Analog Fundamentals of the ECG Signal Chain

Prepared by
Matthew Hann,
Texas Instruments Linear Applications Engineer
Objectives

• Introduce Basic ECG Concepts
• Motivate the Need for TINA and SPICE Simulation for ECG Analysis
• Introduce Discrete Analog Functions of the ECG Signal Chain
• Motivate Need for Low Cost Integrated ECG Conditioning System
• Introduce the ADS1298 and Its Embedded ECG Circuitry and Functions
Analog Fundamentals of the ECG Signal Chain

- What is a Biopotential?
- What is ECG?
- The Einthoven Triangle
- Analog, Lead Definitions, Derivations, and Purpose
- Modeling the Electrode Interface
- Input Filtering and Defibrillation Protection
- Isolation
- The INA front end
- AC vs. DC coupling
- RL Drive Amplifier Selection and Design
- The ECG Shield Drive
- Lead Off Detection
- PACE Detection
- INA post Gain + Analog Filtering
- A/D Conversion Options and Filtering
- **ADS1298** Introduction, Features, and Advantages
What is a Biopotential?
What is a Biopotential
An electric potential measured between living cells

A. Based on source
- Nerve impulse
- Muscle impulse

B. Based on recordings
- Action potential
- Action current
What is a Biopotential

Every cell is like a little battery

Human Cell

-70 mV
Na +
K +
Ca ++
Cl –

Voltage

+20 mV
0 V

Action Potential

Depolarization

Repolarization

-70 mV
What is ECG?
What is ECG?
Biopotentials from cells → electrodes

Electrodes convert ionic signals from the body into electrical signals in wires

Muscle → Machine

Diagnostic Monitor
- ECG
- BP
- Temp
- Resp

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What is ECG?
A measure of the electrical activity of the heart
What is ECG?

ECG and blood pressure waves

120 mm Hg vessel maxpressure head
Pressure signal has slower rise
30 Hz BW, 25 harmonics

60 mm Hg vessel relaxation
ECG signal has faster rise
100-150 Hz BW, 70 harmonics

1 mV_pp

Left heart relaxes
Left heart contracts

P - Systolic
Arterial Pressure

+V

T1

T2

Time

0 - V

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What is ECG?
Actual ECG-normal

Chart speed: 25 mm/sec
10 mm = 1 mV
10 mm = 0.4 sec
24 mm, 0.96 sec
24 mm x 1 sec / 25 mm = 0.96 sec / beat => 1 / 0.96 sec = 1.04 bps

62 BPM at rest
What is ECG?

ECG irregular tracings due to external artifacts

- 50/60 Hz pick-up
- Baseline dc instability
- Alternating Current (AC) Interference
- Irregular Baseline
- Muscle shaking
- Baseline or dc drift
- Somatic Tremor
- Wandering Baseline
What is ECG?
Modeling the electrode interface

Electrical characteristics include a DYNAMIC resistance, capacitance, and offset voltage.
Analog Lead Derivation
Analog Lead Derivation
ECG Einthoven Triangle, 1907

3 Body Electrodes,
3 Derived Leads = I, II, III

LEAD I = $V_{LA-RL} - V_{RA-RL}$
LEAD II = $V_{LL-RL} - V_{RA-RL}$
LEAD III = $V_{LL-RL} - V_{LA-RL}$

Einthoven’s Law

In electrocardiogram at any given instant the potential of any wave in Lead II is equal to the sum of the potentials in Lead I and III.
Analog Lead Derivation

The Wilson Central (WCT) Provides Chest Lead Reference at Center of Einthoven Triangle

Assuming:

\[ R_{RA} = R_{LA} = R_{LL} \]

Then:

\[ \frac{\Phi_{WCT}}{R_{RA}} = \frac{\Phi_{RA} + \Phi_{LA} + \Phi_{LL}}{R_{RA}} \]

\[ \Phi_{WCT} = \frac{\Phi_{RA} + \Phi_{LA} + \Phi_{LL}}{3} \]

