Biomedical sensors

生醫感測器

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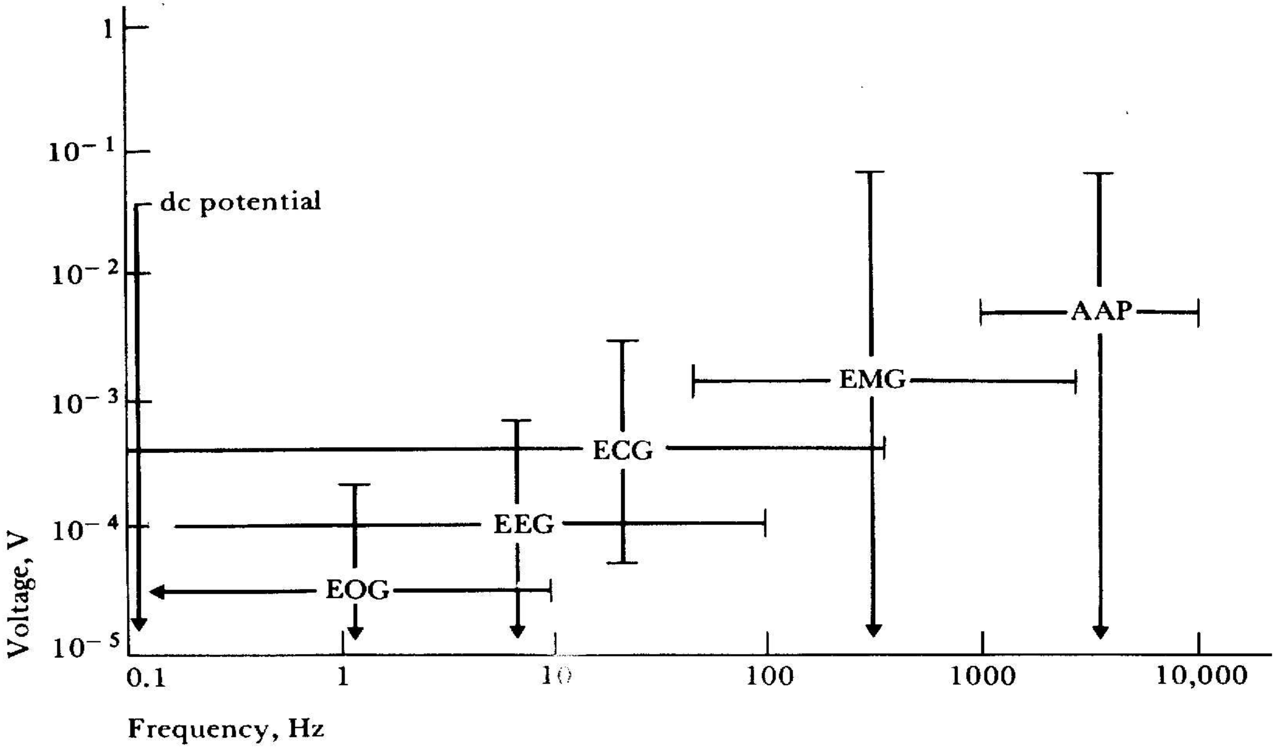
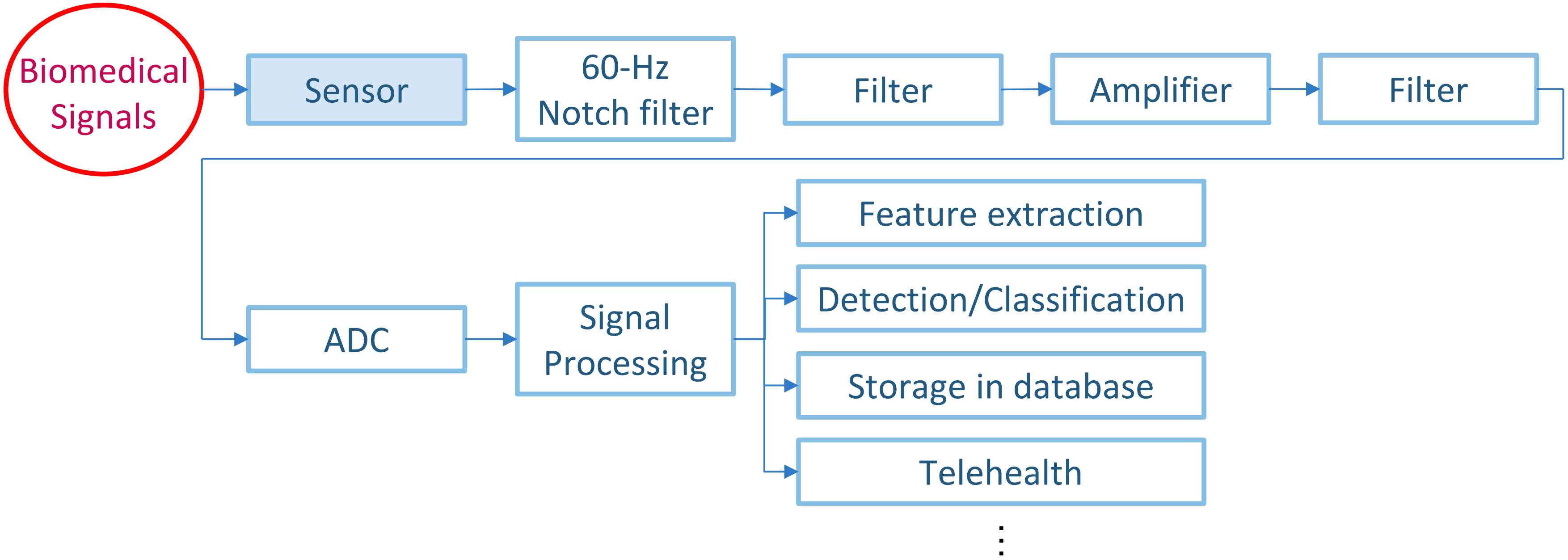
Properties of biomedical signals

- Weak in signal intensity
- Easily interfered by ambient noise
- High variability
- Safety and reliability is important

Range of common bioelectric signals



Flowchart of biosignal measurement



Biomedical sensor

- Transform one signal/energy to another one
  - Also termed as transducer
  - Ex: stress → voltage, temperature → resistance
- To measure a specific physiological parameter
  - In vitro: concentration of electrolytes, enzyme,…
  - In vivo: blood pressure, oxygen saturation level,…
- Accuracy, reliability, and portability

Biomedical sensors

- Biopotential
- Displacement, velocity, force, pressure
- Temperature
- Blood O_2/CO_2, PH value

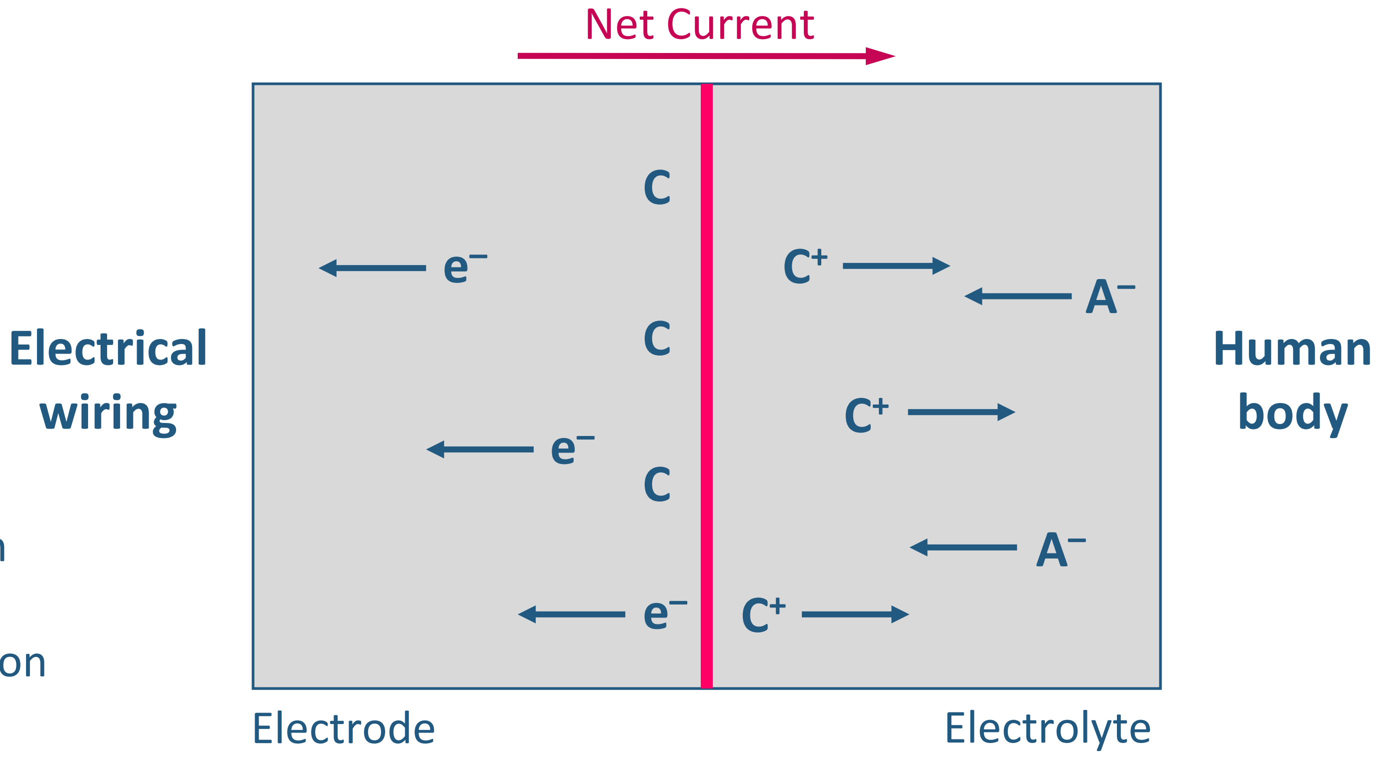
Biopotential sensor

- Electrodes: to sense the ion distribution
- Capable of conducting currents across the interface between the body and the measuring circuit
  - Ionic current → electronic current?
  - High impedance of skin (~MΩ)

How to measure?

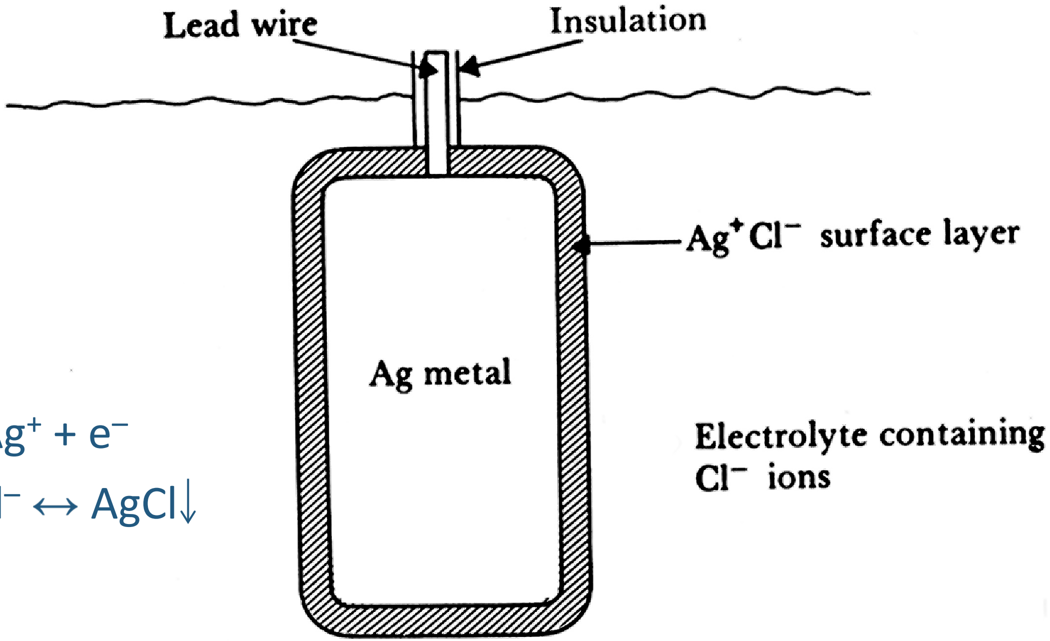
- Ions can not flow into the electric wire directly, and vice versa.
- The ionic flow has to be transformed to an electronic current at the interface.
  - Reduction-oxidation reaction (Redox)

Electrode-electrolyte interface



C^+: cation
A^-: anion
e^-: electron

Ag/AgCl Electrode



$Ag \leftrightarrow Ag^{+} + e^{-}$

$Ag^{+} + Cl^{-} \leftrightarrow AgCl\downarrow$

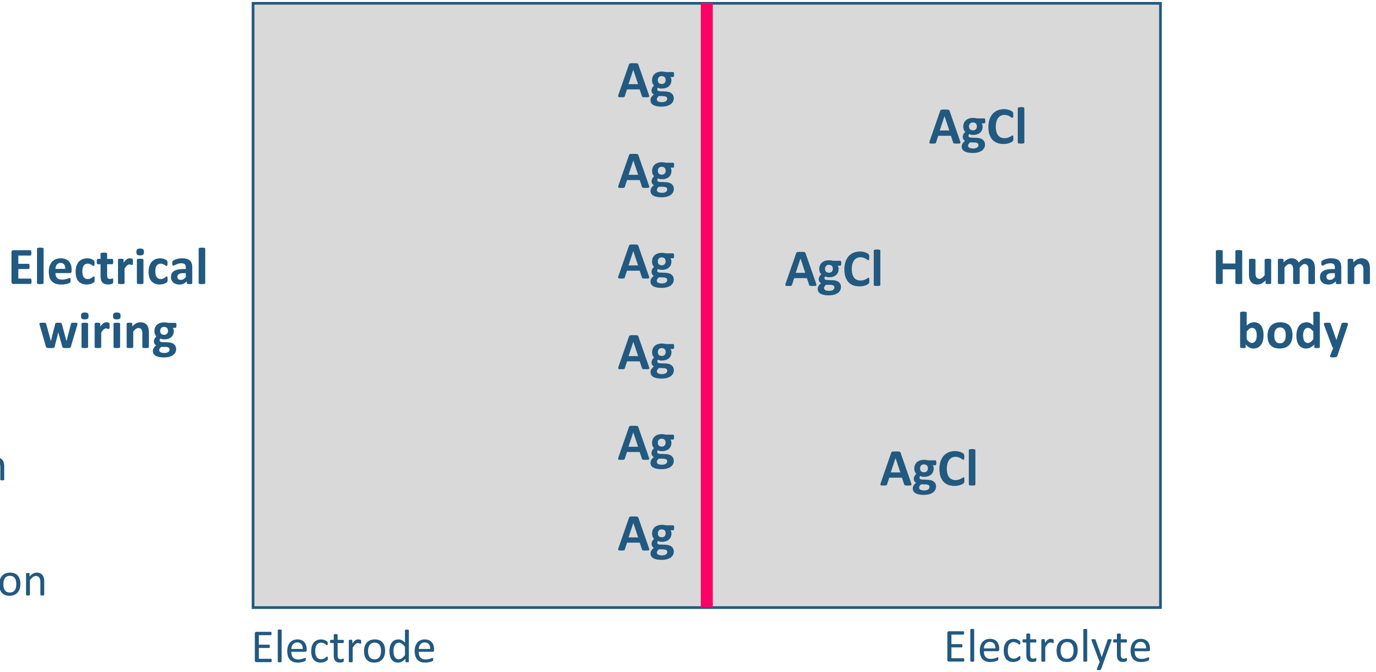
Rich Cl^{-} ions in human body

Improve conductivity of electrodes

- Conductive paste is usually applied on the surface of electrodes as electrolyte.

