Advanced biomedical signal and image processing

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CONTENTS

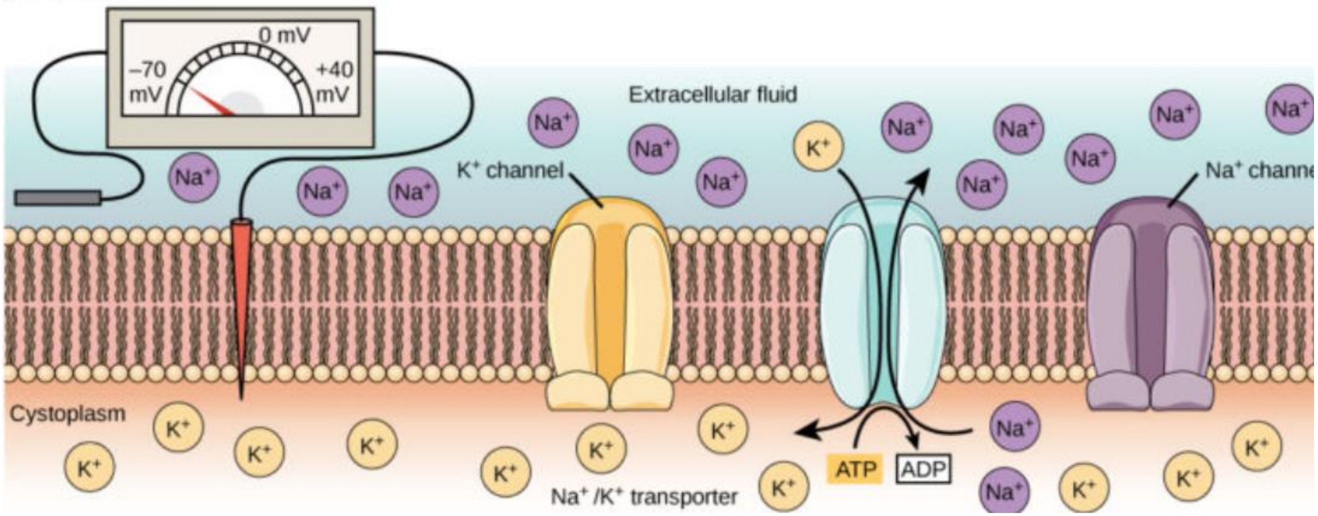
Electric Activities of the Cell

Electric activities in cells involve various physiological processes governed by the movement of ions across the cell membrane.

Electric Activities of the Cell

Resting Membrane Potential

The resting membrane potential (*Vm*) is the voltage difference across the plasma membrane of a cell at rest.



To be watch

https://www.youtube.com/watch?v=YP_P6bYvEjE&t=90s

Electric Activities of the Cell

Resting Membrane Potential

To calculate the equilibrium potential for a specific ion,

we use the Nernst equation:

universal gas constant (8.314 J/(mol·K))

absolute temperature (in Kelvin)

$$E_{ion} = \frac{RT}{zF} \ln \left(\frac{[ion]_{outside}}{[ion]_{inside}} \right)$$

equilibrium potential for the ion (in mV)

valence of the ion

Faraday's constant (96485 C/mol)

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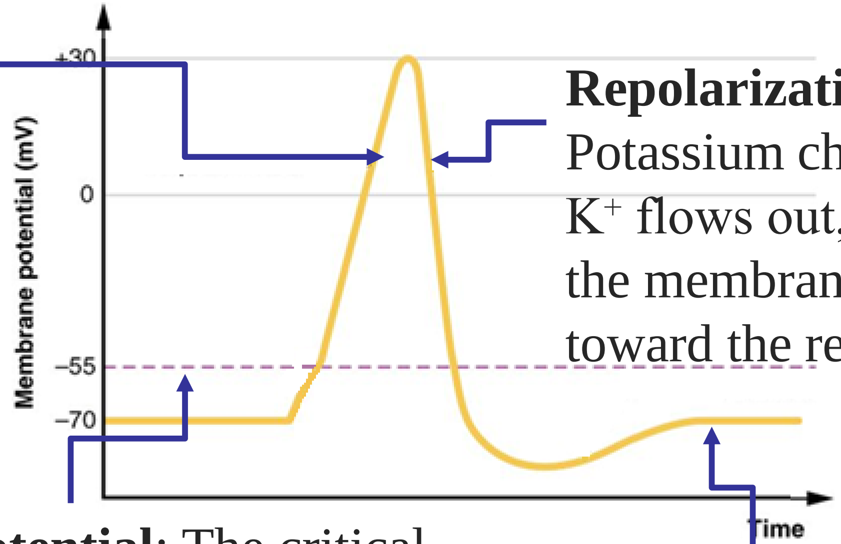
Electric Activities of the Cell

Action Potential

Phases of Action Potential:.

Depolarization: Sodium channels open, and Na^{+} rushes into the cell.



Repolarization: Potassium channels open, K^{+} flows out, returning the membrane potential toward the resting state.

Threshold Potential: The critical level to which the membrane potential must be depolarized to initiate an action potential, typically around -55 mV.

Hyperpolarization: The membrane potential temporarily becomes more negative than the resting potential.

