Electrocardiographic Signal Processing

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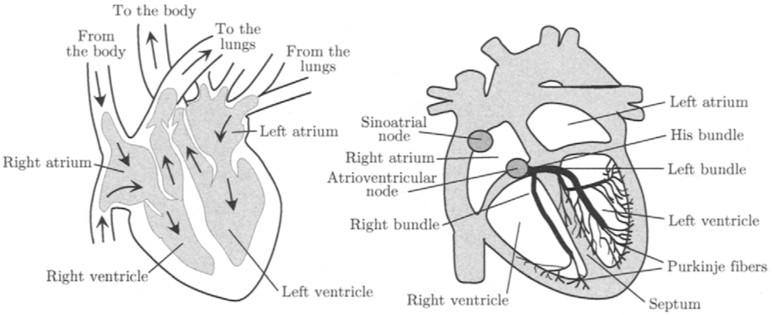
Heart: Mechanical and Electrical Activity

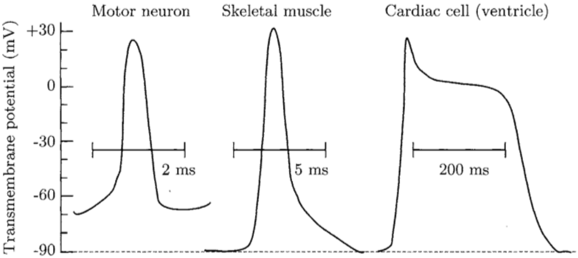
- **Mechanically:** a cardiac cycle starts at the right atrium (RA) and ends at the left ventricle (LV).
- **Electrically:** a cycle starts at the sinoatrial (SA) node in the RA, and the impulses propagate to the left atrium (LA) and the ventricles (with a delay).



Bioelectrical signals: Action potentials (APs)

- **Electrical Cell States:**
  - **Equilibrium potential:** At rest, cells are typically negatively charged (-60 mV to -100 mV).
  - **Depolarization:** When an external stimulus (current) arrives, positively charged ions enter the cell $\Rightarrow$ The cell's potential increases and becomes positive.
  - **Repolarization:** When the positive equilibrium potential is reached, the flow of ions reverses $\Rightarrow$ The cell quickly returns to its equilibrium potential.
  - **Refractory period:** The cell is inactive $\Rightarrow$ It cannot respond to a new stimulus.
- **All-or-nothing principle:**
  - If the stimulus exceeds a threshold level $\Rightarrow$ AP occurs with the same amplitude regardless of the intensity of the stimulus.
  - If the stimulus does not exceed the threshold level $\Rightarrow$ Nothing happens: cell remains at equilibrium potential.

Examples of Action potentials (APs)



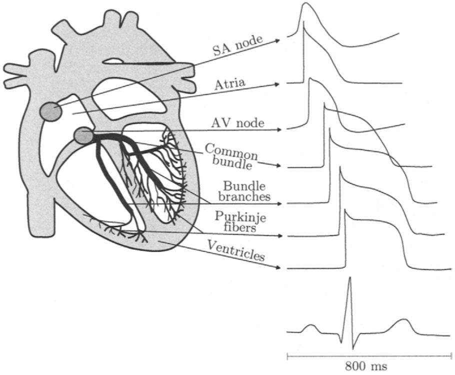
- **Remarks:**
  - The duration of APs varies more than its amplitude.
  - Repolarization can take longer than depolarization.
  - APs can travel from cell to cell $\Rightarrow$ Mechanism for propagation of bioelectrical currents.
  - The refractory period sets an upper limit on the rate of action potentials.

Characteristics of ECG signals

- **Sinoatrial (SA) node:**
  - Group of cells that beat on their own (automaticity) and start/control the electrical cycle.
  - The typ. rate of an SA rhythm is below 220 bpm and decreases with age $\Rightarrow$ max. heart rate = 220 - age.
  - Heart rate control can be taken over by other groups of cells (ectopic focus).
- **Refractory period:**
  - Typ. 200 – 250 ms $\Rightarrow$ max. heart rate: 240 – 300 bpm.
  - Can decrease up to 100 ms during atrial fibrillation (AF) $\Rightarrow$ heart rate up to 600 bpm.
- **Conduction velocity** inside the heart:
  - From only 0.05 m/s at the atrioventricular (AV) node...
  - ...up to 4 m/s at the Purkinje fibers.