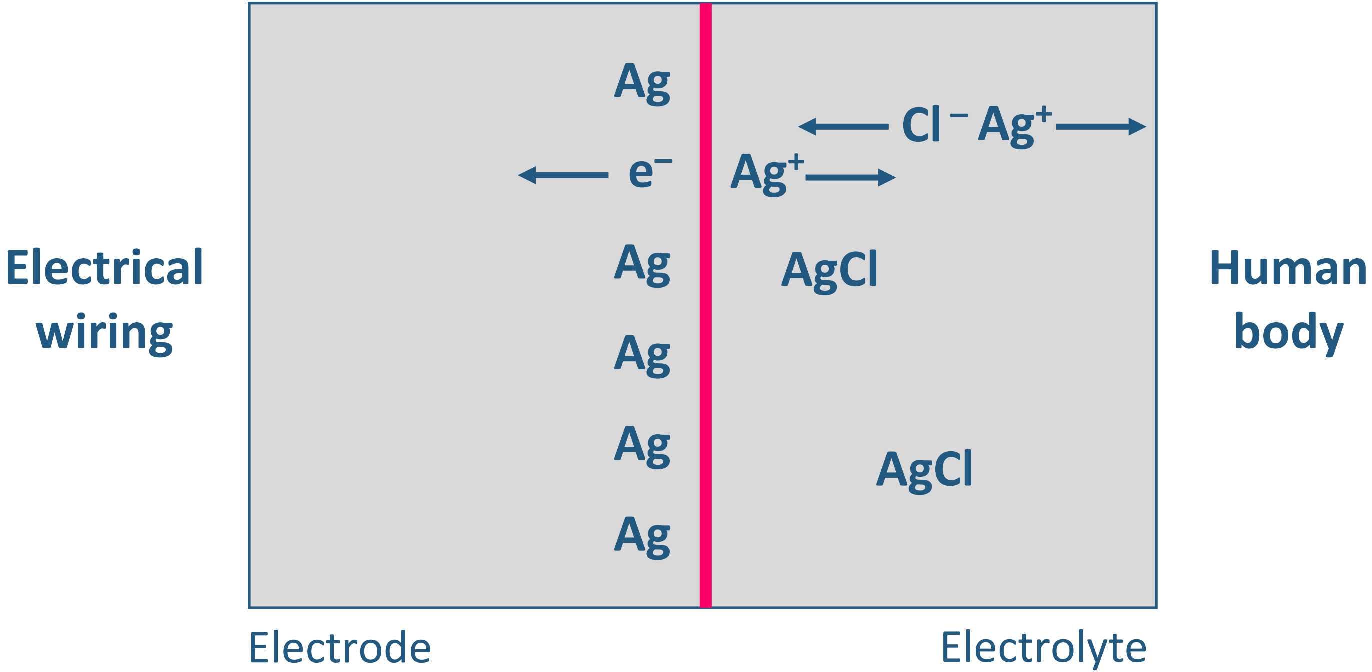
- Half-cell potential
  - An DC offset at the interface

Let check it out from beginning…

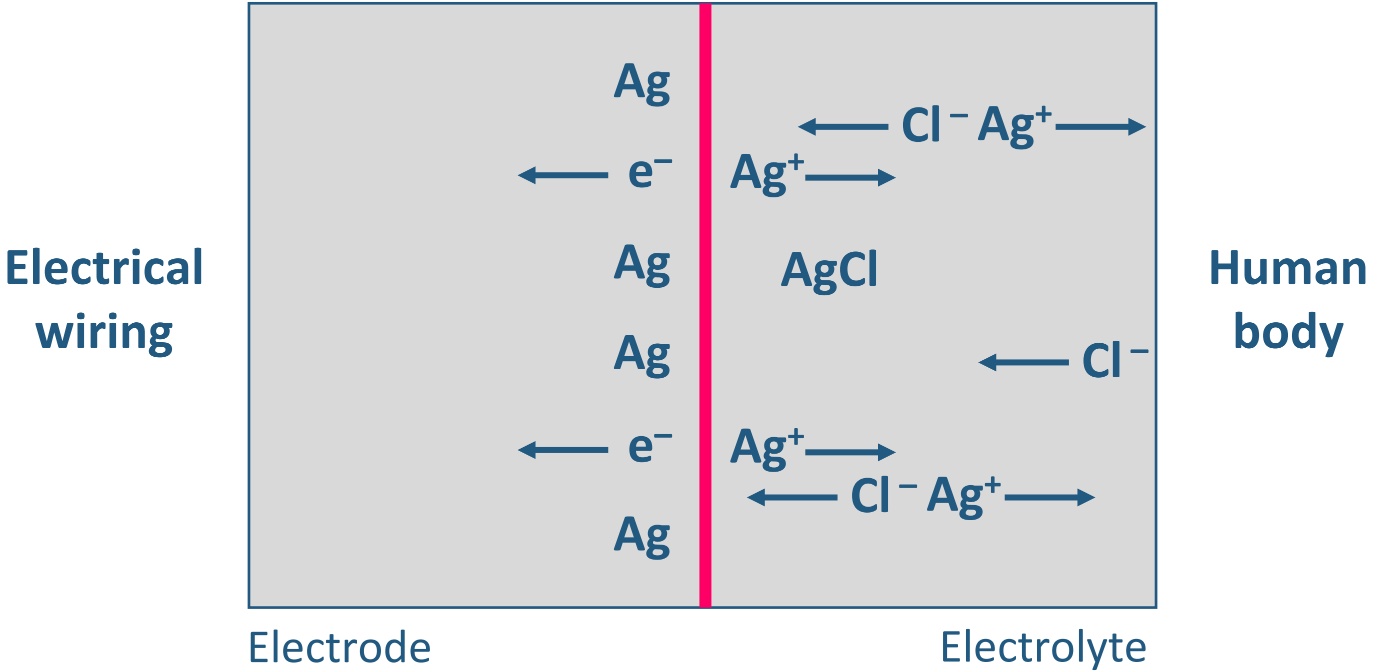


C^{+}: cation
A^{-}: anion
e^{-}: electron

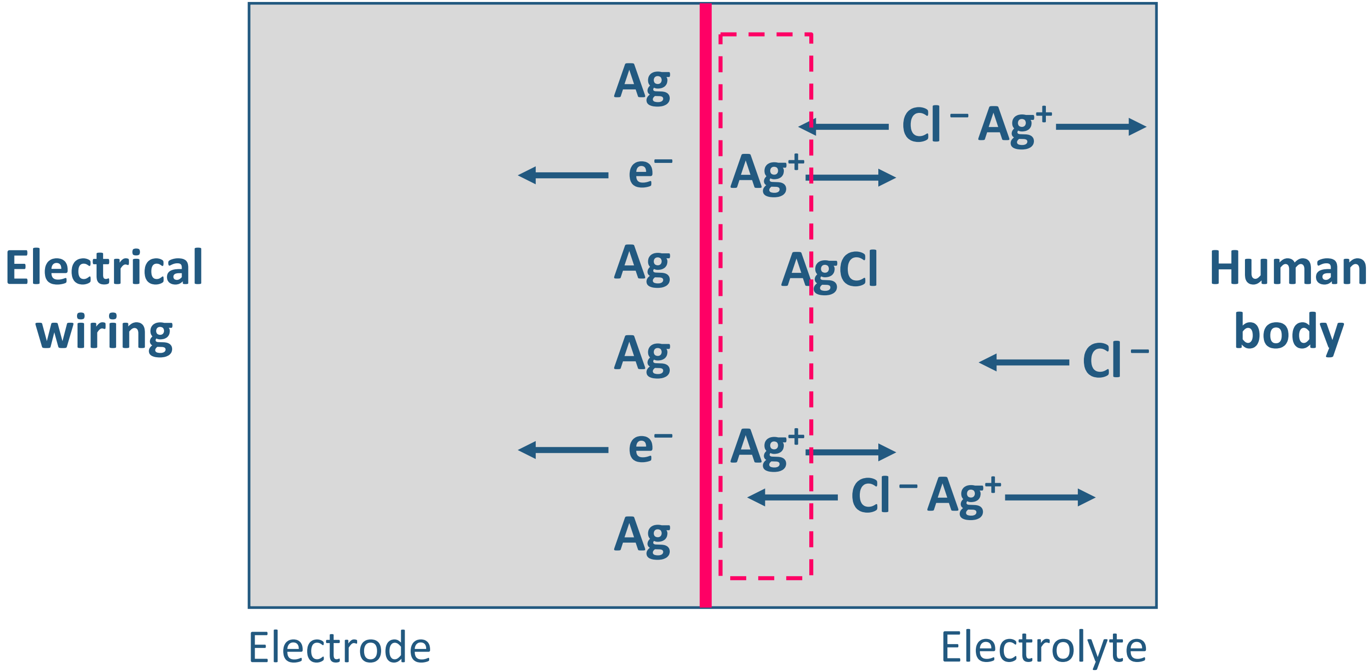
Oxidation of Ag begins…



Oxidation of more Ag …



Helmholtz double layer structure



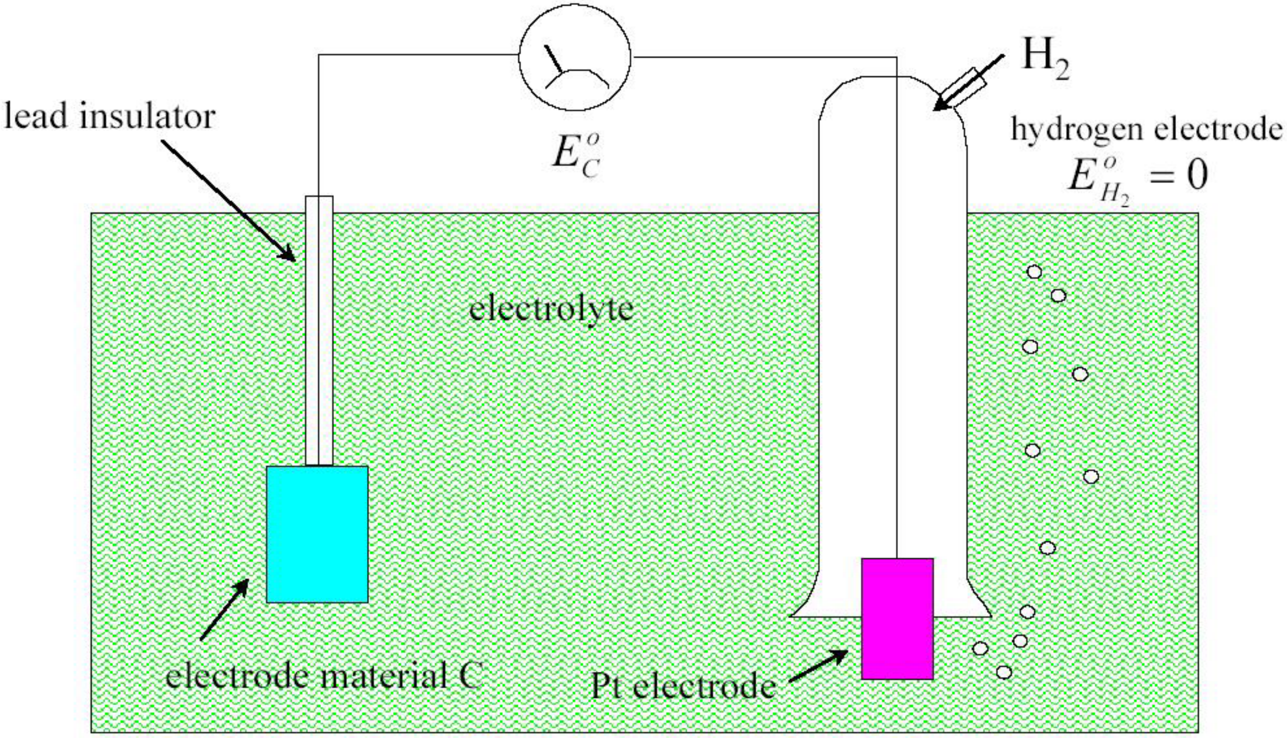
Half-cell potential

- The potential introduced by the double layer structure between the electrode and the electrolyte
- Its value is influenced by the type of metal, ion concentration, temperature…
  - DC offset, which can be removed by high-pass filter