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Electric Activities of the Cell

Action Potential Equation:
The change in membrane potential during an action potential can be modeled using the Hodgkin-Huxley equations, which describe the ionic currents through the membrane:

conductance

$$C_m \frac{dV_m}{dt} = -g_{Na}(V_m - E_{Na}) - g_K(V_m - E_K) - g_L(V_m - E_L)$$

membrane capacitance

equilibrium potentials

Electric Activities of the Cell

Ion Channels and Pumps

Sodium-Potassium Pump (Na^+/K^+ ATPase):

This pump maintains the resting membrane potential by actively transporting ions against their concentration gradients.

$$3\mathrm{Na}^+_{inside} + 2\mathrm{K}^+_{outside} + ATP \rightarrow 3\mathrm{Na}^+_{outside} + 2\mathrm{K}^+_{inside} + ADP + P_i$$

Goldman Equation:

To calculate the resting membrane potential considering multiple ions, we use the Goldman equation:

$$V_m = RT/F \ln\left(\frac{P_K[K^+]_{outside} + P_{Na}[Na^+]_{outside} + P_{Cl}[Cl^-]_{inside}}{P_K[K^+]_{inside} + P_{Na}[Na^+]_{inside} + P_{Cl}[Cl^-]_{outside}}\right)$$

permeability of the ion

Electric Activities of the Cell

Synaptic Transmission

Post-synaptic potentials can be modeled as:

reversal potential of the synapse

post-synaptic potential

$$V_{post} = V_{rest} + g_{syn}(E_{syn} - V_{post}) \cdot t$$

synaptic conductance

time

Electric Activities of the Cell

Electrophysiology Techniques

Patch Clamp Equation:

The current through an ion channel can be described by:

$$I = N \cdot P \cdot (V - E_{ion})$$

- N: number of open channels
- P: single-channel conductance
- V: membrane potential
- E_{ion}: equilibrium potential for the ion.

Electrocardiogram (ECG)

Challenges in biomedical signal processing

- **Accessibility of variables to measurement**
  - Some physiological variables are difficult to measure directly.
  - Requires specialized sensors and techniques.
- **Patient safety & noninvasiveness**
  - Preference for noninvasive methods to minimize discomfort.
  - Balancing accuracy with patient safety considerations.
- **Indirect measurements**
  - Many variables of interest cannot be directly accessed.
  - Requires computational models to estimate the desired parameters.

Electrocardiogram (ECG)

Challenges in biomedical signal processing

- **Signal source variability**
  - Physiological signals exhibit natural fluctuations (e.g., heart rate, EEG).
  - Variability due to age, health conditions, and external factors.
- **Interactions among physiological systems**
  - Multiple systems influence each other (e.g., heart-lung interactions).
  - Signal interpretation must consider cross-system dependencies.
- **acquisition interference**
  - Electrical, motion, and environmental noise can affect signal quality.
  - Requires filtering and advanced signal processing techniques.

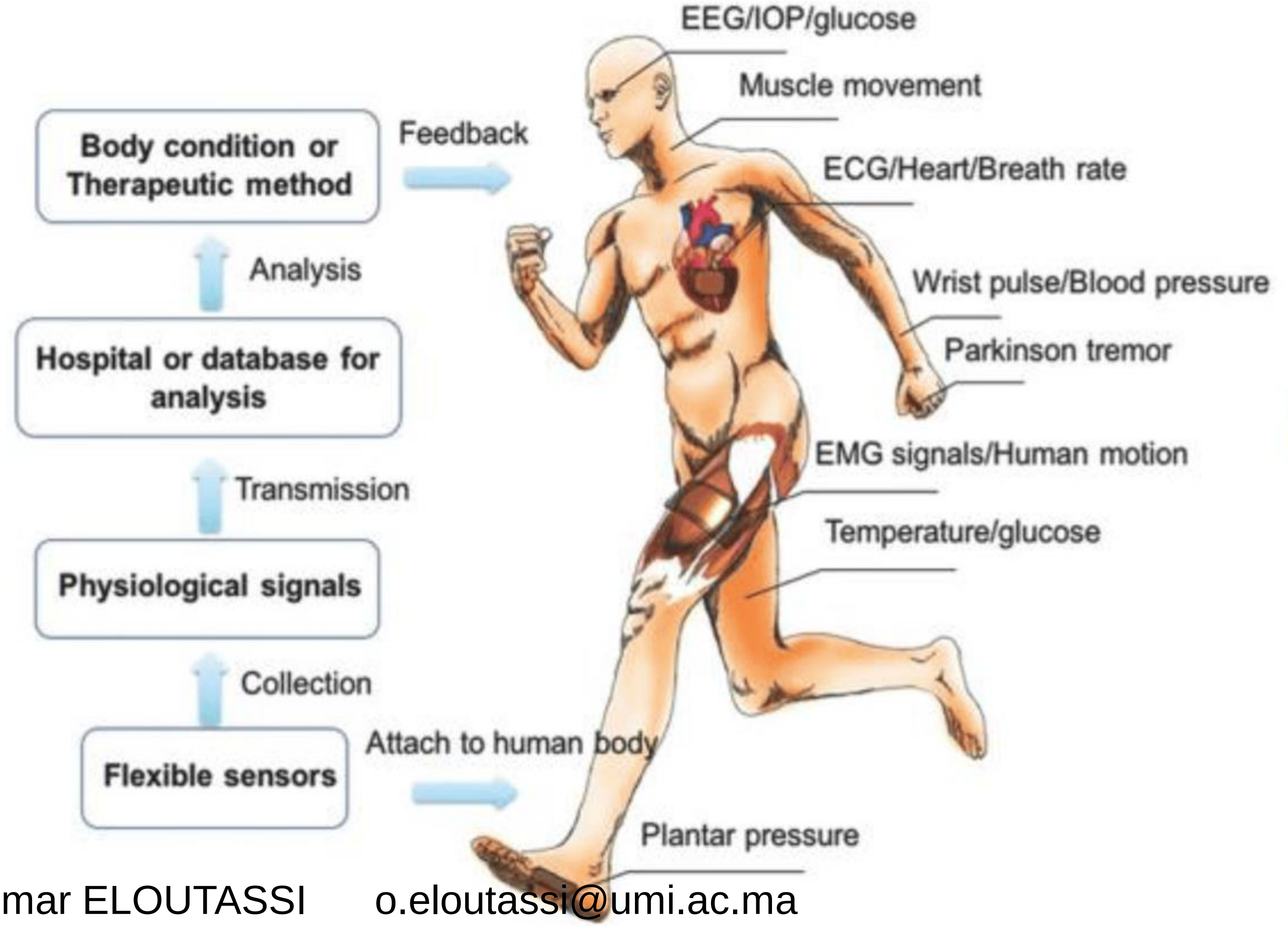
Challenges in biomedical signal processing

