Biopotential Amplifiers

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Operational amplifier

Practical

Ideal

$$V_n$$  $$Z_0$$  $$A_{OL}V_d$$

$$V_p$$

$$V_n$$  $$V_d$$  $$A_{OL}V_d$$

$$V_p$$
Ideal vs. practical OP amp

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<th>理想運算放大器</th>
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<tr>
<td>電壓增益 ($A_{OL}$)</td>
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<td>頻寬 ($BW$)</td>
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<tr>
<td>輸入阻抗 ($Z_i$)</td>
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<td>輸出阻抗 ($Z_o$)</td>
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<td>零</td>
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Differential- and common-mode inputs

\[ V_o = A_d V_d + A_{cm} V_{cm} \]

where \( A_d = A_{ol} \) (open-loop gain)

Ideally, \( A_d = \infty \), \( A_{cm} = 0 \)

\[ CMRR = 20 \log_{10} | A_d / A_{cm} | = \infty \]

or, \( = | A_d / A_{cm} | \)
Inverting amplifier

\[ V_o / V_i = - \left( R_F / R_I \right) \]

Ideally, \( R_{in} = R_I \) and \( R_{out} = 0 \)
Inverting amplifier
Noninverting amplifier

$$\frac{V_o}{V_i} = 1 + \left( \frac{R_2}{R_1} \right)$$

*Ideally, $Z_i = \infty$ and $Z_o = 0$*
Differential Amplifier

\[ R_{id} = R_1 + R_3 \]

\[ V_o = \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4} V_2 - \frac{R_2}{R_1} V_1 \]

\[ = \frac{R_2}{R_1} (V_2 - V_1) \quad \text{if} \quad \frac{R_2}{R_1} = \frac{R_4}{R_3} \]
Differential Amplifier: Imbalance Effect

\[ V_o = \frac{R_1 + R_2 (1 - \varepsilon)}{R_1} \frac{R_2}{R_1 + R_2} (V_{cm} + \frac{V_{dm}}{2}) - \frac{R_2 (1 - \varepsilon)}{R_1} (V_{cm} - \frac{V_{dm}}{2}) \]

\[ V_o = A_{dm} V_{dm} + A_{cm} V_{cm} \]

\[ A_{dm} = \frac{R_2}{R_1} (1 - \frac{R_1 + 2R_2 \varepsilon}{2}) \quad A_{cm} = \frac{R_2}{R_1 + R_2} \varepsilon \]

\[ CMRR = 20 \log_{10} \left| \frac{A_{dm}}{A_{cm}} \right| = 20 \log_{10} \left| \frac{1 + R_2 / R_1}{\varepsilon} \right| \]
Instrumental Amplifier (IA)

- Three OP-AMP IA Realization

\[ V_o = \frac{R_2}{R_1} \left( 1 + \frac{2R'}{R_g} \right) (V_2 - V_1) \]
Analog filters

First-order lowpass active filter

\[ H(s) = \frac{V_o}{V_{in}} = \frac{1 + R_2 / R_1}{1 + sCR} \]

\[ H(jf) = \frac{H_0}{1 + j(f / f_0)} \]

where \( f_0 = \frac{1}{2\pi RC} \) and \( H_0 = 1 + \frac{R_2}{R_1} \)
First-order lowpass filter

\[ H(s) = \frac{V_o}{V_i} = \frac{-R_2 / R_1}{1 + sCR_2} \]

\[ H(jf) = \frac{H_0}{1 + j(f / f_0)} \]

where \( f_0 = \frac{1}{2\pi R_2 C} \) and \( H_0 = -\frac{R_2}{R_1} \)
First-order highpass filter

\[
H(s) = \frac{V_o}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right) \frac{sCR}{1 + sCR}
\]

\[
H(jf) = H_0 \frac{j(f/f_0)}{1 + j(f/f_0)}
\]

