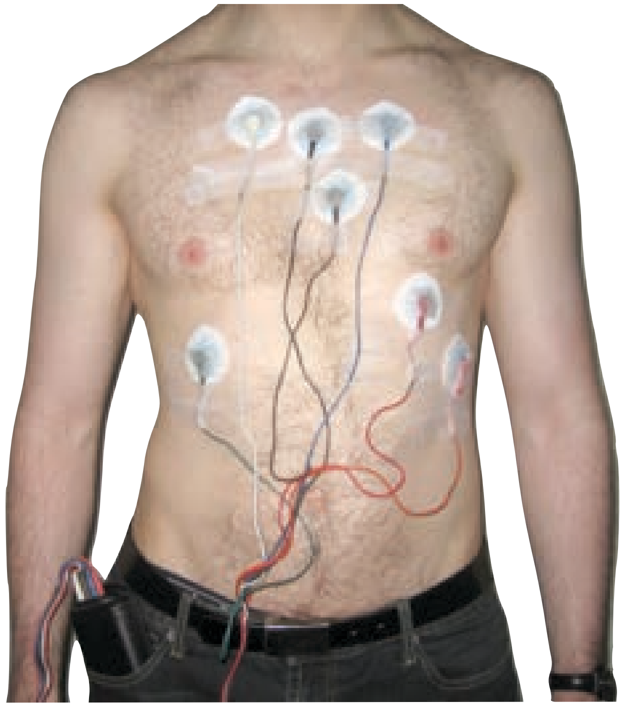
## BENG186 Guest Lecture

# Wireless non-contact ECG and EEG for unobtrusive cardiac and brain monitoring

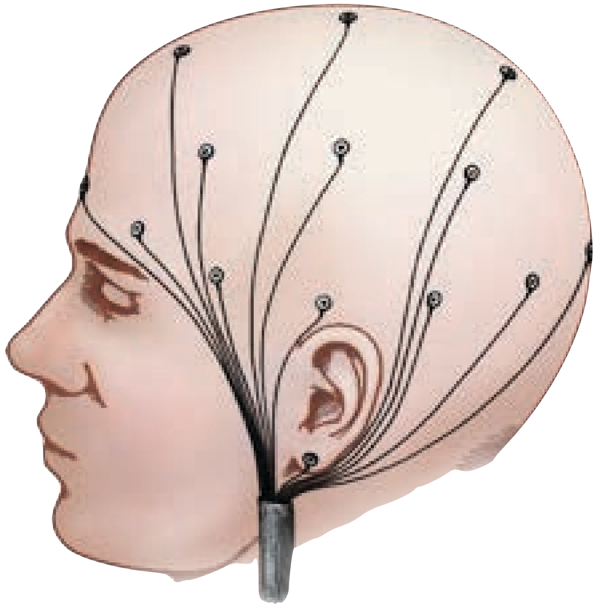
Yu M. Chi and Gert Cauwenberghs

# Motivation



***ECG/EEG:***

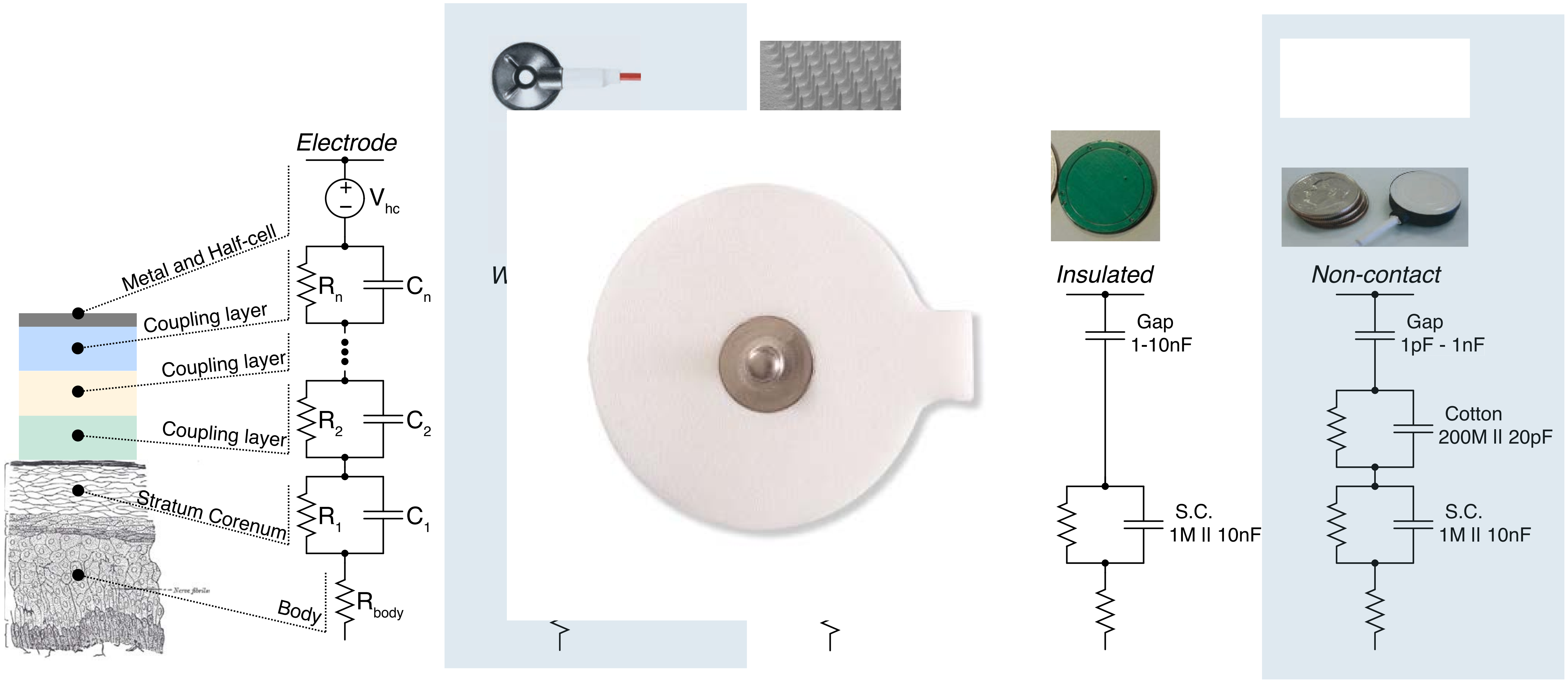
- Simple
- Inexpensive
- Non-invasive
- Widely used
- Diagnostically useful



***Today's ECG/EEG sensors however:***

- Require adhesives and skin-irritating gels
- Number one patient complaint against mobile ECG/EEG devices
- Need for new, patient-friendly, sensor technologies

# Overview of Sensor Technologies

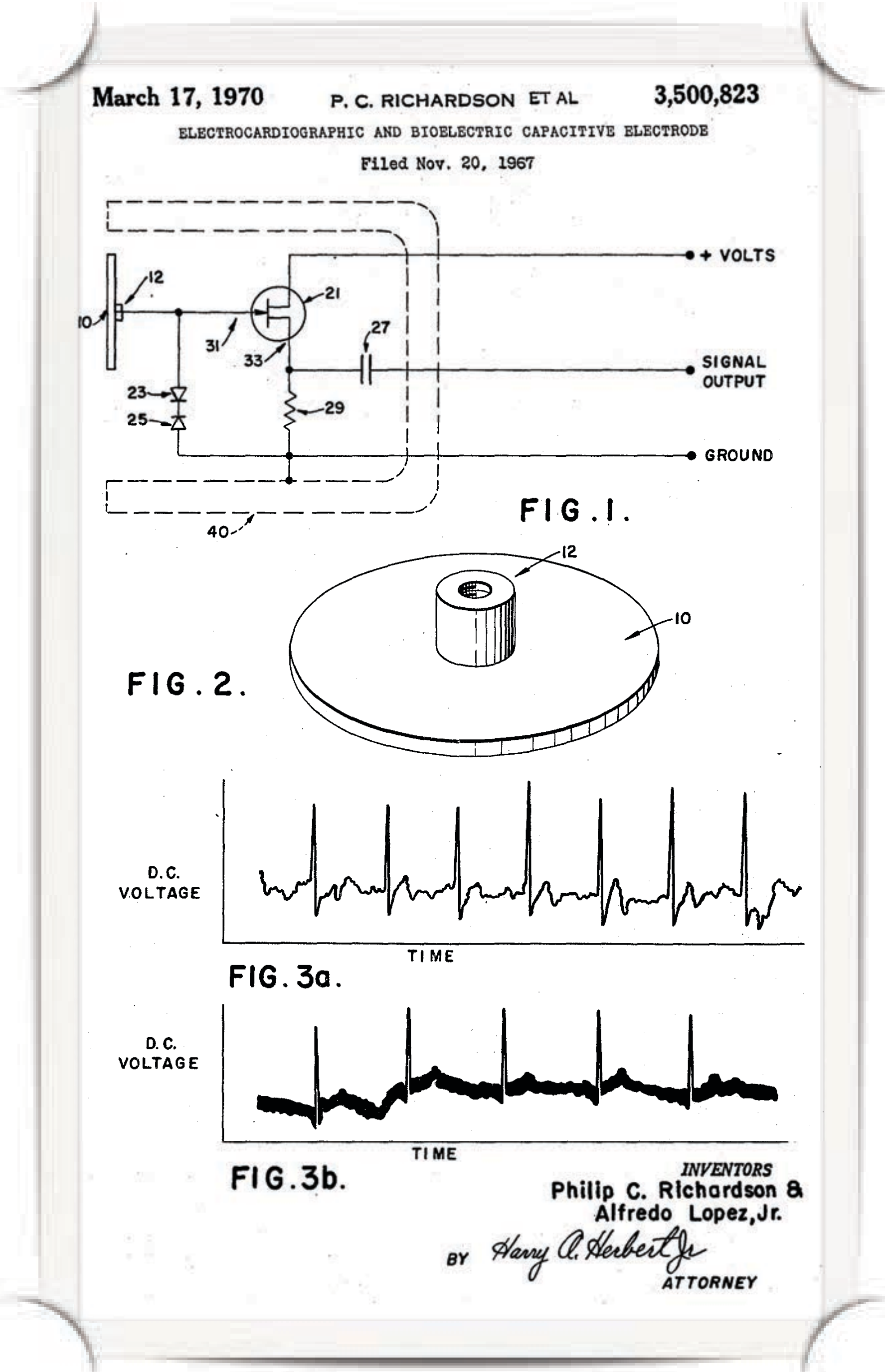



**Adhesive Ag/AgCl electrode is universally used in the clinical world**

**Exploring the use of non-contact sensors for mobile health applications**

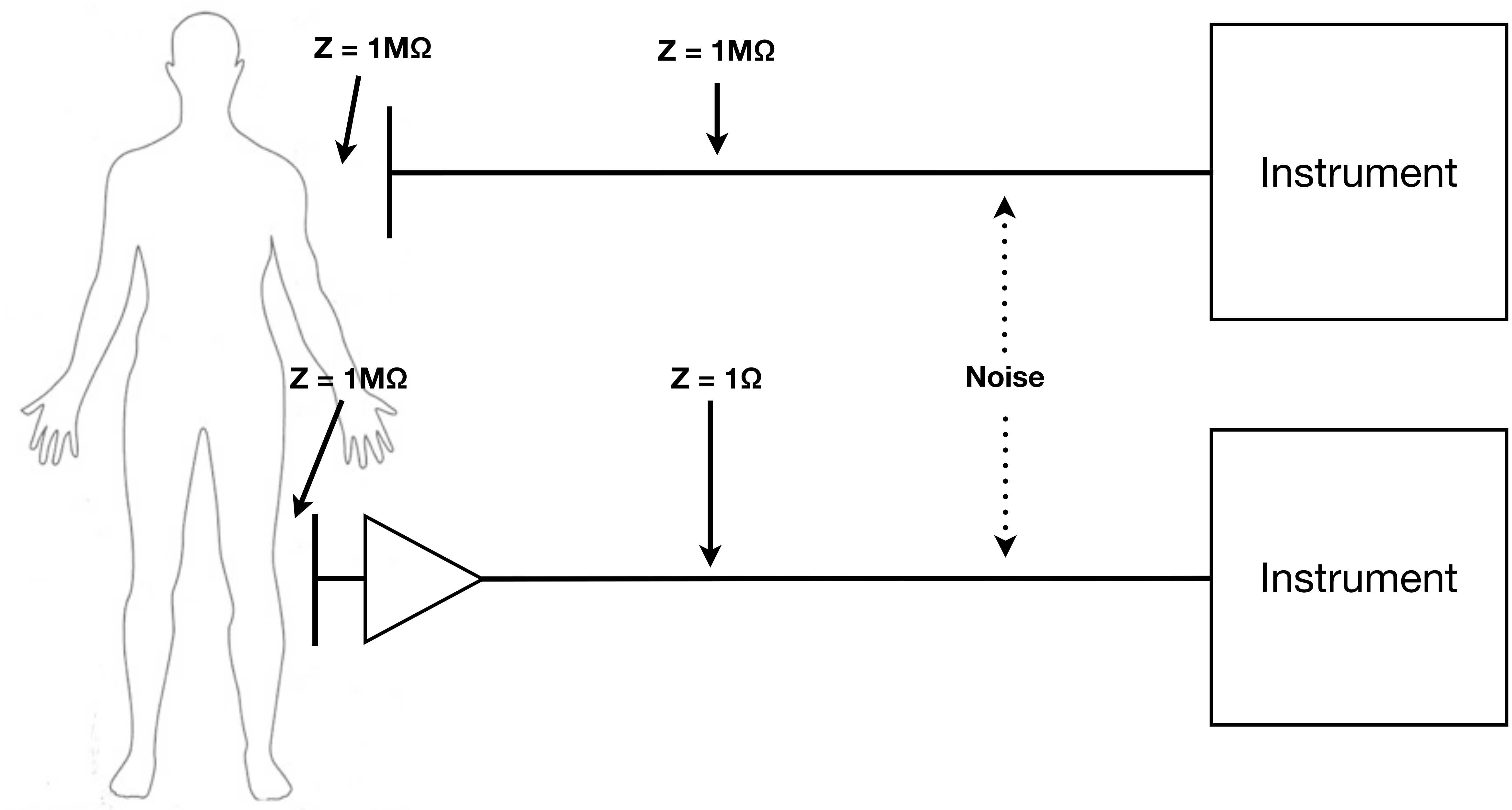
# Non-contact 'Capacitive' Electrodes

- Senses biopotential signals without direct skin contact
  - High impedance signal coupling
  - Absence of electro-gel
  - Acquisition through fabric and hair
- Basic principle is well known
  - First patent in 1968 (Richardson)
  - Active electrode concept taken to the extreme
- Technology is still problematic
  - Noise, interference pickup
  - *Movement artifacts*
  - Circuit complexity, materials, construction, cost
  - Nothing beyond 'lab prototype'




