Oct. 4-6, 2010.

A. Delorme and S. Makeig, "EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics", *J. Neuroscience Methods*, vol. 134, pp. 9-21, 2004.

# Biopotential Sources and Signals






**Action Potentials**

**Local Fields**

**Body Surface Biopotentials**

Paul L. Nunez and Ramesh Srinivasan, *Electric Fields of the Brain—The Neurophysics of EEG*, 2nd Ed., Oxford University Press, 2006.

# Synaptic Currents and Volume Conduction

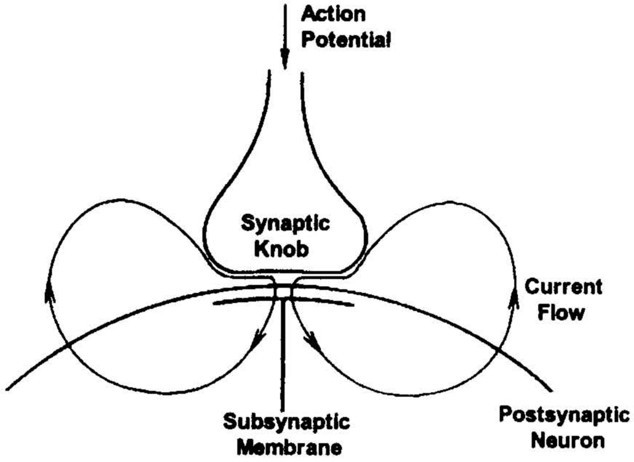



Figure 4-6 Membrane current due to local excitatory synaptic action. An action potential propagating along the presynaptic axon activates a neurotransmitter in the synaptic knob that changes local membrane conductivities to select ions, thereby producing a local current sink and more distant distributed sources to preserve current conservation.

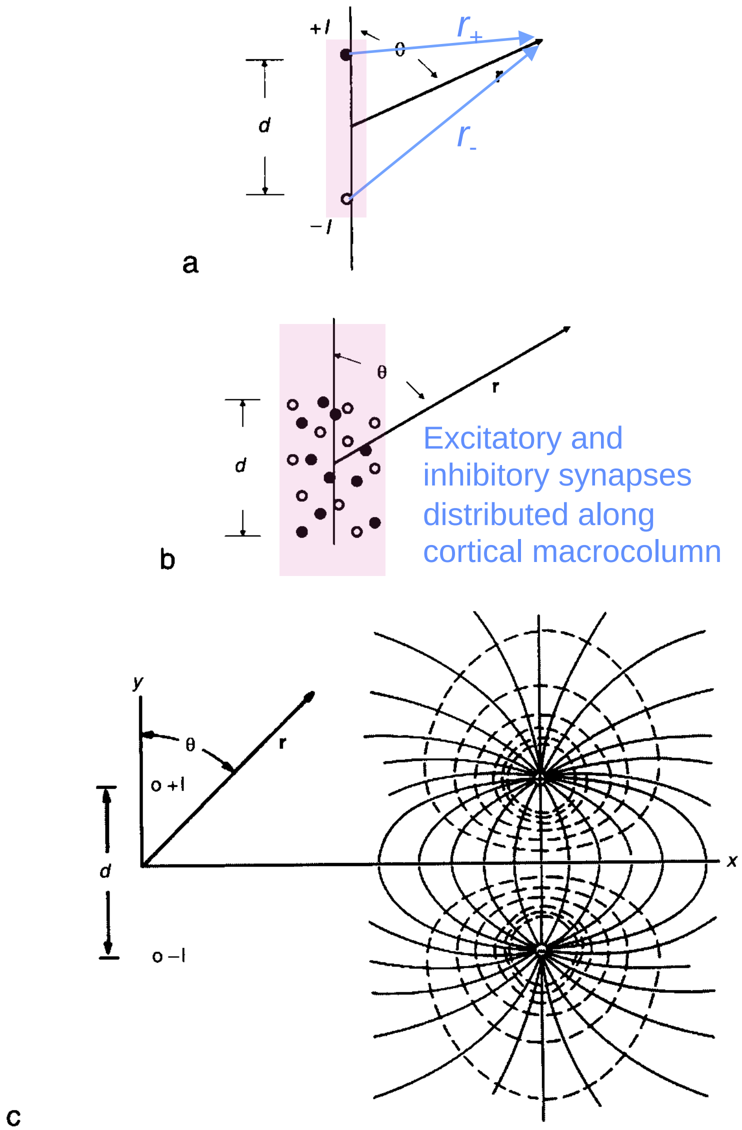
Table 4-1 Typical resistivity of several materials and tissues

| Material | Resistivity (Ω cm) |
|---|---|
| Copper | $2 \times 10^{-6}$ |
| Seawater | 20 |
| CSF | 64 |
| Blood | 150 |
| Spinal cord (longitudinal) | 180 |
| Cortex (5 kHz) | 230 |
| Cortex (5 Hz) | 350 |
| White matter (average) | 650 |
| Spinal cord (transverse) | 1200 |
| Bone (100 Hz) | 8,000–16,000 |
| Pure water | $2 \times 10^{7}$ |
| Active membrane (squid axon) | $2 \times 10^{7}$ |
| Passive membrane (squid axon) | $10^{9}$ |

– Postsynaptic currents triggered by action potentials (spikes) give rise to local field potentials (LFPs) through volume conduction in extracellular space.
  - *Excitatory* synapse: local current *sink*
  - *Inhibitory* synapse: local current *source*

Nunez and Srinivasan 2006, p. 153-154

# Current Source/Sink Dipole Electric Field




– Coherent (synchronous) activity over a distribution of synapses generates, to first order, a dipole field:

$$\Phi(\mathbf{r}) = \frac{I}{4\pi\sigma}\left(\frac{1}{r_+} - \frac{1}{r_-}\right) \cong \frac{I}{4\pi\sigma}\frac{d\cos\theta}{r^2}$$

– Dipoles align along macrocolumns, because of their polarization in the distribution of excitatory and inhibitory synapses.

– Synchronous dipoles add coherently; asynchronous dipoles add incoherently.

Figure 5-8 (a) The usual *current dipole* consisting of a point source $+I$ and a point sink $-I$, separated by a distance $d$. (b) A region of distributed sources and sinks. If local current is conserved, the potential at large distances is also dipolar, but with an effective pole separation $d_{\text{eff}}$ smaller than $d$. With perfect source–sink symmetry, $d_{\text{eff}} \to 0$ and a so-called closed field is generated, as in fig. 5-5. (c) Dipole current lines (solid) and equipotentials (dashed) are plotted. These patterns occur in the saltwater tank if the tank walls and water surface are all located far from the dipole and both recording electrodes. Boundary surfaces tend to compress current lines and increase potentials.

Nunez and Srinivasan 2006, p. 215

# Effect of Skull and Scalp: ECoG and EEG

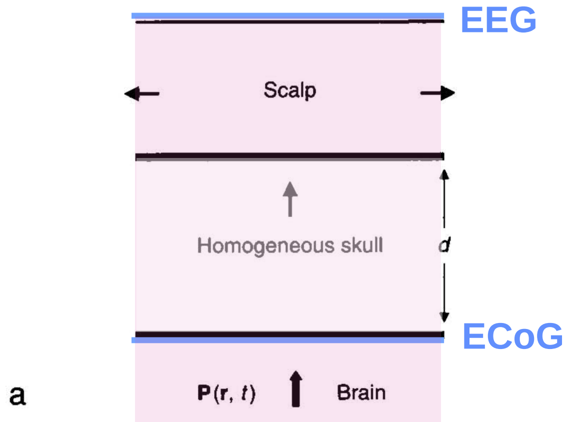
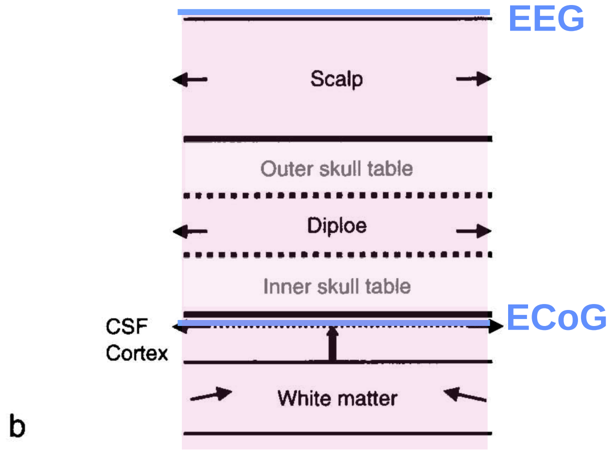