where \(f_0 = \frac{1}{2\pi RC}\) and \(H_0 = 1 + \frac{R_2}{R_1}\)
First-order highpass filter

\[ H(s) = \frac{V_o}{V_i} = \frac{-sCR_2}{1 + sCR_1} \]

\[ H(jf) = H_0 \frac{j(f / f_0)}{1 + j(f / f_0)} \]

where \( f_0 = \frac{1}{2\pi R_1 C} \) and \( H_0 = -\frac{R_2}{R_1} \)

\[ s = j\omega \]
First-order bandpass active filter

\[ H(s) = \frac{V_o}{V_i} = \frac{-sC_1R_2}{(1+sC_1R_1)(1+sC_2R_2)} \]

\[ H(jf) = \frac{-\left(\frac{R_2}{R_1}\right)jf/f_1}{[1+\left(jf/f_1\right)][1+\left(jf/f_2\right)]} \]

where \( f_1 = \frac{1}{2\pi R_1 C_1} \) and \( f_2 = \frac{1}{2\pi R_2 C_2} \)
Instrumental amplifier with first-order highpass filter

\[
\frac{V_o}{V_2 - V_1} = G \cdot \frac{s}{s + \frac{1}{RC}}
\]
Second-order filters

\[ H(s) = \frac{n_2 s^2 + n_1 s + n_0}{s^2 + (\omega_0 / Q)s + \omega_0^2} \]

(1) Low-pass response

\[ n_2 = n_1 = 0, \quad n_0 = \omega_0^2 \]

\[ H(s) = \frac{\omega_0^2}{s^2 + (\omega_0 / Q)s + \omega_0^2} \]

\[ H(jf) = \frac{1}{1 - (f / f_0)^2 + (j / Q)(f / f_0)} \]

(2) High-pass response

\[ n_2 = 1, \quad n_1 = n_0 = 0 \]

\[ H(s) = \frac{s^2}{s^2 + (\omega_0 / Q)s + \omega_0^2} \]

\[ H(jf) = \frac{-(f / f_0)^2}{1 - (f / f_0)^2 + (j / Q)(f / f_0)} \]
Second-order filters

Low-pass response

High-pass response

Second-order Sallen-Key lowpass filter

\[ H(jf) = \frac{1}{1 - (f/f_0)^2 + (j/Q)(f/f_0)} \]

where \( f_0 = \frac{1}{2\pi\sqrt{mnRC}} \) and \( Q = \frac{\sqrt{mn}}{m+1} \)
Second-order Sallen-Key highpass filter

\[
H(jf) = \frac{-(f/f_0)^2}{1-(f/f_0)^2 + (j/Q)(f/f_0)}
\]

where \( f_0 = \frac{1}{2\pi\sqrt{mnRC}} \) and \( Q = \frac{\sqrt{mn}}{n+1} \)
Second-order filters

(3) Band-pass response

\[ n_2 = 0, \quad n_1 = \frac{\omega_0}{Q}, \quad n_0 = 0 \]

\[ H(s) = \frac{(\omega_0 / Q)s}{s^2 + (\omega_0 / Q)s + \omega_0^2} \]

\[ H(jf) = \frac{(j/Q)(f/f_0)^2}{1 - (f/f_0)^2 + (j/Q)(f/f_0)} \]

(4) Band-reject response

\[ n_2 = 1, \quad n_1 = 0, \quad n_0 = \omega_0^2 \]

\[ H(s) = \frac{s^2 + \omega_0^2}{s^2 + (\omega_0 / Q)s + \omega_0^2} \]

\[ H(jf) = \frac{1 - (f/f_0)^2}{1 - (f/f_0)^2 + (j/Q)(f/f_0)} \]
Second-order band-reject filters

Twin-T notch filter

\[ H(jf) = \frac{1 - (f / f_0)^2}{1 - (f / f_0)^2 + (j / Q)(f / f_0)} \]

where \( f_0 = \frac{1}{2\pi RC} \), and \( Q = \frac{1}{4\left(1 - \frac{R_1}{R_1 + R_2}\right)} \)
Twin-T notch filter

* For 50Hz use 3.16MΩ and 6.37MΩ
  Gain = 101
Twin-T notch filter (Cont.)