*Drawing Taken From Bioelectromagnetism, Jaako Malmivuo and Robert Plonsey*
Analog Lead Derivation

The Wilson Central is the AVERAGE potential between RA, LA, and LL

\[ V_{\text{OUT}} = V_{(1-6)} - V_{\text{WCT}} \]

The Wilson Central is used to derive a reference potential for the Chest Leads, \( V_1 - V_6 \)
**Analog Lead Derivation**

Chest Lead Signals Provide Different Information at Different Cross-Sectional Angles

- Unique ECG Signature
- Enhanced Pattern Recognition
Analog Lead Derivation

The Goldberger Terminal represents the AUGMENTED lead derivation from the Wilson Central

\[ V_{LL} = \frac{2\Phi_{LL} - (\Phi_{RA} + \Phi_{LA})}{3} \]

\[ V_{AVf} = \Phi_{LL} - \frac{\Phi_{WCT}}{aVf} = \frac{2\Phi_{LL} - \Phi_{LA} - \Phi_{RA}}{2} \]

*Example Derivation for AVL

*Drawing Taken From Bioelectromagnetism, Jaako Malmivuo and Robert Plonsey
Analog Lead Derivation
What is the Purpose of All the Different Leads?

- Each lead provides **unique** information about the ECG Output Signal
- Multiple Angles Give a Better Than 2-D *Picture* of the ECG Output

Each lead provides **unique** information about the ECG Output Signal

Multiple Angles Give a Better Than 2-D *Picture* of the ECG Output
Analog Lead Derivation
IEC60601-2-51—Diagnostic

Table 109 – Connection of ELECTRODES for a particular LEAD

<table>
<thead>
<tr>
<th>LEAD</th>
<th>Positive ELECTRODE</th>
<th>Negative ELECTRODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>L</td>
<td>R</td>
</tr>
<tr>
<td>II</td>
<td>F</td>
<td>R</td>
</tr>
<tr>
<td>III</td>
<td>F</td>
<td>L</td>
</tr>
<tr>
<td>V1 (l = 1...6)</td>
<td>C1 (l = 1...6)</td>
<td>L, R, F</td>
</tr>
<tr>
<td>aVR</td>
<td>L, F</td>
<td>R</td>
</tr>
<tr>
<td>aVL</td>
<td>L</td>
<td>R, F</td>
</tr>
<tr>
<td>aVF</td>
<td>F</td>
<td>R, L</td>
</tr>
</tbody>
</table>

* Other negative LEADS may be used too.

Table 110 – LEADS and their identification (nomenclature and definition)

<table>
<thead>
<tr>
<th>Code 1 LEAD Nomenclature</th>
<th>Definition</th>
<th>Name of the LEAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>I = L-R</td>
<td>Bipolar extremity LEADS</td>
</tr>
<tr>
<td>II</td>
<td>II = F-R</td>
<td>(Limb LEADS Einthoven)</td>
</tr>
<tr>
<td>III</td>
<td>III = F-L</td>
<td>Augmented LEADS Goldberger</td>
</tr>
<tr>
<td>aVR</td>
<td>aVR = R-(L+F)/2</td>
<td>(From one of the ELECTRODES on the limbs to a REFERENCE POINT ACCORDING TO Goldberger)</td>
</tr>
<tr>
<td>aVL</td>
<td>aVL = L-(R+F)/2</td>
<td>Unipolar chest LEADS Wilson</td>
</tr>
<tr>
<td>aVF</td>
<td>aVF = F-(L+R)/2</td>
<td>From one of the ELECTRODES on the chest to the CENTRAL TERMINAL ACCORDING TO WILSON (CT)</td>
</tr>
<tr>
<td>V1</td>
<td>V1 = C1-CT</td>
<td>V2 = C2-CT</td>
</tr>
<tr>
<td>V2</td>
<td></td>
<td>Unipolar chest LEADS Wilson</td>
</tr>
<tr>
<td>V3</td>
<td>V3 = C3-CT</td>
<td>V4 = C4-CT</td>
</tr>
<tr>
<td>V4</td>
<td></td>
<td>From one of the ELECTRODES on the chest to the CENTRAL TERMINAL ACCORDING TO WILSON (CT)</td>
</tr>
<tr>
<td>V5</td>
<td>V5 = C5-CT</td>
<td>V6 = C6-CT</td>
</tr>
<tr>
<td>V6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standards | Electrodes Needed
--- | ---
1 Lead | LA, RA
3 Lead | LA, RA, LL
6 Leads | LA, RA, LL
12 Leads | LA, RA, LL, V1-6
ECG Input Filtering, Defibrillation Protection, and Isolation
ECG Input Filtering and Protection