Table 4-2 Skull resistivity reported in the literature

| Skull condition | Resistivity (Ω cm) | Frequency (Hz) | Reference |
|---|---|---|---|
| Dead, dry | $10^{13}$ | | Rush and Driscoll 1969 |
| Dead, hydrated | 10,000–20,000 | 500 | Rush and Driscoll 1969 |
| Dead, hydrated | 13,000–21,000 | 100 | Law 1993 |
| Dead, suitures | 3,500–10,000 | 100 | Law 1993 |
| Dead, hydrated | 13,000–86,000 | 20 | Akhatari et al. 2000 |
| Live, 3 layers | 4,600–21,000 | 20 | Akhatari et al. 2000 |
| Live | 7,700 | 10–1000 | Oostendorp et al. 2000 |
| Dead, hydrated | 6,700 | $10–10^5$ | Oostendorp et al. 2000 |
| Live | 1,200–3,100 | 10 | Hoekema et al. 2003 |

Modified from Hoekema et al. (2003).




- **Electrocorticogram (ECoG)**
  - *Intracranial (invasive), on the cortical surface*
  - *Local features (cortical surface LFPs)*
  - *Epilepsy monitoring and mapping*
- **Electroencephalogram (EEG)**
  - *Non-invasive, on the scalp*
  - *Global features (brain waves)*
  - *Brain-computer interfaces (BCI)*

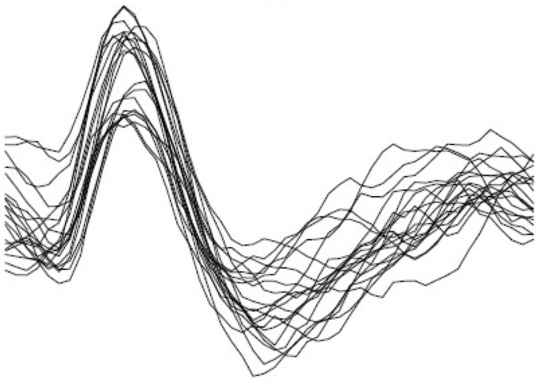
Figure 4-4 (a) A common volume conductor model of the head is the *three-sphere model*. It consists of an inner sphere (brain) and surrounded by two concentric spherical shells (skull and scalp). More complicated models may not be more accurate if tissue boundaries and (especially) tissue resistivities are not known with sufficient accuracy. (b) A more realistic geometric model consists of two additional skull layers and a layer of cerebral spinal fluid (CSF). Current shunting through the middle skull layer (diploe), CSF, and scalp is indicated by arrows. The effective skull resistivity in the *three-sphere model* (a) is larger than the actual skull resistivity in (b).

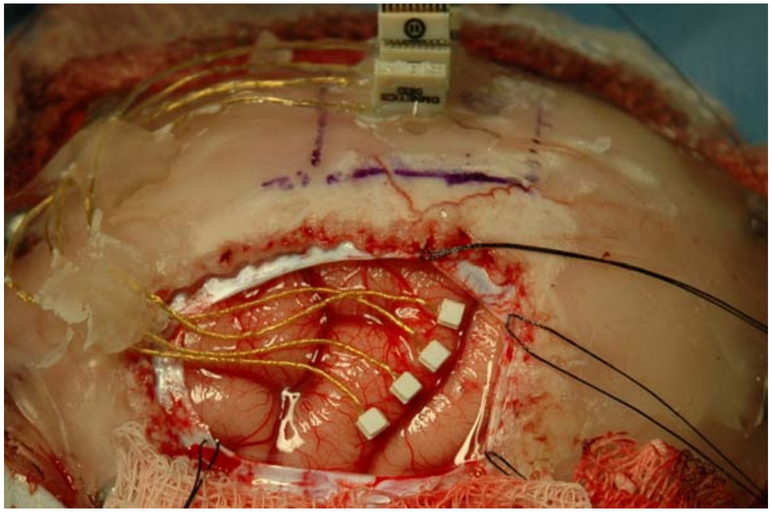
Nunez and Srinivasan 2006, p. 156-157

# Neural Signals - Spikes

**(Action Potentials)**

- Single unit firings.
- Recorded via microelectrodes placed close to the neuron cell body.
- Amplitude as high as 500 μV and frequency content up to 7 kHz.



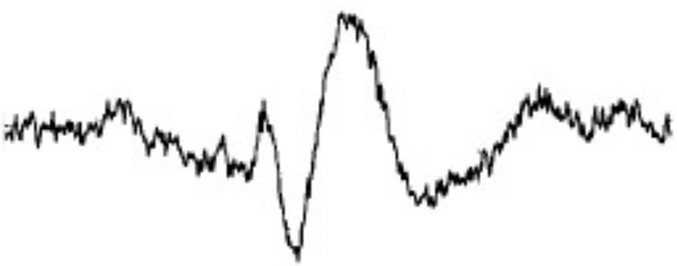


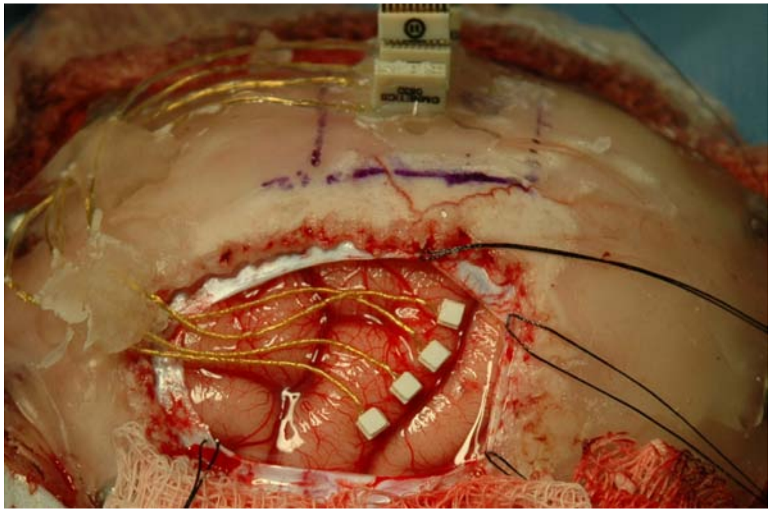
Mollazadeh et al.

# Neural Signals - LFP

**(Local Field Potentials)**

- Summation of pre- and postsynaptic activity from a population of neurons around the electrode tip.
- Recorded via microelectrodes or lower impedance electrodes.
- Amplitude as high as 1 mV and frequency content up to 200 Hz.



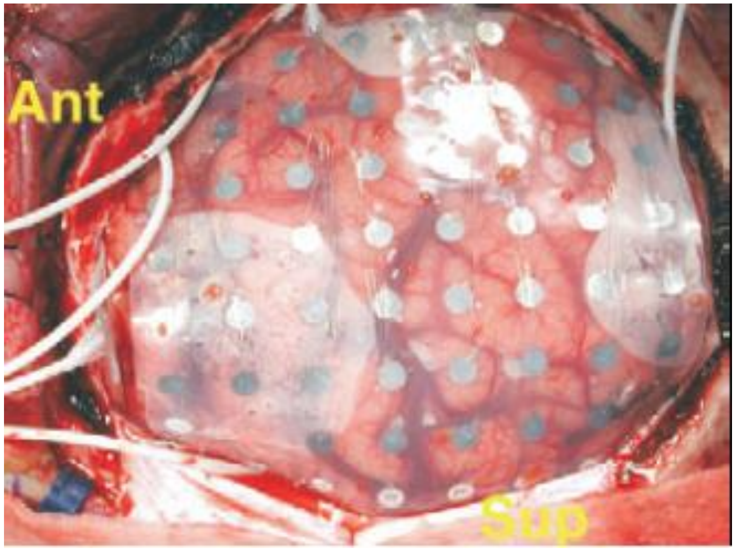


Mollazadeh et al.