Overcoming these challenges requires advanced sensor technology, signal processing, and innovative computational models to ensure reliable biomedical signal acquisition.

Centralized healthcare system

Challenges in biomedical signal processing

Wearable health sensors or monitors

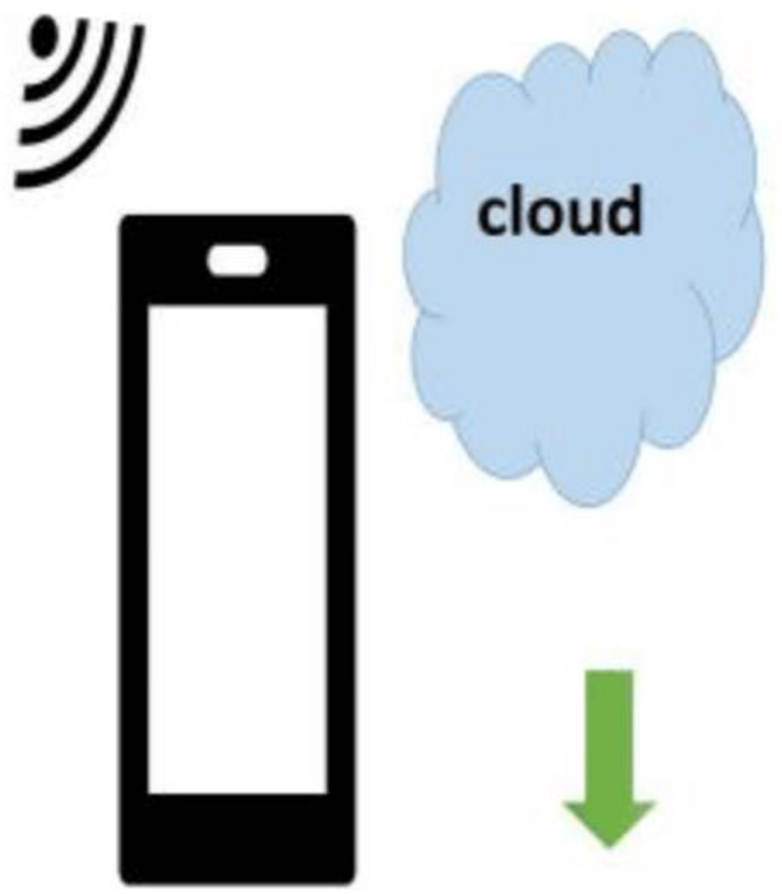


Challenges in biomedical signal processing

AI based

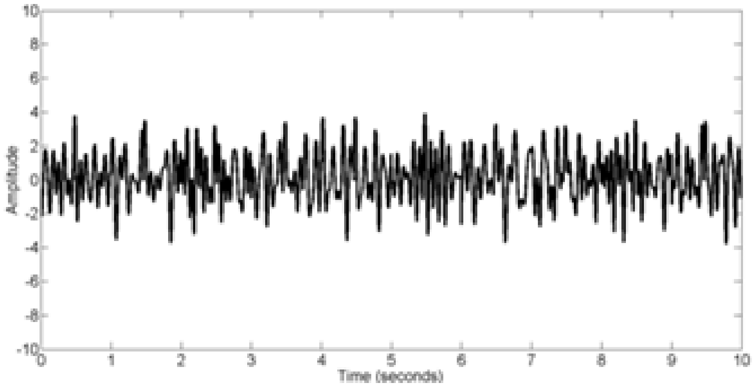
wearable

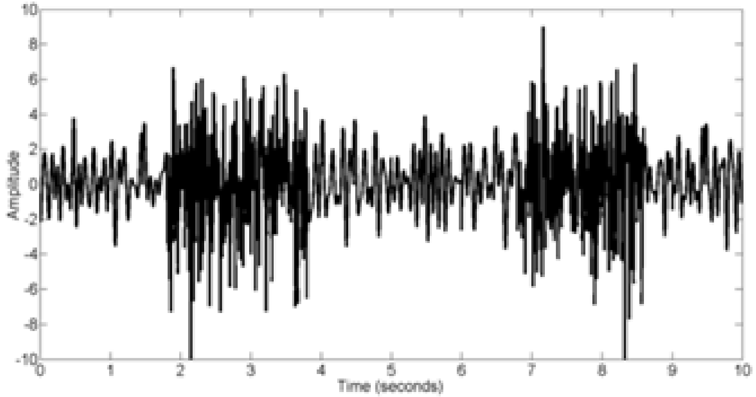
sensors



Challenges in biomedical signal processing
Artifacts and interference

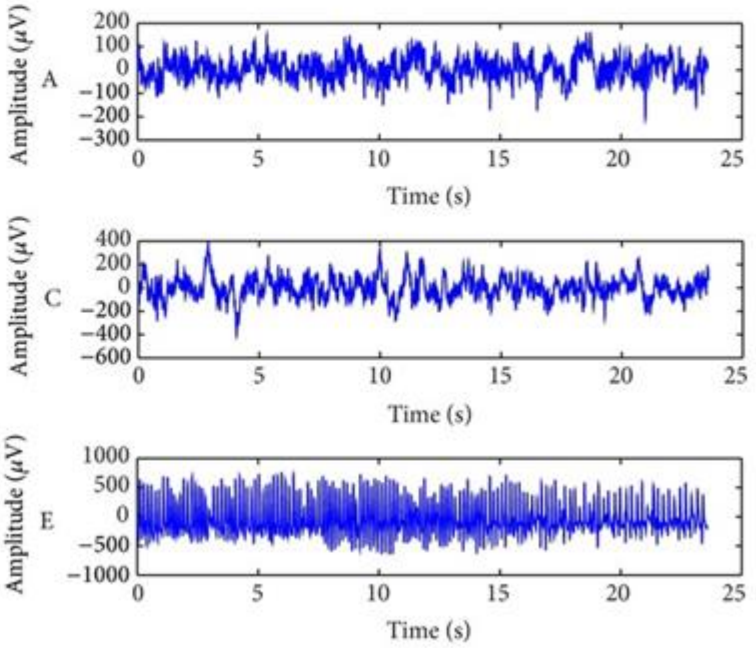
- **Interference from Other Systems**
  - Example: Muscle artifacts in EEG recordings.





Challenges in biomedical signal processing
Artifacts and interference

- **Low-Level Signals (e.g., EEG)**
  - Measured in microvolts.
  - Require highly sensitive amplifiers.
  - Easily affected by interference.

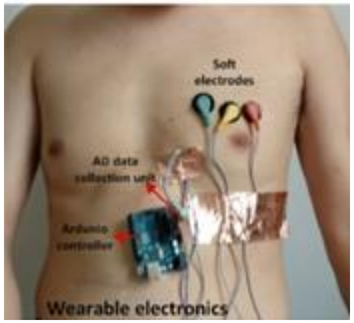