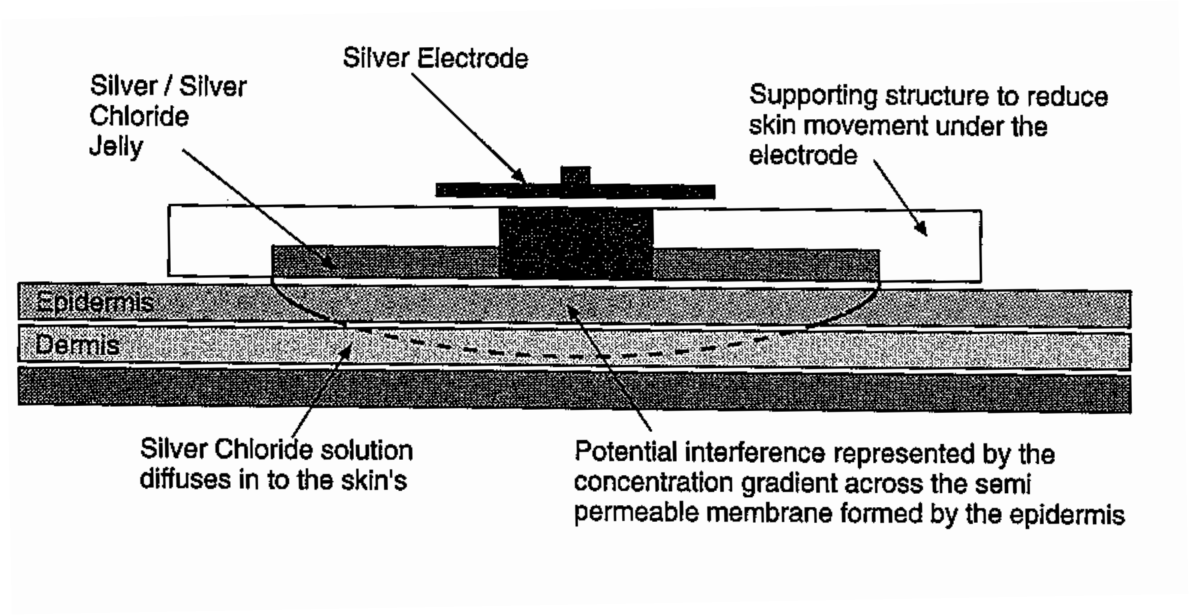
Half-cell potentials at 25℃

reduction reaction	E^o (V)	
$Al^{3+} + 3e^- \rightarrow Al$	-1.662	
$Zn^{2+} + 2e^- \rightarrow Zn$	-0.762	
$Cr^{3+} + 3e^- \rightarrow Cr$	-0.744	
$Fe^{2+} + 2e^- \rightarrow Fe$	-0.447	
$Cd^{2+} + 2e^- \rightarrow Cd$	-0.403	
$Ni^{2+} + 2e^- \rightarrow Ni$	-0.257	
$Pb^{2+} + 2e^- \rightarrow Pb$	-0.126	
$2H^+ + 2e^- \rightarrow H_2$	0.000	→ By definition
$AgCl + e^- \rightarrow Ag + Cl^-$	$+0.222$	→ Commonly adopted as ECG electrodes due to its high stability and low half-cell potential
$Hg_2Cl_2 + 2e^- \rightarrow 2Hg + 2Cl^-$	$+0.268$	
$Cu^{2+} + 2e^- \rightarrow Cu$	$+0.342$	
$Cu^+ + e^- \rightarrow Cu$	$+0.521$	
$Ag^+ + e^- \rightarrow Ag$	$+0.780$	

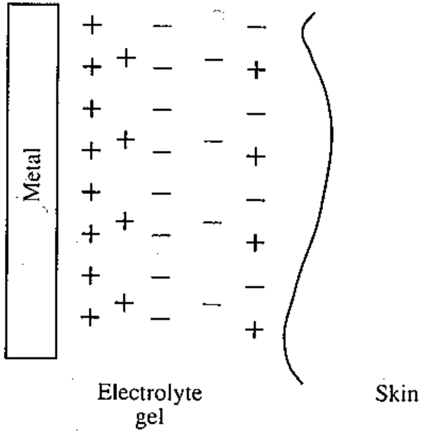
Measurement of half-cell potential

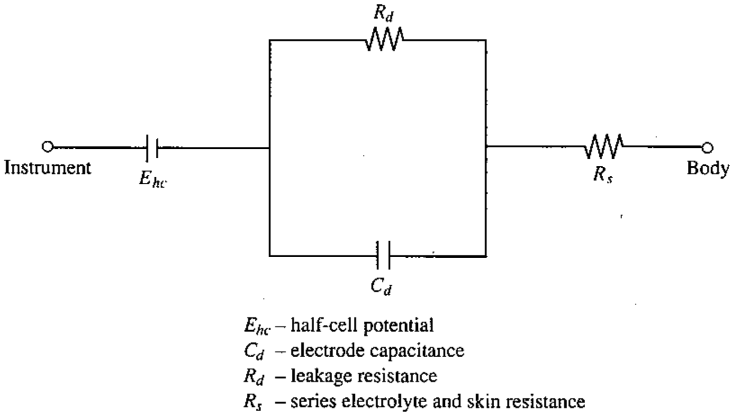


Ag/AgCl Electrode



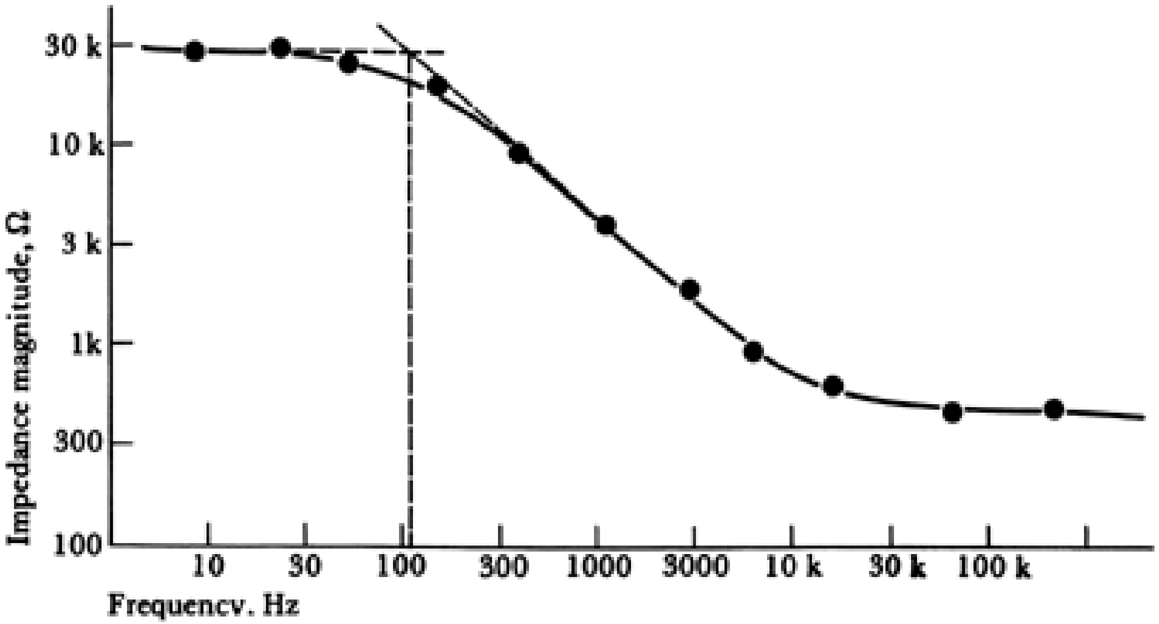
Equivalent circuit of an electrode





$$Z = R_s + \frac{R_d}{1 + j2\pi f C_d R_d}$$

Frequency response of impedance

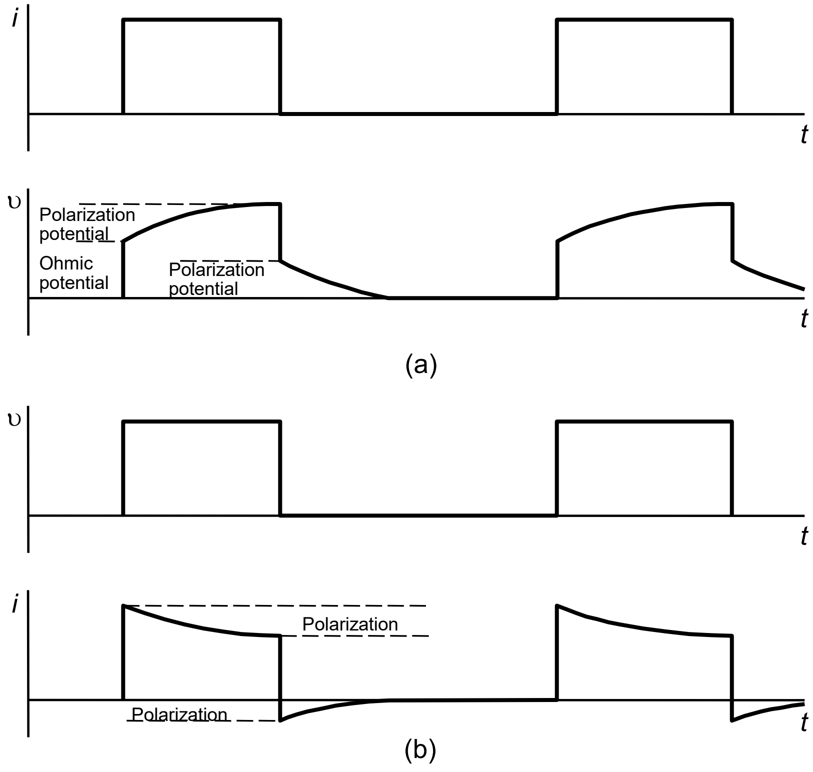


Experimentally determined magnitude of impedance

V/I waveforms for stimulations

(a) Constant-current stimulation

(b) Constant-voltage stimulation

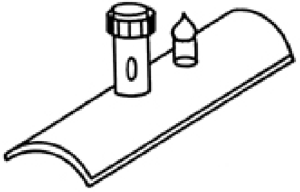


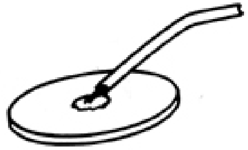
Motion artifacts of electrodes

- Distribution of ions across the interface would reach an equilibrium.
  - Double layer structure
- Once the electrode moves, the re-distribution of ions results in changes of potentials immediately.
  - Interference for measurement of biopotentials