# Neural Signals - ECoG

(Electro-cortico-gram)

- Electrical activity on the cortical surface resulting from volume conduction of coherent collective neural activity throughout cortex.
- Recorded via surface (disk) electrodes.
- Amplitude as high as 5 mV and frequency content up to 200 Hz.

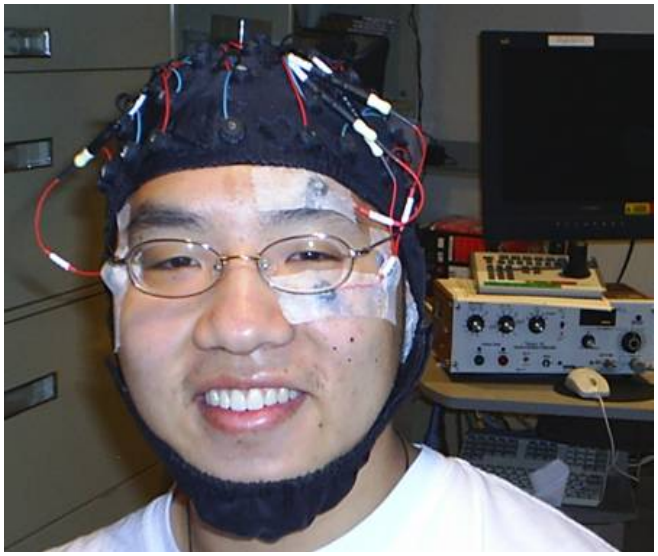



Leuthhardt et al.

# Neural Signals - EEG

(Electro-encephalo-gram)

- Electrical activity on the scalp resulting from volume conduction of coherent collective neural activity through the brain and skull, and laterally along the scalp.
- Recorded via surface (disk) electrodes.
- Amplitude as high as 300 μV and frequency content up to 100 Hz.

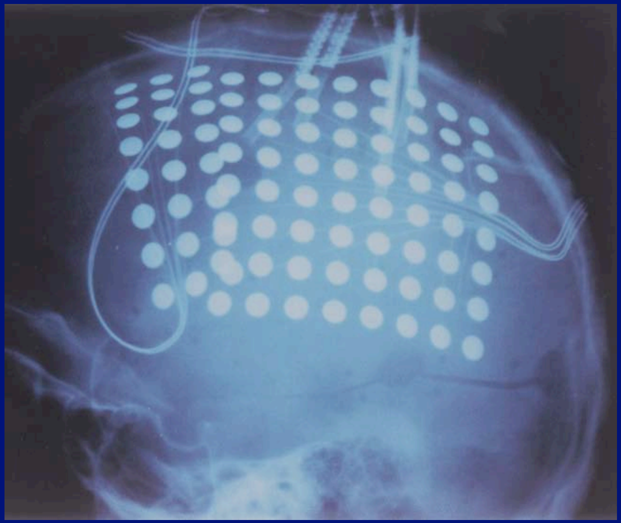


Acharya et al.

# Other Biopotential Signals on Scalp

- ***Surface electromyograms* (EMG)**
  - 10 μVpp-1mVpp, 10Hz-1kHz
  - recorded on the skin near muscles of interest
  - conveying neural activity controlling muscle contraction and particularly useful for motor prostheses
- ***Electrooculograms* (EOG)**
  - 100 μVpp-1mVpp, 10Hz-1kHz
  - recorded on the frontal skull near the eyes
  - electrostatic dipoles of eyeballs conveying gaze direction useful for eye tracking in human-computer interfaces
- ***Electrocardiograms* (ECG)**
  - 10 μVpp-10mVpp, 0.1-100Hz
  - recorded on the chest
  - conveying heart activity for monitoring of health in cardiac patients and also useful in athletic fitness monitoring and detection of emotional state.

# Biosignal Recording



**Electrodes**

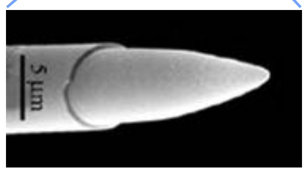
**Amplifiers**

**Signal Processing**

**Telemetry**

# Electrodes

needle microelectrode
Kation Scientific



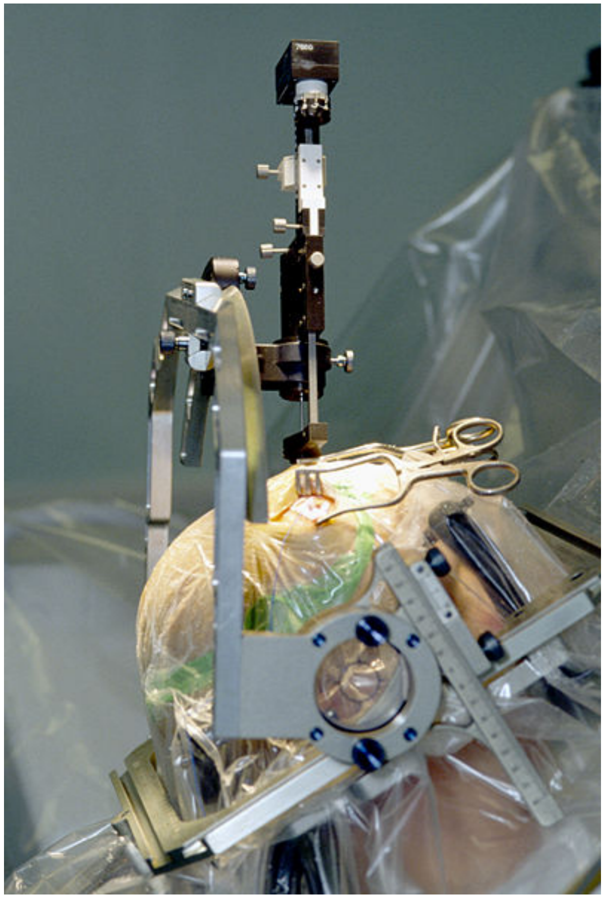

- **Needle electrode**
  - Metal, typically Tungsten
  - Electrical contact impedance in 10kΩ to 1MΩ range
  - Penetration through neural tissue


active EEG gel-contact electrode
Biosemi

- **Flat electrode**
  - Higher impedance
  - Mostly for external use and on neural surface
    - *scalp EEG (electroencephalogram) recording*
    - *retinal implants*

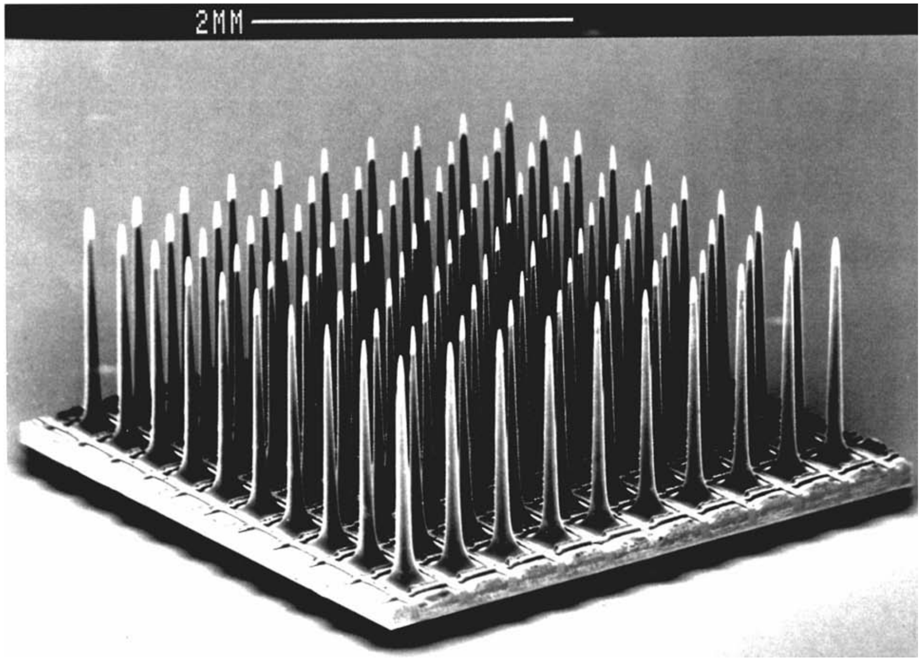
# Deep Brain Stimulation (DBS)
## *for Parkinson's Disease Tremor Remediation*