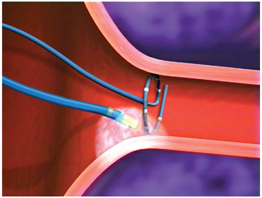
Electrocardiogram (ECG)

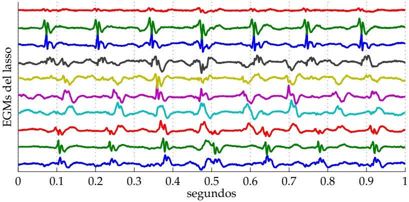
- Electrocardiograms (ECGs) record the electrical activity of the heart at different sites:
  - External or surface ECGs.
  - Intracardiac ECGs or electrograms (EGMs).



Intracardiac ECGs or Electrograms (EGMs)

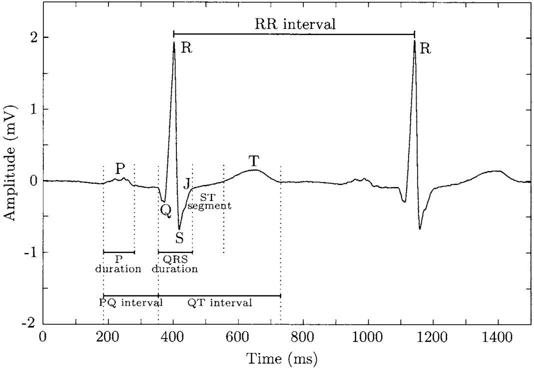
- Intracardiac ECGs (Electrograms):
  - ECGs obtained placing a catheter directly in contact with the heart tissue (invasive and hard to obtain).
  - More localized information than standard ECGs.
  - Waveforms change over time and channels.
- Applications:
  - Implantable devices (pacemakers and defibrillators).
  - RF catheter ablation for atrial fibrillation (AF) patients.





External ECGs

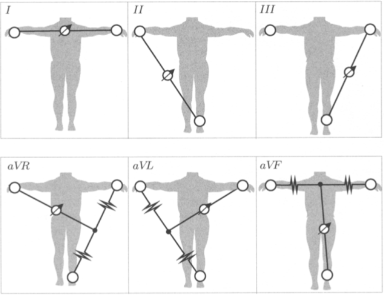
- Obtained placing electrodes in the surface of the body.
- Routinely acquired in many clinical situations:
  - Non-invasive, easy and cheap to acquire, allows detecting many cardiac pathologies, well-defined shape.
  - Low spatial resolution, records ventricular activity.

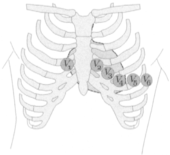


ECG Acquisition

- Recorded by measuring the difference in voltage between a pair of electrodes (lead).
- Types of leads:
  - **Unipolar:** Records voltage variation w.r.t. a reference electrode s.t. its voltage is almost constant.
  - **Bipolar:** Records voltage variation between two electrodes.
- Multiple-lead configurations typically used: unipolar, bipolar or mixed.
- ECG amplitude ranges from μV to 1 V $\Rightarrow$ amplifier with high gain and large dynamic range required.

Standard 12-lead ECG





(c)

- Bipolar limb leads:

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

- Augmented unipolar limb leads:

$$aVR = V_{RA} - \frac{V_{LA} + V_{LL}}{2}$$
$$aVL = V_{LA} - \frac{V_{RA} + V_{LL}}{2}$$
$$aVF = V_{LL} - \frac{V_{LA} + V_{RA}}{2}$$

