Components of the Electrocardiogram (ECG)

- **Source(s)**
  - Potential differences within the heart
  - Spatially distributed and time varying

- **Volume conductor**
  - Inhomogeneous and anisotropic
  - Unique to each individual
  - Boundary effects

- **ECG measurement**
  - Lead systems
  - Bipolar versus unipolar measurements
  - Mapping procedures

- **Analysis**
  - Signal analysis
  - Spatial analysis
  - Dipole analysis
  - Simulation and modeling approaches
ECG History and Basics

- Represents electrical activity (not contraction)
- Marey, 1867, first electrical measurement from the heart.
- Waller, 1887, first human ECG published.
- Einthoven, 1895, names waves, 1912 invents triangle, 1924, wins Nobel Prize.
- Goldberger, 1924, adds precordial leads

Electrophysiology Overview

- Pacemaker cells
  - SA Node
  - AV Node
  - Purkinje Fibers
  - Overdrive suppression
- Conduction system
  - Varied propagation
- Ventricular myocytes
  - Electrical coupling
  - Anisotropy
- The Electrocardiogram (ECG)
ECG Source Basics

Cell Membrane

Outside

Inside

Charging Currents

Depolarizing Currents

Gap Junctions

Tissue bundle

Activated

Resting
Dipole(s) Source

Equivalent Sources

- Match cell/tissue structure to current sources
- Multiple models possible depending on formulation and assumptions
- Typical assumptions:
  - uniform characteristics of tissue
  - simple geometries
- Primary (versus secondary) sources
Cardiac Sources

- Formulation in terms of cells impossible
- Dipole(s), multipoles: simple but incomplete
- Volume dipole density: hard to describe
- Surface dipole density: good compromise in some problems
- All require some model of time dependence (propagation)

Heart Dipole Approaches

- Treat the heart as single dipole
- Fixed in space but free to rotate and change amplitude
- Einthoven triangle
- Vector ECG (Vectorcardiogram)
- Lead fields: generalization of heart dipole
Heart Dipole and the ECG

- Represent the heart as a single moving dipole
- ECG measures projection of the dipole vector
- Why a dipole?
- Is this a good model?
- How can we tell?

Cardiac Activation Sequence and ECG
Cardiac Activation Sequence as a Moving Dipole

- Oriented from active to inactive tissue
- Changes location and magnitude
- Gross simplification that is clinical important

Electrocardiographic Lead Systems

- Einthoven Limb Leads (1895--1912): heart vector, Einthoven triangle, string galvanometer
- Goldberger, 1924: adds augmented and precordial leads, the standard ECG
- Wilson Central Terminal (1944): the "indifferent" reference
- Frank Lead System (1956): based on threedimensional Dipole
- Body Surface Potential Mapping (Taccardi, 1963)
Einthoven ECG

- Bipolar limb leads
- Einthoven Triangle
- Based on heart vector

\[ V_I = \Phi_{LA} - \Phi_{RA} \]
\[ V_{II} = \Phi_{LL} - \Phi_{RA} \]
\[ V_{III} = \Phi_{LL} - \Phi_{LA} \]  
(Note typo in text)

Applying Kirchoff’s Laws to these definitions yields:

\[ V_I + V_{III} = V_{II} \]

Augmented Leads

- Provide projections in additional directions
- Redundant to limb leads, i.e., no new information.

\[ aVL = V_I - \frac{1}{2} V_{II} \]
\[ aVF = V_{II} - \frac{1}{2} V_I \]
\[ aVR = -\frac{1}{2}(V_I + V_{II}) \]
Wilson Central Terminal

- Goldberger (1924) and Wilson (1944)
- “Invariant” reference
- “Unipolar” leads
- Standard in clinical applications
- Driven right leg circuit

\[ I_R + I_F + I_L = 0 \]

\[ \frac{\Phi_{CT} - \Phi_{RA}}{5000} + \frac{\Phi_{CT} - \Phi_{LA}}{5000} + \frac{\Phi_{CT} - \Phi_{LL}}{5000} = 0 \]

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

Precordial Leads

- Modern clinical standard (V1-V6)
- Note enhanced precordials on right side of chest and V7
Projection Summary

![Diagram of different planes and projections for ECG/EEG]

Standard (12-lead) ECG

- 1mm = 100 μV
- 50 mm = 1 s  1 mm = 40 ms

![ECG trace with different leads and measurement scales]

ECG/EEG
Sample ECG

Vectorcardiographic Lead Systems

Frank Lead System
Lead Vector

Burger and van Milaan (1940’s)

Recall that for a dipole:
\[ \Phi(r) = -\frac{p_s \Omega}{4\pi \sigma} \]

Now generalize this idea to
\[ V_{AB} = \Phi_A - \Phi_B = L_x p_x + L_y p_y + L_z p_z \]
\[ V_{AB} = \vec{L} \cdot \vec{p} \]

\( L = \) lead vector, depends on lead location, dipole location, and torso geometry and conductivity.