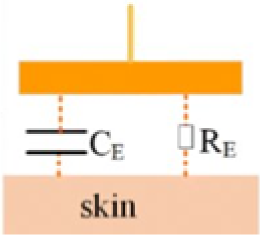
Challenges in biomedical signal processing
Artifacts and interference

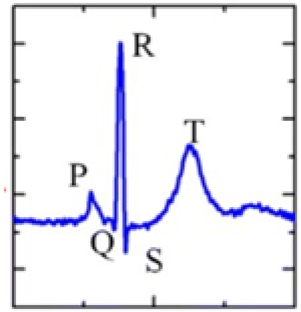
- **Protection and system behavior**
- **Limited shielding options**
  - Difficult to fully protect signals from interference.
- **Nonlinear nature of biological systems**
  - Most biological systems are nonlinear.
  - Many methods assume linearity, leading to challenges.
- **Obscurity of biological systems**
  - Exact structures and true functions are often unknown.

Application-ECG

- **What is an electrocardiogram (ECG)?**
  - A time-varying signal reflecting ionic current flow.
  - Causes cardiac fibers to contract and relax.
- **ECG is Obtained using surface ECG Recording**
  - Measured by recording potential difference between two electrodes placed on the skin's surface.







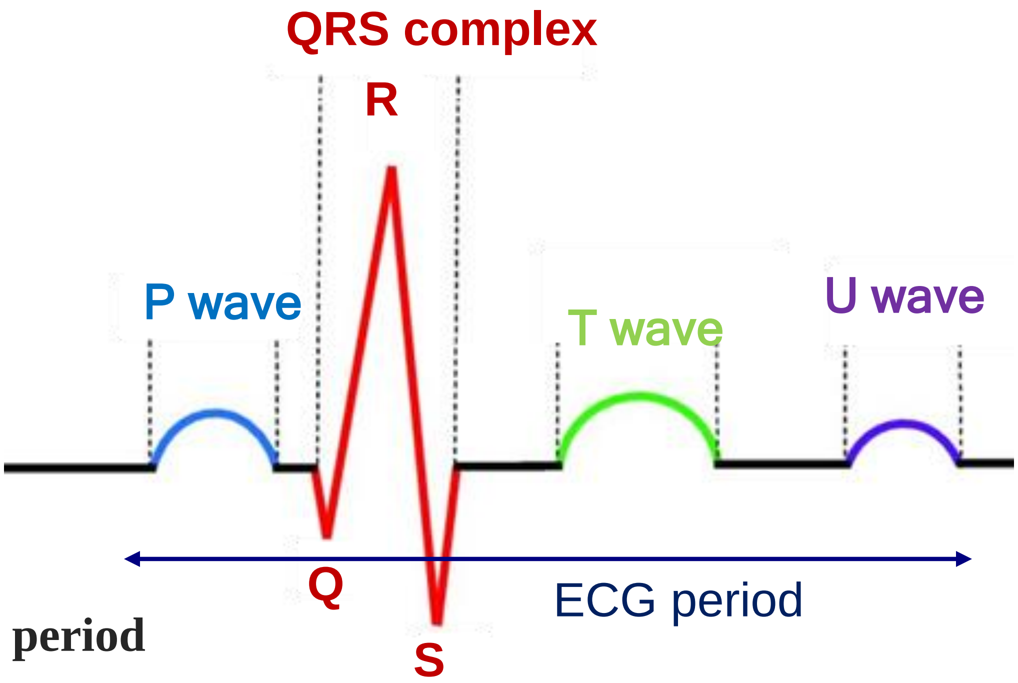
- **ECG Measures** and records electrical activity of the heart.