[1] C.J. Harland, T.D. Clark, and R.J. Prance. *Electric potential probes - new directions in the remote sensing of the human body.* Measurement Science and Technology, 2:163–169, February 2002.
[2] A. Lopez and P. C. Richardson. *Capacitive electrocardiographic and bioelectric electrodes.* IEEE Transactions on Biomedical Engineering, 16:299–300, 1969.
[3] P. Park, P.H. Chou, Y. Bai, R. Matthews, and A. Hibbs. *An ultra- wearable, wireless, low power ECG monitoring system.* Proc. IEEE International Conference on Complex Medical Engineering, pages 241–244, Nov 2006.

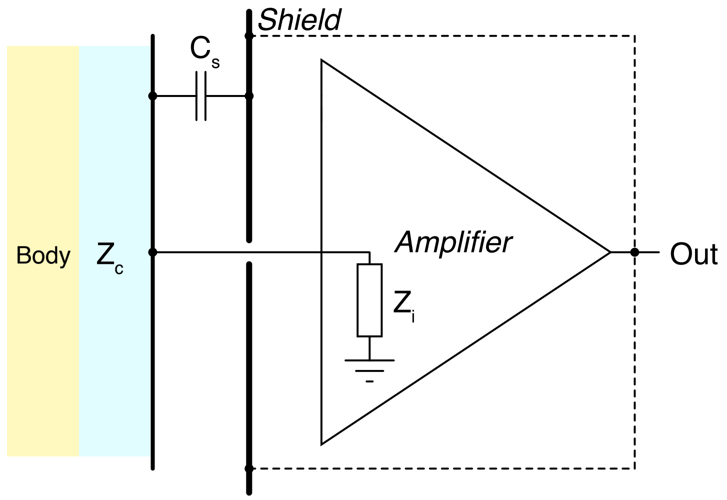
# Active Electrode Concept




**Reduce interference by transforming impedance at the electrode - tolerate much higher electrode impedances (no skin prep)**

**Superior to shielding wires in terms of noise and circuit stability**

# Challenges in Non-contact Sensing




**Biopotentials are at low frequencies .05 - 100Hz (few kHz for EMG)**

**Standard wet adhesive electrodes offer a low impedance (5k to 100k)**

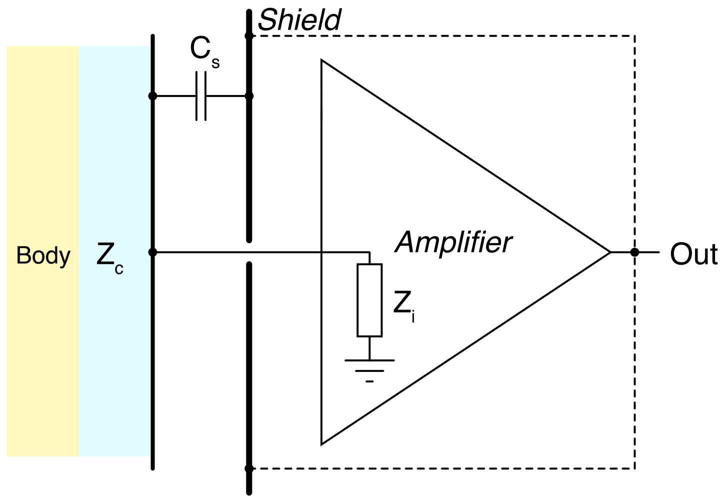
**Zc << Zi**

**Non-contact sensors couple via extremely high impedances - 1 to 50pF same order of magnitude as an amplifier's input impedance. No reliable DC path.**

**Zc ~ Zi**

**Gain, CMRR, noise and interference rejection are all significantly compromised**

# Challenges - CMRR and Biasing




**Electrodes with input capacitance of 5pF, coupling with 20pF and 25pF to body:**

$$CMRR \approx \frac{|Z_{in}|}{|Z_1 - Z_2|} \approx \frac{C_1 C_2}{C_{in}|C_1 - C_2|}$$

**CMRR ~ 26dB!, Can add DRL for additional 40dB of CMRR (ok for wireless)**

**If input capacitance is 60fF, CMRR = 64dB (much better)**

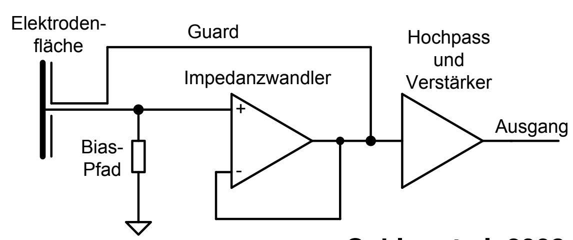
**Coupling with 25pF, want 0.05Hz HP cutoff for diagnostic ECG**

$$f_{hp} = \frac{1}{2\pi C_1 R_i}$$

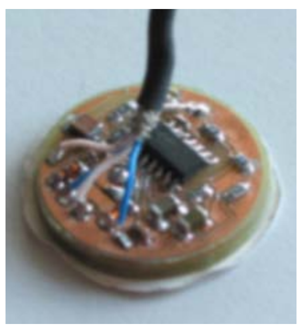
**Need 127G resistor (!), very hard to find**

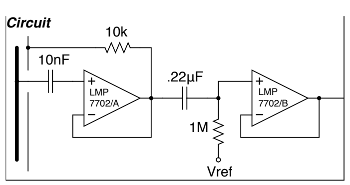
# Review of Sensor Implementations

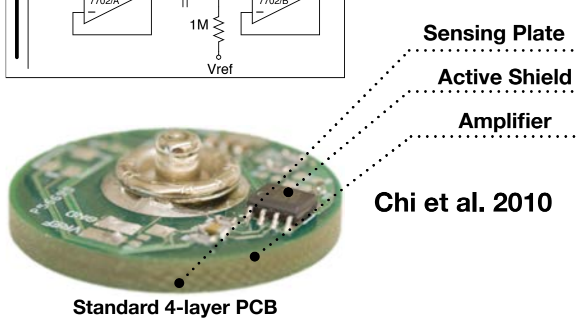
## Active field with numerous papers and dissertations on the topic:




Oehler et al. 2008

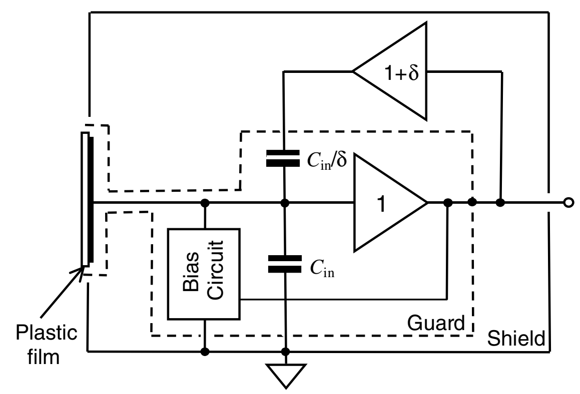


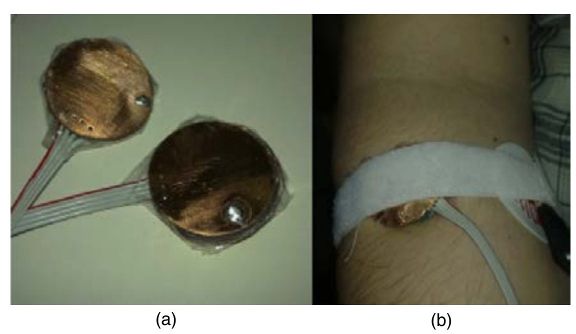



Chi et al. 2010

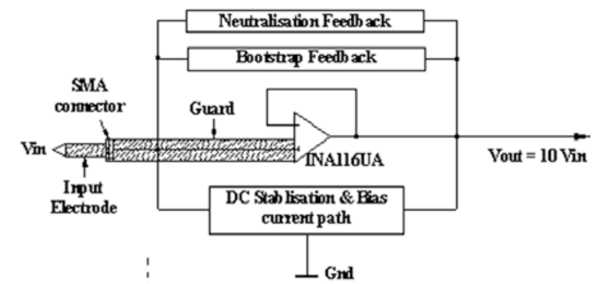
Many designs are fairly ‘conventional’

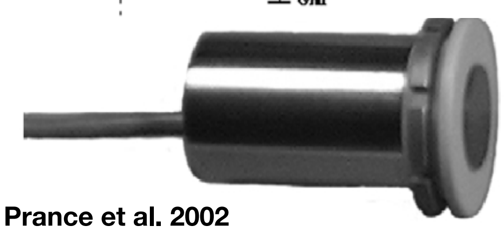



Spinelli et al. 2010

Some designs use clever tricks - here a insulated wire wrapped around the input pin of the opamp implements a >1T biasing resistor

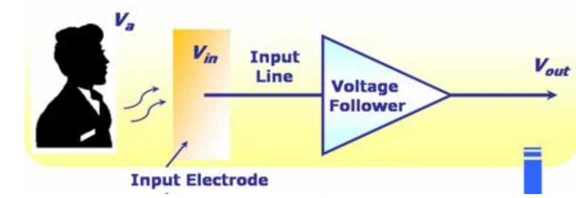


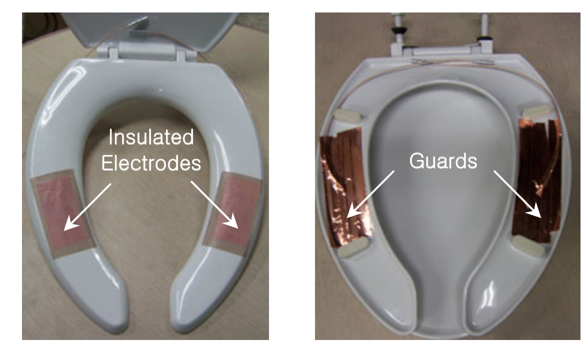



Prance et al. 2002

Quasar, Inc.

Others are secretive with their designs and make extraordinary claims - sub fF input capacitance