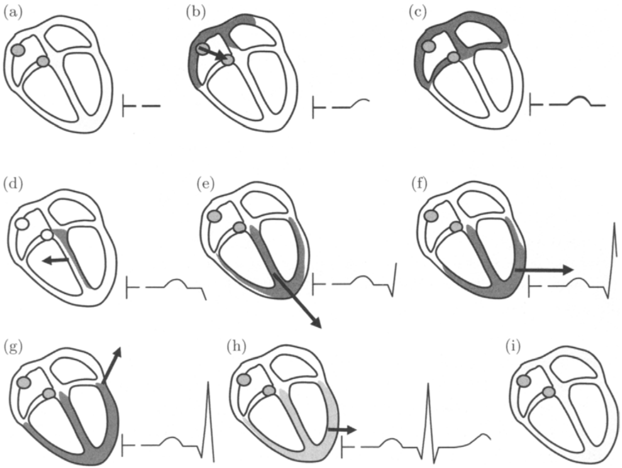
- Unipolar precordial leads:

$$V_i - \frac{V_{LA} + V_{RA} + V_{LL}}{3}$$

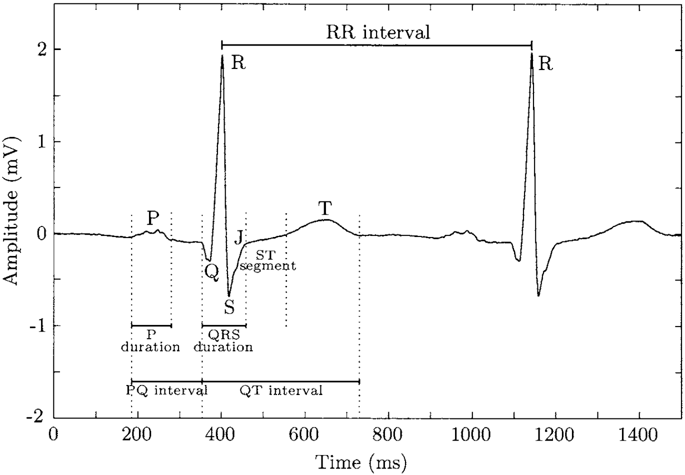
Standard 12-lead ECG (II)

- **Einthoven triangle:** Formed by I, II & III $\Rightarrow$ Describe the cardiac electrical activity in three different directions of the frontal plane.
- **Augmented limb leads:** Fill in the gaps of the bipolar limb leads.
- **Precordial leads:**
  - V_1 & V_2 $\Rightarrow$ Reflect activity of the right ventricle.
  - V_3 & V_4 $\Rightarrow$ Reflect activity in the front of the left ventricle.
  - V_5 & V_6 $\Rightarrow$ Reflect activity in the lateral wall of the left ventricle.
- The six limb leads have lower amplitude and more noise than the precordial leads.
- Other lead systems (vectorcardiogram) can be synthesized from the 12-lead system.

ECG Generation



ECG waves and time intervals (I)



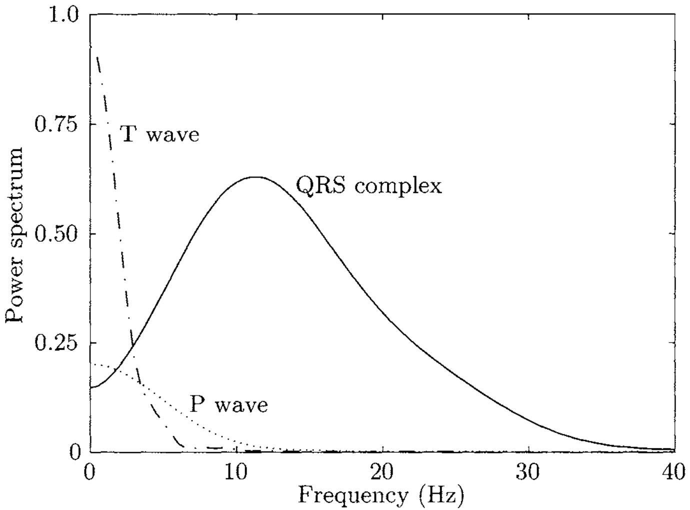
ECG waves and time intervals (II)