From WJ. Tompkins, JG. Webster. Design of Microcomputer-Based Medical Instrumentation, Prentice-Hall, 1981.
Dipole field of heart when R is maximum
Electrocardiogram (ECG) measurements

\[ I - II + III = 0 \]
Augmented Leads
Augmented Leads
Relation of different-lead ECG

Einthoven triangle

Relation of different-lead ECG (Cont.)


\[ i \times R + i \times R - \Pi = 0 \]
\[ i \times R = \frac{\Pi}{2} \]
\[ -i \times R + \text{III} + a\text{VL} = 0 \]
\[ a\text{VL} = i \times R - \text{III} \]
\[ a\text{VL} = \frac{\Pi}{2} - \text{III} = \frac{\Pi - 2 \times \text{III}}{2} \]
Wilson’s central terminal
Chest leads
ECG measurement using chest leads

ECG at chest leads
12-Lead ECG

Einthoven leads: I, II & III

Goldberger augmented leads: $V_R$, $V_L$, & $V_F$

Precordial leads: $V_1$-$V_6$
Vectorcardiogram (VCG)
ECG amplifier

“Drievn-right-leg” circuit
(1) Reduce common-mode voltage
(2) R1 limits the current to patient. C1 maintains stability of the circuit.

Gain = \frac{49.4\,k\Omega}{R_g} + 1
Interferences in ECG

Power-line interference

Electromyographic interference
Power interference in ECG measurement

Power line, 120V, 50/60 Hz
Common-mode voltage by power-line interference

\[ v_{cm} = i_{db} Z_G \]

Typical value

\[ v_{cm} = (0.2 \ \mu A) (50 \ k\Omega) \]

\[ = 10 \ mV \]
Impedance mismatch in ECG measurement

- Degradation of CMRR due to nonzero source resistance and parasitic capacitance

\[ V_1 \neq V_2 \text{ due to } R_s C_1 \neq R_s C_2 \]
Driven-right-leg circuit
Driven-right-leg circuit (cont.)

\[
\frac{V_{cm}}{R_a/2} + \frac{V_o}{R_f} = 0
\]

\[\Rightarrow V_o = -\frac{2R_f}{R_a} V_{cm}\]

\[-\frac{2R_f}{R_a} V_{cm} = V_{cm} - i_d R_{cm}\]

\[\Rightarrow V_{cm} = \frac{i_d R_{cm}}{1 + 2R_f / R_a}\]
Driven-right-leg circuit (cont.)

<EX> \[ i_d = 0.2 \, \mu A. \] A worst-case electrode resistance \( R_{cm} = 100 \, k\Omega \), \( R_a \) and \( R_f \) are selected as \( 25 \, k\Omega \) and \( 5 \, M\Omega \) respectively.

Find \( V_{cm} \).

\[
V_{cm} = \frac{100k\Omega \times 0.2\mu A}{1 + 2 \times 5M\Omega / 25k\Omega} = 50\mu V
\]

If no right-leg-driven circuit

\[
V_{cm} = i_d \times R_{cm} = 100k\Omega \times 0.2\mu A = 20mV
\]
ECG Amplifier: One-Lead ECG Front-End

Buffers, Stage1, Gain = 10  Diff Amp, Stage2, Gain = 1  Out Amp, Stage3, Gain = 50  Total Gain = 500

Six-Leads ECG Front-End (Five Patient Electrodes)

Voltage at WCT is equal to dc and 60 Hz common-mode voltage

RL Drive: Inversion of common-mode interference

Magnetic-field pickup in ECG measurement
Isolation amplifier

- Basic architecture

- Isolation barrier, can be magnetic transformer, optical, capacitive

- Equivalent: $10^8 \sim 10^{12} \, \Omega$
Isolation amplifier (cont.)