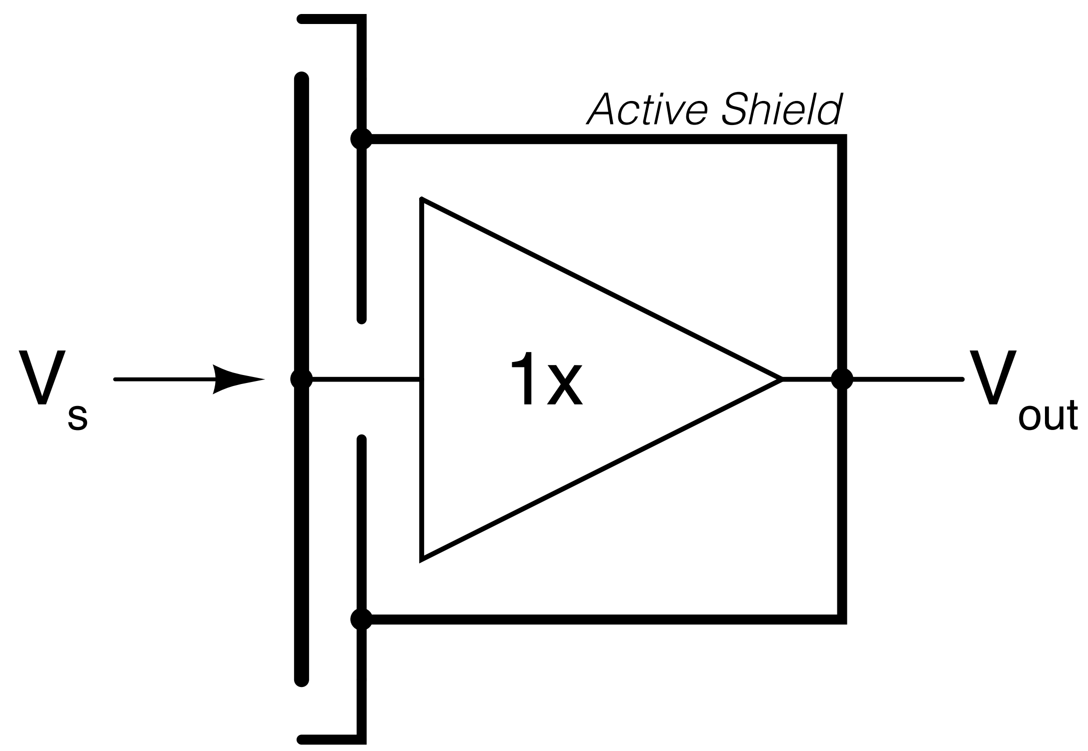

Kim et al. 2004

A few imaginative applications can be found - for example a toilet mounted ECG

**All have significant problems in unconstrained usage**

# Review of Current Sensors

## All current known designs at the core boil down to:

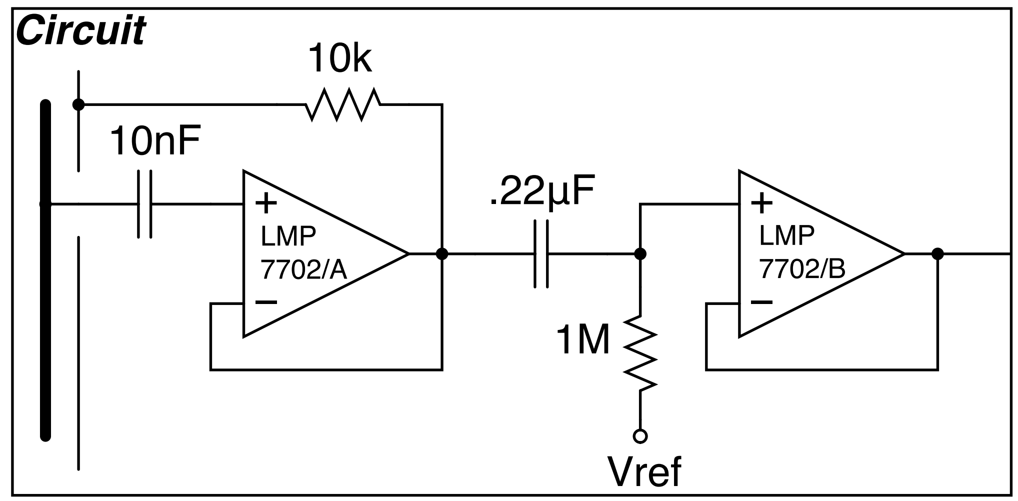



**An impedance converter with a discrete FET input opamp or instrumentation amp (eg. TI IN116 or similar)**

**Current sensors all share very similar off-the-shelf components and performance specifications. The vast majority of the differences are accounted in the execution details of the system. For example our wireless high-resolution DAQ will naturally be less noisy than a implementation using a NI-DAQ card in a desktop (and safer). Mechanical construction is also very important.**

# Discrete Component Sensor Design

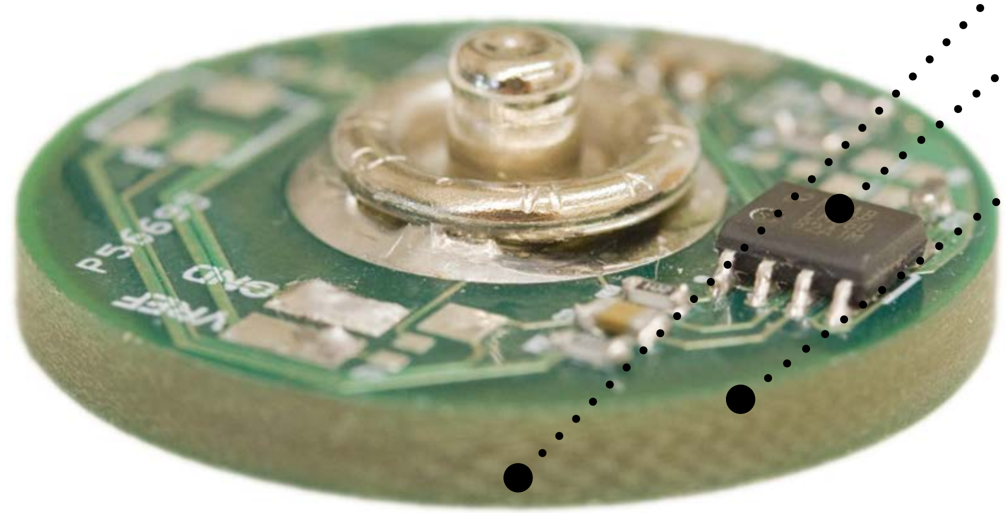
- **Non-contact sensor fabricated on a printed circuit board substrate**
- **Advantages**
  - **Robust circuit**
  - **Inexpensive production**
  - **Safe, no sharp edges or fingers, can be made flexible**
  - **Very low power (<50uW/sensor)**
  - **Strong immunity to external noise**