- **P wave:**
  - Reflects atrial depolarization.
  - Positive polarity & smooth, monophasic morphology.
  - Amplitude < 300 μV & Duration < 120 ms.
  - Frequency content below 10 – 15 Hz.
  - Onset & termination difficult to determine precisely.
- **QRS complex:**
  - Reflects ventricular depolarization.
  - Typically composed of 3 waves:
    - Q wave $\Rightarrow$ 1st negative deflection.
    - R wave $\Rightarrow$ 1st positive deflection.
    - S wave $\Rightarrow$ 1st negative deflection after R wave.
  - Morphology highly variable, depending on the origin of the beat (sometimes has more or less than 3 signals)
  - Amplitude up to 2 – 3 mV & Typ. duration 70 – 120 ms (can last up to 250 ms for ectopic beats).
  - Frequency content concentrated in 5 – 40 Hz.

ECG waves and time intervals (III)

- **ST segment:**
  - Interval during which the ventricles are in an active, depolarized state.
  - Begins at the end of the S wave and proceeds almost horizontally until the T wave.
- **T wave:**
  - Reflects ventricular repolarization.
  - Round & smooth morphology.
  - Frequency content below 10 Hz.
  - Extends up to 300 ms after the QRS complex.
  - Position depends on heart rate: narrower and closer to QRS complex at rapid rates.
  - Can merge with the following P wave.

Spectrum of ECG signals

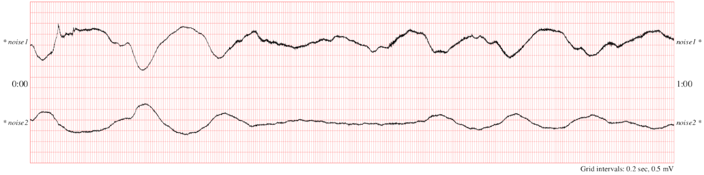


ECG & Heart Rhythms: Sinus Rhythm vs. Arrhythmias

- **Sinus rhythm:**
  - Originates at the SA node and has a regular rate of 60 – 100 bpm at rest.
  - Even in the absence of external perturbations, the heart rate has some small variability.
- **Arrhythmias:** Any deviation from the normal sinus rhythm. Classification:
  - According to Heart Rate (HR):
    - Bradyarrhythmia ⇒ HR < 60 bpm.
    - Tachyarrhythmia ⇒ HR > 100 bpm.
  - According to its duration:
    - Paroxysmal ⇒ Suddenly begins and ends.
    - Persistent/permanent ⇒ Does not end.
  - According to its origin:
    - Atrial.
    - Ventricular.

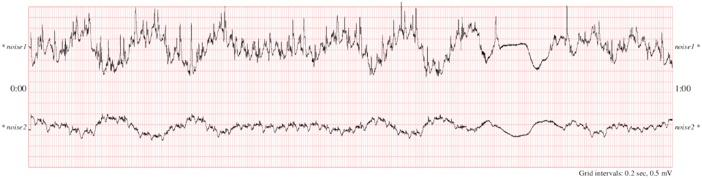
Noise & Artifacts: Baseline wander

- Extraneous, low-frequency activity in the ECG.
- Always present (up to some extent) in the recordings.
- Caused (partly) by respiration (typ. 12–20 breaths/min):
  - Fluctuation in the baseline.
  - Amplitude modulation in QRS complexes.
- Frequency content typically below 1 Hz.



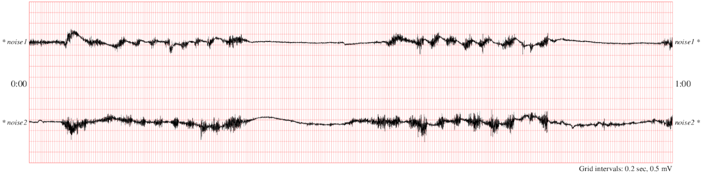
Noise & Artifacts: Electrode motion

- Caused by alterations in electrode-skin impedance due to movement.
- Frequency content in the range 1 – 10 Hz (i.e., overlap with PQRST complex).
- Can result in large amplitude waveforms that R peak detectors can erroneously identify as QRS complexes.