- "Brain's pacemaker"
  - *Electrode is implanted in the brain's thalamus*
  - *Periodic (130-185Hz) activation of electrical impulses delivered by the electrode suppresses Parkinson-induced tremor*
- Invasive procedure
  - *Surgical insertion of electrode and stimulation electronics*
  - *Battery needs to be replaced*



Surgery to insert electrode deep in the brain. Parkinson's patient remains awake during surgery.
http://en.wikipedia.org/wiki/Deep_brain_stimulation

# Electrode Arrays

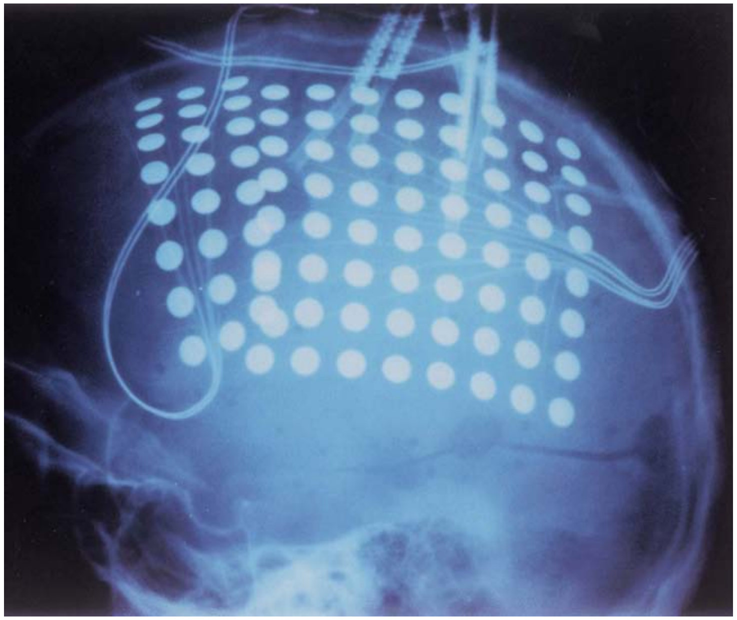



"Utah array"
Normann laboratory, University of Utah, 2003

- **Penetrating electrode arrays**
  - Typically silicon based, fabricated in MEMS (microelectromechanical systems) process
  - Cortical vision implants
- **Flat electrode arrays**
  - Retinal implants
  - Electrocorticogram (ECoG) monitoring systems

# Electrocorticogram (ECoG)

Implanted epilepsy
grid electrodes
*www.mayoclinic.com*



- **Cortical surface electrodes**
  - Higher spatial resolution than scalp EEG
- **Epilepsy monitoring**
  - Preparation for surgery to remove focus of epileptic activity, avoiding critical brain functional areas

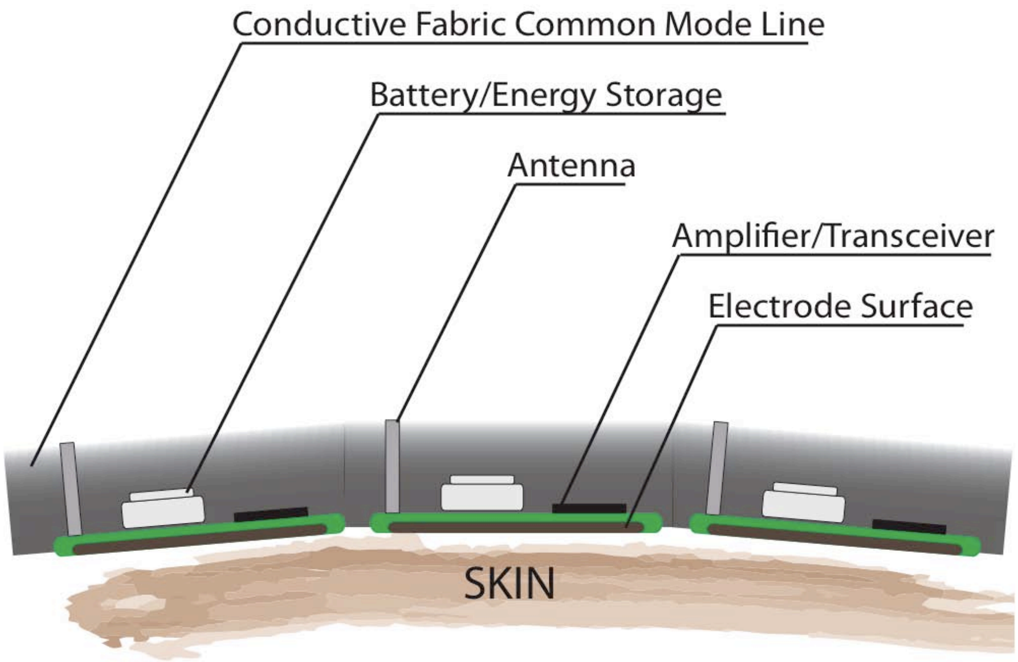
# Scalp EEG Recording

BioSemi Active2
*www.biosemi.com*

- **State of the art EEG recording**
  - 32-256 channels
  - Gel contact electrodes
  - Tethered to acquisition box
  - Off-line analysis

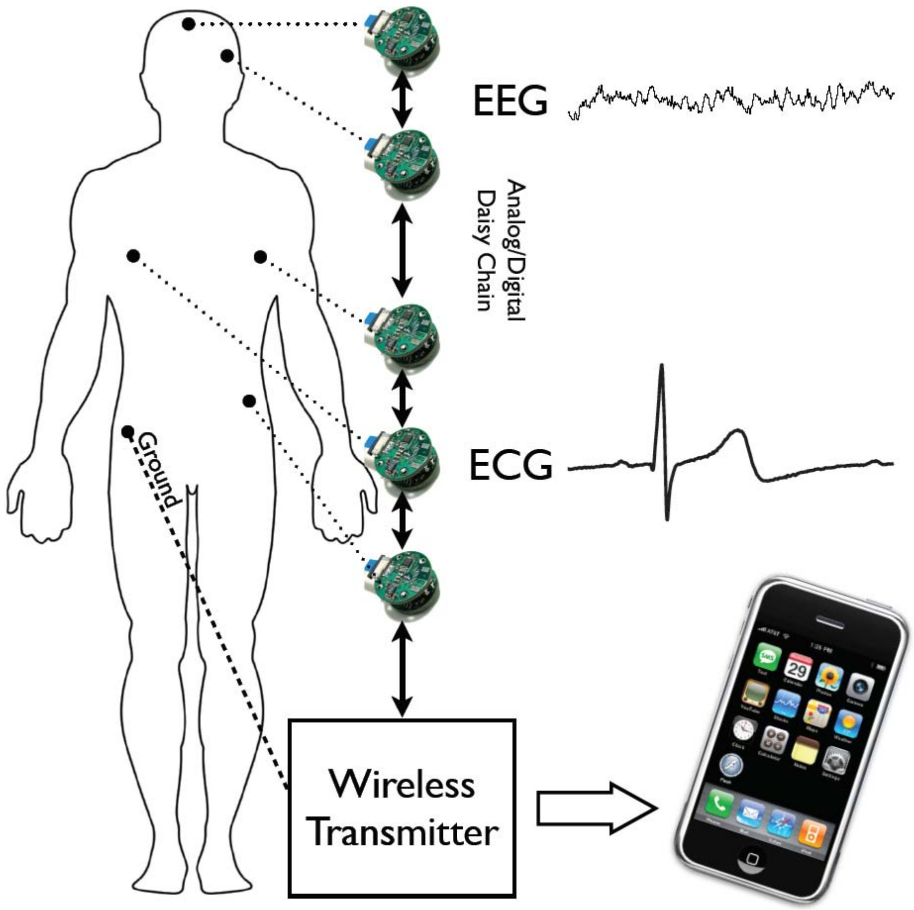
# Wearable, High-Density EEG and ECG

- **Non-contact electrode**
  - No skin/subject preparation
  - Insulated, embeddable in elastic fabric
- **Fully integrated**
  - On board power, signal processing, wireless transceiver
- **Applications**
  - Brain computer interface
  - Mobile, health monitoring