B & vM used phantom model of torso with dipole source to estimate \( L \).

\[ \text{http://www.bem.fi/book/} \]

Lead Field Based Leads

- McFee and Johnston, 1950’s
  - Tried to define leads such that \( E \) and \( I \) were constant over the heart volume. This way, dipole movement would not change \( L \)
  - Developed lead system on this basis from torso phantom measurements
  - Performance was improved for homogenous torso but the same for realistic torso.
Multipoles

- Higher order expansion of solution to Poisson’s equation
- Monopole, dipole, quadropole, octopole…
- Example: two wavefronts in cardiac tissue

Multipole Based Models
Body Surface Potential Mapping

- Measurements over entire torso
- Showed that resulting pattern was not (always) dipolar
- More complex source model than dipole required

Taccardi et al, Circ., 1963
BSPM History

Small version:
http://www.sci.utah.edu/gallery2/v/cibc/taccardi_sm.html

Large version:
http://www.sci.utah.edu/gallery2/v/cibc/taccardi_lg.html

State of the Art

Products

ActiveTwo: 200-channel DC-sampler, 54-bit resolution, biopotential measurement system with ActiveElectrode

- 208-channel, DC-sampler, 54-bit resolution, biopotential measurement system
- Black and white, easy-to-read interface
- Suitable for EEG, ECG, and EMG measurements
- Developed and engineered using MATLAB on PC and Mac
- Full range of auxiliary sensors available
- Microcontroller-based digital system

- Up to 200-channel electrode + 7 sensor channels in a single compact box.
- Second-generation active electrode: smaller size & less weight.
- Flexible printed circuit board interface.
- 24-bit ADC per channel, unprocessed SNR ratio and linearity.
- Improved digital resolution, compression, and linearity.
- Full DC operation, largest input range in the industry (500mVpp).
- User-selectable bandwidths (0.05-150 Hz)

ECG/EEG
Sample Map Display

Surface #1
p2_3200_77_torso_new_mat_1

Surface #2
p2_3200_77_torso_new_mat_1

Sample Map Display

Surface #1
p2_3200_77_torso_new_mat_1

Surface #2
p2_3200_77_torso_new_mat_1
Feature/Pattern Analysis

PTCA Mapping

LAD  RCA  LCx

• Use spatial features to identify underlying conditions
  – maxima, minima, zero lines, etc.
  – very condition dependent

Basics of the EEG

• Sources
  – Cortical layer 5 pyramidal cells
    • currents of -0.78 to 2.97 pAm
  – Burst of 10,000-50,000 synchronously active pyramidal cells required for detection
    • Equivalent to 1 mm² of activated cells
  – Modeled as a current dipole

• EEG Measurements
  – Return current (like ECG)
  – Strongly affected by head conductivities
  – Sensitive to radially and tangentially oriented sources
EEG Recording

- Scalp and cortex recording
- Unipolar and bipolar modes
- Filtering/averaging critical

EEG Montages

- Many systems (montages), 10-20 is standard
- Reference electrode variable
- Electrode placement critical

Nunez, http://www.scholarpedia.org/article/Electroencephalogram
EEG Analysis

• Frequency based
  – Delta: < 3.5 Hz
  – Theta: 3.5-7.5 Hz
  – Alpha: 7.5-13 Hz
  – Beta: > 13 Hz
  – Rhythmic, arrhythmic, disrhythmic
• Voltage
• Morphology

MEG Measurement

• Measures magnetic field mostly induced from primary current and some from return current
• Not so affected by tissue conductivity
• Poor sensitivity to radially oriented sources
• Good sensitivity to tangentially oriented sources
**Tangential vs. Radial Sources**

A) Tangential
- Negative potential
- Positive potential
- Acute

B) Tangential
- Positive potential
- "Dipole"

C) EEG tangential
- 8 cm from centre

MRG tangential
- 8 cm from centre

EEG radial
- 4 cm from centre

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http://www.mrc-cbu.cam.ac.uk/research/eeg/eeg_intro.html

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**Surface #1**
Correct_Alpha_matlab@ 1

**Surface #2**
Correct_Delta_matlab@ 1