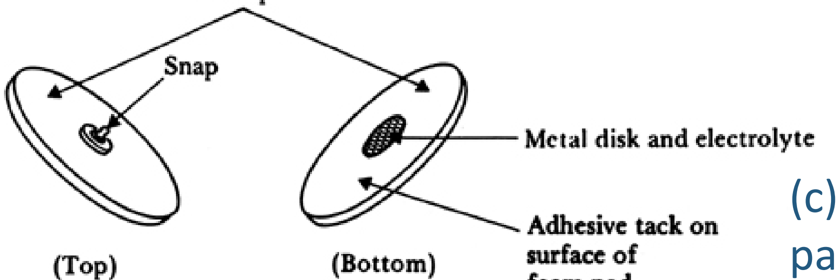
Body-surface electrodes

(a) Metal-plate electrode for limbs



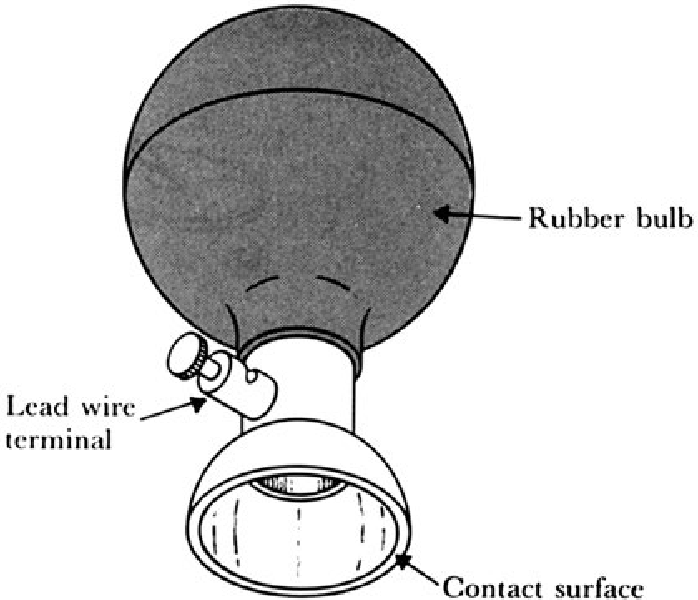


(b) Metal-disk electrode applied with surgical tape



(c) Disposable foam-pad electrodes

Suction electrodes



量心電圖兼拔罐？

Electrodes for ECG

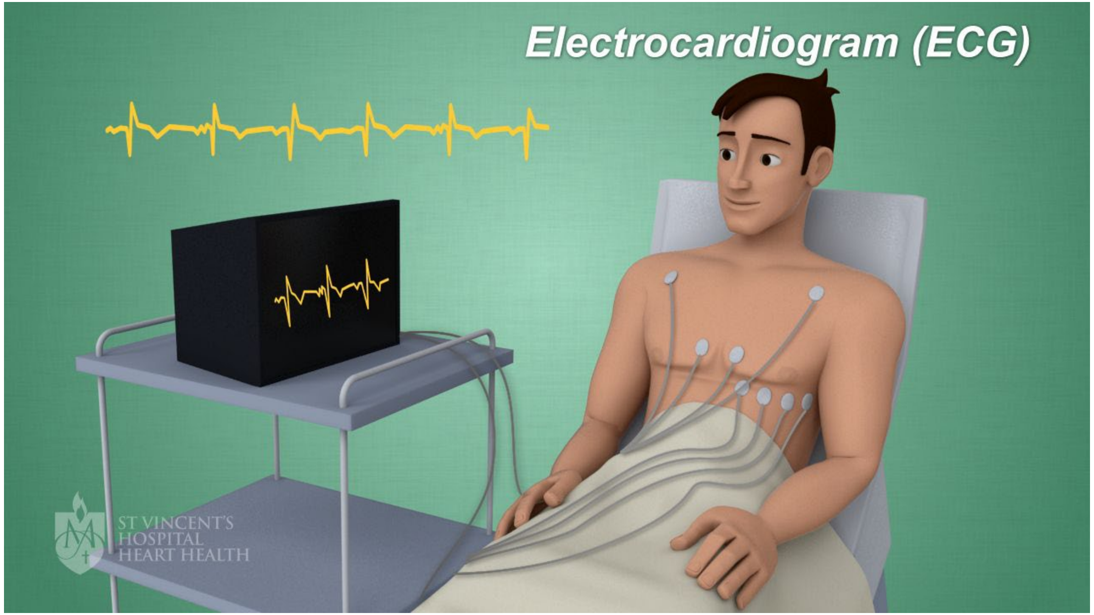
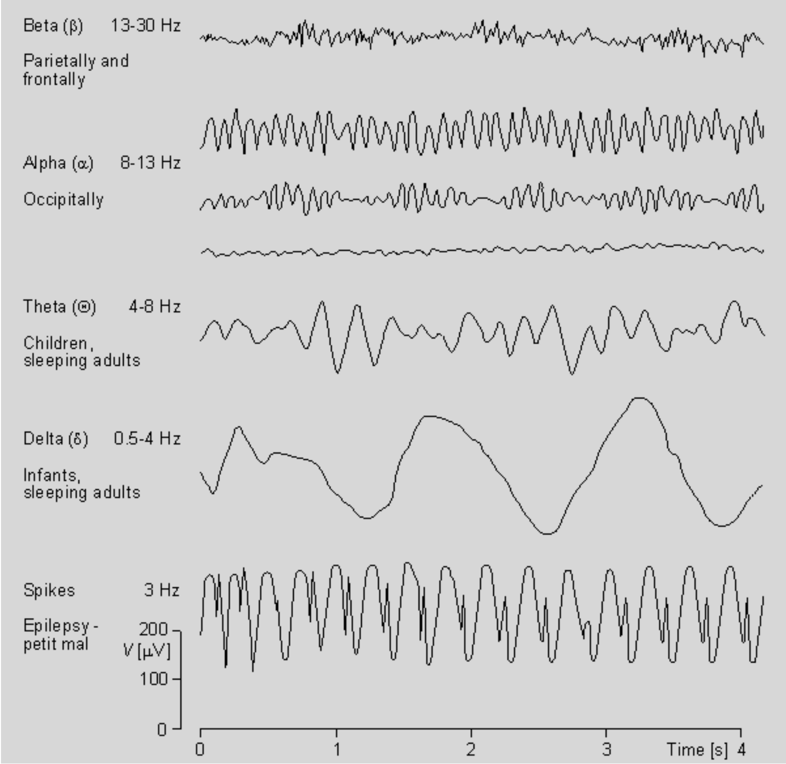


Photo credit: St Vincent's Hospital Heart Health, Sydney, NSW, Australia

Electrode cap for EEG



Wet and dry electrodes

- Wet electrodes
  - Good conductivity and good quality of signals
  - Disposable, low risk of infection
  - Commonly used for clinical routine and research
  - Long-term or frequent use may cause discomfort and/or allergic reaction.

Wet and dry electrodes

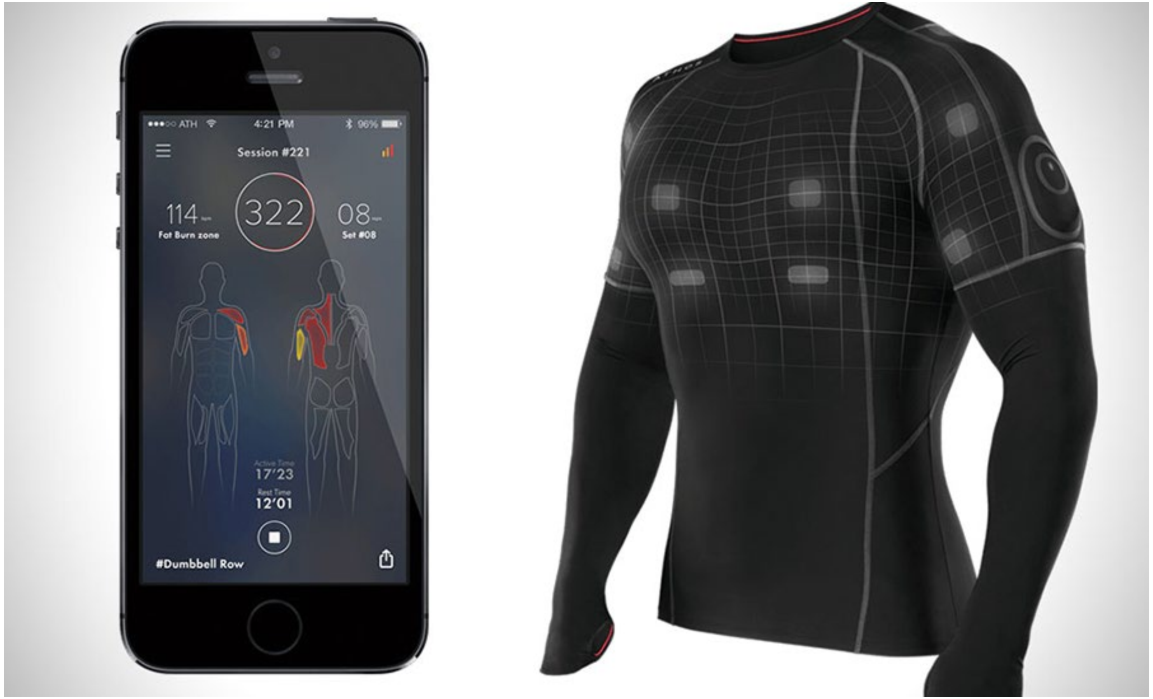
- Dry electrodes
  - Use stainless steel or platinum as contact to skin
  - Without using adhesives and conductive gels
  - Convenient and sustainable
  - Higher impedance, more sensitive to motion artifact than wet electrodes (sweat helps!)

Dry electrodes

Portable/mobile ECG

Fitness devices

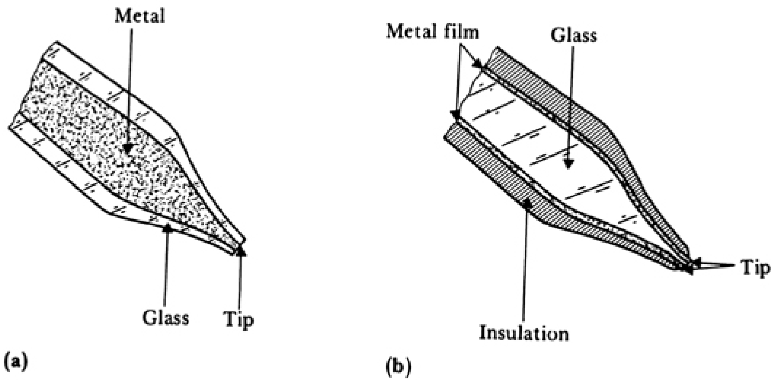
Textile electrode for wearable devices



Conductive fibers are knitted into textile and integrated with embed sensors.

Microelectrodes

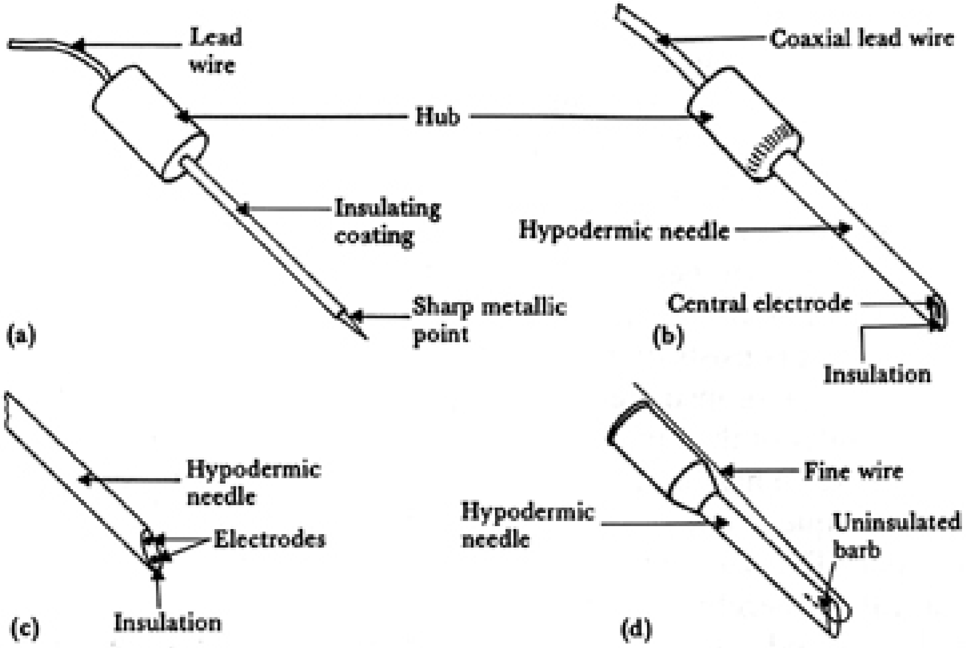
- To measure membrane potential (50-100 mV in amplitude)
  - Relatively higher than common biopotentials
- Glass/metal tips for penetration of the membrane
- Very high impedance
  - Small contact area



Percutaneous electrodes

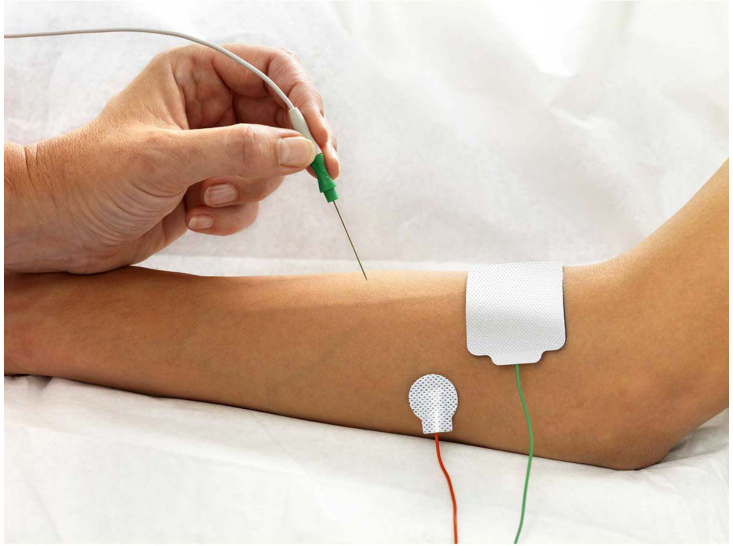
- The electrode or its lead wire penetrates through skin for invasive measurement of biopotentials.
  - No need for conductive paste/gel
  - Suitable for EMG of deep or a specific region of muscle
  - Discomfort, higher risk of infection

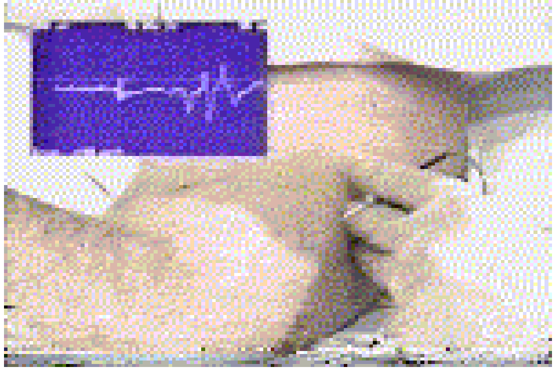
Various needle and wire electrodes



(a) Insulated needle electrode
(b) Coaxial needle electrode
(c) Bipolar coaxial electrode
(d) Fine-wire electrode connected to hypodermic needle