**Sensing Plate**

**Active Shield**

**Amplifier**



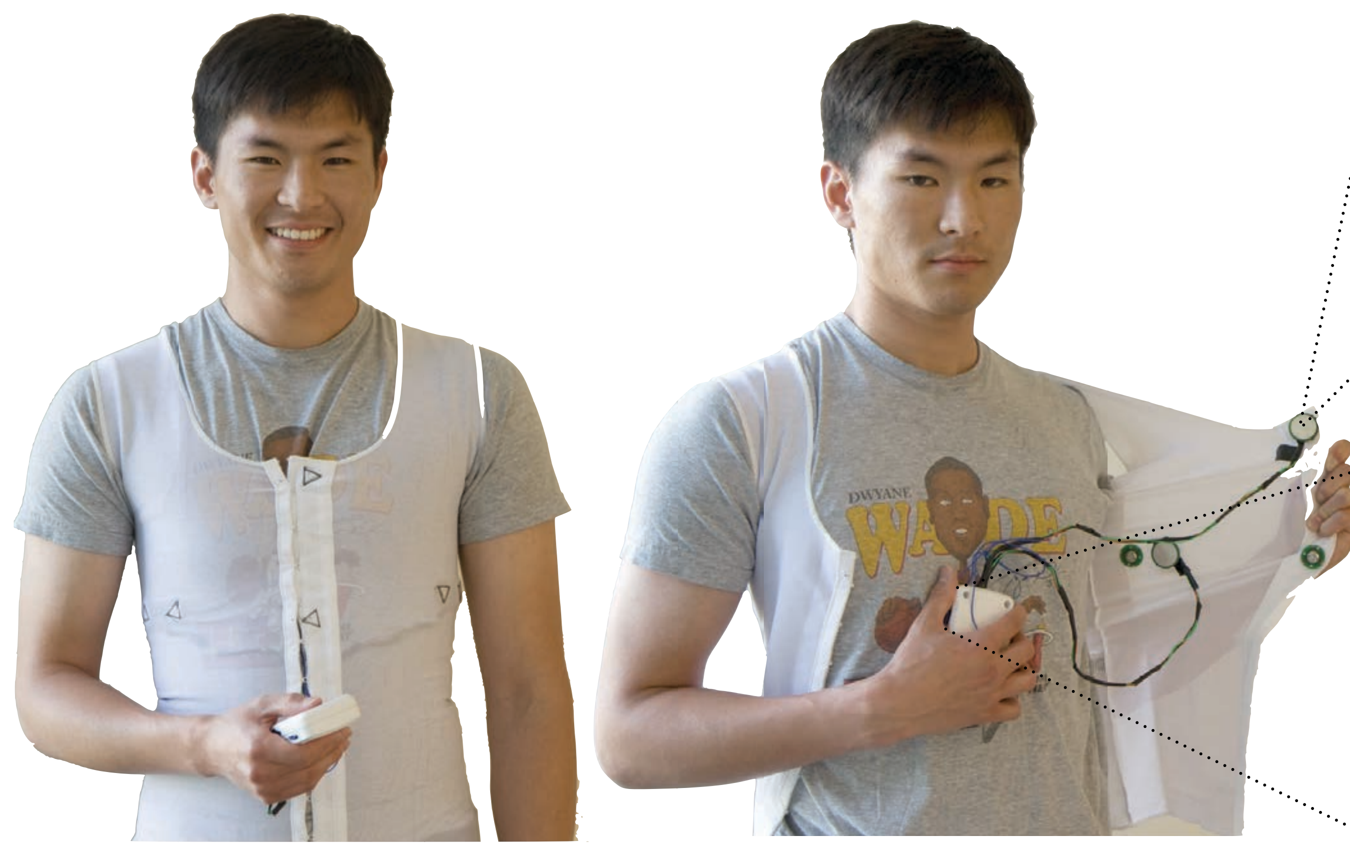
**Standard 4-layer PCB**

# Wearable Wireless EEG/ECG System

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

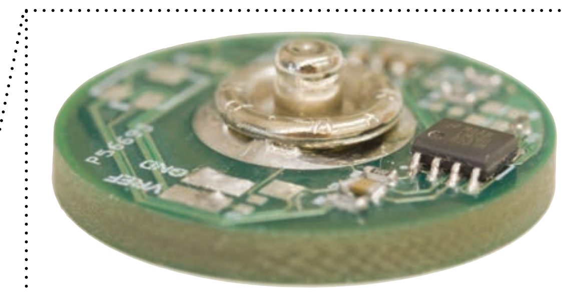
**EEG Hand-band**

**ECG Chest Harness**

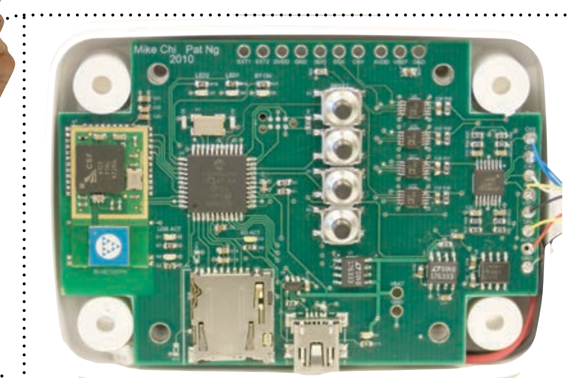


**Electronics**

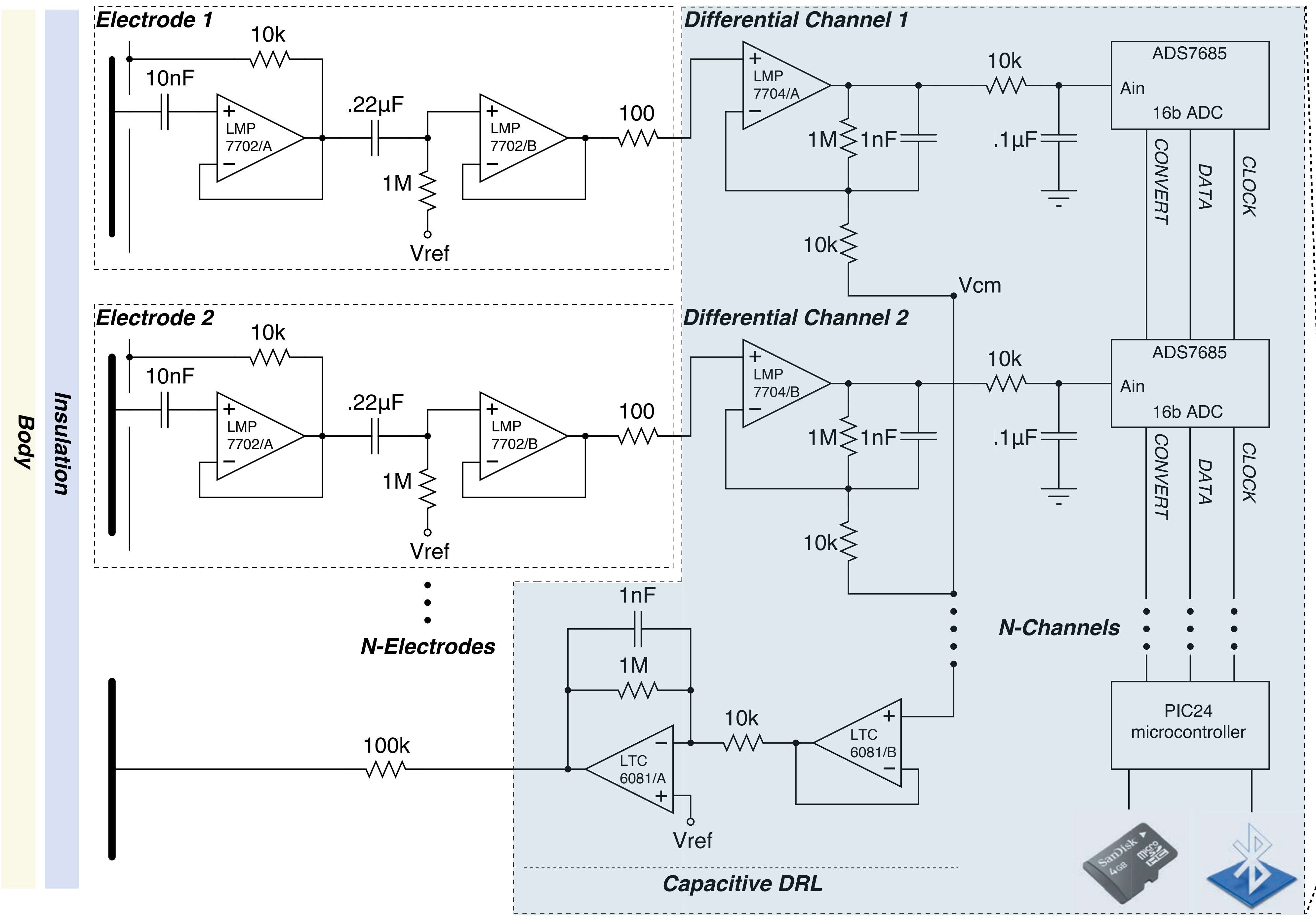
**Sensor**

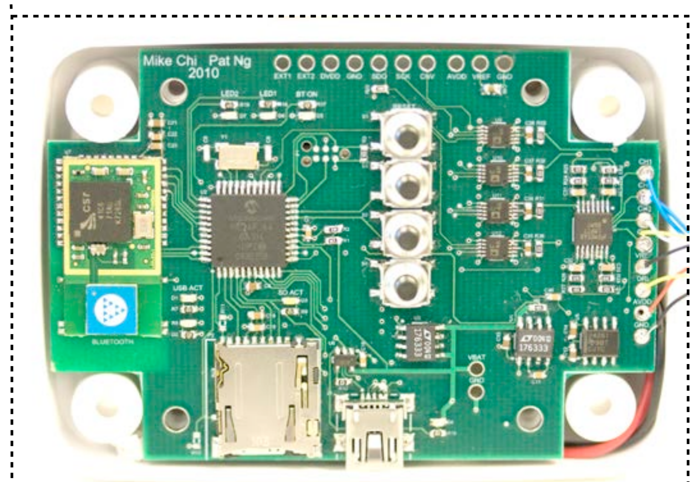


**Wireless Base**



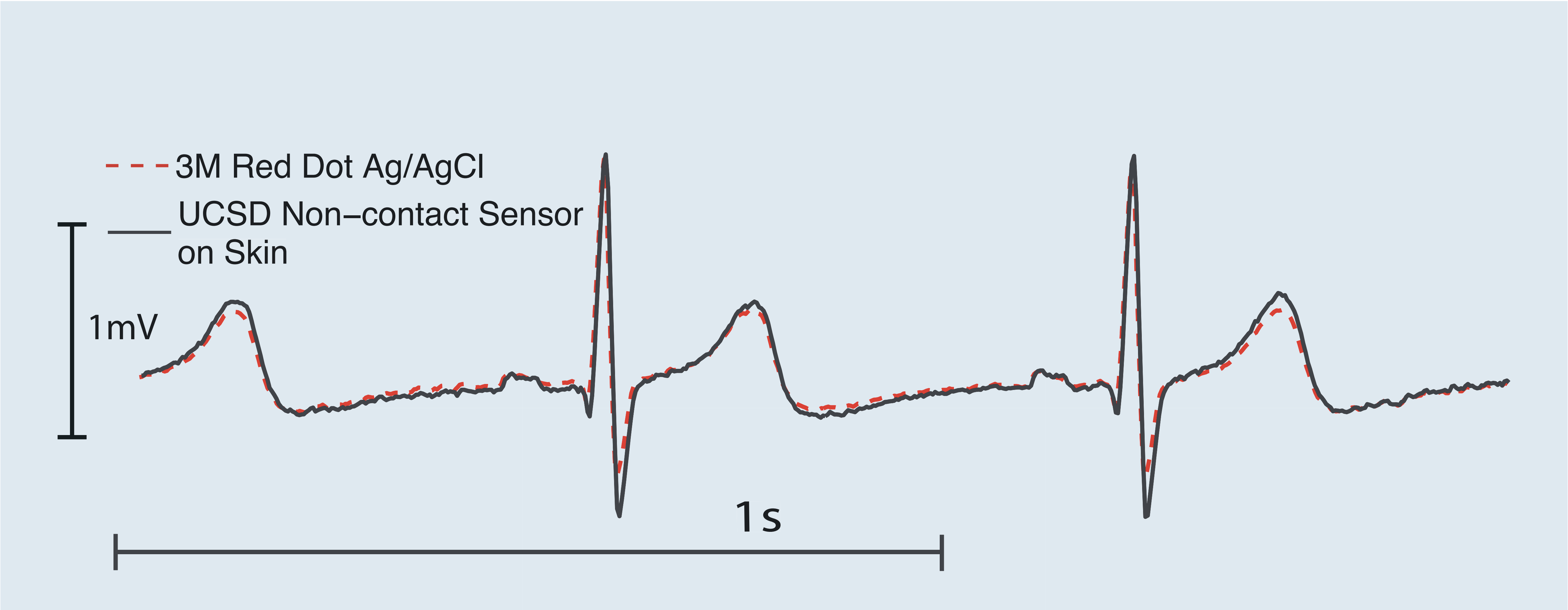
# Wireless Data Acquisition



Telemetry Unit

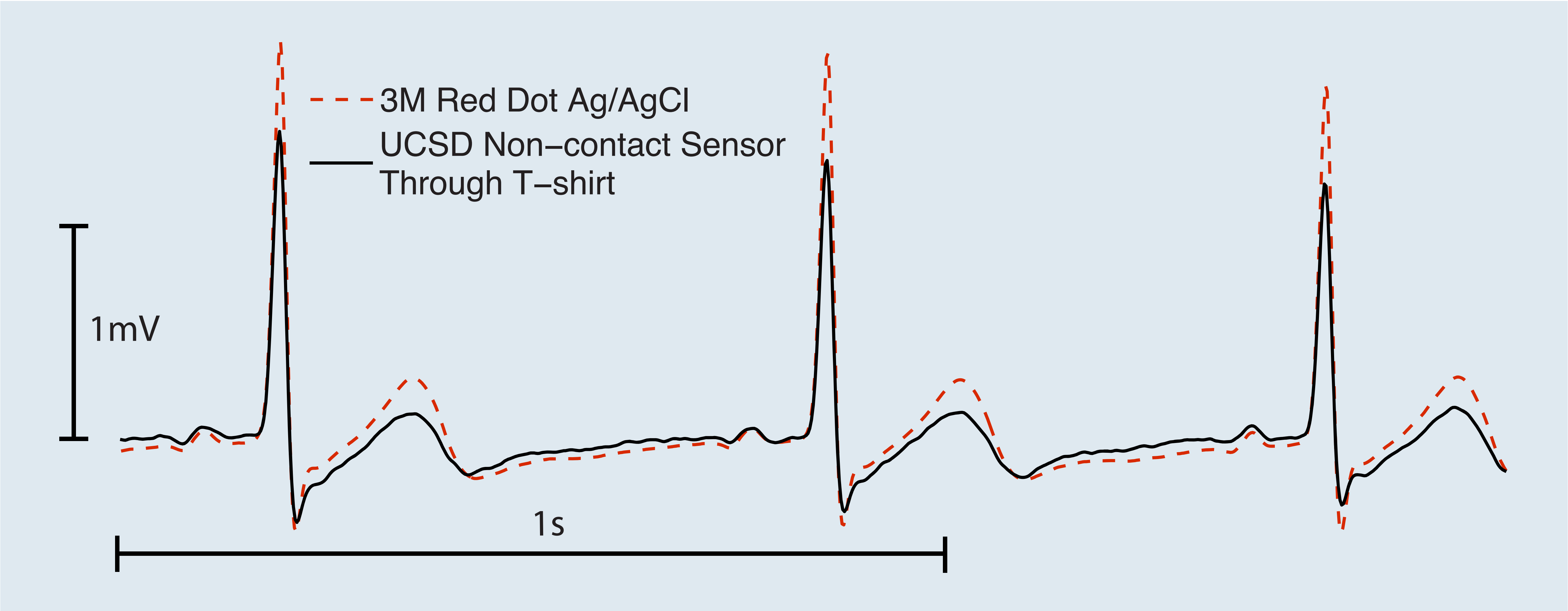
# ECG Comparison - On Skin




**Simultaneously acquired ECG in laboratory setting - 0.5Hz to 100Hz BW**

**No 60Hz Filter - Combination of shielding and capacitive DRL minimizes interference pickup**

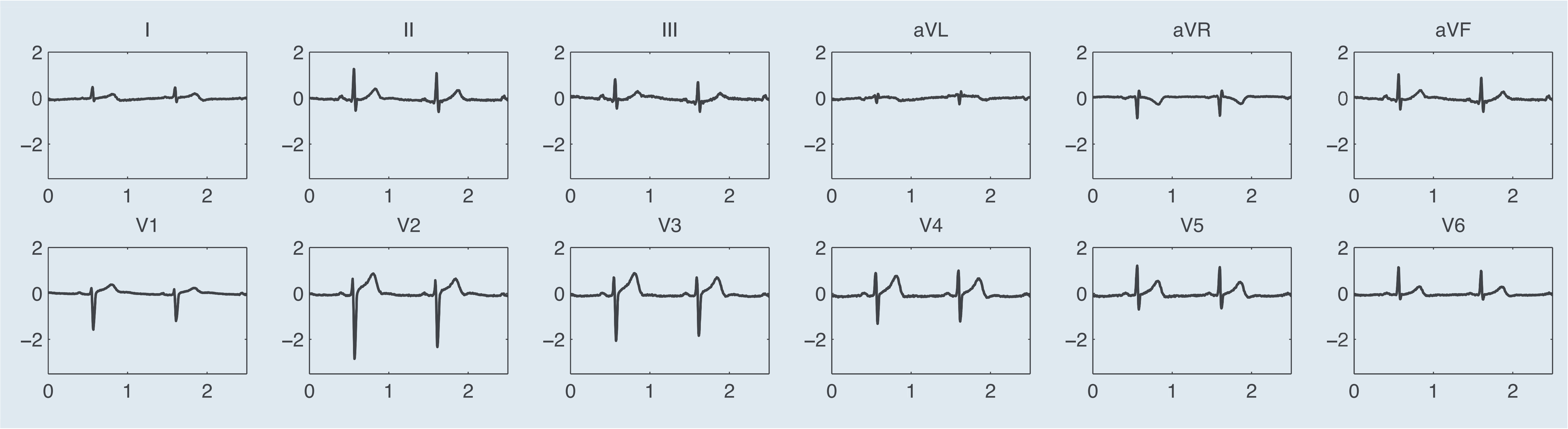