Application- ECG

- **Normal ECG Cycle**
- **Components of a normal ECG cycle**
  - Represents:
    - Atrial depolarization and repolarization.
    - Ventricular depolarization and repolarization.
  - Occurs with every heartbeat.

Application- ECG

- **Typical ECG Waves**



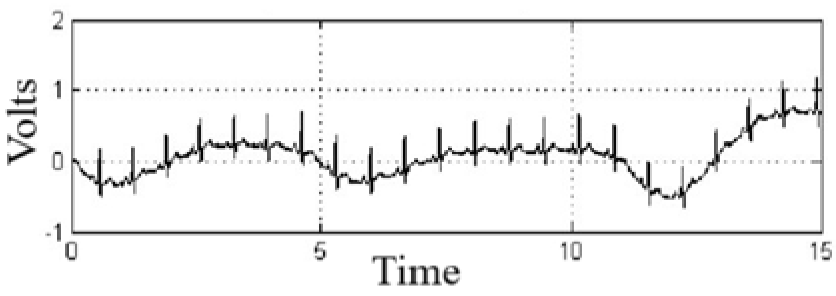
- **Components of a typical ECG period**
- **that includes**
  - QRS complex
  - P wave: the sequential activation (depolarization) of the right and left atria QRS complexes: right and left ventricular depolarization
  - T wave: ventricular repolarization
  - U wave: origin not clear, probably ”afterdepolarizations” in the ventricles

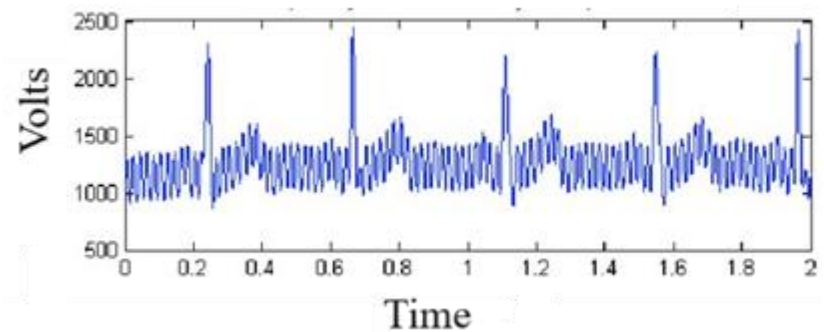
Application
ECG filtering

- Three common noise sources
  - Baseline wander
  - Power line interference
  - Muscle noise
- When filtering any biomedical signal care should be taken not to alter the desired information in any way
- A major concern is how the QRS complex influences the output of the filter; to the filter they often pose a large unwanted impulse
- Possible distortion caused by the filter should be carefully quantified

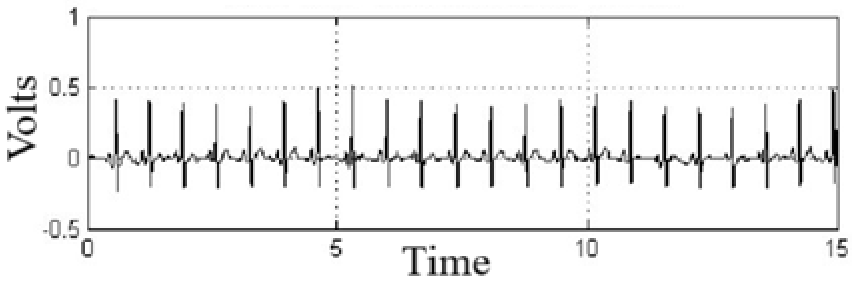
Application
ECG filtering

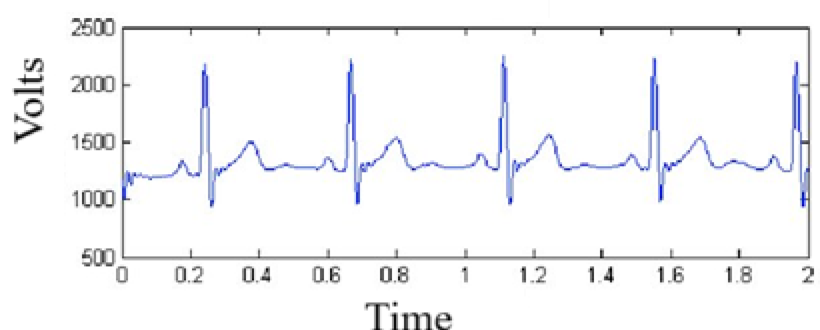
- Both baseline wander and power line interference removal are mainly a question of filtering out a narrow band of lower-than-ECG frequency interference.