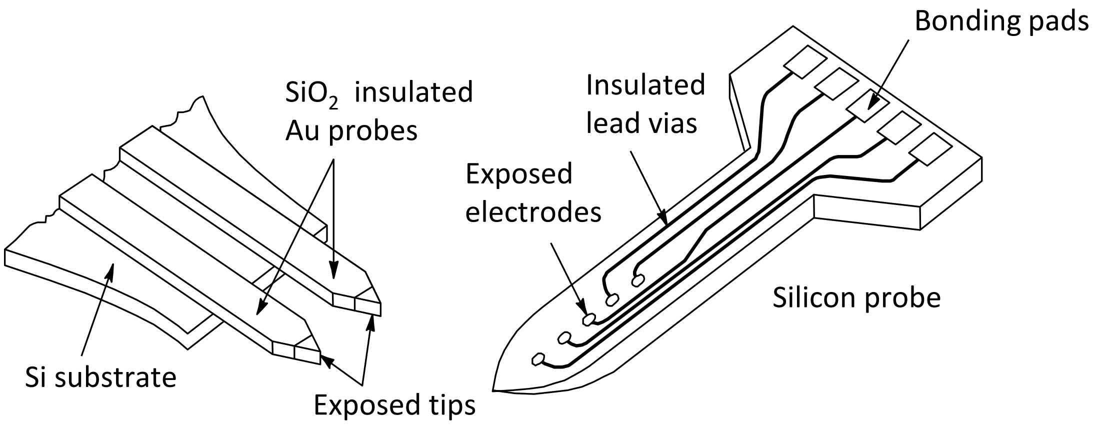
Needle electrode for EMG



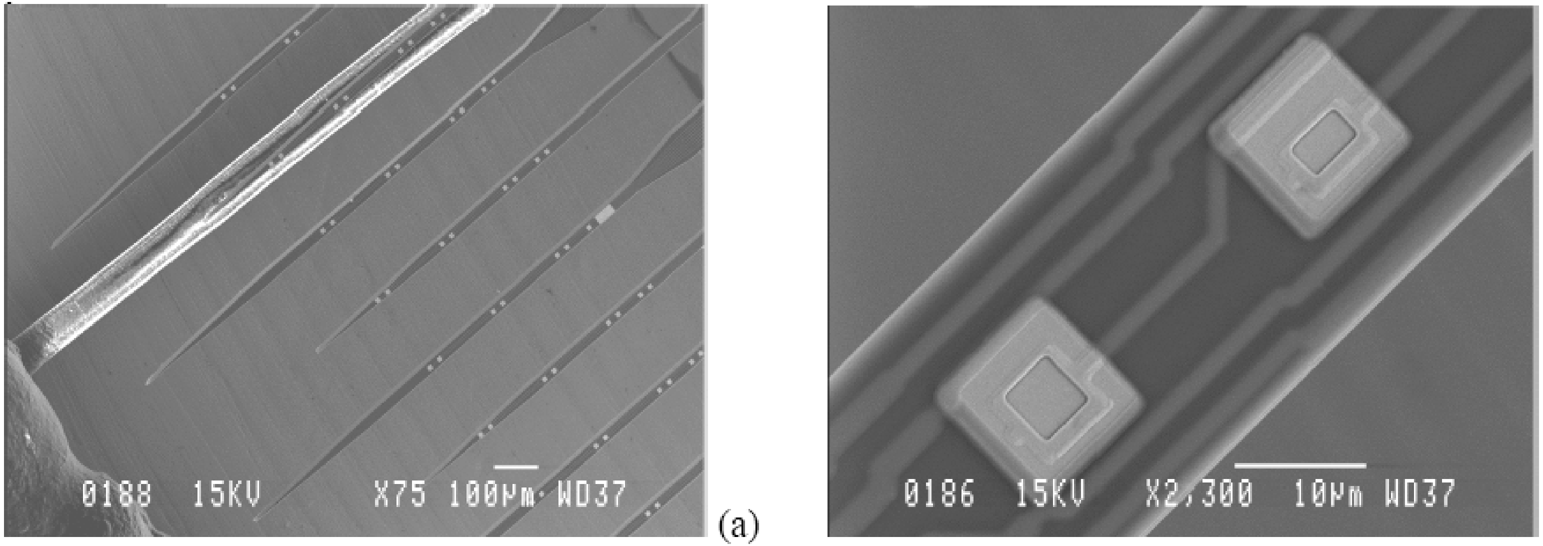


Microelectrodes

- Microelectrodes, consisting of metal, Si and SiO_2, can be fabricated using modern microelectronic technology.



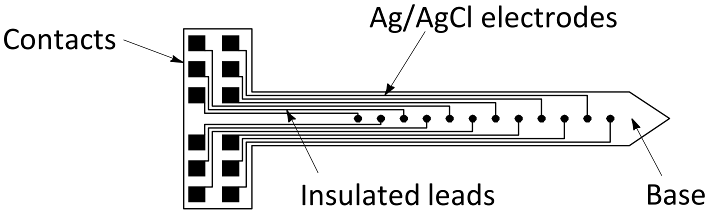
Microelectrodes for neural recording

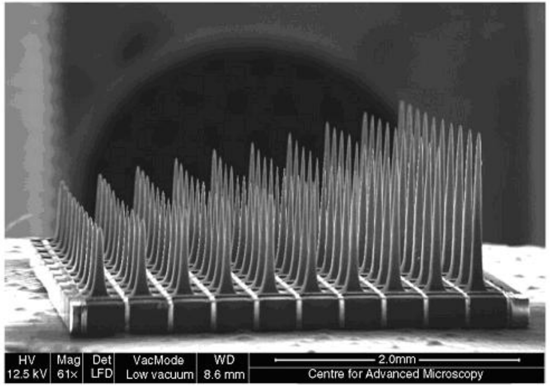


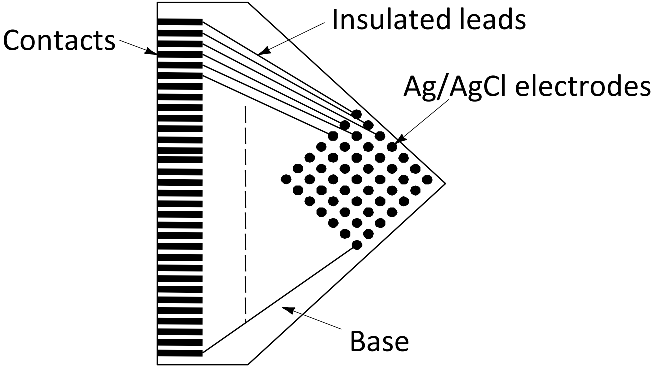
(a) (b)

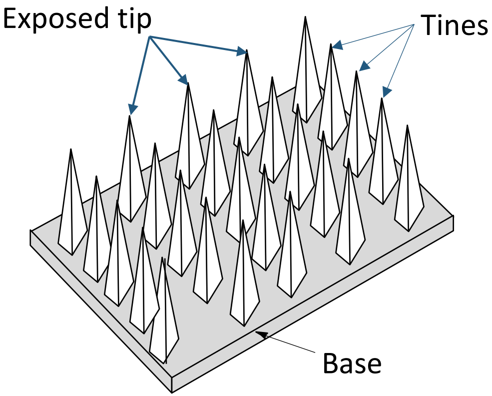
***Figure 3**. (a) 8 shafts, each with 8 electrodes, compared to a human hair. (b) Close up of 2 electrodes.*

1D and 2D electrode arrays

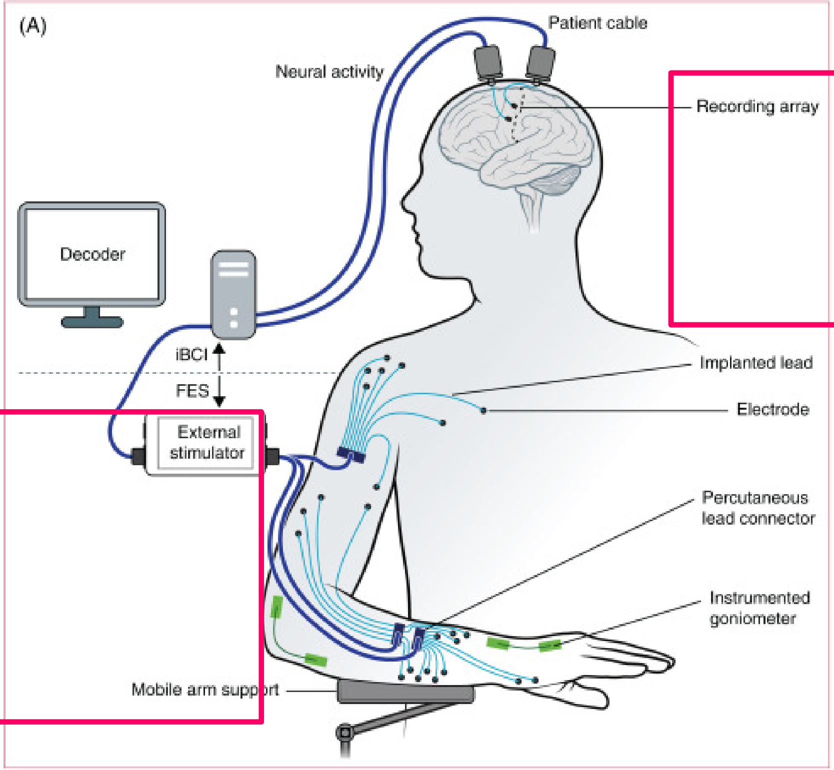








EEG detection and muscle stimulation



Two 96-channel microelectrode arrays implanted on the hand area of motor cortex

36 percutaneous electrodes used to stimulate 18 muscles in the upper and lower arm

Ref: Ajiboye *et al.* "Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: A proof-of-concept demonstration", Lancet, 389:10081, pp. 1821-1830, 2017

Biomedical sensors

- Biopotential
- Displacement, velocity, force, pressure
- Temperature
- Blood O_2/CO_2, PH value

Possible biomedical applications?

- Displacement
- Velocity and/or acceleration
- Force
- Pressure

Sensor for detection of movement

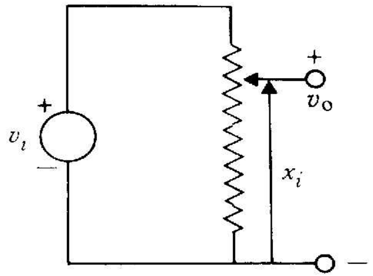
- Transformation of the deformation (or its associated physical phenomenon) into electrical signals
  - Transfer function
  - Voltage or current as the output of sensor
  - The electrical output is fed into a measurement circuit for amplification, filtering, and conversion.

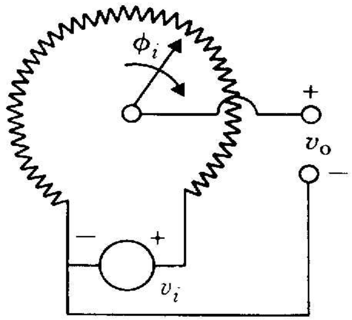
Types of movement sensor

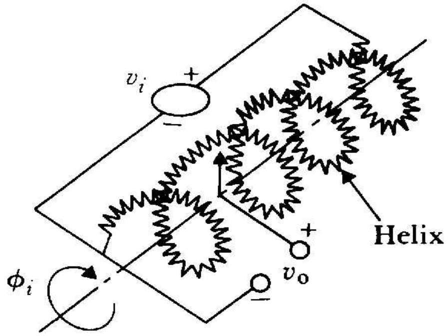
- Resistive
- Inductive
- Capacitive
- Piezoelectric

Resistive: potentiometers

- Use a voltage divider to measure displacement or rotation as a continuous function







Resistive: strain gauges

- Deformation of conductive materials may induce change of its resistance.
  - Dimensional effect (Ex: diameter of metal leads/wires)
  - Piezoresistive effect (Ex: semiconductor materials)

Resistive: strain gauges

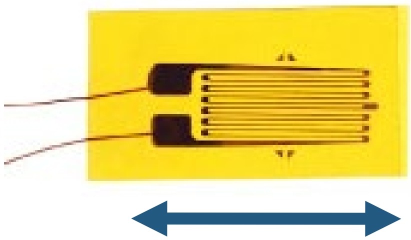
- Dimensional effect of resistance (R)

$$R = \rho \frac{L}{A}$$

  - Stretching of the wire would make it longer and narrower, leading to higher resistance, and vice versa.
- Small-scale deformation of metal
  - Suitable for small displacement

Resistive: strain gauges

- Thin wire in zig-zag pattern
- Mounted on a flexible foil



Direction of deformation

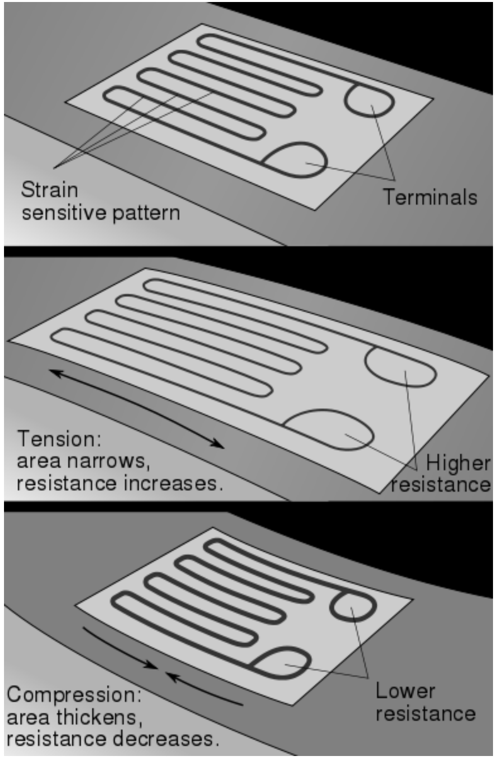
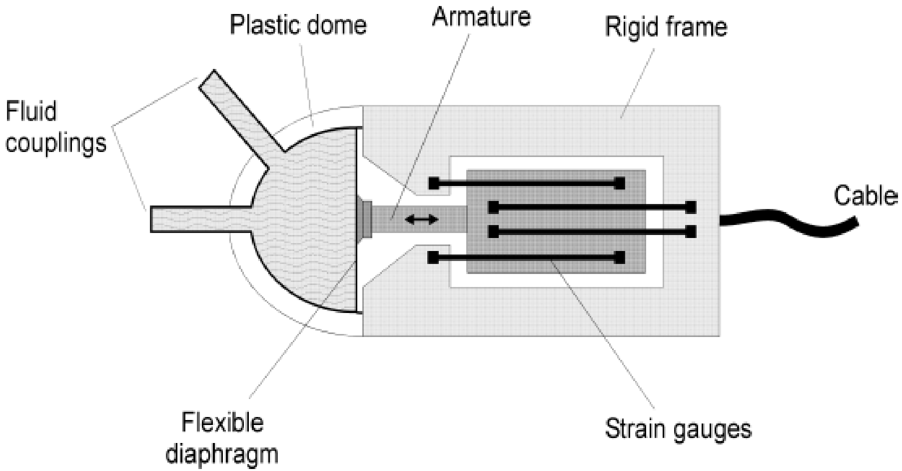
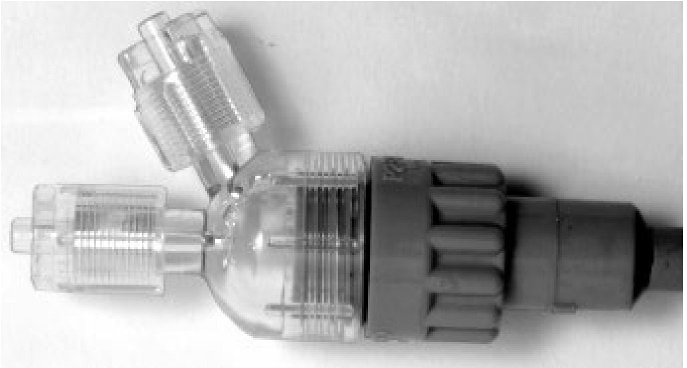