# ECG Comparison - Through Cotton




**Simultaneously acquired ECG in laboratory setting - 0.5Hz to 100Hz BW**

**No 60Hz Filter - Combination of shielding and capacitive DRL minimizes interference pickup**

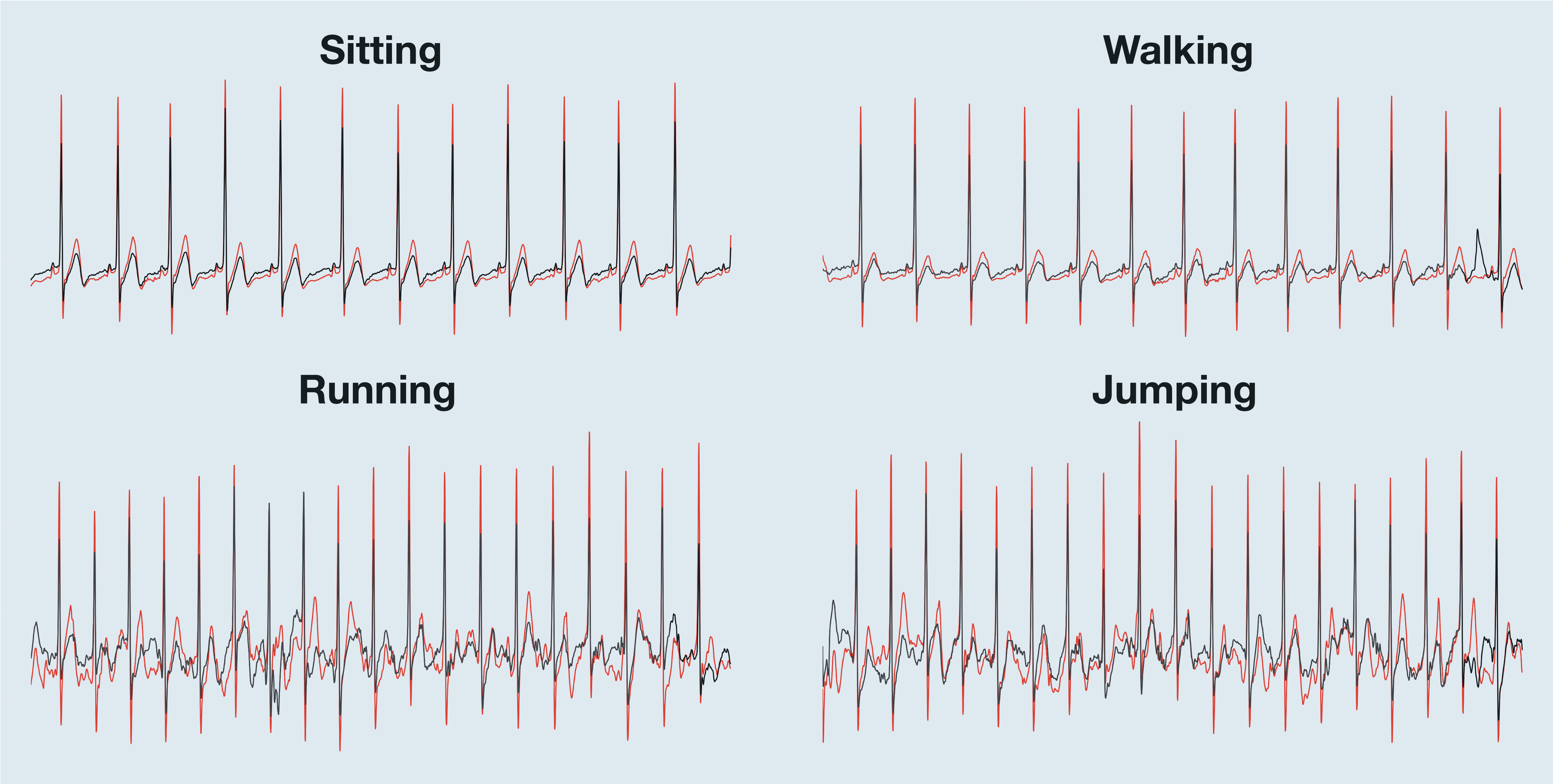
# Derived 12-Lead




**Non-contact sensor designed to be functionally equivalent to standard Ag/AgCl for signal acquisition**

**Can obtain standard vectors as conventional ECG by using correct electrode positions**

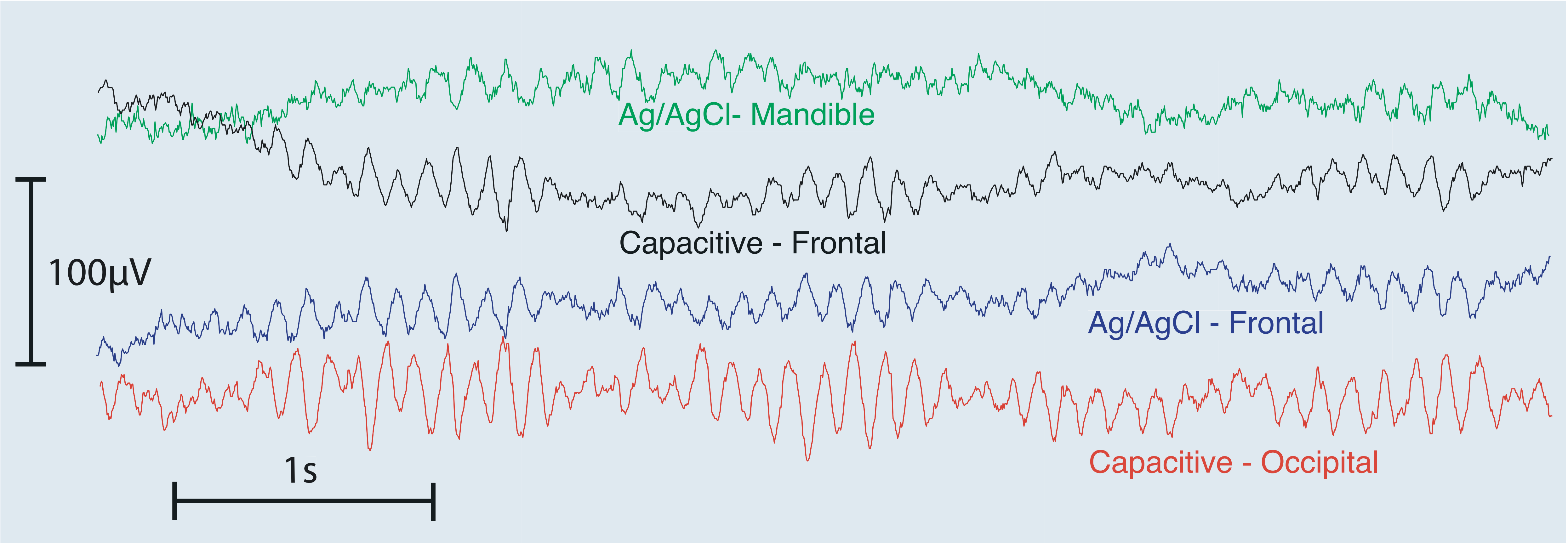
# ECG Under Motion




3M Red Dot Ag/AgCl

UCSD Non-contact

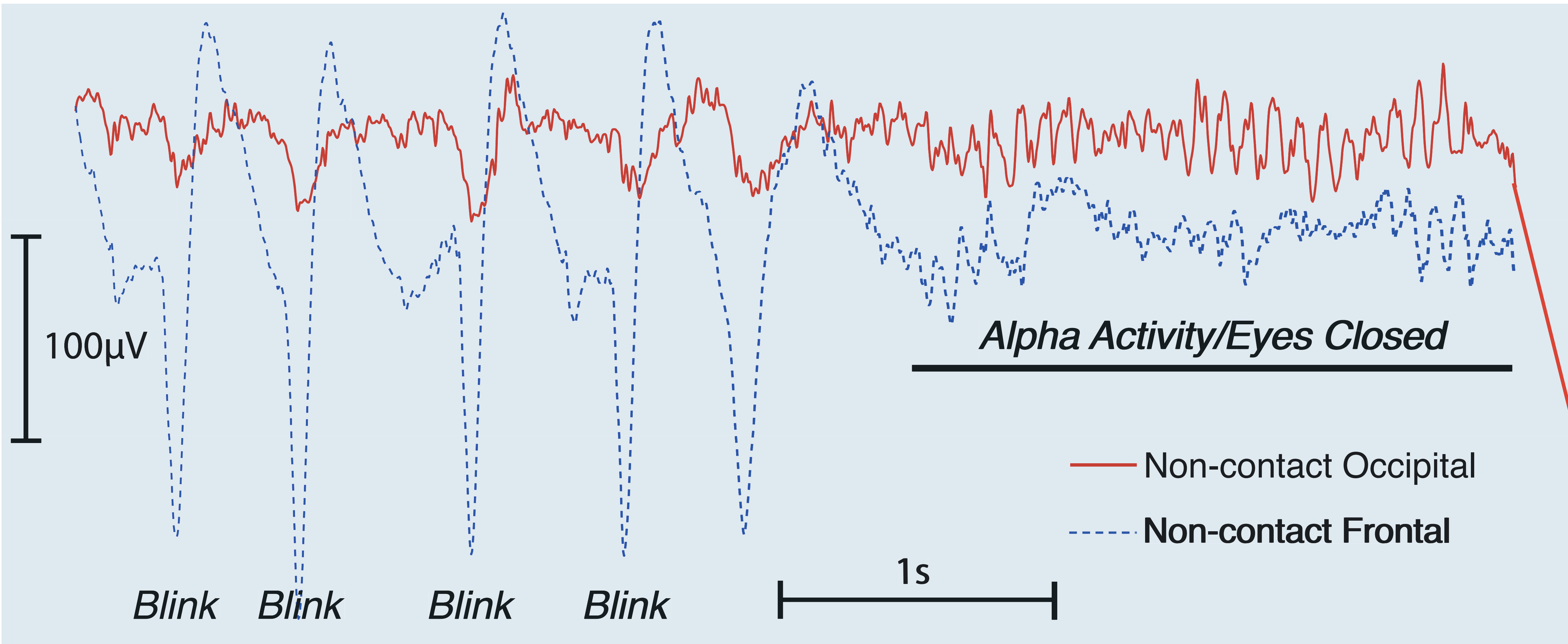
# EEG Signals




**Stationary subject with closed eyes**

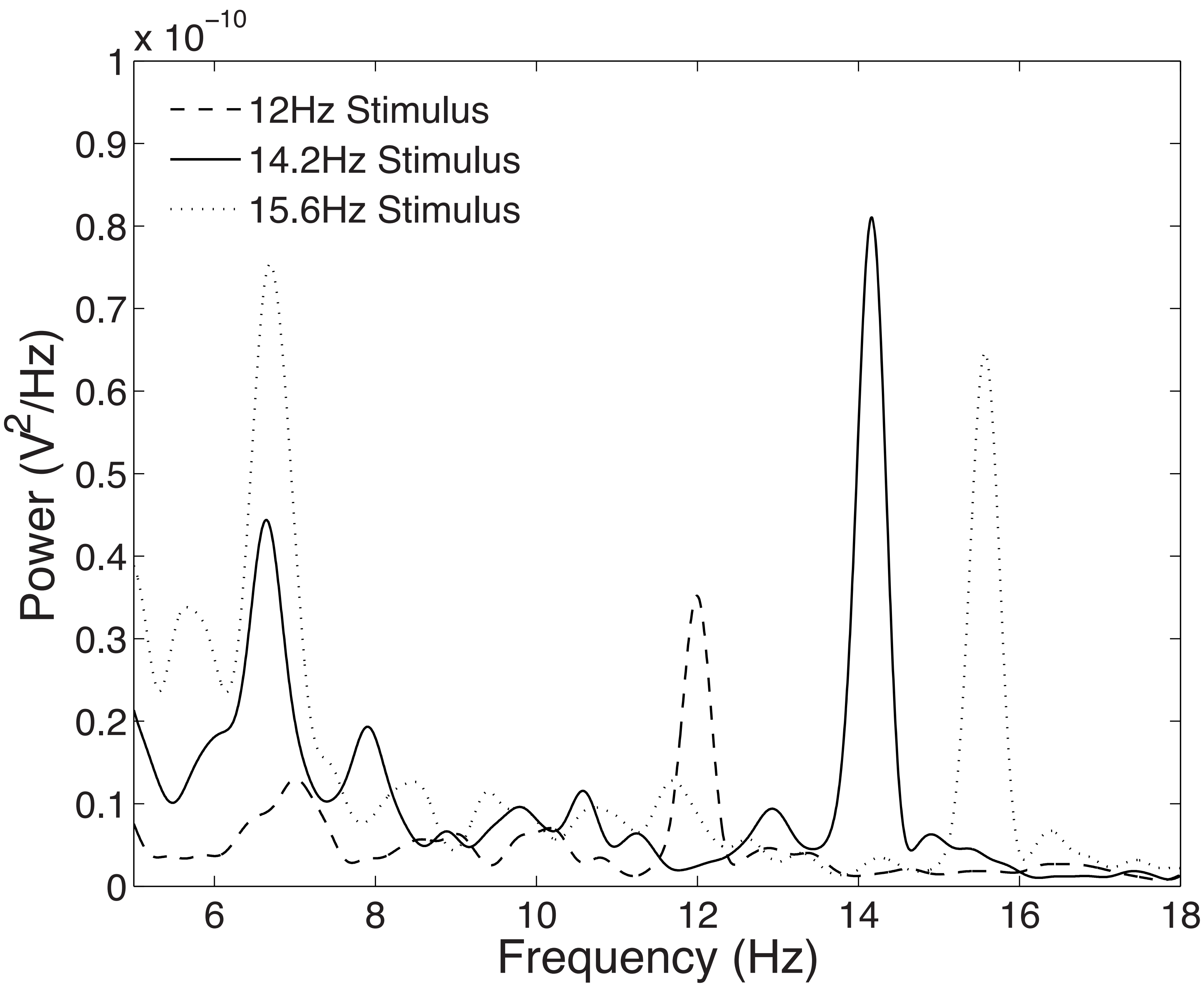
**Full bandwidth (.5-100Hz), unfiltered, signal showing alpha wave activity**

# EEG Applications

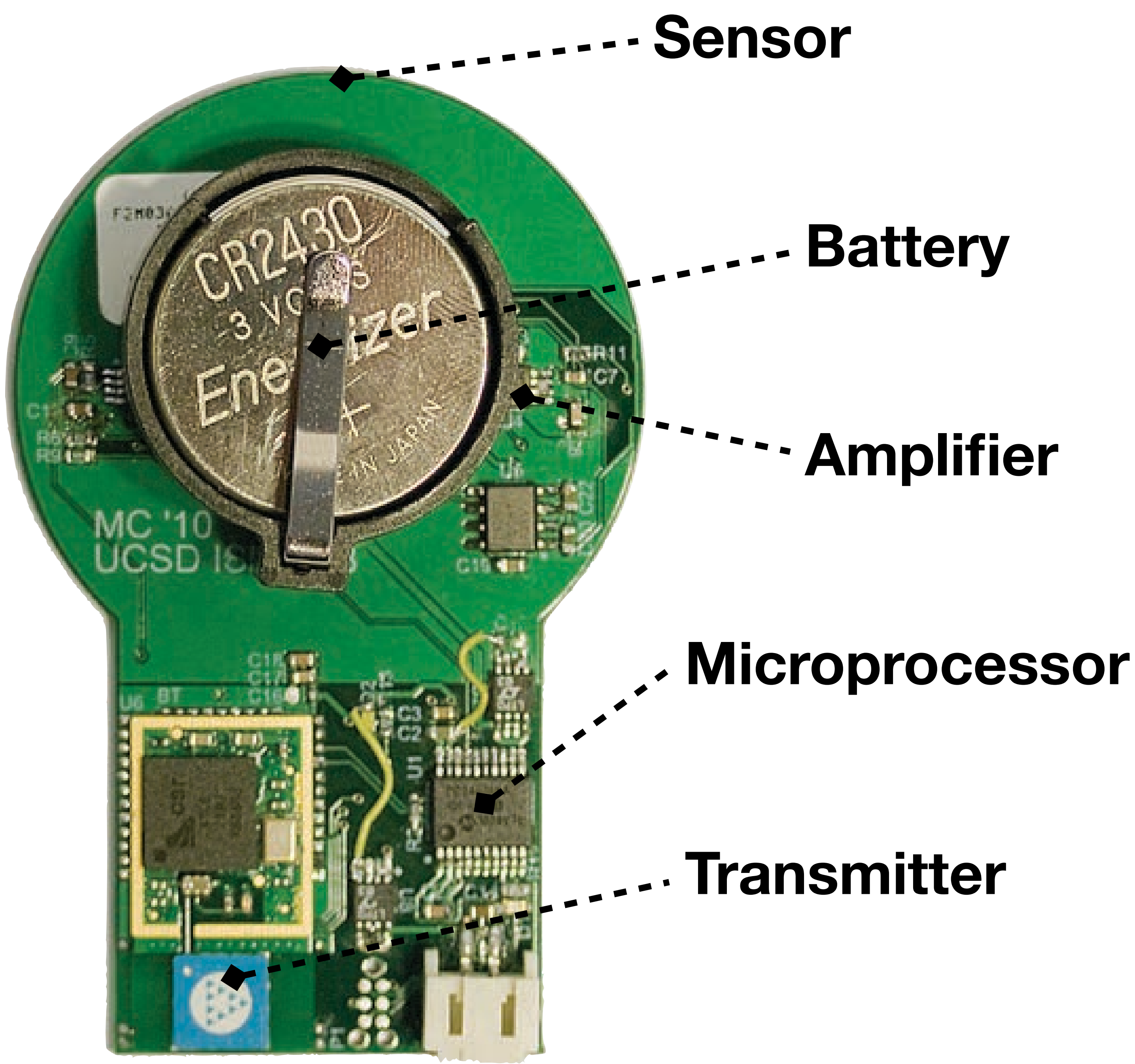



- **Access to hair-covered areas of the head without gels or slap-contact**
- **EEG data available only from the posterior**
  - **P300 (Brain-computer control, memory recognition)**
  - **SSVP (Brain-computer control)**

