Biopotential Amplifiers

- Basic function
  - to increase the amplitude of a weak electric signal of biological origin (next slide)
  - typically process voltages
    - but in some cases also process currents

- Typical bio-amp requirements
  - high input impedance - greater than 10 Mohms
  - safety: protect the organism being studied
    - careful design to prevent macro and microshocks
    - isolation and protection circuitry to limit the current through the electrode to safe level
  - output impedance of the amplifier
    - should be low to drive any external load with minimal distortion
  - gain greater than 1000
    - biopotentials are typically less than a millivolt
  - most biopotential amplifiers are differential
    - signals are recorded using a bipolar electrodes which are symmetrically located
  - high common mode rejection ratio
    - biopotentials ride on a large offset signals
  - rapid calibration of the amplifier in laboratory conditions
  - adjustable gains
    - often the change in scale is automatic
    - therefore calibration of the equipment is very important
Electrocardiograph amplifiers

- Beating heart generates electric signal
  - monitored to understand heart functions
- Measurements are functions of
  - location at which the signal is detected
  - time-dependence of the signal amplitude
- Different pairs of electrodes at different locations yield different measurements
  - hence placement is standardized
- Electrical model of heart
  - electric dipole located in a partially conducting medium (thorax)
  - dipole represented as a cardiac vector $\mathbf{M}$
    - $M$ is the dipole moment
    - during the cardiac cycle
      - magnitude and direction of the dipole vector will vary
    - electric potentials appears throughout the body and on its surface

\[ v_{al} = \mathbf{M} \cdot \mathbf{a}_1, \quad v_{al} = |\mathbf{M}| \cos \theta \]

Electrocardiograph Leads

- In clinical electrocardiography
  - more than one lead must be recorded to describe the heart's electric activity fully
  - several leads are taken in the frontal plane and the transverse plane
    - frontal plane: parallel to the back when lying
    - transverse plane: parallel to the ground when standing
- Frontal plane lead placement
  - called Eindhoven's triangle
- Additional leads
  - unipolar measurements
    - potential measured at electrodes wrt a reference; average of the 2 electrodes
  - Wilson central terminal
    - three limb electrodes connected through equal-valued resistors to a common node
  - augmented leads
    - some nodes disconnected
    - increase the amplitude of measurement using
Problems in ECG Measurement

- Frequency distortion
  - if filter specification does not match the frequency content of biopotential
  - then the result is high and low frequency distortion
- Saturation or cutoff distortion
  - high electrode offset voltage or improperly calibrated amplifiers can drive the amplifier into saturation
  - then the peaks of QRS waveforms are cut off
- Ground loops
  - if two monitoring instruments are placed at disjoint ground points
  - then small current could flow through the patient’s body
- Electric/magnetic field coupling
  - open lead wires (floating connections) pick up EMI
  - long leads produce loop that picks up EMI (induces loop current)
- Interference from power lines (common mode interference)
  - can couple onto ECG signal

60Hz supply noise coupled to ECG
Interference Reduction Techniques

Common-mode voltages can be responsible for much of the interference in biopotential amplifiers.

• Solution 1:
  • amplifier with a very high common-mode rejection

• Solution 2:
  • eliminate the source of interference

Ways to eliminate interference

• Use shielding techniques
  • electrostatic shielding: Place a grounded conducting plane between the source of the electric field and the measurement system
    • very important for EEG measurement
  • Magnetic shield
    • use high permeability materials (sheet steel)
    • Use twisted cables to reduce magnetic flux, reduce lead loop area

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Differential Amplifier

• One-amp differential amplifier
  • gain determination
    • Rule 1: virtual short at op-amp inputs
    • Rule 2: no current into op-amp
    \[
    v_5 = \frac{v_{in+}R_4}{R_3 + R_4} \quad i = \frac{v_{in-} - v_5}{R_3} = \frac{v_5 - v_o}{R_4}
    \]
    \[
    \Rightarrow v_o = \frac{(v_{in+} - v_{in-})R_4}{R_3}
    \]
  Gain of differential amplifier (not gain of op-amp)
  \[
  \frac{v_o}{v_{in}} = \frac{R_4}{R_3} = G_d
  \]

• characteristics
  • no common mode gain, Gc = 1
  • input resistance of the diff. amp is lower than ideal op-amp
    • OK for low resistance sources (like Wheatstone bridge), but not good for many biomedical applications

common mode rejection ratio: \[ CMRR = \frac{G_d}{G_c} \]
Differential Amplifier

• How do we fix low input resistance of 1-op-amp diff amp?

• Option 1: Add voltage follower to each input
  • Problem: ?

• Option 2: Add non-inverting amp at each input
  • Provides additional gain
  • Problem: ?