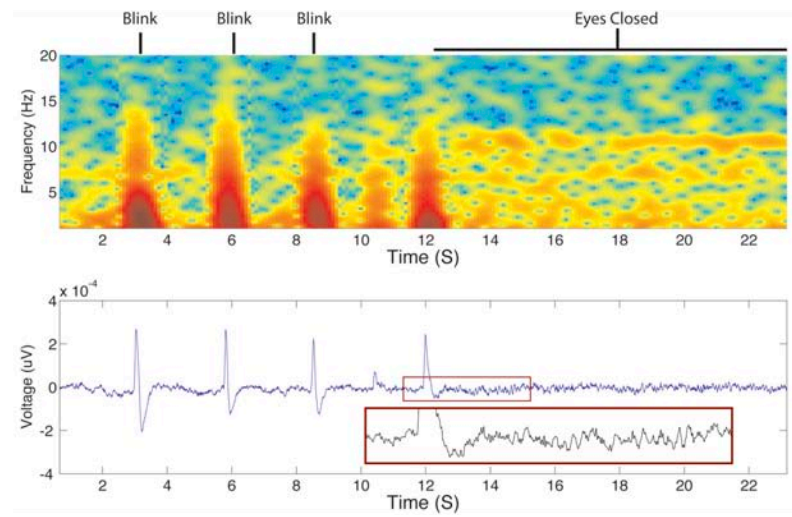


# Wireless Non-Contact Biopotential Sensors

*Mike Yu Chi and Gert Cauwenberghs, 2010*



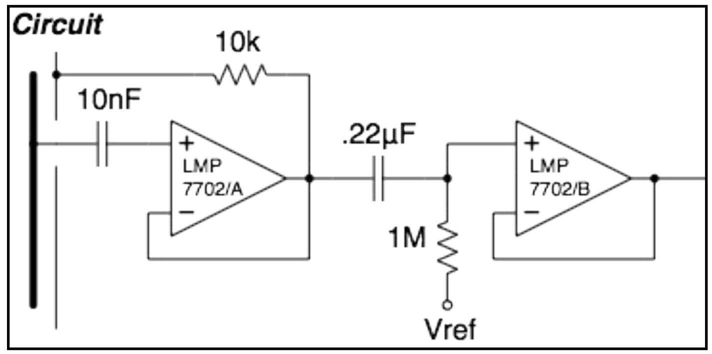


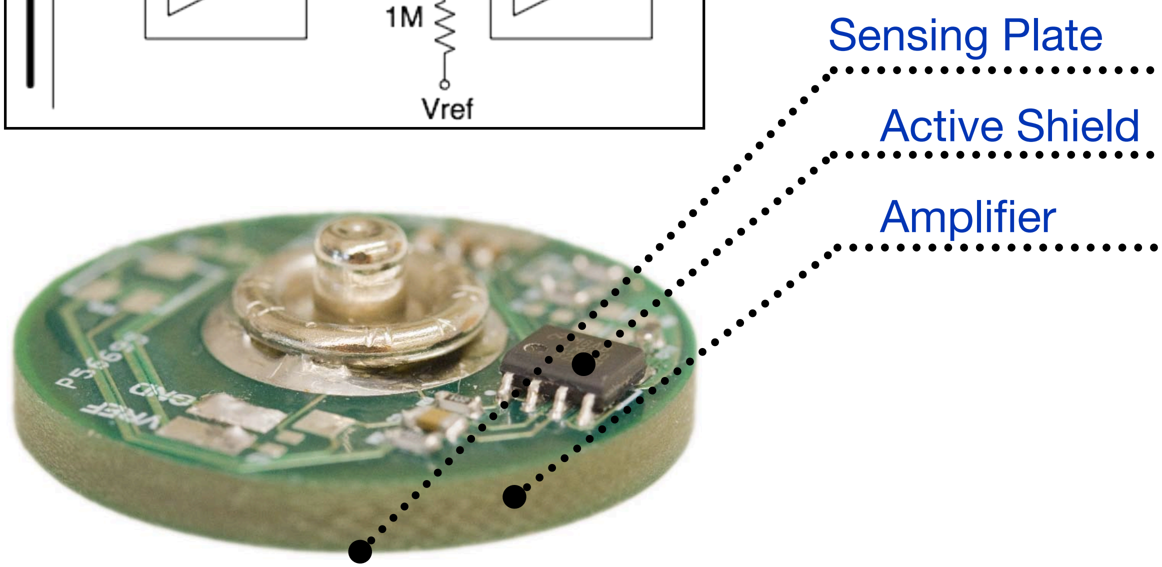



EEG alpha and eye blink activity recorded on the occipital lobe over haired skull

# Non-Contact Sensor Design

- **Non-contact sensor fabricated on a printed circuit board substrate**


Standard 4-layer PCB

- **Advantages:**
  - Robust circuit
  - Inexpensive production
  - Safe, no sharp edges or fingers, can be made flexible
  - Very low power (<100µW/sensor)
  - Strong immunity to external noise

*Chi and Cauwenberghs, 2010*

# Wearable Wireless EEG/ECG System

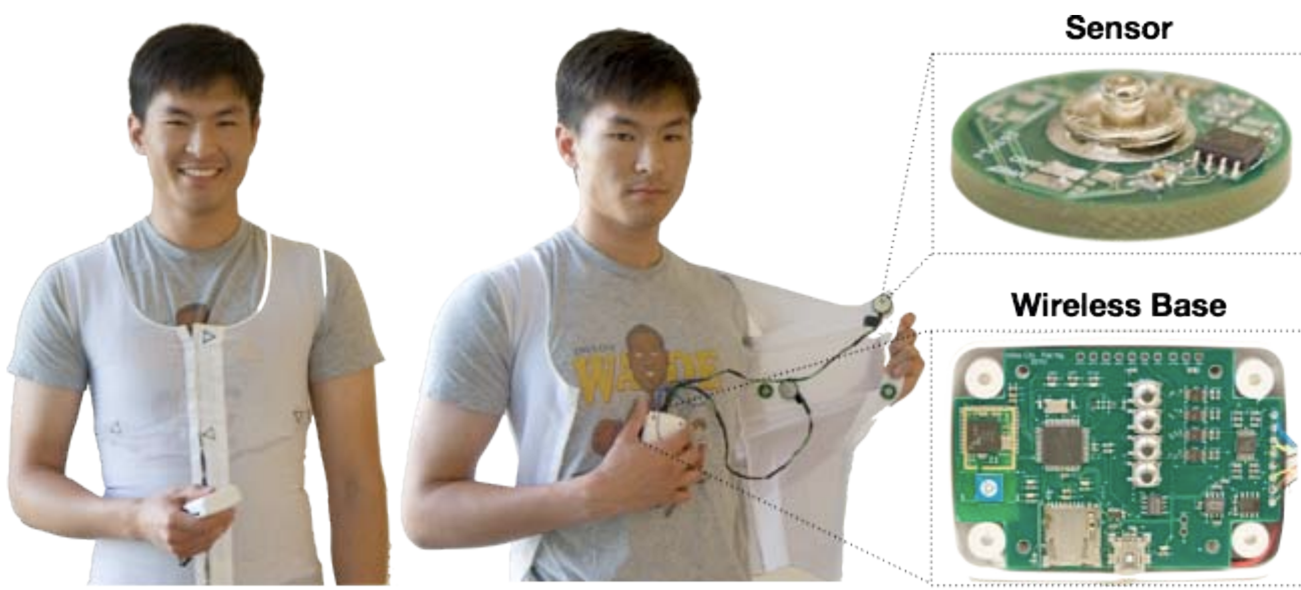
*Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010*