# EEG SSVP

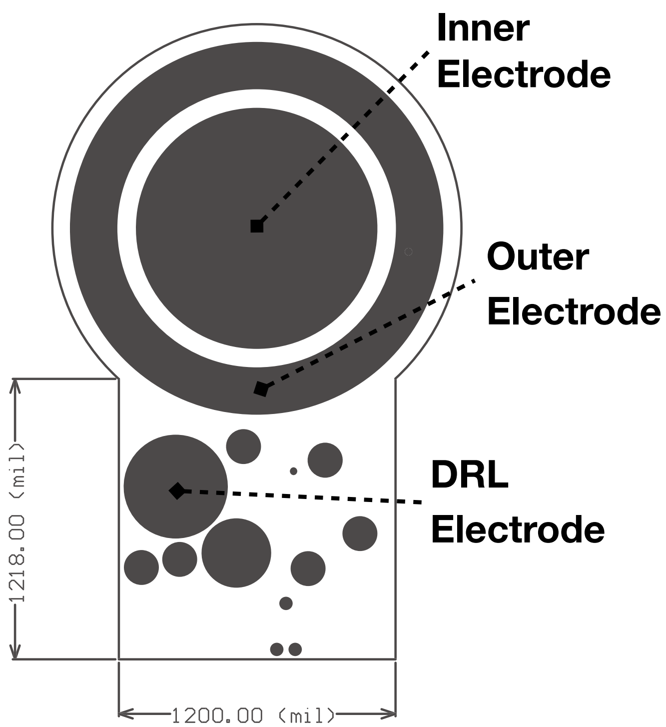

x 10^−10
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Power (V^2/Hz)
12Hz Stimulus
14.2Hz Stimulus
15.6Hz Stimulus
6
8
10
12
14
16
18
Frequency (Hz)

# ECG Tag



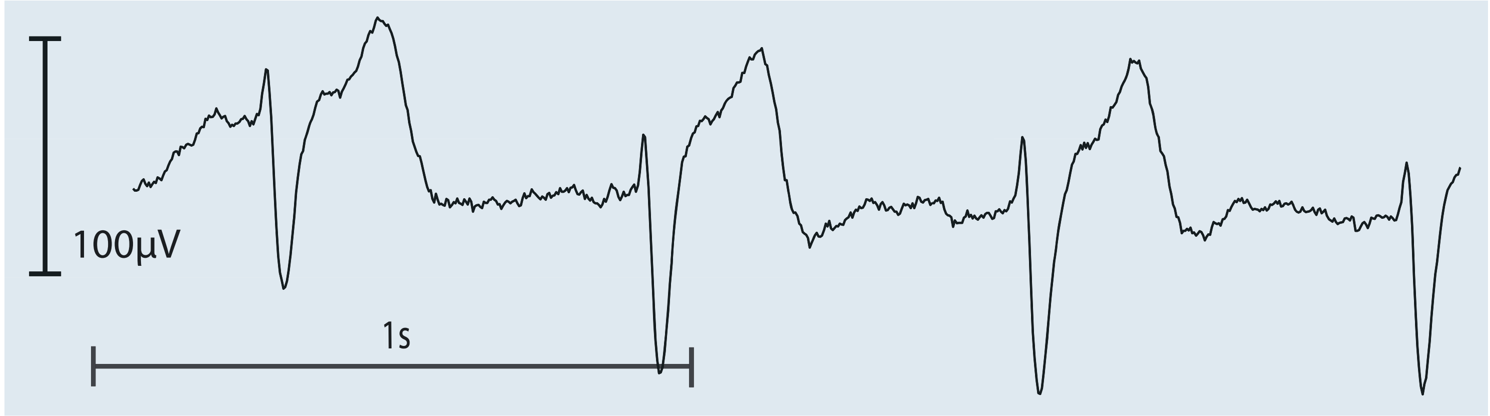

- A self-contained and truly wireless ECG sensor tag
  - No external connections, ground or reference
  - Both contact and non-contact operation
- Can obtain ECG signal on the chest, near the heart
  - QRST usually visible
- Preliminary design
  - Limited by discrete components
  - Need smaller package and lower power consumption (TX)

# ECG Tag Signals

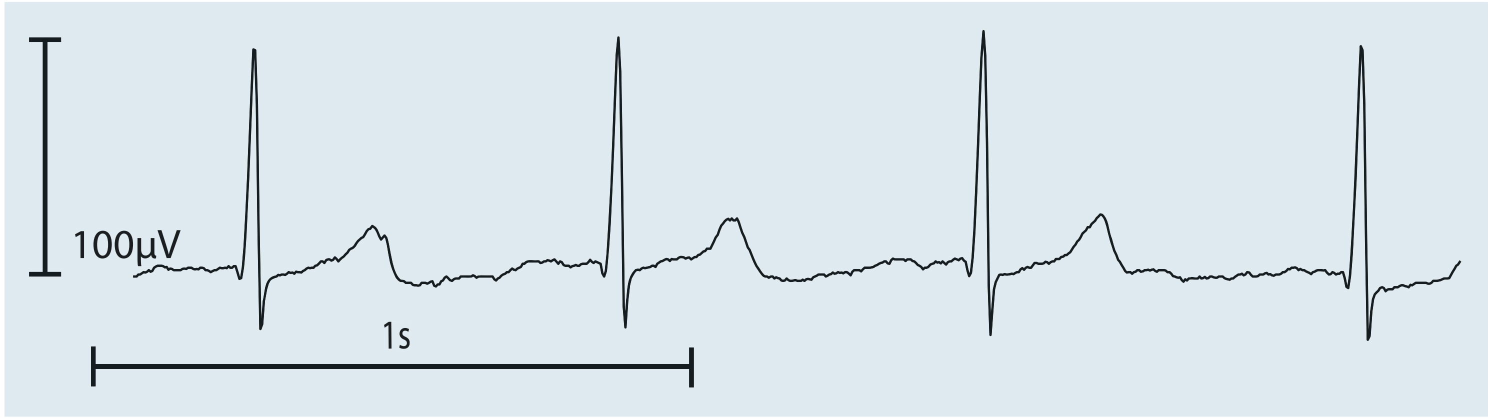



**On Skin**


**Through Shirt**




**Alternative Position**



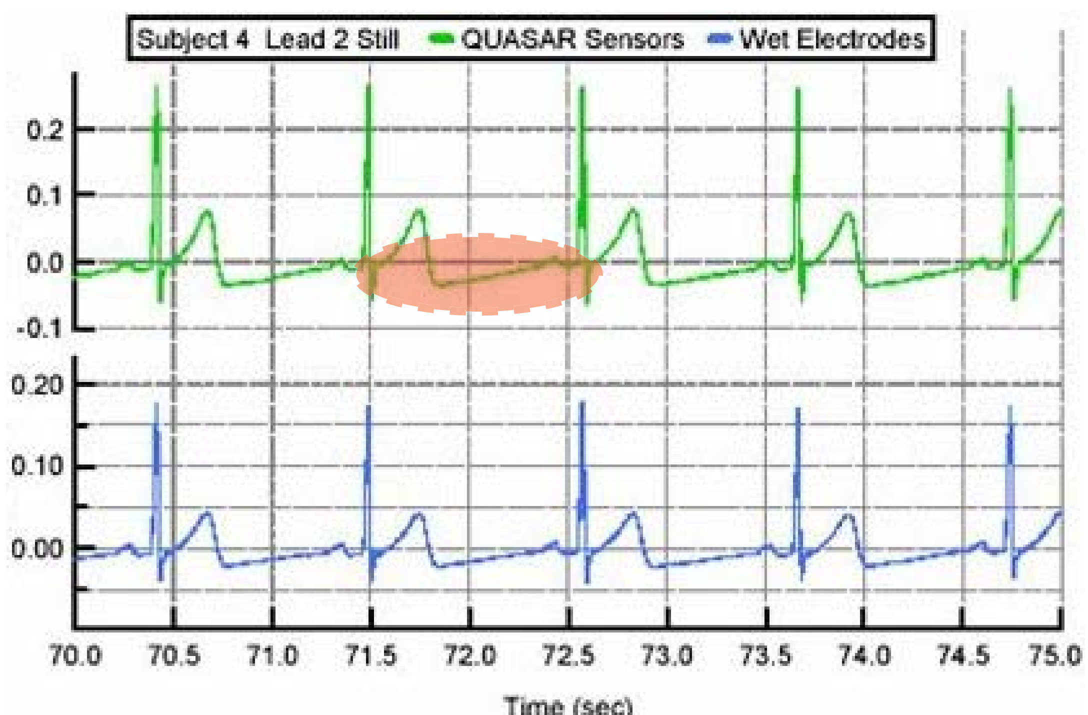


Region where ECG can be obtained

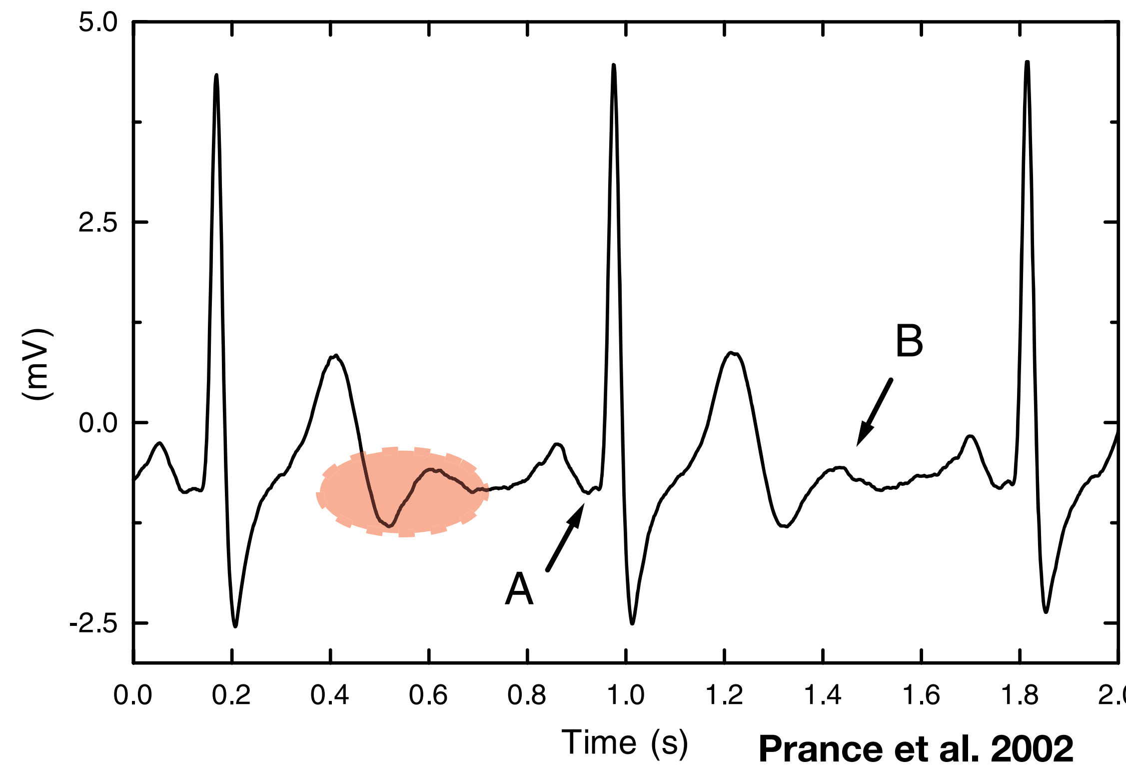
**First known report of a non-contact, self-contained, wireless ECG module**