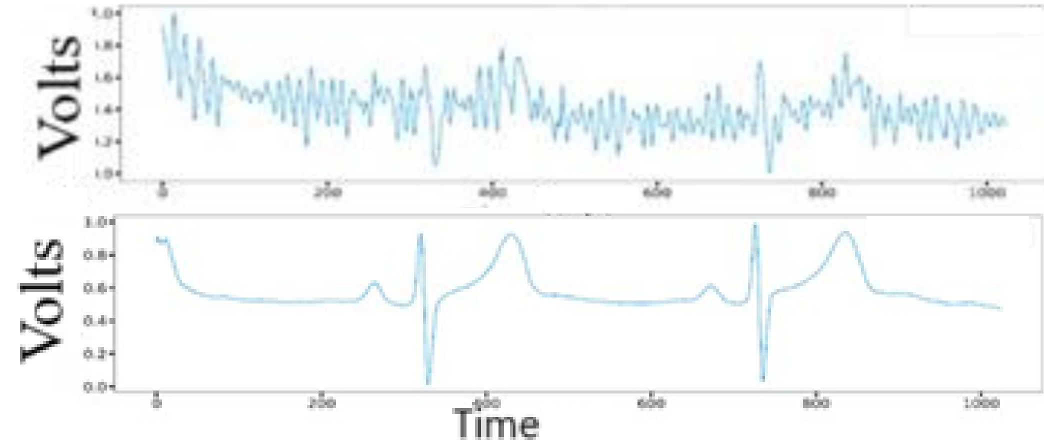
- The main problems are the resulting artifacts and how to optimally remove the noise





Application
ECG filtering

- Muscle noise, on the other hand, is more difficult as it overlaps with actual ECG data

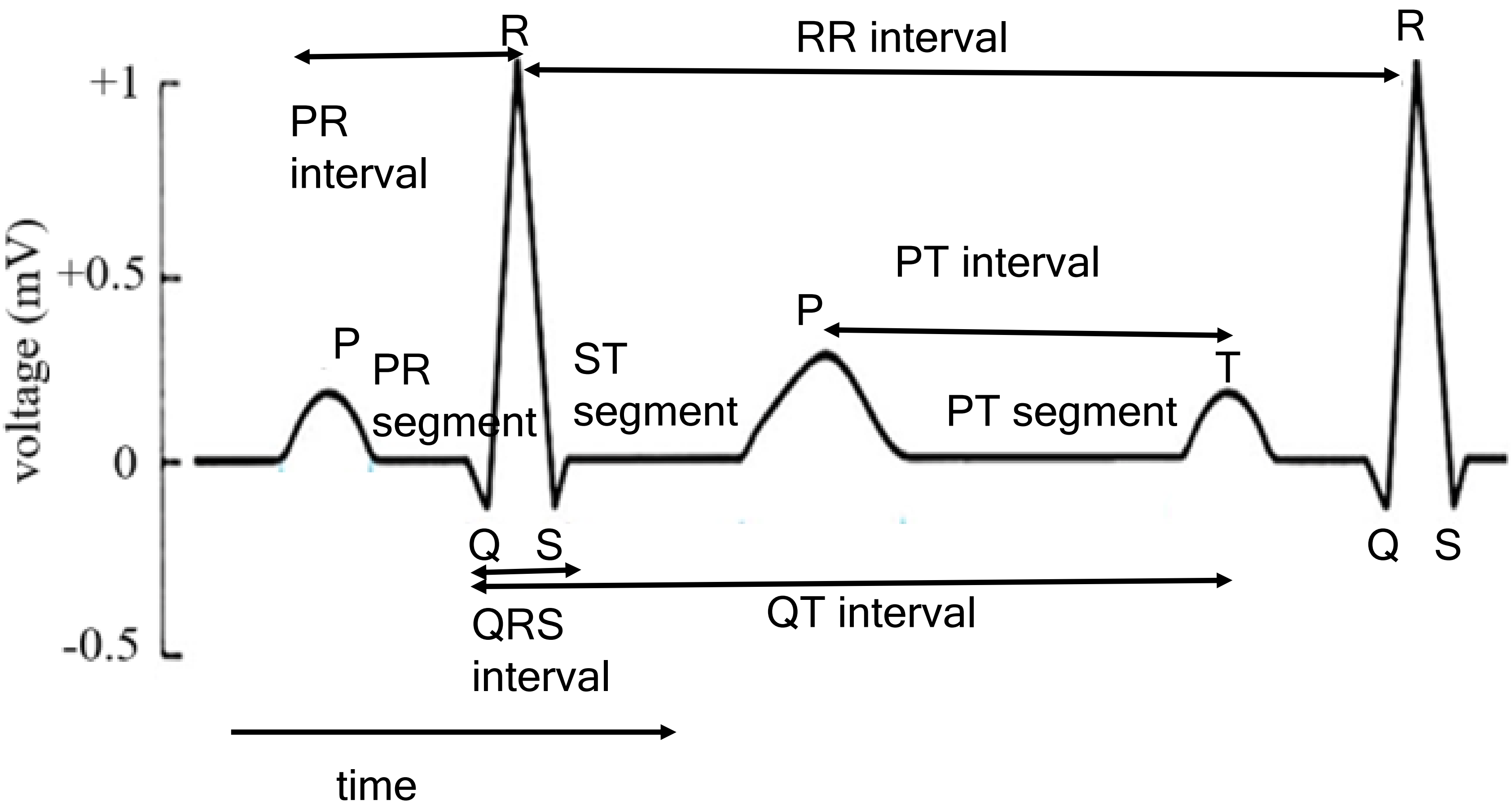


- For the varying noise types (baseline wander and muscle noise)
  - adaptive approach seems quite appropriate
  - For power line interference
  - the nonlinear approach seems valid as ringing artifacts are almost unavoidable otherwise