Example: LEAD I Protection with Input Filtering

- **Series Resistance** Limits Input Current
- **$C_F$, $C_{cm}$, and $C_{diff}$** form **LPF**
- **Protection Diodes**
- **Neon Gas Lamps** Protect Against Defibrillation Voltages
- $C_{diff} = 10 \times C_{cm}$
ECG Input Filtering and Protection

TINA Simulation Circuit For Defibrillation Pulse

ECG Protection Circuit

- ECG Model
- R3 100m
- R21 1k
- R20 1k
- R24 1k
- C6 47n
- ECGp
- ECGn
- R25 1k
- Ne2Lamp
- Ne2Lamp
- Vlamp1
- C19 33p
- Vlamp2
- Odif = 10x Ccm
- A
- inP
- inN
- Vpulse
- Vout
- VCC
- Zener Diode
- Clamping Diodes
- VCM
- VCVS 1
- VCMN
- VCC
- VCMN
- VCC
- VCM
ECG Input Filtering and Protection

Current, Voltage, and Output Response to 3000V Defibrillation Pulse
ECG Input Filtering and Protection
Isolation Techniques

**Opto Couple**

- Provide as much as $10^{12}$ $\Omega$ of isolation between Patient and Power Mains
- Patient Safety
- Physician Safety

**Capacitive Couple**

**Transformer Couple**
The INA Front End
The INA Front End
Key Features of the INA Front End

*Important*
- Input Bias Current
- Input Impedance
- Input Current Noise
- Input Voltage Noise
- Power Consumption
- DC/AC CMRR

Less Important
- Input Offset Voltage
- Input Offset Voltage Drift
- Gain Error
- Nonlinearity
- PSRR

*DC Errors such as VOS are swamped out by the Offsets Introduced by the Skin-Electrode Contacts*
The INA Front End

Example: Ideal INA Front End with REF = 2.5V

$V_{out}$ is the output of the INA and is the difference between ECGp and ECGn centered about $V_{ref} = 2.5V$. 

ECGp and ECGn are the electrodes connected to the patient. Filtering is applied through various resistors and capacitors to clean the signal. The INA (Instrumentation Amplifier) amplifies the filtered signal to produce $V_{out}$. The diagram shows the circuit components and their connections.
The INA Front End
Ideal Simulation Circuit with Current and Voltage Noise Sources

ECG + Skin Impedance

Electrode Impedance + Offset

Input CM + Differential Filtering

Ideal INA Front End
The INA Front End
Simulation Showing Output-Referred Total RMS Noise vs. Bandwidth (G = 1-10)
The INA Front End
TINA Simulations Showing Output-Referred ECG Signal
(G = 1-10)

Snapshot of R Wave from ECG Waveform

ECG Signal Varies LINEARLY with Increase in Gain
The INA Front End

What is the MAX gain on the INA When Using a DC Removal Circuit?

Integrator Removes Gained up DC offsets and servos INA output to $V_{\text{ref}}$

(1) Electrode Offset MAX = +/- 300mV

(2) Swing of INA = $V(\text{+}) - 50\text{mV}$

(3) Integrator Compliance = $(\text{ECG}_p + \text{ECG}_n + \text{VOS} + \text{VOS}_{\text{electrode}}) \times \text{Gain} < V_{\text{CC}} - V_{\text{ref}}$
The INA Front End
Simulation Circuit with Ideal INA and $V_{\text{ref}} = 2.5\text{V}$ as Integrator Input

OPA333 Used as Integrator to Remove DC and Simulate Real Response During Saturation
As the output of the Integrator Saturates from Increased Gain, $V_{out}$ of the INA pulls away from $V_{ref}$. 