Photo credit: Wikipedia (Strain gauge)

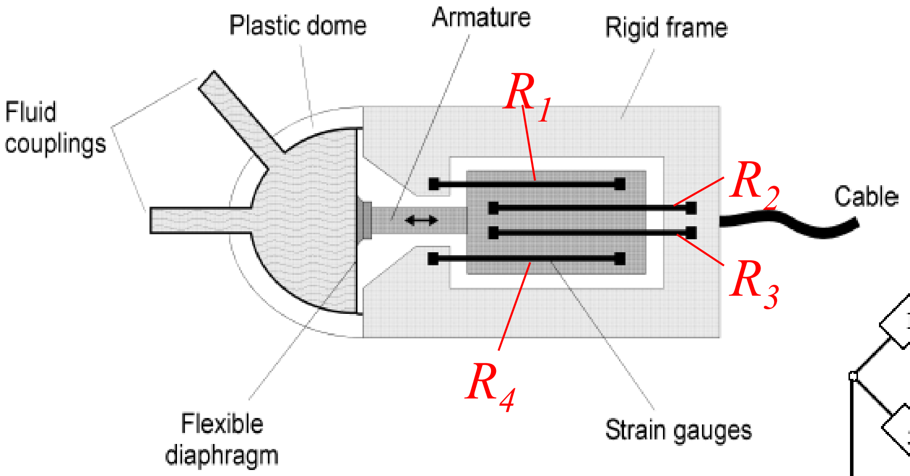
Application of strain gauge

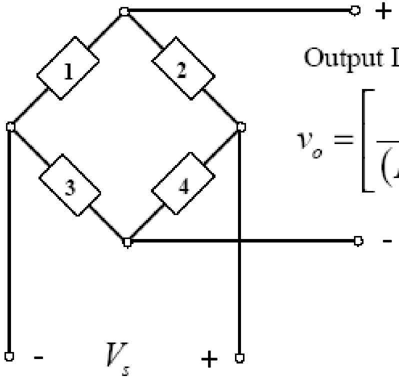




Arterial blood pressure transducer

Wheatstone bridge configuration





Output DC voltage

$$v_o = \left[\frac{R_1 R_4 - R_2 R_3}{(R_1 + R_2)(R_3 + R_4)} \right] \cdot V_s$$

Null condition is satisfied when: $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

Change of resistance (ΔR) can be measured by output voltage of Wheatstone bridge (V_0)

Semiconductor strain gauge

- Pressure sensors made on Si substrate
  - MEMS manufacture
  - Higher sensitivity, but also more sensitive to temperature and more fragile than metal SG
- Possible applications: mini- pressure sensors attached on skin, mounted on catheter, or embedded in wearable devices

Strain gauge on a smart catheter

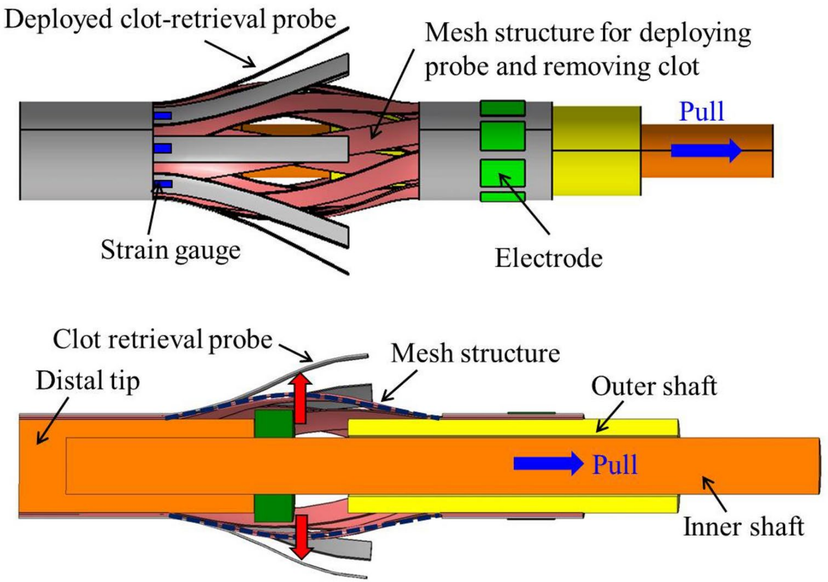
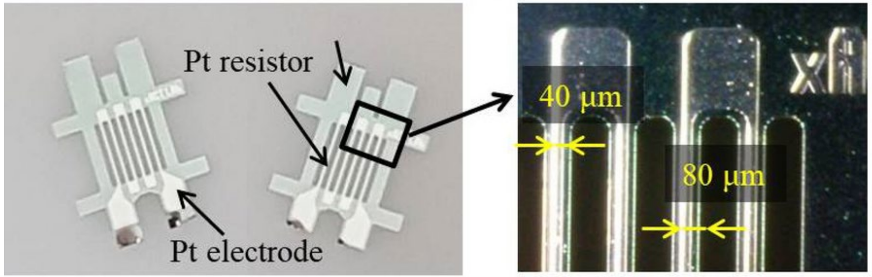


Diagram of a MEM-based smart catheter



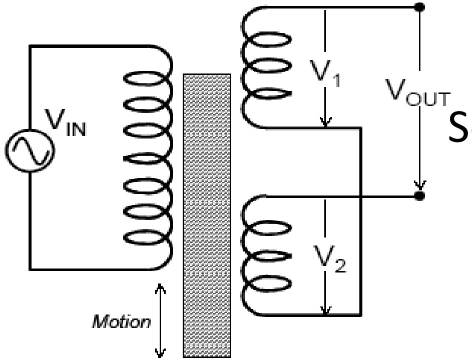
Expansion of the mesh structure deploys the probe to monitor the internal shape of the blood vessel.

Ref: Kim Y *et al.* "Development of platinum strain gauge based on Ni-Co metal substrate for smart catheter application", Micro and Nano Systems Letters, volume 8:15, 2020

Inductive sensor

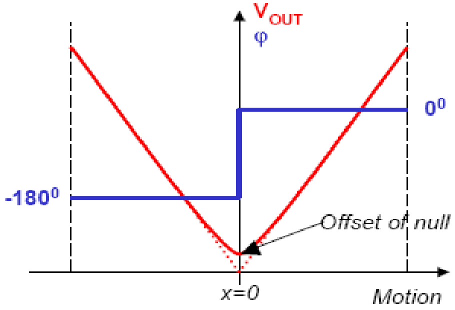
- An inductive sensor is a device that uses the principle of electromagnetic induction to detect objects or its movement.
  - Inductance: a coil of wire over a ferrous core

Primary coil



Secondary coil

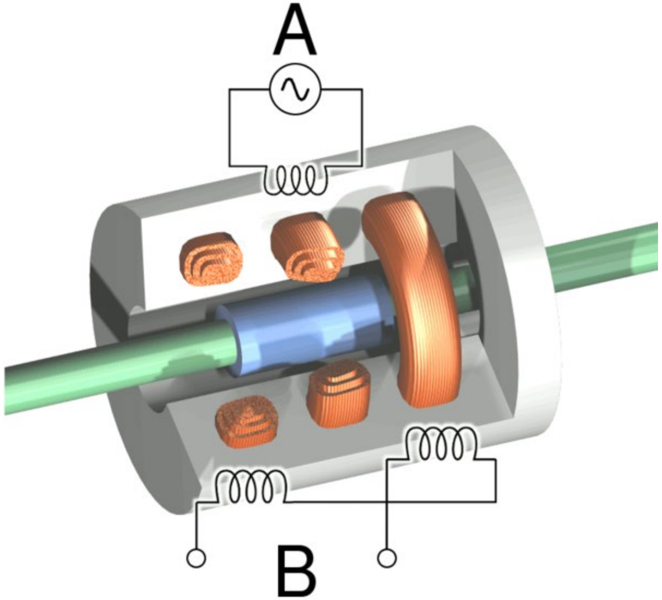
Transformer

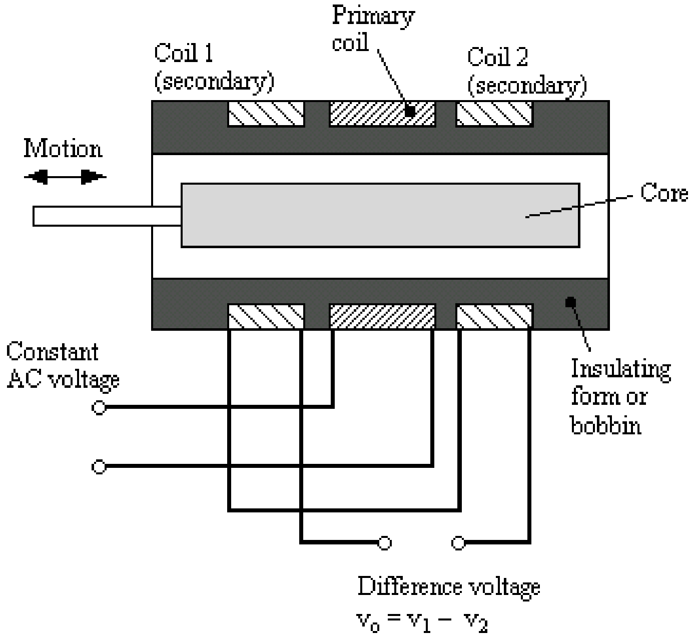


Inductive sensor

- Physical contact is not necessary
- Capable of operate in wet or dirty conditions
- Commonly used in daily life
  - Metal detectors, vehicle detection loops installed at intersections or parking spaces…

Linear variable differential transformer

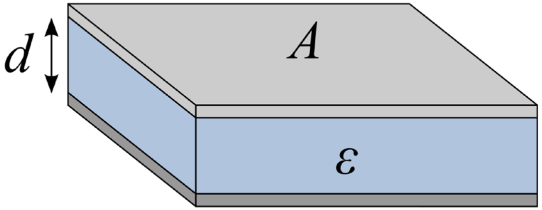




LVDT is used to detect linear displacement robustly

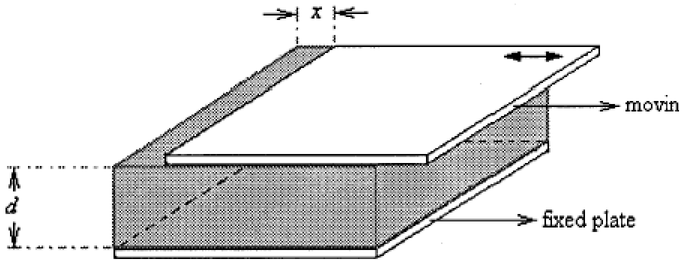
Capacitive sensor

- A capacitive sensor is used to measure movement by detecting the associated change of capacitance coupling.
  - Capacitance: $C = \varepsilon \frac{A}{d} = \varepsilon_0 \varepsilon_r \frac{A}{d}$



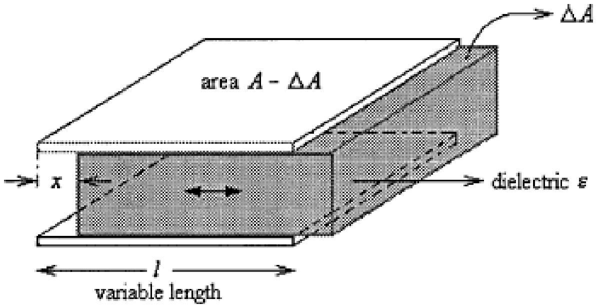
ε: dielectric constant
ε_0: vacuum dielectric constant
ε_r: relative dielectric constant
A: the overlapping area of two plates
d: the distance of two plates

Capacitive sensor: basic concepts



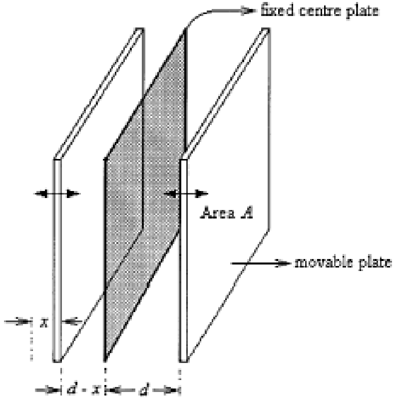
Variable area mode

$$C = \varepsilon_0 \varepsilon_r \frac{(A - wx)}{d}$$



Variable dielectric mode

$$C = \varepsilon_0 w \frac{\varepsilon_1 (l - x) + \varepsilon_2 x}{d}$$

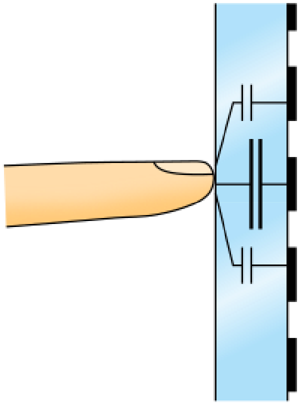


Differential mode

$$C = \varepsilon_0 \varepsilon_r \frac{A}{2d - x}$$

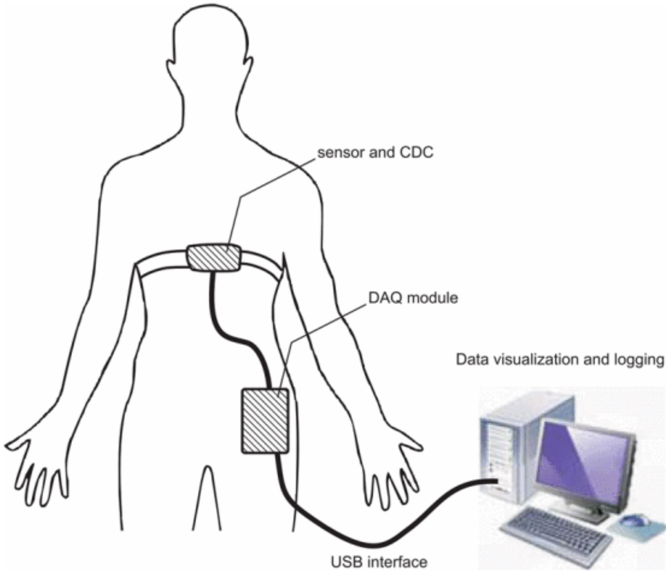
Capacitive sensor: applications

- Project capacitance touch technology
  - Touch screen/panel
- Respiration monitoring system
  - Robust and low-cost
- Implantable pressure sensor
  - Fabricated by semiconductor technology