Watch this video

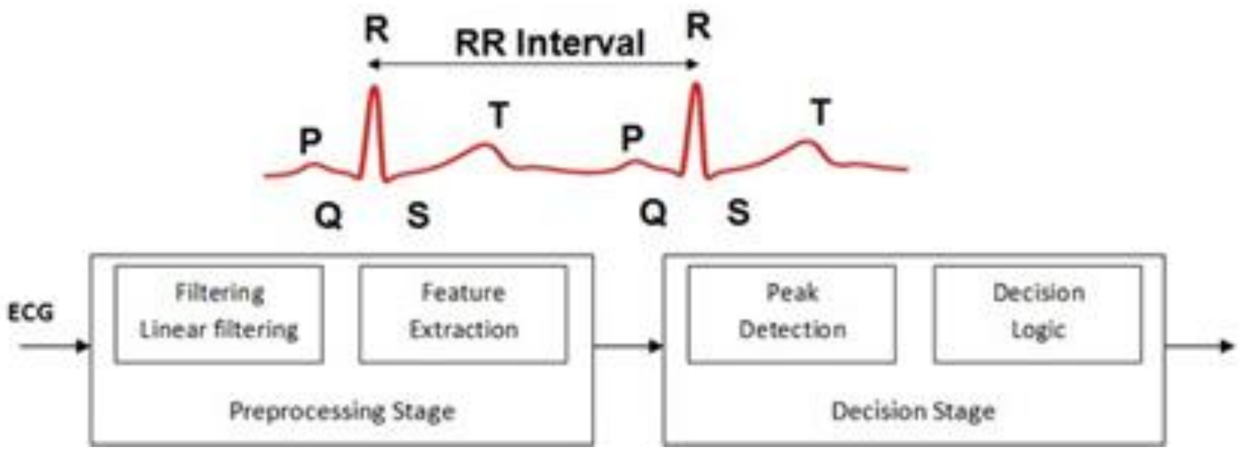
Application
QRS detection

- QRS detection is important in all kinds of ECG signal processing



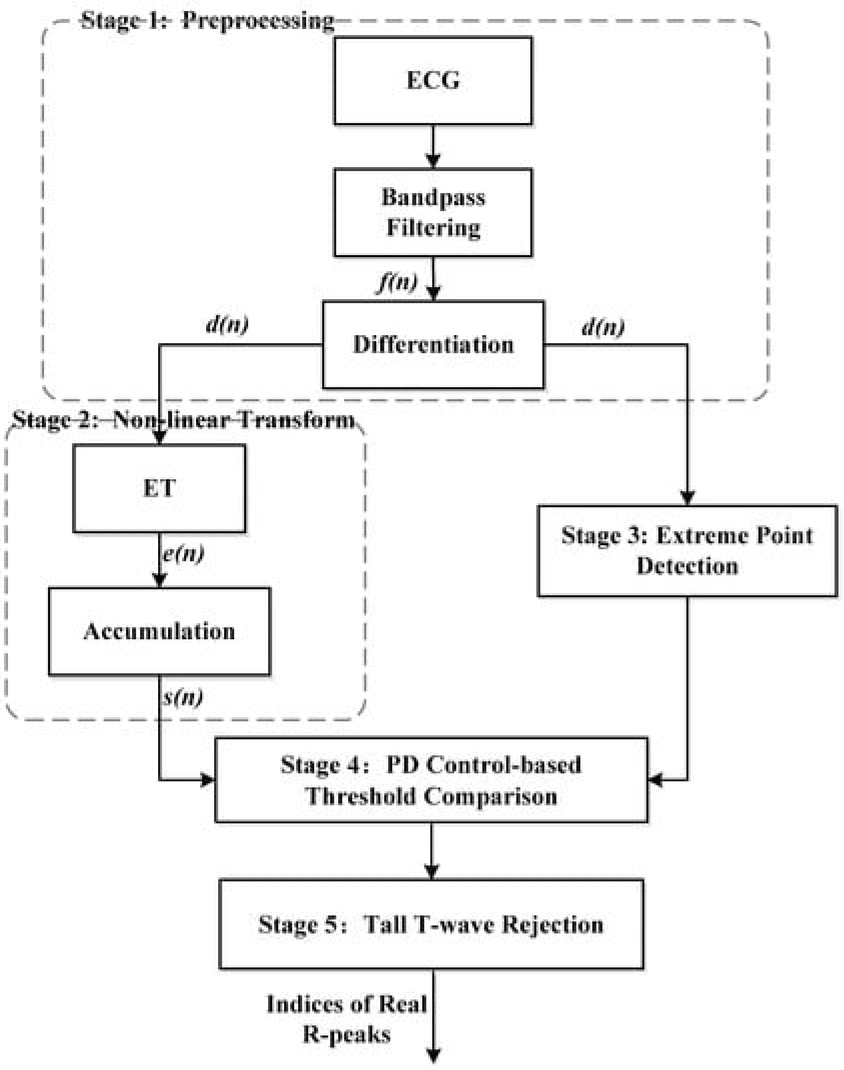
Application
QRS detection

- QRS detector must be able to detect a large number of different QRS morphologies
- QRS detector must not lock onto certain types of rhythms but treat next possible detection as if it could occur almost anywhere