- **Prototype non-contact sensor system with 4-channels**
  - Bluetooth wireless telemetry and microSD data storage
  - Rechargeable battery
- **Mounted in both head and chest harnesses**

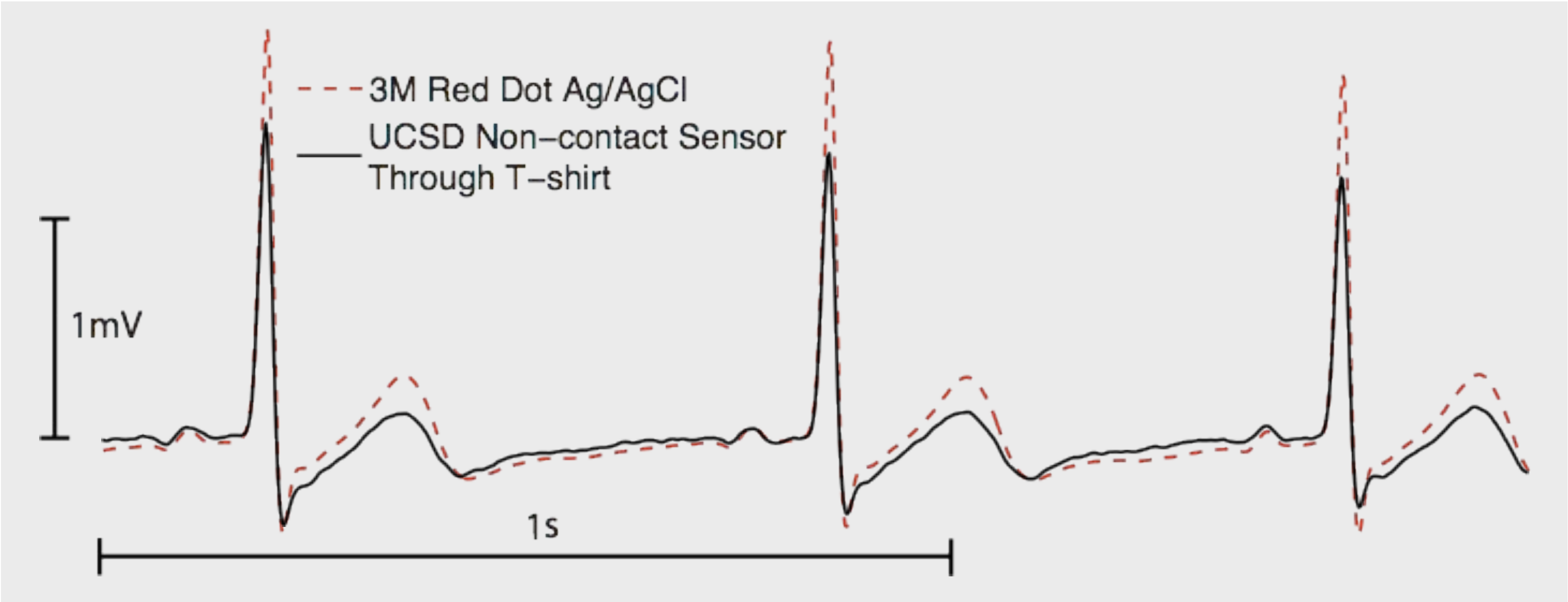
EEG Hand-band

ECG Chest Harness

Electronics



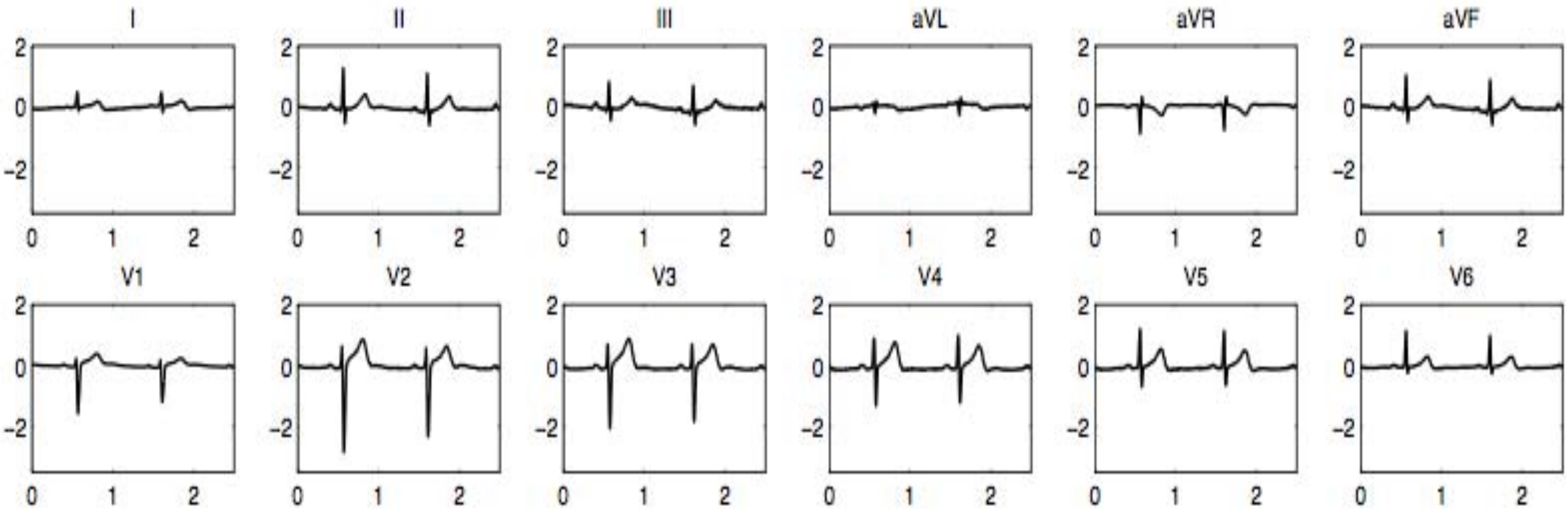
# ECG Comparison




Simultaneously acquired ECG in laboratory setting
No 60Hz Filter

*Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010*