Project-capacitive touch panel

Capacitive sensor for respiratory monitoring



CDC: capacitance-to-digital converter
DAQ: data acquisition

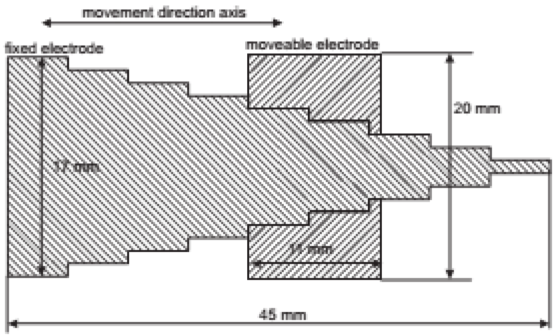
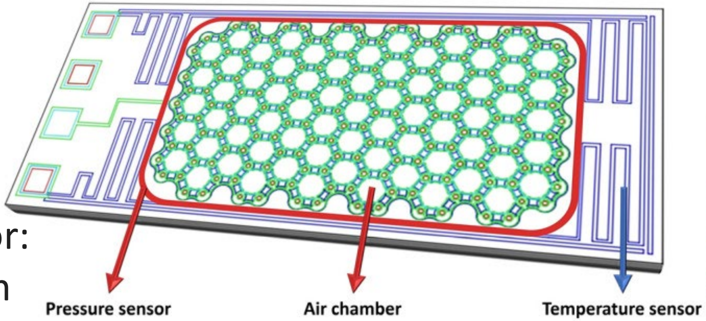


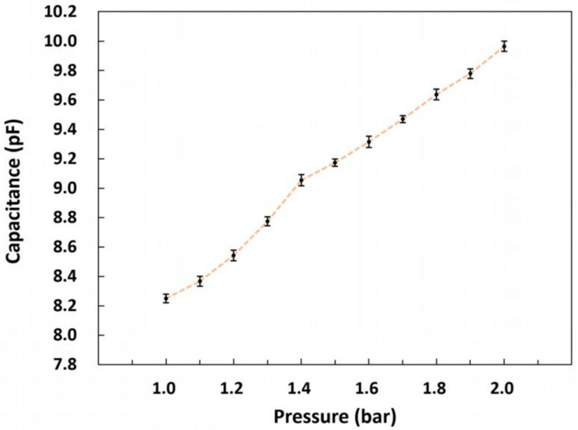
Diagram of the capacitive sensor:
The capacitance between the fixed triangular electrode and the sliding rectangular electrode is related to the extension of the respiratory belt.

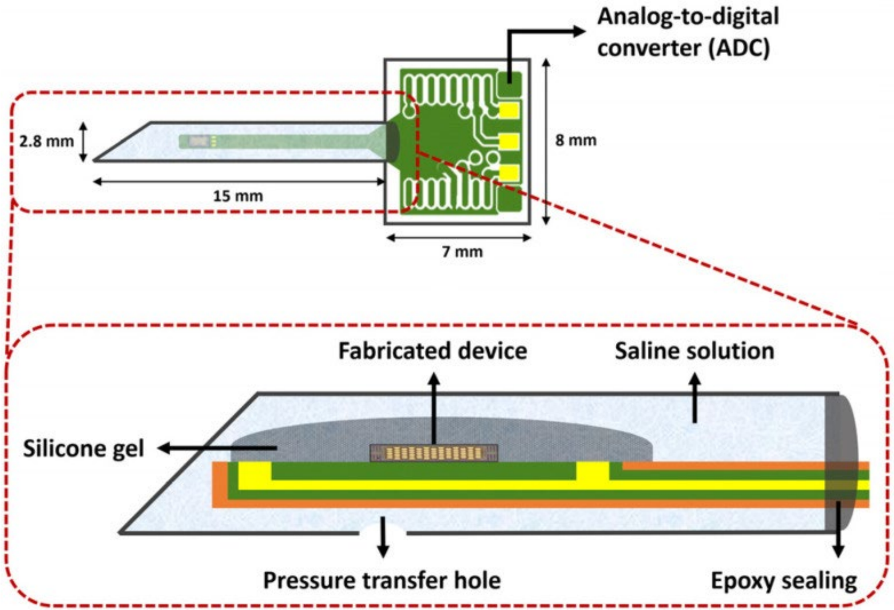
Ref: Grlica J, Martinovic T, and Dzapo H. "Capacitive sensor for respiration monitoring", Proc. IEEE Sensors Appl. Symp. (SAS), pp. 1-6, Apr. 2015

Capacitive implantable pressure sensor

Size of sensor:
0.5 × 1.2 mm







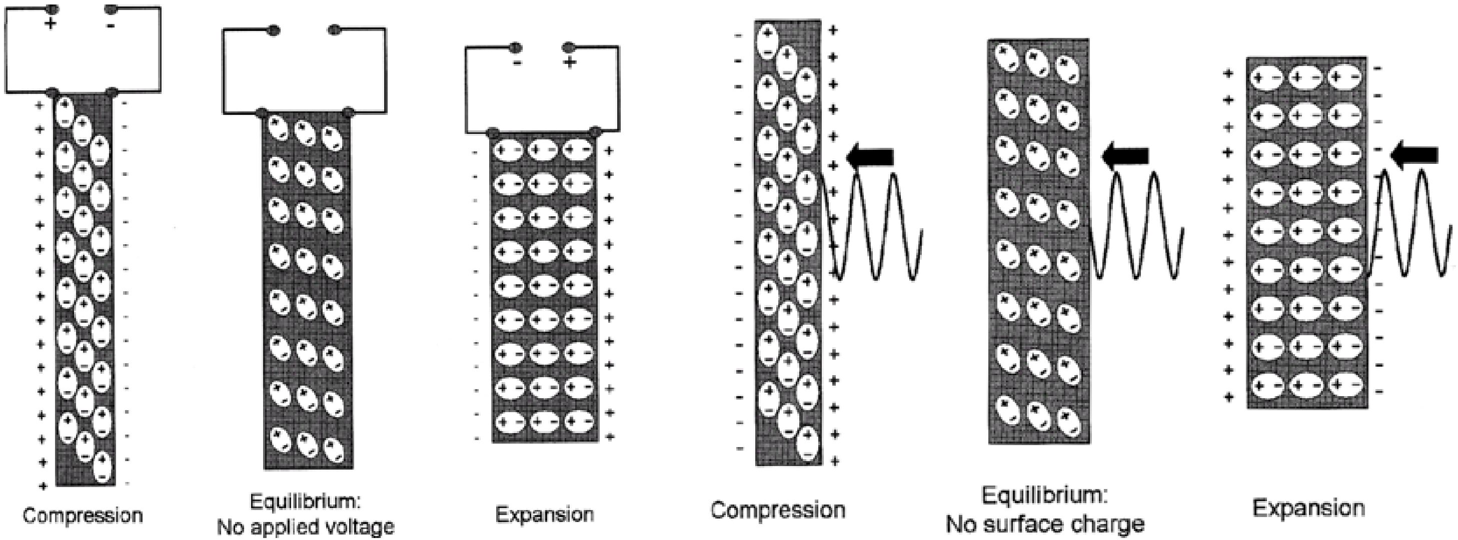
Schematic of the packaged sensor

Ref: Roh JH, Shin KS, Song TH, Kim J, Lee DS. “Development of an Implantable Capacitive Pressure Sensor for Biomedical Applications”, Micromachines (Basel),14(5):975, 2023.

Piezoelectric sensor

- Piezoelectric effect: the ability of certain materials to generate an electrical charge in response to mechanical stress
  - Piezo-: "press" in Greek
  - Stress → Electric potential
  - Reversible: Electric potential → Stress

Piezoelectric effect

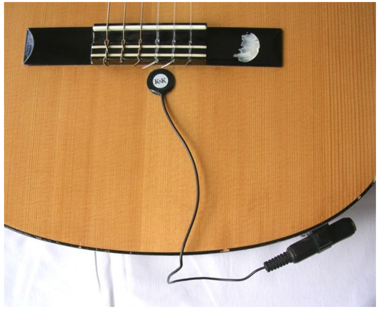


Stress → Electric potential

Electric potential → Stress

Piezoelectric sensor

- Suitable for detection of rapid and small movements
  - PZT (lead zirconate titanate, 鋯鈦酸鉛) is deformed by about 0.1% of the original dimension.
  - Applications: ultrasound transducers, microphone for instruments (guitar pickups)...



Biomedical sensors

- Biopotential
- Displacement, velocity, force, pressure
- Temperature
- Blood O_2/CO_2, PH value

Temperature sensor

- Resistance thermometer 熱電阻溫度計
  - Resistance temperature detector (RTD)
- Thermistor 熱敏電阻
- Thermocouples 熱電偶
- Radiation thermometry
  - Infrared thermometer

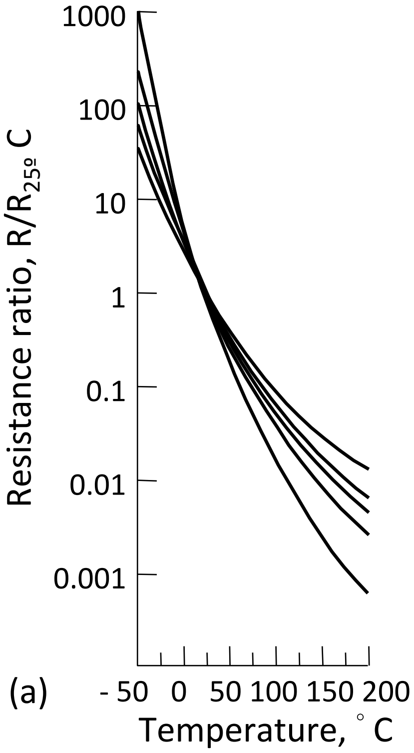
Resistance Temperature Detector

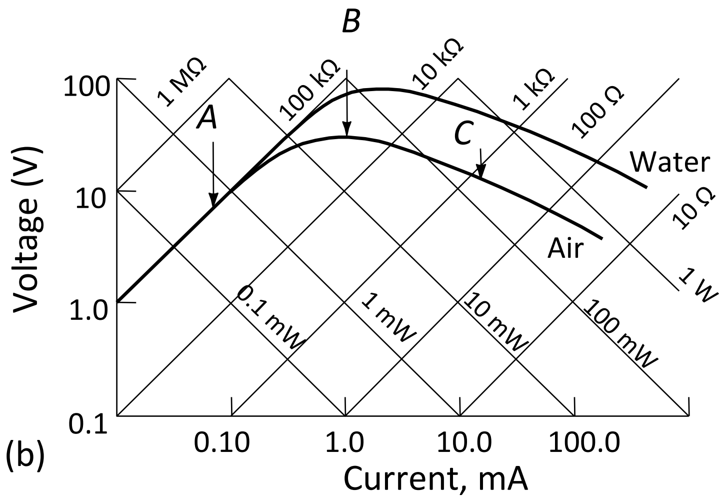
- RTD wire is usually pure metal, such as platinum (Pt), nickel (Ni), and copper (Cu).
- Resistance of RTD increases at higher temperature.
  - Positive temperature coefficient of resistance
  - $R_T = R_0(1 + \alpha_1 T + \alpha_2 T^2 + \cdots + \alpha_n T^n) \cong R_0(1 + \alpha_1 T)$
- Accurate, stable, and large temperature range

Thermistor

- Resistance of this semiconductor type of resistor decreases at higher temperatures
  - Negative temperature coefficient of resistance
  - $R_T = R_0 e^{\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)}$
- In comparison, thermistors usually achieve better precision within a limited temperature range
  - Typically -90°C to 130°C

Thermistor





(a) Relationship of resistance ratio and temperature of various thermistors

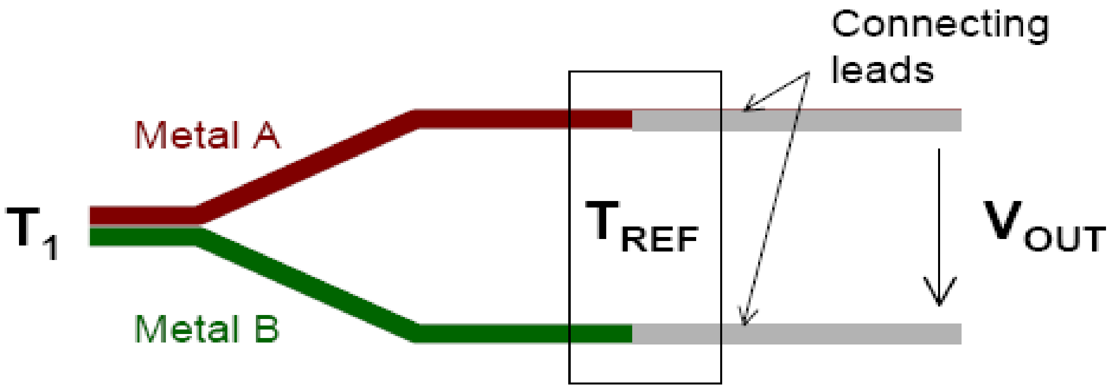
(b) Non-linearity of resistance at high currents

Thermocouple

- Seebeck effect: an electromotive force generates across two points of a conductive material when there's a temperature difference between them
  - Thermoelectric effect
- Thermocouple: two dissimilar conductors (metals) forming an electric junction with a temperature-dependent voltage