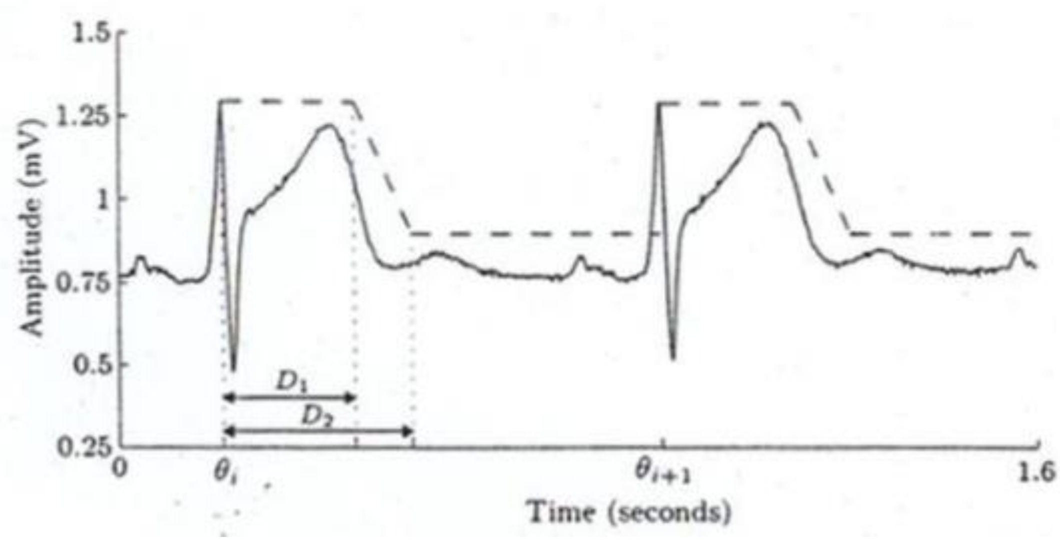
Application
QRS detection

- Typical structure of QRS detector algorithm: preprocessing (linear filter, nonlinear transformation) and decision rule



Application
QRS detection

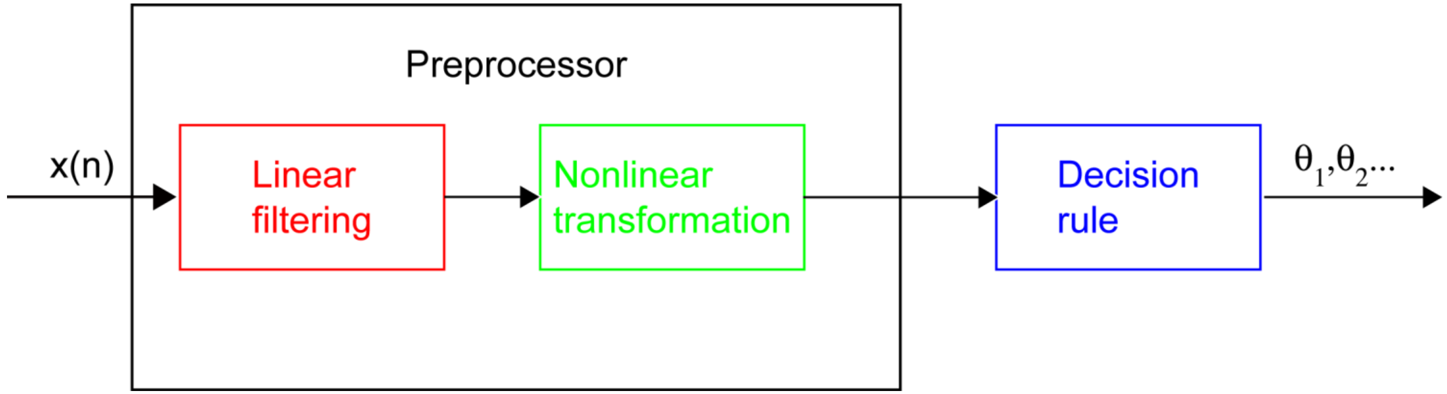
- For different purposes (e.g. stress testing or intensive care monitoring), different kinds of filtering, transformations and thresholding are needed



- Multi-lead QRS detectors

Application
QRS detection

- Bandpass characteristics to preserve essential spectral content (e.g. enhance QRS, suppress P and T wave), typical center frequency 10 - 25 Hz and bandwidth 5 - 10 Hz
- Enhance QRS complex from background noise, transform each QRS complex into single positive peak
- Test whether a QRS complex is present or not (e.g. a simple amplitude threshold)



Application
Estimation problem

- Maximum likelihood (ML) estimation technique to derive detector structure
- Starting point: same signal model as for derivation of Woody method for alignment of evoked responses with varying latencies

$$x(n) = \begin{cases} u(n) & 0 \le n \le t-1 \\ s(n-\theta)+u(n) & t \le n \le t+D-1 \\ u(n) & t+D \le n \le N-1 \end{cases}$$

noise

QRS occurrence time

observed signal

duration of s (n)

QRS, known morphology

observation interval

END