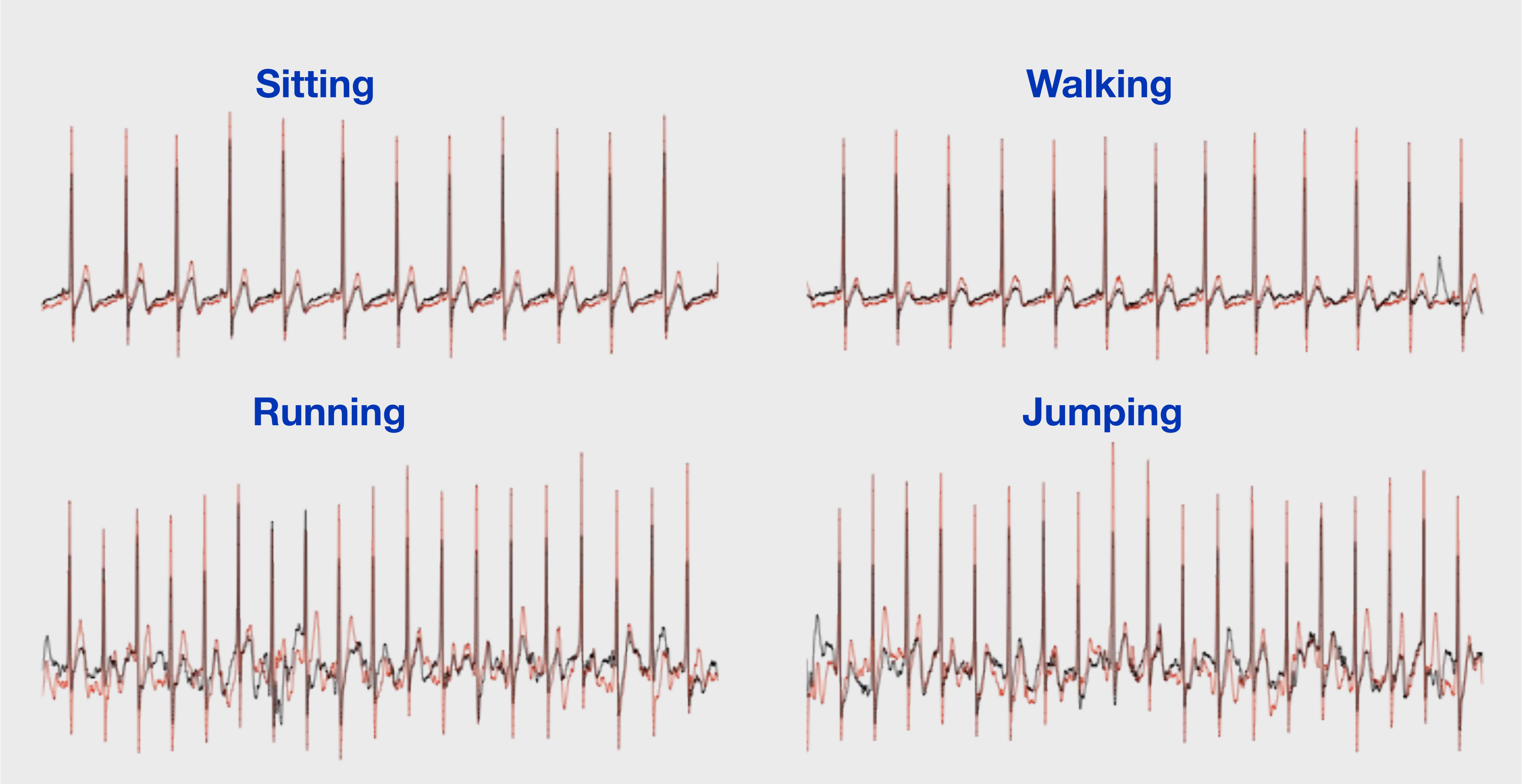
# Sample ECG Data




Derived 12-lead ECG from 4 electrodes mounted in chest harness

*Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010*

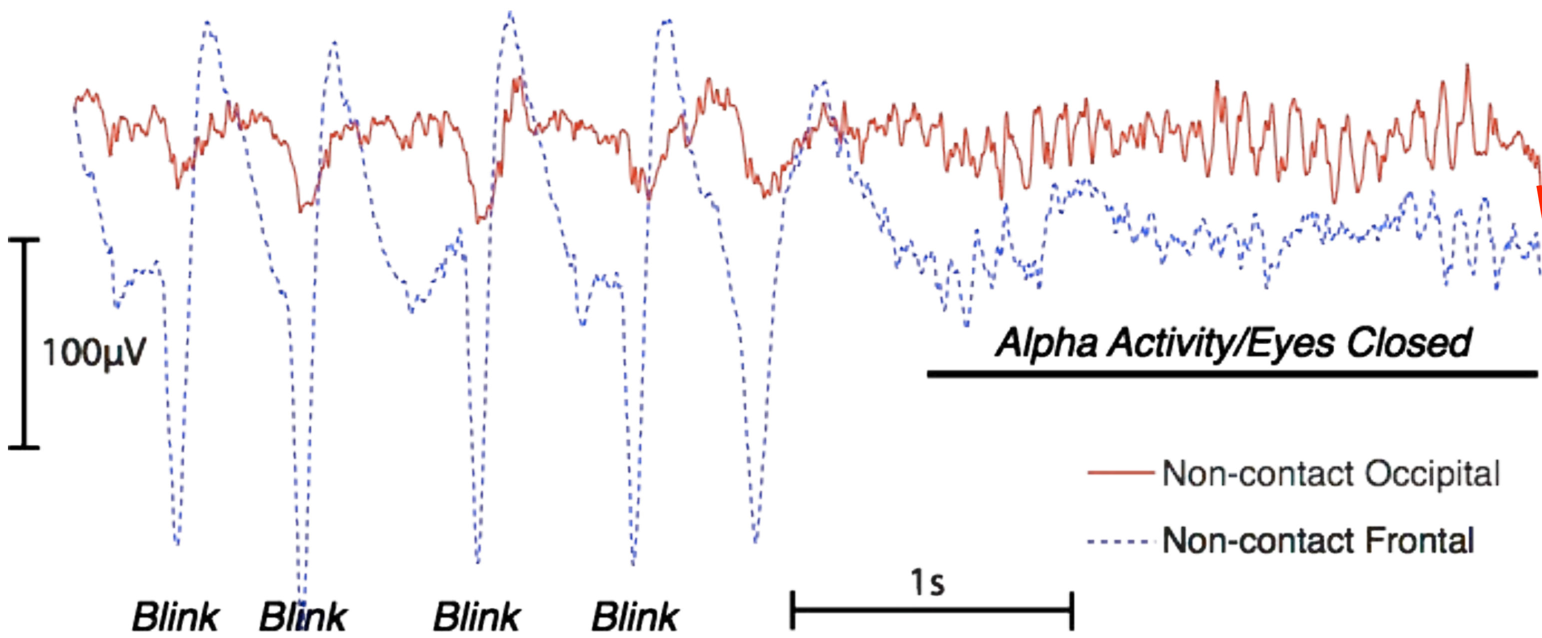
# ECG Under Motion




*Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010*

# Non-Contact EEG Recording over Haired Scalp

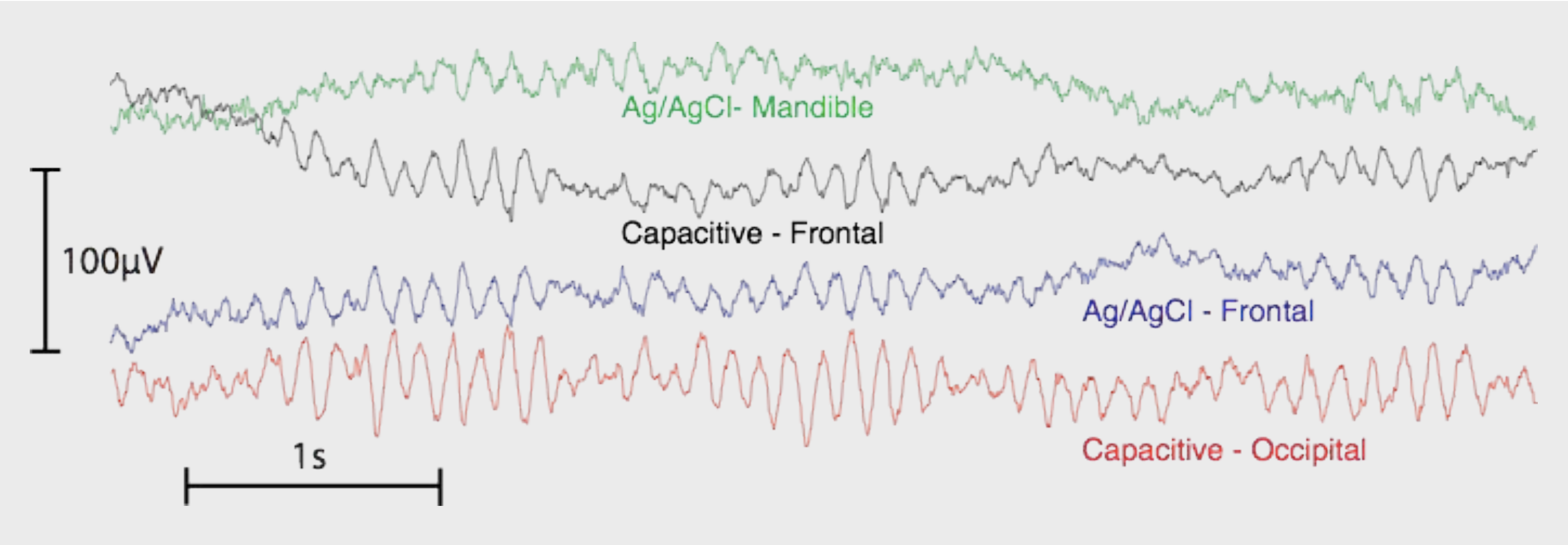
*Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010*