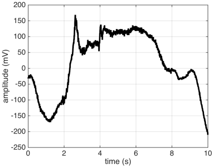


Noise & Artifacts: Electromyogram (EMG)

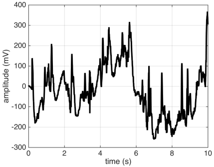
- Caused by the electrical activity associated to muscle contractions.
- Particularly important for ECGs recorded during ambulatory monitoring or exercise.
- Frequency content overlaps with QRS complex, extending also to higher frequencies.



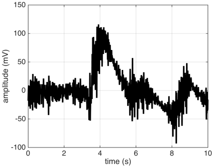
Noise: Spectrum



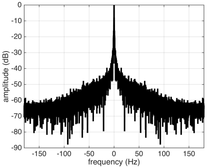
(a) Baseline wander



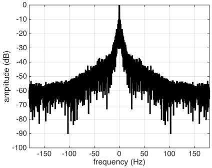
(b) Electrode motion



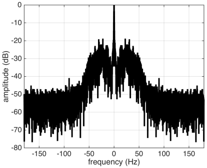
(c) EMG noise



(d) Baseline wander



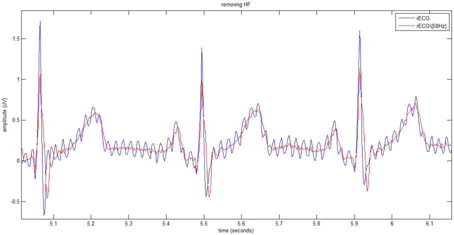
(e) Electrode motion



(f) EMG noise

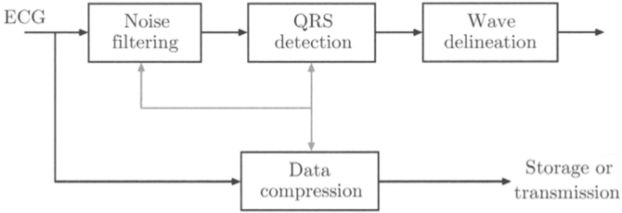
Noise & Artifacts: Others

- **Powerline interference:**
  - Caused by improper grounding and interference from other electronic equipments.
  - Characterized by a strong component at 50/60 Hz and its harmonics.



- **Electrode contact noise:**
  - Caused by loss of contact between electrode and skin (intermitent or permanent).
  - Results in large artifacts and useless ECG.

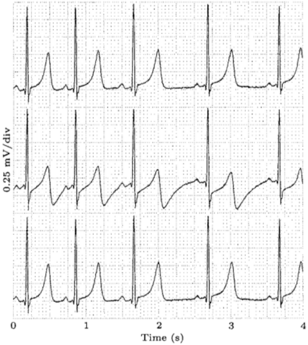
Basic ECG signal processing blocks

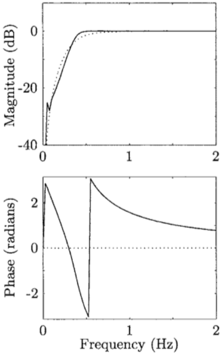


- Processing tailored to application & acquisition conditions.
- **Noise filtering:** Removes baseline wander & powerline noise.
- **QRS detection:** Basic info. for all types of ECG signal processing.
- **Wave delineation:** Finds duration and amplitude of heartbeats.
- **Data compression:** Exploits redundancy in data to reduce storage/tx. requirements without compromising quality.

Noise removal: Baseline wander (I)

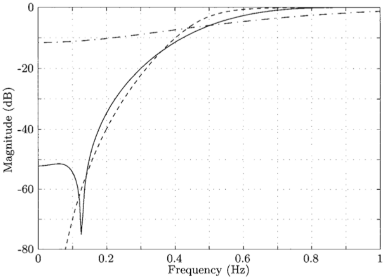
- Baseline wander depends on measurement conditions:
  - For ECGs acquired in rest conditions $\Rightarrow f_M < 0.5$ Hz.
  - For stress tests $\Rightarrow$ Increased frequency content.
- Can be removed by a high-pass filter:
  - Cut-off frequency $f_c = 0.5$ Hz.
  - Linear phase to avoid phase distortion.