- Isolation mode rejection ratio (IMRR)

\[ V_{OUT} = (V_{IN} + \frac{V_{IM}}{IMRR}) \times \text{Gain} = V_{IN} \times \text{Gain} + \frac{V_{IM}}{IMRR} \times \text{Gain} \]

where IMR = \(20\log_{10}\) IMRR
Isolation amplifier (cont.)

- IMRR v.s. Frequency

![Graph showing IMR vs Frequency](image)
Isolation amplifier vs. instrument amplifier

**Instrumentation Amplifier**
- More residual noise
- \[ V_{out} = V_{in} \times \text{Gain} + V_{CM\,\text{Noise\,error}} \]
- CMR = 105 dB

**Isolation Amplifier**
- Less residual noise
- \[ V_{out} = V_{in} \times \text{Gain} + V_{IM\,\text{Noise\,error}} \]
- IMR = 125 dB

Conclusion: Iso amp does a better job of rejecting noise, because IMR_{ISO} >> CMR_{IA}.
**IMRR vs. CMRR**

\[ V_{\text{OUT}} = (V_{\text{IN}} + \frac{V_{\text{CM}}}{\text{CMRR}} + \frac{V_{\text{IM}}}{\text{IMRR}}) \times \text{Gain} \]

\[ V_{\text{OUT}} = \text{Gain} \left( V_{\text{SIG}} + \frac{V_{\text{CM}}}{\text{CMRR}} + \frac{V_{\text{IM}}}{\text{IMRR}} \right) \]

\[ \text{IMR}_{1\text{SO}} >> \text{CMR}_{1\text{A}} > \text{CMR}_{1\text{SO}} \]

ISO: Isolation amplifier

IA: Instrumental amplifier
Transformer-coupled isolation amplifier
Transformer-coupled isolation amplifier (ISO212, Burr-Brown Corporation)
Optical-coupled isolation amplifier
Optical-coupled isolation amplifier (ISO100, Burr-Brown Corporation)

Connect pins 15 and 16 for bipolar and pins 16 and 17 for unipolar.

Connect pins 7 and 8 for bipolar and pins 8 and 9 for unipolar.
Capacitive isolation amplifier  
(ISO121, Burr-Brown Corporation)
Analog channel-to-channel isolation

Analog isolation

Digital isolation

Digitization trend in physiological monitoring

Old
12-Bit With Analog DC Restoration

ECG Signal

12-Bit Resolution

New
19-Bit Without Analog DC Restoration

DC Offset

$\frac{1}{2^{12}} \times 1 \text{mVp-p} = 0.2 \mu\text{Vp-p}$

$\frac{1}{2^{10}} \times 1 \text{mVp-p} = 1 \mu\text{Vp-p}$

$\frac{1}{2^{10}} \times 1 \text{mVp-p} = \mu\text{Vp-p}$

$0.5 \text{V DC Electrode Offset}$

$\Rightarrow 0.0002\% \Rightarrow 1 \text{LSB of 19 Bits}$
Multichannel EEG recordings: Neuroscan™
Monopolar measurements

[Diagram showing EEG electrode placements and signal amplification]
Bipolar measurements
Pasteless biopotential electrodes

- Monitoring of pilots’ alertness
  - Detection of gravitationally induced loss of consciousness caused by extreme g-forces during sharp high-speed flight
  - Brain state by EEG
  - Muscle fatigue and eye blinks and eyeball movement by EMG
- Skin preparation to decrease skin-electrode impedance is unacceptable for routine preflight procedures
Capacitive active electrode array to record frontal EEG signals

Dry electrode
Reference

- J.G. Webster, Medical Instrumentation, application and design, 3rd, Houghton Mifflin, 2000.
- 生物醫學工程導論，滄海書局，2008.