The INA Front End
ECG + Integrator Output of INA vs. Gain for $V_{ref} = 2.5V$
The INA Front End

If it is Advantageous to Maximize Gain with a Low Noise INA up Front, Why not AC Couple?

*AC Coupling Removes Electrode Offsets so that Higher Gain Can Be Used for Potentially Better SNR in the Signal Chain Path
The INA Front End
TINA Simulation Circuit to Show AC-Coupled INA Gain Sweep
The INA Front End

INA Gain = 1-1000 with $V_{REF} = 2.5V$ AC Coupled
The INA Front End

What is CMRR? Why is it Important in ECG?

\[ \Delta V_{out} = \Delta V_{OS} \cdot \text{Gain} \]

Lower CMRR = More Unwanted Output Signal

\[ \text{CMRR} = -20 \log_{10} \left( \frac{\Delta V_{CM}}{\Delta V_{OS}} \right) = -20 \left( \frac{\Delta V_{CM} \cdot \text{Gain}}{\Delta V_{out}} \right) \]

\[ V_{out} = \left( \text{ECGp} - \text{ECGn} + \text{VOS}_{\text{electrode}} + \text{VOS}_{\text{OPA}} + \frac{\Delta V_{CM}}{- \text{CMRR}} \cdot \frac{10}{20} \right) \cdot \text{Gain} \]
The INA includes the R and C and must be considered in the overall CMRR Analysis

The INA \textbf{includes} the R and C and must be considered in the overall CMRR Analysis.

- Mismatch in \( R_p \) and \( C_c \) causes a \textit{differential} signal error.
- Even a 1% tolerance on \( C_c \) causes a 20\text{dB} attenuation in CMRR.

The INA Front End
What is CMRR? Why is it Important in ECG?

\[ V_{\text{diff\_actual}} = V_{\text{inp}} \sqrt{\frac{R_p^2}{R_p^2 + \left( \frac{j}{\omega C_{c1}} \right)^2}} - V_{\text{inn}} \sqrt{\frac{R_p^2}{R_p^2 + \left( \frac{j}{\omega C_{c2}} \right)^2}} \]
The INA Front End

50/60Hz Common Mode Simulation Circuit with 1μF Coupling Capacitors Mismatched

CMR TINA Circuit Test By Sweep of *Mismatch* of Input Coupling Capacitors
The INA Front End

Plot of CMRR vs. Frequency for .01 - .5% Coupling Capacitor Mismatch

- .5% Mismatch
- 0% Mismatch
The INA Front End
Plot of ECG Response to 5Hz CM Input Signal (0%-.5%) CC Mismatch

Lower Frequency Signals **Couple** Directly Into the ECG Signal to the Output
The INA Front End

Plot of ECG Response to 50/60 Hz CM Input Signal

- 50/60 Hz Noise Rejection is Virtually **Unaffected** by AC Coupling
- Dependent Primarily on the Noise Magnitude and the **CMRR** of the Front End INA
The Right Leg Drive Amplifier
The RL Drive Amplifier

The RL Drive Amplifier Serves 2 Purposes: (1) Common Mode Bias (2) Noise Cancellation

Average VCM is Inverted and Fed Back to RL; Cancels 50/60Hz noise

\[ \frac{(V_{cm} + ECG_p) + (V_{cm} + ECG_n)}{2} = V_{cm} + \frac{ECG_p + ECG_n}{2} \]

*Tapping off center of split gain resistor feeds the following voltage to the RL Drive Circuit*
The INA Front End
Simulation Circuit for Response to 50/60 Hz CM Noise Injection Source

= Included for TINA spice Convergence
The INA Front End

TINA Simulation with NO RL Drive; CM Noise is Coupled to Output
The INA Front End
TINA Simulation with RL Drive; Output Noise is Reduced

![Graph showing ECGn, ECGp, Noise, and Vout over time](image)

- **ECGn**: The signal for ECGn shows a smooth trend with slight fluctuations.
- **ECGp**: The signal for ECGp exhibits a sharp peak at 282.16m, indicating a response to the RL Drive.
- **Noise**: The noise signal is periodic, with a consistent amplitude.
- **Vout**: The output voltage shows a peak at 282.16m, followed by a drop to a stable level.