Noise removal: Baseline wander (II)

- Linear Time Invariant (LTI) filtering:
  - Finite Impulse Response (FIR) filters ⇒ linear phase, very long impulse response.
  - Infinite Impulse Response (IIR) filters ⇒ much shorter, non-linear phase ⇒ forward-backward filtering.

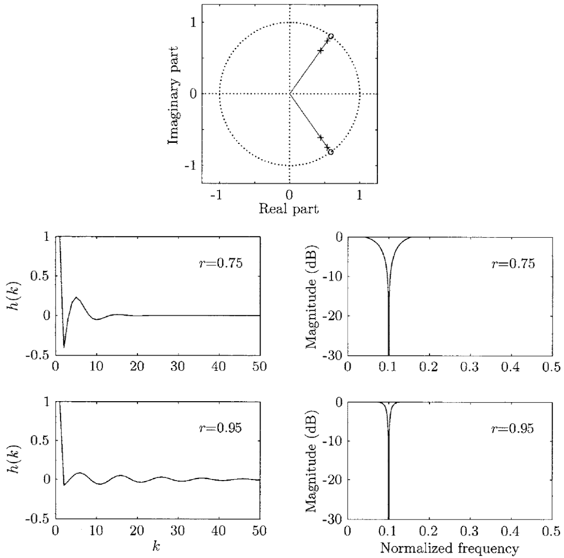


- **Other alternatives:** Linear Time Variant (LTV) filtering, polynomial fitting, compressed sensing, etc.

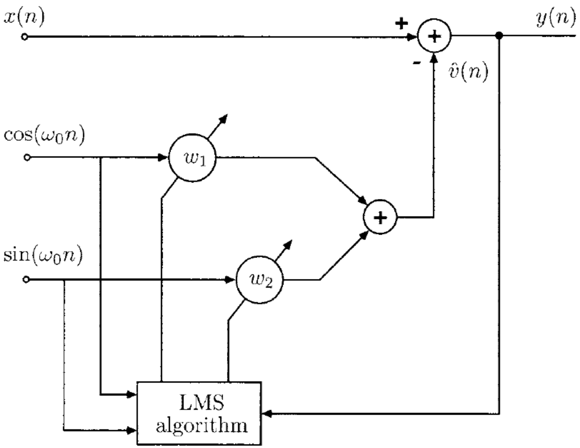
Noise removal: Powerline interference

- Corresponds to a 50/60 Hz plus harmonics.
- Usually not a problem for QRS detection, but can affect waveform delineation.
- Easily removed by a notch filter. **Drawbacks:**
  - Attenuation of frequencies close to 50/60 Hz.
  - Ringing $\Rightarrow$ Small oscillations caused by the transient behaviour of the filter.
- Other techniques can be used:
  - Nonlinear fitering.
  - Estimation-substraction.

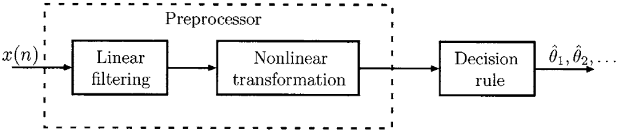
Powerline interference: Notch filter



Powerline interference: Estimation-substraction



QRS Detectors: Block Diagram



- **Linear Filter:**
  - Preserves the essential content of QRS complex and removes other components (P and T waves) and noise.
  - Center frequency: 10 – 25 Hz. Bandwidth: 5 – 10 Hz.
  - Focus on improving SNR, waveform distortion not an issue.
- **Nonlinear Transformation:**
  - Enhance QRS complex w.r.t. background noise.
  - Transforms each QRS complex into single peak for detection.
  - Simple memoriless operation (e.g., rectification or squaring) or more complex transformation with memory.
- **Decision Rule:**
  - Threshold procedure to determine presence of QRS complex.
  - May include additional tests (e.g., waveform duration).