Instrumentation Amplifier

• Better option:
  • connect Ri’s of input amps together
  • eliminate ground connection

• This 3-op-amp circuit is called an instrumentation amplifier

• Input stage characteristics
  • low common-mode gain - rejects common mode voltages (noise)
  • high input impedance
  • input stage gain adjusted by \( R_1 \)
    \[ G_d = \frac{v_3 - v_4}{v_1 - v_2} = \frac{2R_2 + R_4}{R_1} \]
Instrumentation Amplifier

- **Input stage**
  - high input impedance
  - buffers gain stage
  - no common mode gain
  - can have differential gain

- **Gain stage**
  - differential gain, low input impedance

- **Overall amplifier**
  - amplifies only the differential component
  - high common mode rejection ratio
  - high input impedance suitable for biopotential electrodes with high output impedance

\[
G_d = \frac{2R_2 + R_1}{R_1} \left( \frac{R_4}{R_3} \right)
\]

ECG Amplifier

With 776 op amps, the circuit was found to have a CMRR of 86 dB at 100 Hz and a noise level of 40 mV peak to peak at the output. The frequency response was 0.04 to 150 Hz for ±3 dB and was flat over 4 to 40 Hz. The total gain is 25 (instrument amp) x 32 (non-inverting amp) = 800.
Driven Right Leg System

- **Motivation**
  - reduce interference in amplifier
  - improve patient safety

- **Approach**
  - patient right leg tied to output of an auxiliary amp rather than ground
  - common mode voltage on body sensed by averaging resistors, Ra's & fed back to right leg
  - provides negative feedback to reduce common mode voltage
  - if high voltage appears between patient and ground, auxiliary amp effectively un-grounds the patient to stop current flow

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Driven Right Leg System: Example

- **Problem**: Determine the common-mode voltage $v_{cm}$ on the patient in the driven-right-leg circuit of Slide 13 when a displacement current $i_d$ flows to the patient from the power lines. Choose appropriate values for the resistances in the circuit so that the common-mode voltage is minimal and there is only a high-resistance path to ground when the auxiliary operational amplifier saturates.

- **Answer**: The equivalent circuit is shown here. Note that because the common-mode gain of the input stage is 1, and because the input stage as shown has a very high input impedance, $v_{cm}$ at the input is isolated from the output circuit. $R_{RL}$ represents the resistance of the right-leg electrode. Summing the currents at the negative input of the operational amplifier, we get

\[
\frac{2v_{cm}}{R_a} + \frac{v_o}{R_f} = 0
\]

- this gives

\[
v_o = -\frac{2R_f}{R_a}v_{cm}
\]

but

\[
v_{cm} = R_{RL}i_d + v_o
\]

- thus, substituting (1) into (2) yields

\[
v_{cm} = \frac{R_{RL}i_d}{1 + 2R_f/R_a}
\]
Example continued

- The effective resistance between the right leg and ground is the resistance of the right-leg electrode divided by 1 plus the gain of the auxiliary operational-amplifier circuit. When the amplifier saturates, as would occur during a large transient $v_{cm}$, its output appears as the saturation voltage $v_s$. The right leg is now connected to ground through this source and the parallel resistances $R_f$ and $R_o$. To limit the current, $R_f$ and $R_o$ should be large. Values as high as 5 MΩ are used.
- When the amplifier is not saturated, we would like $v_{cm}$ to be as small as possible or, in other words, to be an effective low-resistance path to ground. This can be achieved by making $R_f$ large and $R_a$ relatively small. $R_f$ can be equal to $R_o$, but $R_a$ can be much smaller.
- A typical value of $R_a$ would be 25 kΩ. A worst-case electrode resistance $R_{el}$ would be 100 kΩ. The effective resistance between the right leg and ground would then be

$$\frac{100 \text{kΩ}}{1 + \frac{2 \times 5 \text{ MΩ}}{25 \text{kΩ}}} = 249 \text{ Ω}$$

- For the 0.2 μA displacement current, the common-mode voltage is

$$v_{cm} = 249 \text{ Ω} \times 0.2 \text{ μA} = 50 \text{ μV}$$

Compensation of electrode artifacts

- Microelectrodes detect potentials on the order of 50-100mV.
- Small size implies high source impedance which also results in a large shunting capacitance.
- Degraded frequency response.
Compensation of electrode artifacts

- Compensate large shunt capacitance using a positive feedback
- Circuit below realizes a negative capacitance

\[ v_i = \frac{1}{C_f} \int i_t \, dt + A_v v_i \]

\[ v_i = \frac{1}{(1 - A_v)C_f} \int i_t \, dt \]

- Total capacitance

\[ C = C_s + (1 - A_v)C_f \]

- Compensation criteria

\[ C_s = (A_v - 1)C_f \]