**Time (s)**: 5.46m, 282.16m, 558.86m

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The INA Front End
Determining MAX Gain for the RLD Amplifier

More Gain = Better CMRR
Gain Limited By Electrode Offset (MAX = ±300mV), VOS_{A1}, and VOS_{RLD}

\[
V_{RL} = \left[ \frac{(V_{ref} - V_{outA1})}{R_I} \right] \cdot R_F + V_{ref}
\]

\[
V_{outA1} = \left[ \frac{(V_{cm} + V_{ECGp} + V_{ep}) - (V_{cm} + V_{ECGn} + V_{en})}{R_G} \right] \cdot \left( \frac{R_G}{2} \right) + (\text{VOS}_{A1})
\]
The INA Front End
RL Drive Stability Simulation Circuit

Electrode Resistance Varies With Contact and Moisture, Presents Problems for RLD Stability

Local RLD Loop is Broken to Ensure Proper Phase Margin Over Range of Electrode Resistance
The INA Front End

RL Drive Simulation Showing 1/Beta Variation With Electrode Resistance

> 20dB/dec ROC (Rate of Closure) = INSTABILITY

Gain (dB)

AOL

R\text{electrode} = 100k\Omega

R\text{electrode} = 1k\Omega

Frequency (Hz)
The INA Front End
Using RLD Simulation to Compensate for 1/Beta Variation With Electrode Resistance

Variation in AOL vs. Process

Intersection of 1/ß and AOL curve > 40dB/dec

Feedback Comp Placed vs. Worst Case Electrode Resistance and RLD AOL
The INA Front End
RL Drive Stability Simulation Circuit of Feedback #1
The INA Front End
RL Drive Stability Simulation Circuit of Feedback #2
The INA Front End
RL Drive Stability Simulation of Separate Feedback Paths

Gain (dB)

Frequency (Hz)

1.00 10.00 100.00 1.00k 10.00k 100.00k 1.00M 10.00M

Gain (dB)

-20.00 0.00 20.00 40.00 60.00 80.00 100.00 120.00

AOL
Feedback #2
Feedback #1

Composite 1/β
The INA Front End
RLD Stability Circuit with Compensated Amplifier
The INA Front End
Compensated RLD Circuit Simulation of 1/Beta and AOL Intersection

Intersection of 1/Beta and AOL curve is 20dB/dec = STABLE
The INA Front End
Gain and Phase Margin Plots of Compensated RLD Amplifier

Loop Gain Phase Margin @ 0dB = 70 degrees
The INA Front End
Step Response of RLD Amplifier and ECG Output

Vout_INA

Vtest

VoA

Time (s)
The ECG Shield Drive
The ECG Shield Drive
Shield drive eliminates leakage to ECG Inputs

- Shield is driven to \((V_{IN(+) - V_{IN(-)})/2}\)
- Eliminates Leakage from \(C_{P1}\) and \(C_{P2}\)

- Capacitance of cable can be 500 pF to 1.5 nF
- Isolation resistor Necessary for improved EMI/RFI filtering
The ECG Shield Drive
AC Stability Simulation Circuit for OPA333 as Shield Driver

Effective Cable Shield Capacitance
The ECG Shield Drive

AOL + 1/Beta Response of OPA333 Shield Drive and 1nF Cable Capacitance

Gain (dB)

Frequency (Hz)

-40dB/decade Intersection of AOL and 1/Beta = UNSTABLE
The ECG Shield Drive
TINA Simulation Circuit for Stabilized OPA333 Shield Driver