- **Easy access to hair-covered areas of the head without gels or slap-contact**
- **EEG data available only from the posterior**
  - P300 (Brain-computer control, memory recognition)
  - SSVP (Brain-computer control)

# Non-Contact *vs.* Ag/AgCl Comparison

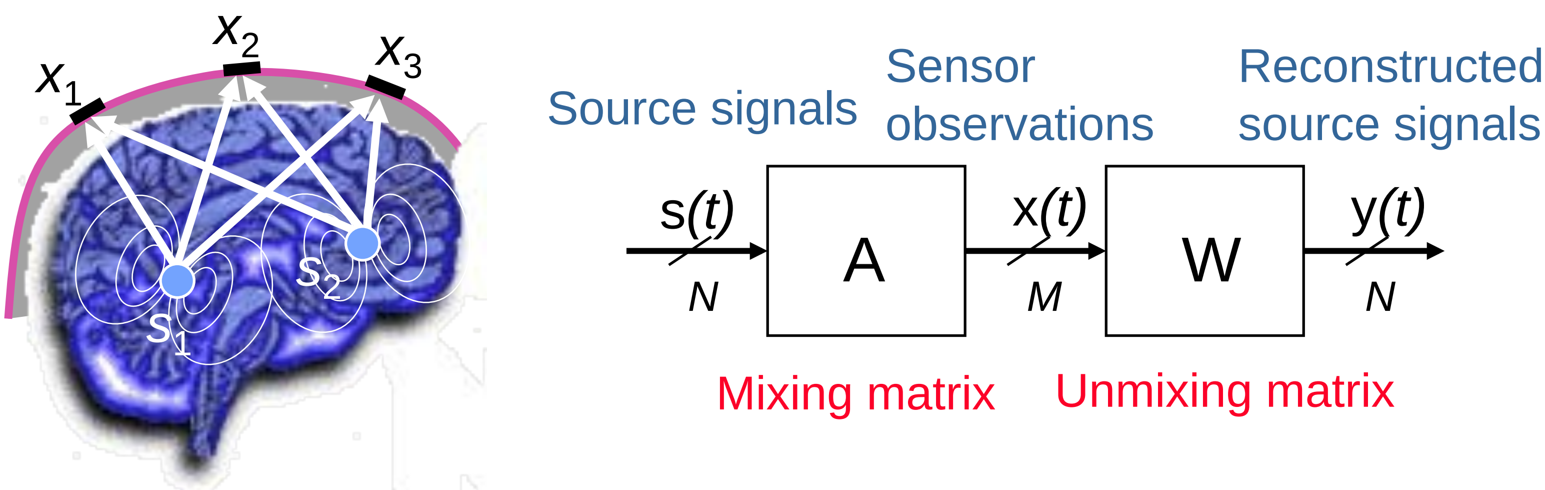
*Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010*




Subject's eyes closed showing alpha wave activity
Full bandwidth, unfiltered, signal show (.5-100Hz)

# Independent Component Analysis

- *Blind source separation* (BSS) allows to untangle linear mixtures in sensor observations of several "independent" sources of brain activity, without knowing anything *a priori* about the source signals or their locations.

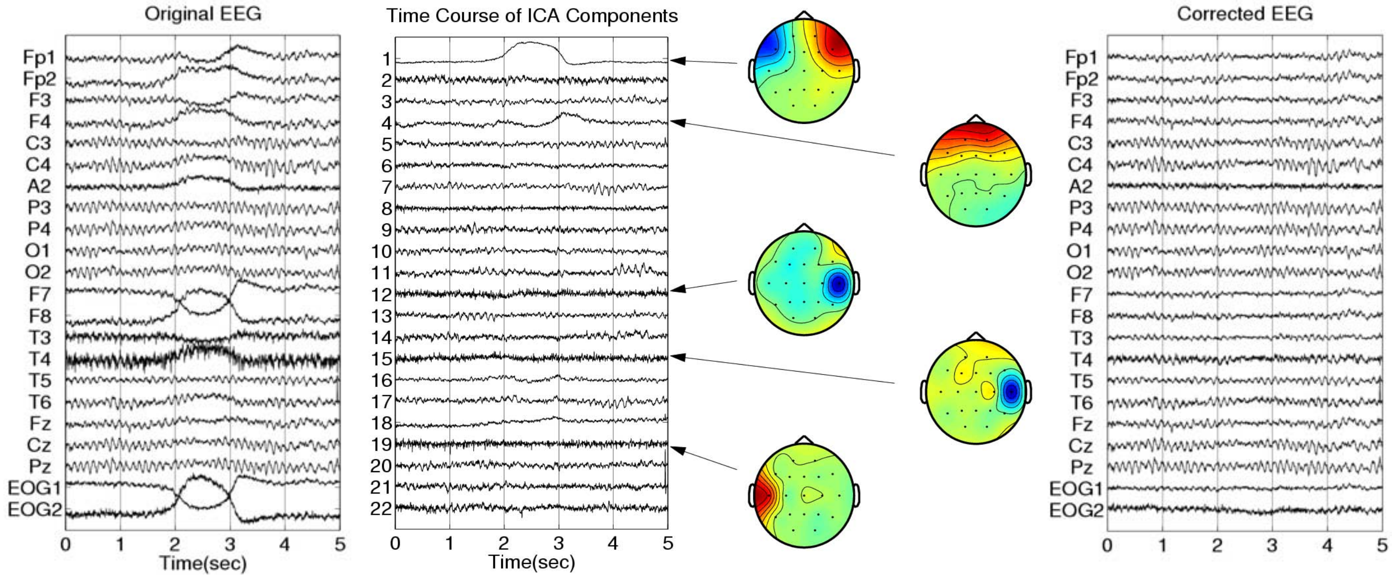



- *Independent component analysis* (ICA) recovers these individual sources by estimating an unmixing matrix that minimizes higher-order statistical dependencies between the reconstructed signals.
- Columns of the unmixing matrix reveal the spatial profiles for each of the estimated sources of brain activities, projected onto the *scalp map* (sensor locations). *Inverse methods* then yield estimates for the location of the centers of each of the dipole sources.

# EEG Independent Component Analysis

Swartz Center for Computational Neuroscience, UCSD
*http://sccn.ucsd.edu/*

- ICA on *single-trial* EEG array data identifies and localizes sources of brain activity.
- ICA can also be used to identify and remove unwanted biopotential signals and other artifacts.
  - *EMG muscle activity*
  - *60Hz line noise*




Left: 5 seconds of EEG containing eye movement artifacts. Center: Time courses and scalp maps of 5 independent component processes, extracted from the data by decomposing 3 minutes of 31-channel EEG data from the same session and then applied to the same 5-s data epoch. The scalp maps show the projections of lateral eye movement and eye blink (top 2) and temporal muscle artifacts (bottom 3) to the scalp signals. Right: The same 5 s of data with the five mapped component processes removed from the data [Jung et al., 2000].