# Limitations of Current Sensors

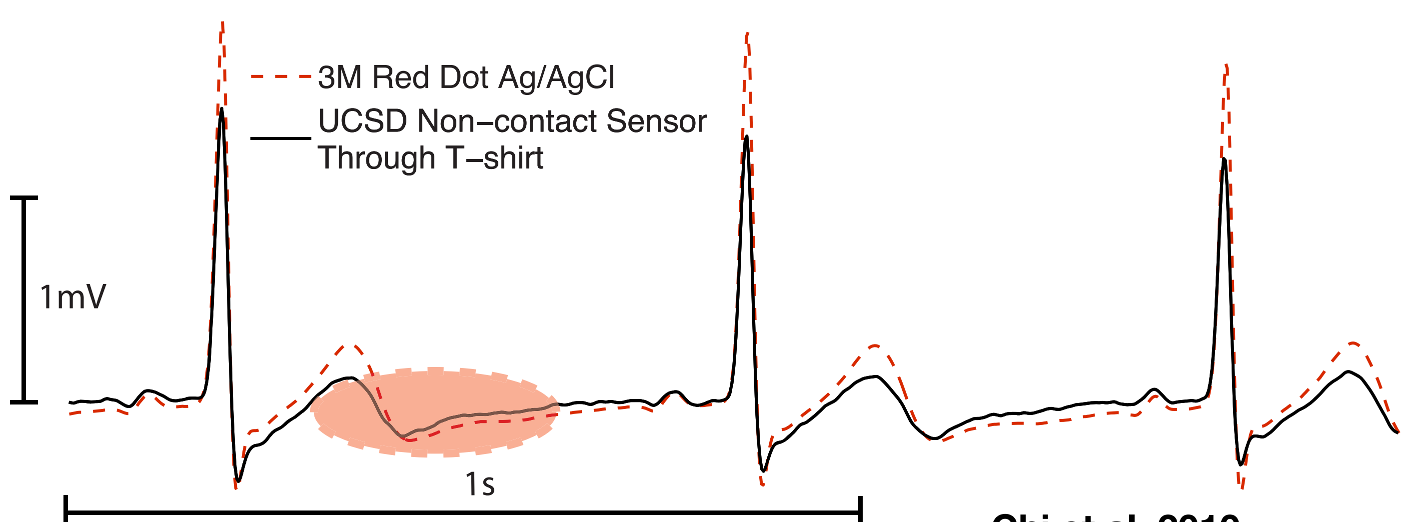
**Inadequate frequency response for clinical ECG (AAMI requires down to 0.05Hz):**




**Quasar, Inc.**




**Prance et al. 2002**

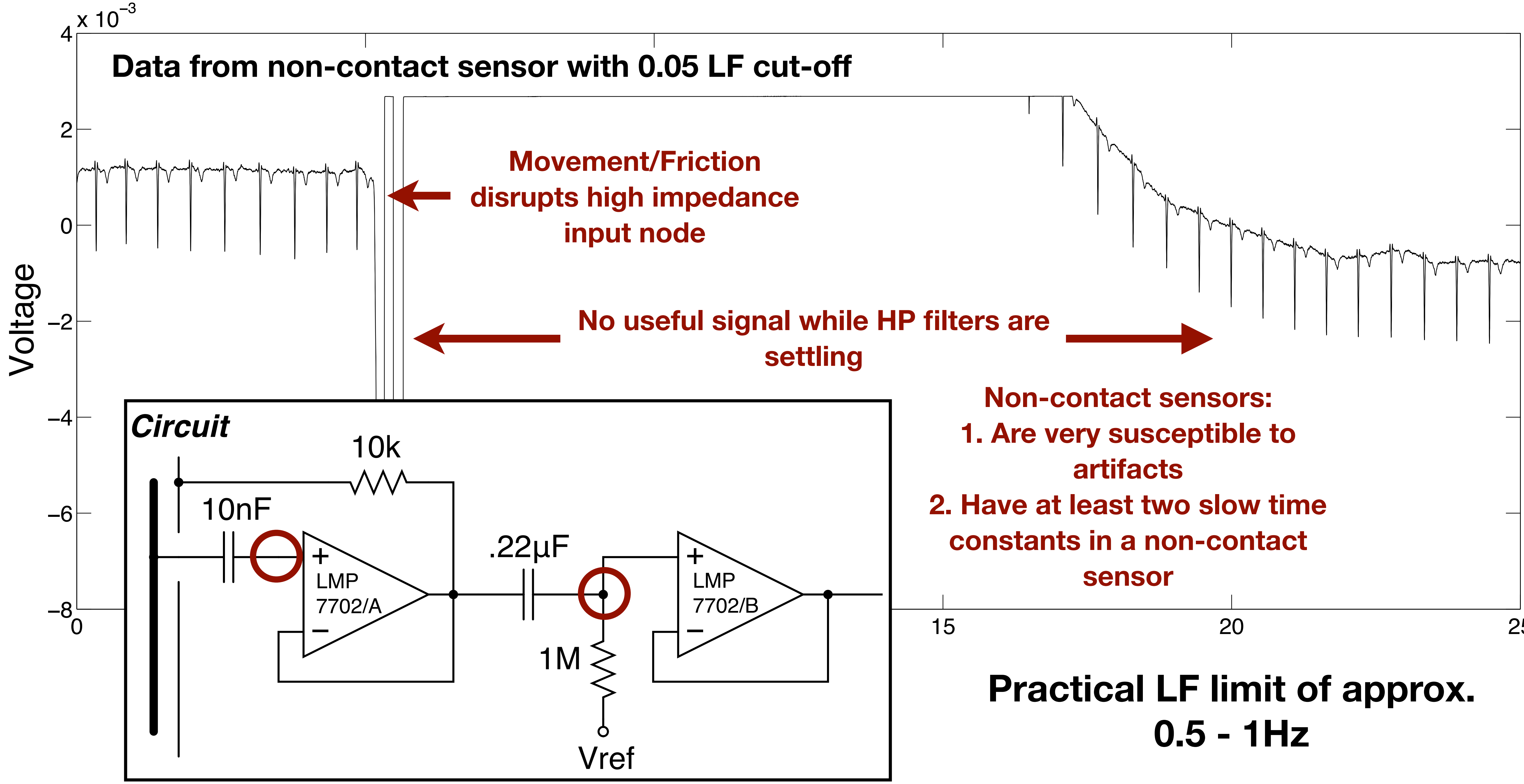



**Chi et al. 2010**

**Signs of excessive filtering ($f_{HP}$~0.5Hz) showing difficulty in maintaining stable low frequency operation**

# Limitations - Motion Artifacts

**Ideally want sensor to have frequency response to 0.05Hz for clinical ECG**



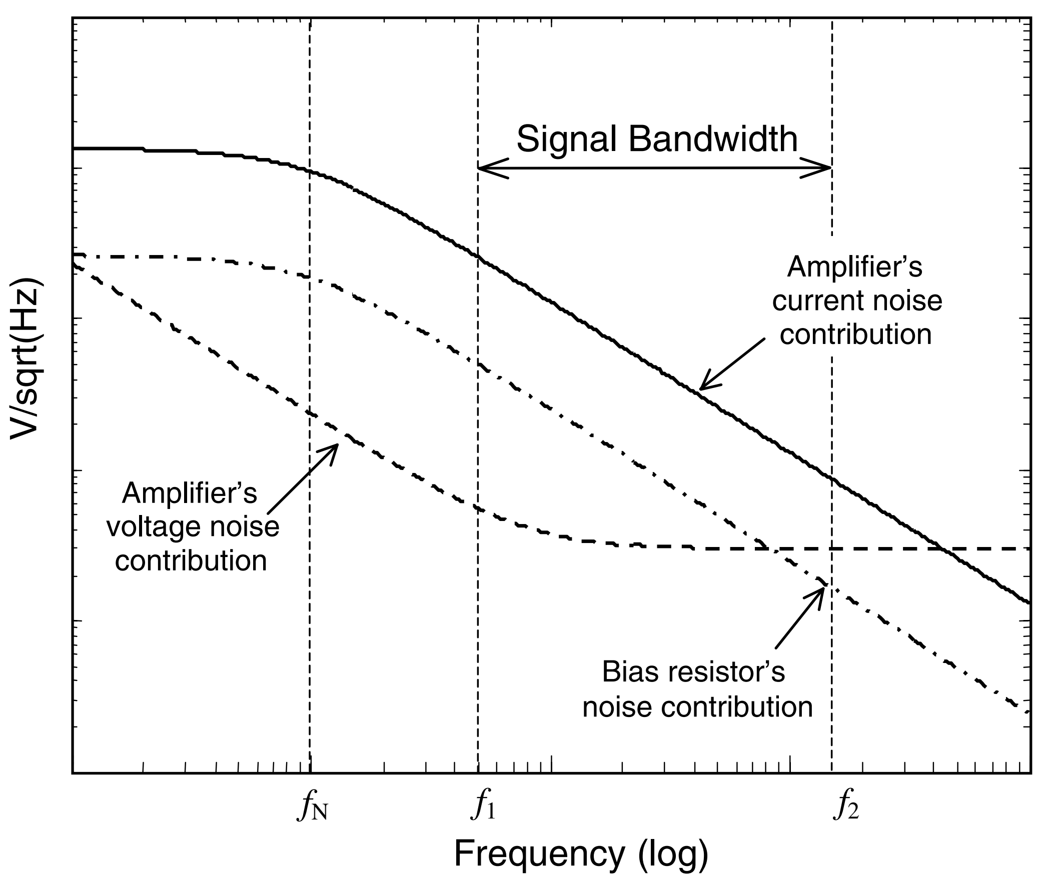

**Practical LF limit of approx. 0.5 - 1Hz**

**Unresolved tradeoff between low-frequency stability/recovery time versus signal accuracy**

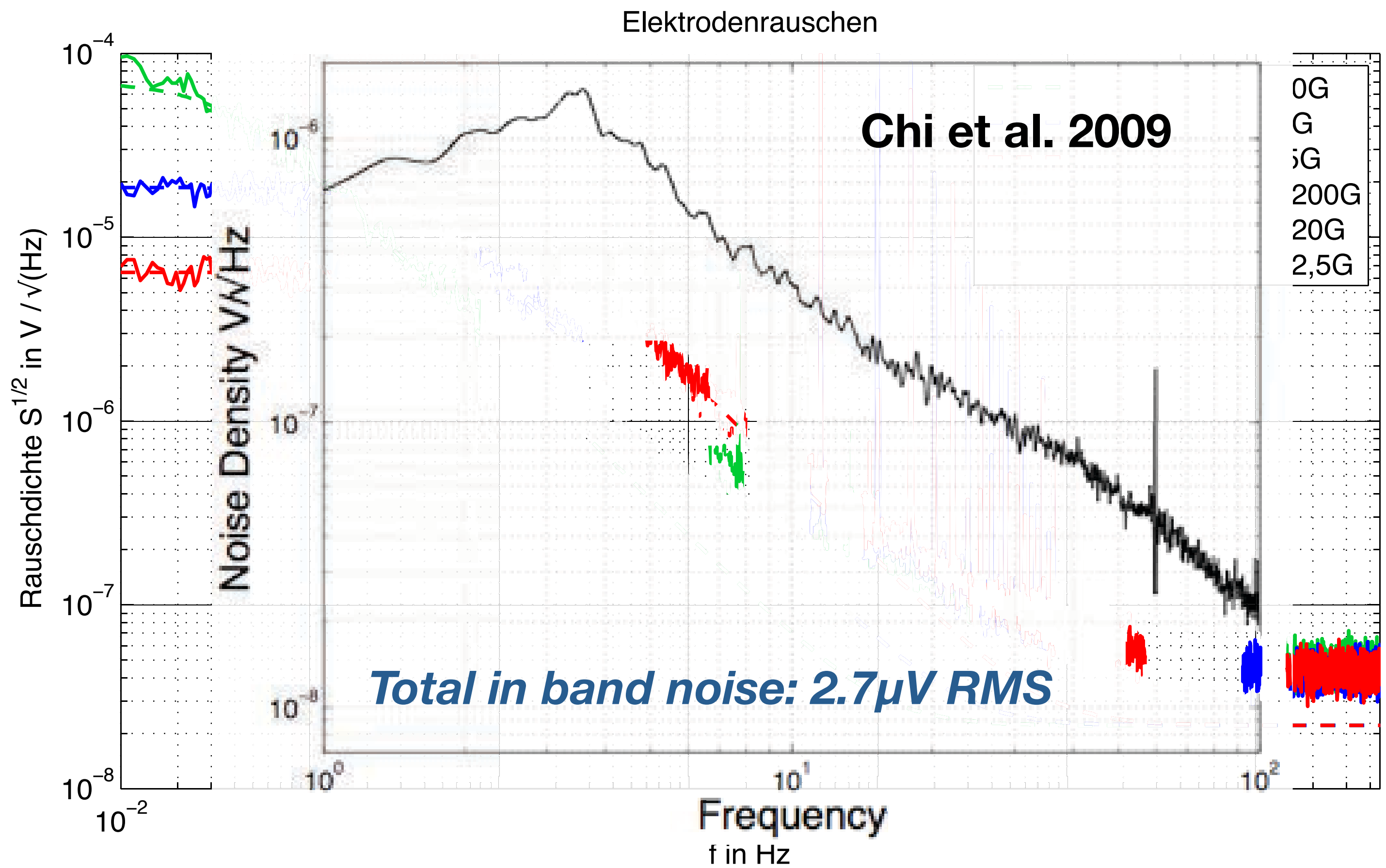
# Previous Attempts at Noise Modeling

**Noise limits based on coupling to purely capacitive source:**

$$v_n^2 = [v_{na}^2(1 + \frac{C_{in,0}}{C_s})^2 + \frac{i_n^2}{\omega^2 C_s^2}]\Delta f$$