Shield Drive Compensation Network
The ECG Shield Drive

TINA Simulation Shows > 45 Degrees Phase Margin for OPA333 Shield Driver
Lead Off Detection
Lead Off Detection
Lead Off Differentiates a Bad Lead from an Arrhythmia

Body-Electrode Model

- Pull up Resistors Force +IN to Comparator High When Lead is Removed
- Comparator Voltage triggers ALERT
- Lead Off Indicative of “Weak Lead”
Lead Off Detection

TINA Simulation Circuit for Lead Off Detect
Pace Detection
**Pace Detect**

Pace Maker Pulse Specifications

\[
\begin{align*}
\text{a}_p &= \text{Amplitude (2-700mV)} \\
\text{a}_o &= \text{Overshoot} \\
\text{d}_p &= \text{Pulse Width (.1-100us)} \\
\text{t}_0 &= \text{Overshoot Time Constant (4-100ms)} \\
\text{Rise Time} &= 100\text{us}
\end{align*}
\]
Pace Detect
Pace Detect Circuitry in Parallel with ECG Signal Path

• AC Coupled Input Blocks ECG Signal and Retains the PACER Pulse
• Window Comparator Triggers if PACER Signal Detected
• Separate PACER Processing Circuitry
Pace Detect

PACE Signal Extracted From PACE + ECG Waveform

![Graph showing Pace Detect and PACE Signal Extracted From PACE + ECG Waveform](image)
Pace Detect
Output Plots of Pace Detect Circuitry

- VPDetect
- Vout
- Vpace1
- Vpace2

PACER Input Signal to Comparators
DC Coupled Output of INA
PACE Comparator 1
PACE Comparator 2

Time (s):
- 181.60m
- 207.91m
- 234.23m
INA Post Gain and Filtering

Choice of High Gain + SAR ADC OR Low Gain + 24 bit Delta Sigma ADC

SAR + filter Option Results in Same Input-Referred Noise as the DC Coupled Delta-Sigma, but at what COST?
INA Post Gain and Filtering
INA + Post Gain Amp With Differential Noise Source
INA Post Gain and Filtering

Noise Coupled Differentially Translates to Output

50/60 Hz Couples Differentially; How Do We Get Rid of It?
INA Post Gain and Filtering
Use Filter Pro to Design a 50/60 Hz Notch

**Texas Instruments FilterPro**

Enter number of poles—
1, 2, 3... to 10

The number of poles affects the rolloff rate of the filter. The greater the number of poles, the better the filter approximates an ideal brick-wall response. Complexity increases proportionally. The maximum number of poles for bandpass and notch is 5.

Section A

**Note:** Phase response is not corrected 180° for inverting stages.
INA Post Gain and Filtering
ECG Circuit with Added 50/60Hz Notch + Post Gain
INA Post Gain and Filtering
Plots of ECG Output with Gain and 60Hz Notch
INA Post Gain and Filtering

Line Cycle Sampling with SAR converter on ‘T’ Wave at Common Frequency Multiples of 50/60Hz

\[ F_{\text{sample}} (\text{Hz}) = n \times \left( \frac{1}{50\text{Hz}} + \frac{1}{60\text{Hz}} \right)^{-1} = n \times (27.27) \text{ Hz} \]
INA Post Gain and Filtering

Comparison of Delta Sigma ADC vs. Lower Resolution SAR ADC

Using a low resolution ADC

Using a high resolution ADC

- Reduced Hardware
- Filter Requirements Relaxed
- Lower Power
- Lower System Cost
- Electrode Offset Info Retained
A single ADC in the MUX approach does not necessarily mean lower power due to the higher speed needed to perform MUX switching.
ADS1298 Introduction
ADS129x
Input Amplifier Specifications for Single Channel AFE

- CMOS input PGA
- High input impedance
- Low input current noise
- Rail to rail input

- Low Input Voltage Noise
- Current Noise = 0.1pA/√Hz Over Bandwidth
- No Output Phase Reversal
- 75dB AOL @ 50/60 Hz
- 60dB CMR @ 50/60 Hz
- IB = 150pA MAX vs. Temperature
- ZIN >100MΩ, CIN = 100pF max