Thermocouple

- The output voltage (V_{OUT}) depends on temperature difference (T_1 - T_{REF}) and the type of metals



Thermocouple

- Pros: self-powered, inexpensive, wide variety of probes, large range of temperature measurement
  - 0°C to >1000°C
- Cons: reference temperature required, relative low sensitivity (V_{OUT}: µV to mV)
  - Thermopile: thermocouples connected in series to increase sensitivity

Radiation thermometry

- Thermal radiation: as the temperature of a black body decreases, the emitted radiation decreases in intensity and its maximum moves to longer λ
  - Black-body radiation
  - The maximum of thermal radiation at body temperature corresponds to infrared
  - Infrared thermometer: non-invasive and non-contact

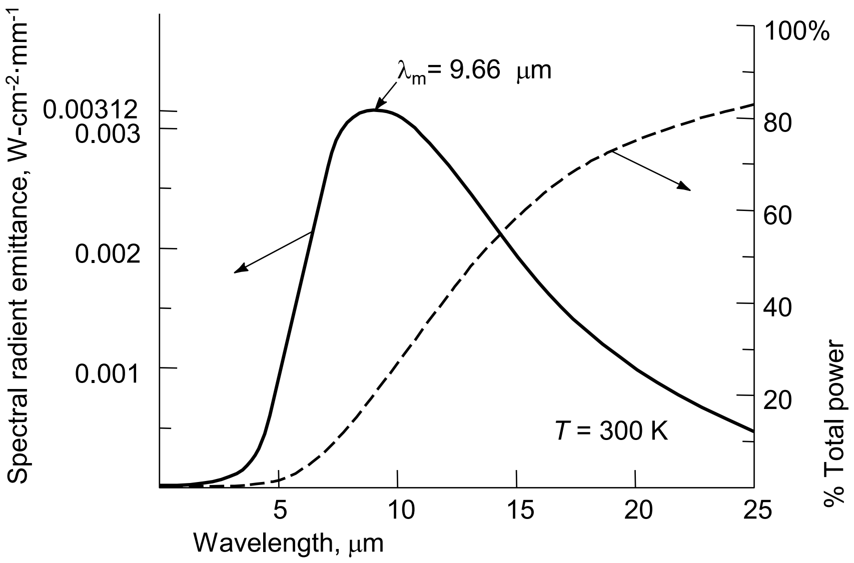
Radiation spectrum at 300 K

- Wavelength of maximal spectral radiance

$$\lambda_m = \frac{2898}{T} \ (\mu m)$$

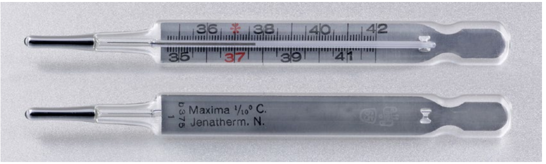
- Total radiant power

$$W_T = \varepsilon\sigma T^4$$

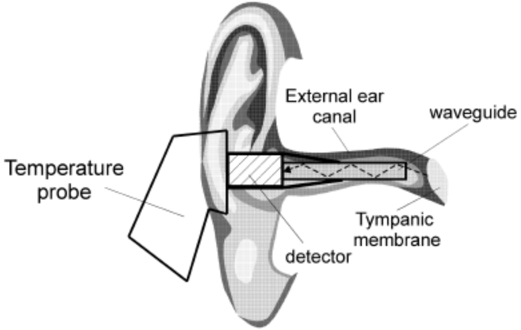


Measuring body temperature with…

- Mercury thermometer
- Thermistor with a digital readout
- Infrared thermometer
  - Ear/forehead thermometer, thermal camera



- Pros and cons?



Biomedical sensors

- Biopotential
- Displacement, velocity, force, pressure
- Temperature
- Blood O_2/CO_2, pH value

Blood gas: O_2 and CO_2

- Only 2% of O_2 is dissolved in the plasma. 98% of O_2 is combined with hemoglobin (as HbO_2) in the red blood cells.
  - pO_2: the efficiency of alveolar ventilation
  - SO_2(oxygen saturation): amount of O_2 in blood
- Most CO_2 is transformed into HCO_3^- in blood
  - pCO_2 is directly correlated with pH value at 10-90 mmHg

Clark-type pO_2 sensor

- Reduction-oxidation reaction
- Cathode: reduction

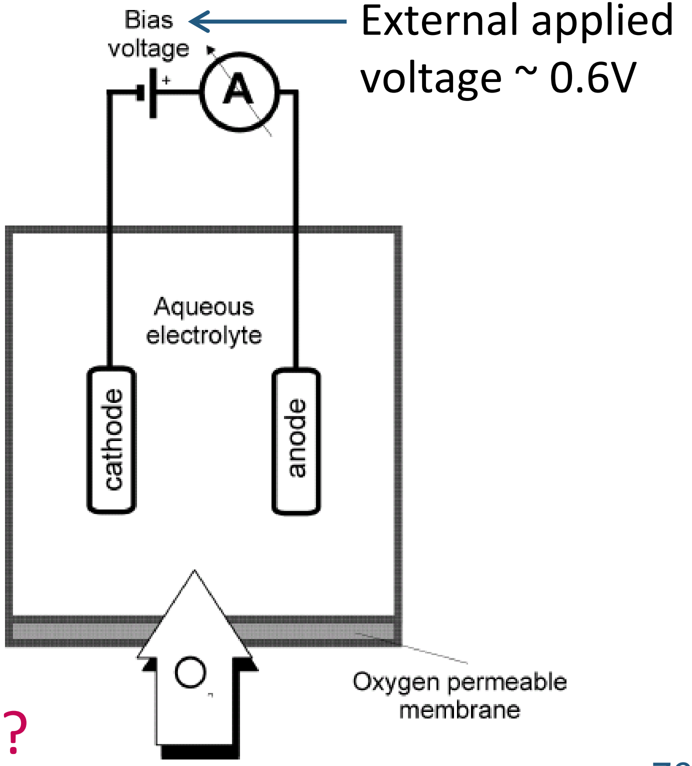
$$O_2 + 2H_2O + 4e^- \leftrightarrow 4OH^-$$

- Anode: oxidation

$$Ag \leftrightarrow Ag^+ + e^-$$

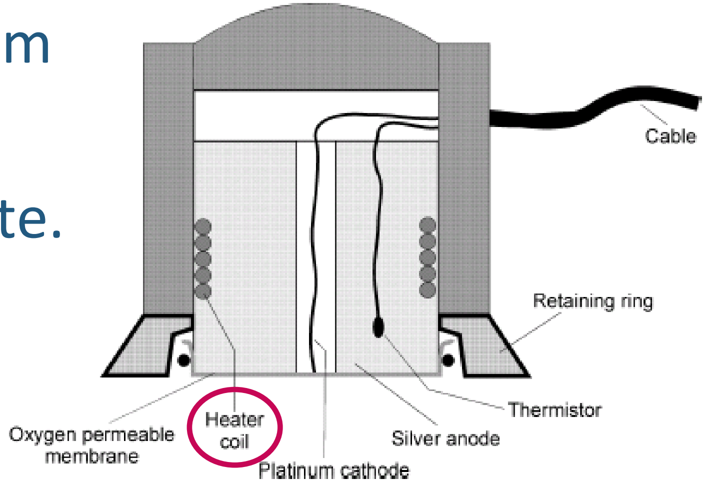
$$Ag^+ + Cl^- \leftrightarrow AgCl\downarrow$$

Q: As pO_2 goes higher, the current will?



Transcutaneous pO_2 sensor

- Attached on the skin, instead of being immersed in blood or tissue fluid.
  - Measure oxygen diffusing from blood through the skin.
  - Non-invasive, but less accurate.



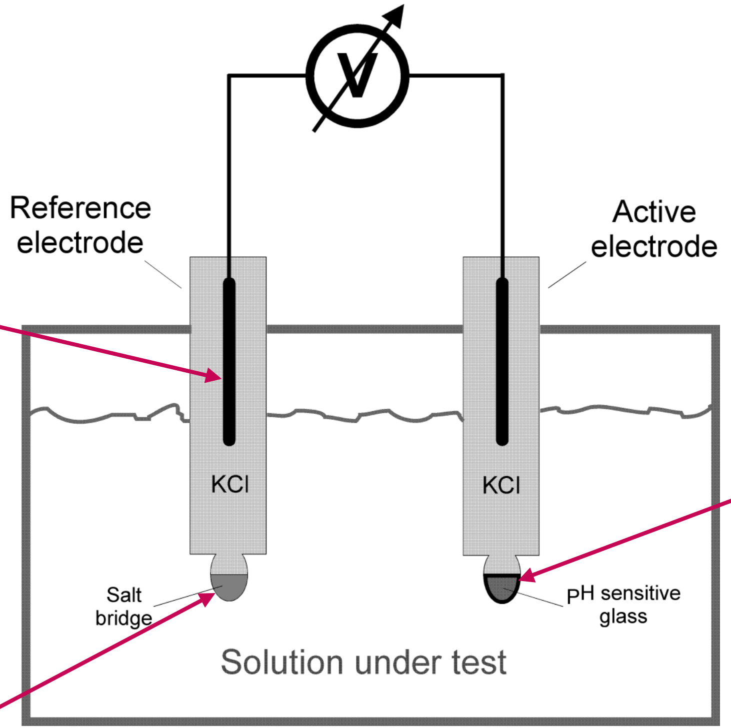
Detection of pCO_2 and pH value

- $\log(pCO_2)$ is linearly dependent on pH value at 10-90 mmHg
  - Normal range of pCO_2: 33-48 mmHg
  - $H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$
- $pH = -\log_{10}[H^+]$
  - $[H^+][OH^-] = 10^{-14}$ at 25°C

pH electrode

Ag/AgCl electrode

Permeable for all ions, keeping reference potential unchanged



A lithium-doped glass electrode, of which only H^+ ions can bind on the surface to develop an electric potential

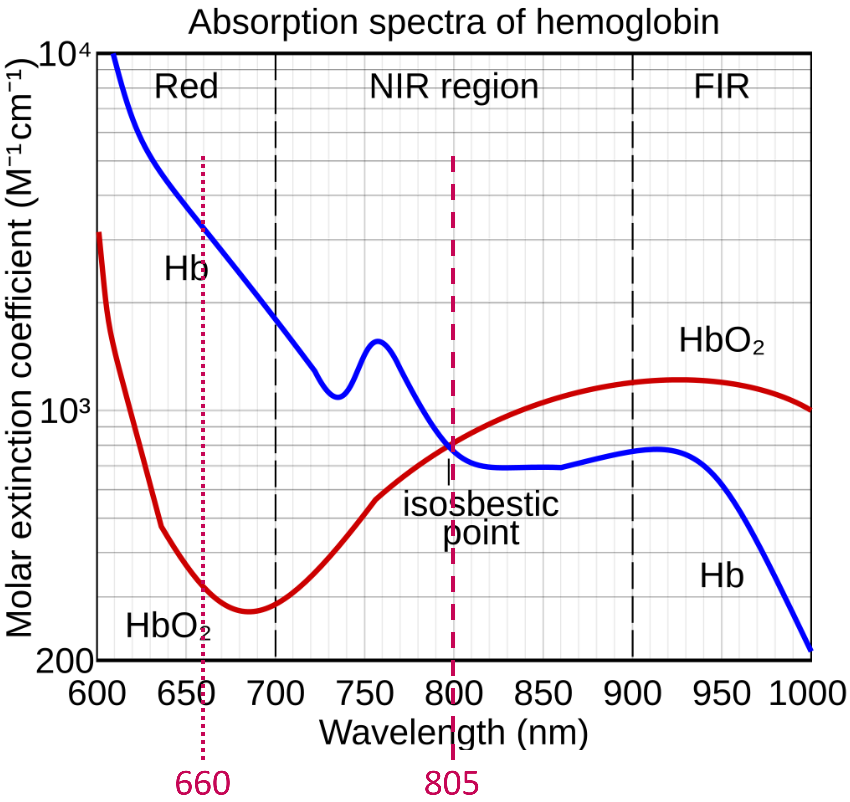
pH electrode

- Equivalent to a battery model
  - +: active electrode (or measuring electrode)
  - −: reference electrode
- When both electrodes are immersed in the solution under test, a potential directly related to $[H^+]$ is developed across electrodes.

Oxygen saturation level (SO_2)

- Two wavelengths of light are applied on blood to measure their absorbance respectively.
  - Ex: red light (660 nm) and infrared (805 nm)
- The absorption rates of HbO_2 and Hb are independent functions of wavelength.
  - Use the absorption rates at two wavelengths to estimate the ratio of HbO_2

Absorptivities of HbO_2 and Hb



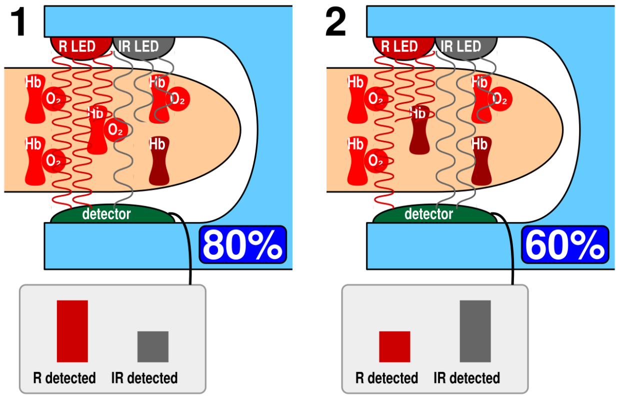


Photo credit: Wikipedia (Pulse oximetry)

Summary

- Biopotential sensor
- Displacement, velocity, force, pressure
- Temperature
- Blood O_2/CO_2, PH value
- And a lot more…

生醫工程導論：生醫感測器

Reference chapters:

Chapter 9: Biomedical sensors, “Introduction to Biomedical Engineering”, John Enderle, Susan Blanchard, and Joseph Bronzio.

Chapter 2: Basic sensor and principles and Chapter 5: Biopotential electrodes, “Medical Instrumentation: Application and Design”, John G. Webster.

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