**Spinelli et al. 2010**




**Oehler et al. 2008**

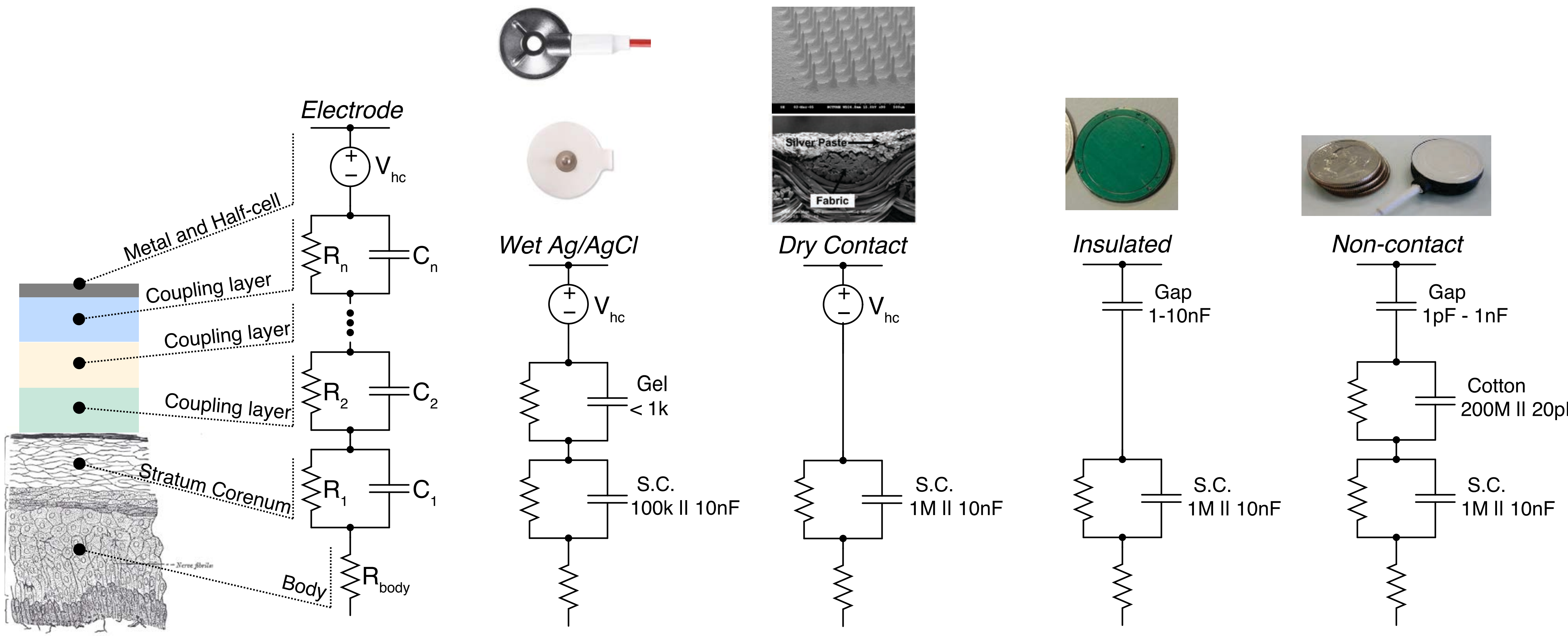
**Previous understanding in literature has always used the model of an ideal capacitive source for noise modeling - assumption that noise can be reduced with improved circuit design and components (eg. lower current noise).**

**While benchtop measurements corroborate theory - actual noise for ECG/EEG on subjects is *always much higher than what the noise equations predict.***

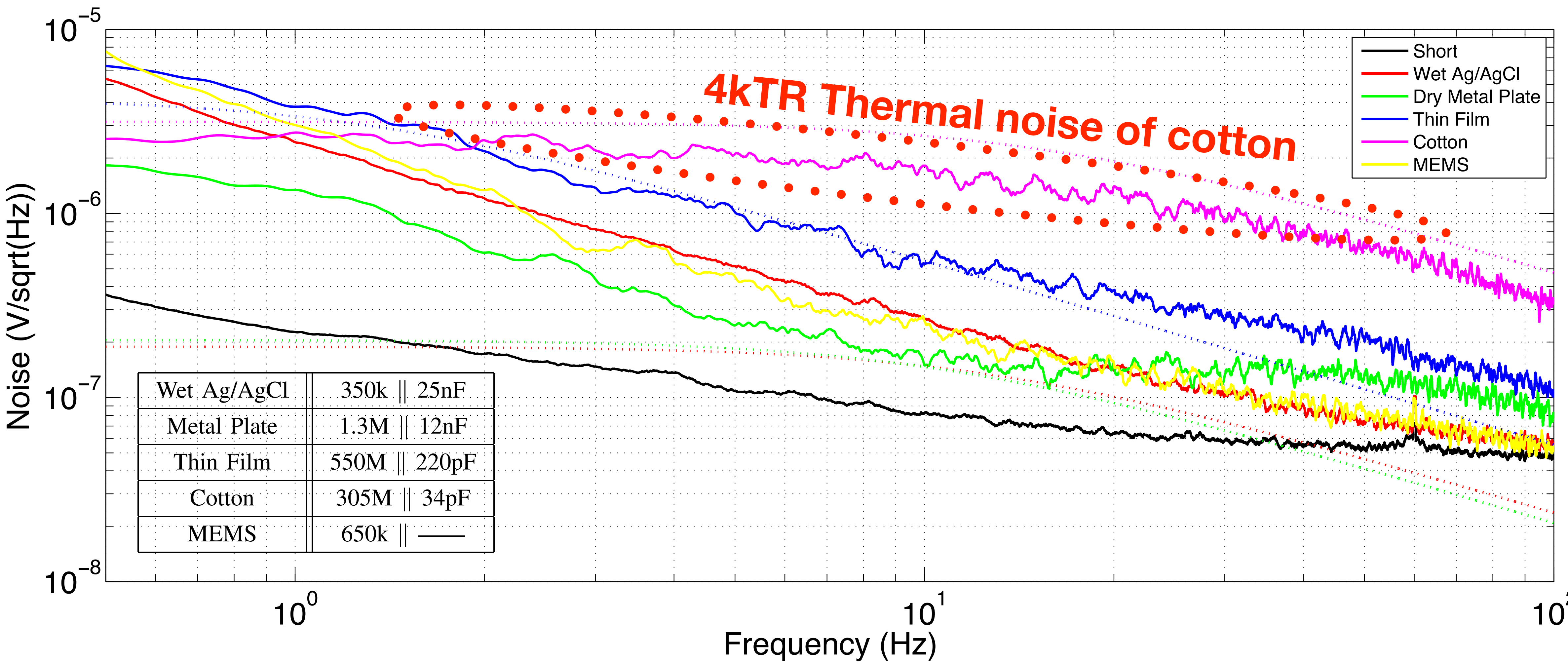
# Noise in ‘Capacitive’ Biopotential Electrodes

**Noise equations work if the coupling was through a near ideal dielectric (eg. air gap) - not practical for E*G applications**

**Must also consider the properties of the coupling medium between the sensor and body - cotton, hair, etc.**



# Measured Interface Noise Spectra

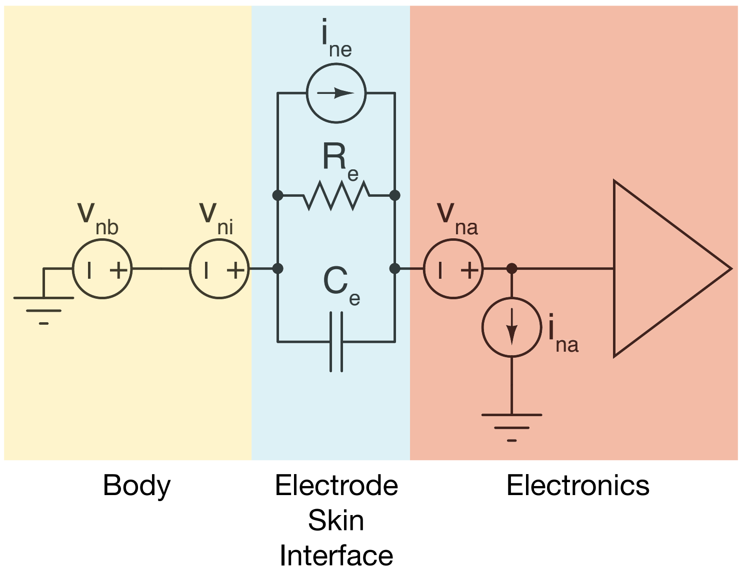



**Coupling media may actually generate the largest amount of noise within the signal bandwidth:**

**Cotton shirt - 3µV/Hz$^{1/2}$**

Yu M. Chi, Tzyy-Ping Jung, Gert Cauwenberghs, IEEE Reviews in Biomedical Engineering, 2010

# Implications for Non-contact Sensors



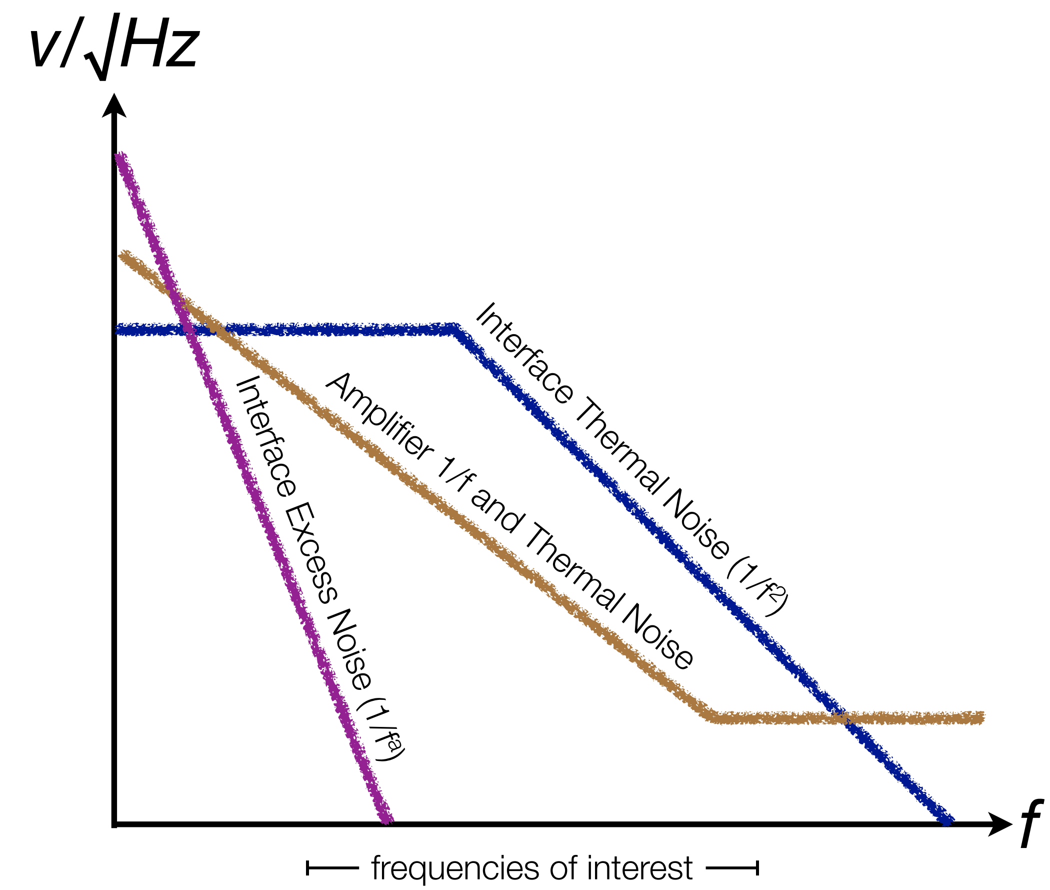

**$V_{nb}$ - biological noise**
**$V_{ni}$ - electrochemical interface noise, $1/f^a$, ~1uV/Hz$^{1/2}$ at 1Hz**

**Interface thermal noise:**

$$v_{ne}^2 = \frac{4kTR_e}{1+\omega^2 C_e^2 R_e^2}\Delta f$$

**R = 0 and R = ∞ are optimal (!)**

**Electronic noise - same as previously analyzed**




**Key Difficulty:**

**Some insulation (eg. cotton) generate large amounts of thermal noise (300MΩ) yet do not have enough shunt capacitance (~20pF) within ECG/EEG frequency bands**

**Not all insulations are created equal - materials is also a very important consideration**

**Yu M. Chi, Tzyy-Ping Jung, Gert Cauwenberghs, IEEE Reviews in Biomedical Engineering, 2010**

# Summary

- **Designed, simple and robust non-contact sensor based on standard electronics technology**
  - **Several prototypes, including a fully wireless version**
  - **Signal quality can be comparable to Ag/AgCl electrodes**
  - **Enabler of ubiquitous, wearable, wireless and mHealth applications**
- **Challenges**
  - **Interference, 60Hz rejection and most electronics problems are well understood and can be solved with careful design**
  - **Coping with motion artifacts remain the one hard unsolved, engineering problem. Mechanical and signal processing innovation will be important.**
  - **Finding the right application**