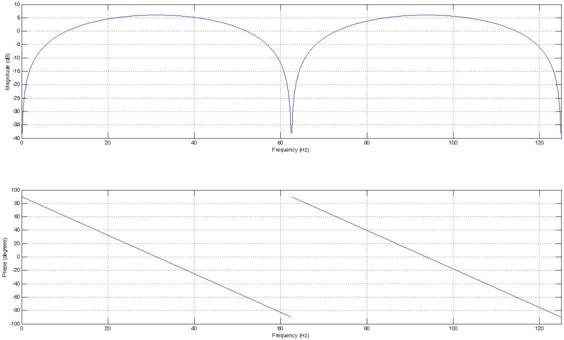
QRS Detectors: Characteristics

- Most QRS detectors described in the literature have been developed from ad hoc reasoning and experimental insight. **[Sornmo & Laguna, 2005]**
- **Desired Features:**
  - Detect a large number of different QRS morphologies.
  - Follow changes of the prevailing QRS morphology.
  - Not lock into any particular heart rhythm.
  - Show robustness w.r.t. typical ECG noise.
- Many QRS detectors are only designed to detect heartbeats (i.e., low temporal resolution) $\Rightarrow$ May need another algorithm for time alignment.
- **Type of QRS Detectors:**
  - Amplitude and first derivative.
  - First derivative.
  - First and second derivative.
  - Digital filters.

Engelese & Zeelenberg Algorithm [SQRS]: Differentiator

- Let us assume an ECG, $x[n]$, sampled at $f_s = 250$ Hz.
- **First stage:** Differentiator + 62.5 Hz notch filter (to remove 60 Hz powerline noise):

$$y[n] = x[n] - x[n-4].$$

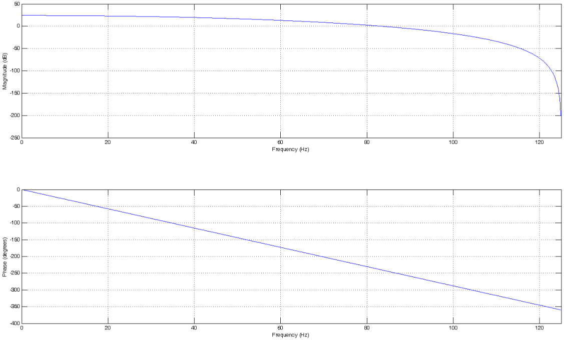


freqz([1 0 0 0 -1], 1, 1000, 250)

Engelese & Zeelenberg Algorithm [SQRS]: Low-Pass Filter

- **Second stage:** Low-pass filtering:

$$z[n] = y[n] + 4y[n-1] + 6y[n-2] + 4y[n-3] + y[n-4].$$



freqz([1 4 6 4 1], 1, 1000, 250)

Engelese & Zeelenberg Algorithm [SQRS]: Decision

- Based on two thresholds with equal magnitude and opposite polarity ($\pm\gamma$).
- **Procedure:**
  - Scan $z[n]$ until finding $z[n] > \gamma$ at $n = n^*$.
  - Perform a search within the next 160 ms (40 samples):
    - If no other threshold crossing occurs $\Rightarrow$ Baseline shift.
    - Classify the event as a QRS complex if any of these conditions hold ($0 < j < k < \ell < 40$):

$$
\begin{aligned}
&z[n^* + j] < -\gamma \\
&z[n^* + j] < -\gamma \quad \& \quad z[n^* + k] > \gamma \\
&z[n^* + j] < -\gamma \quad \& \quad z[n^* + k] > \gamma \quad \& \quad z[n^* + \ell] < -\gamma
\end{aligned}
$$

    - Additional threshold crossings $\Rightarrow$ Noise.

Pan & Tompkins Algorithm: Bandpass Filter & Differentiator (I)

- Let us assume an ECG, $x[n]$, sampled at $f_s = 200$ Hz.
- **First stage:** Bandpass filter from 5 to 15 Hz to maximize the QRS energy:
  - Low-pass filter (cutoff at $f_c = 12$ Hz):

$$y[n] = 2y[n-1] - y[n-2] + x[n] - 2x[n-6] + x[n-12].$$

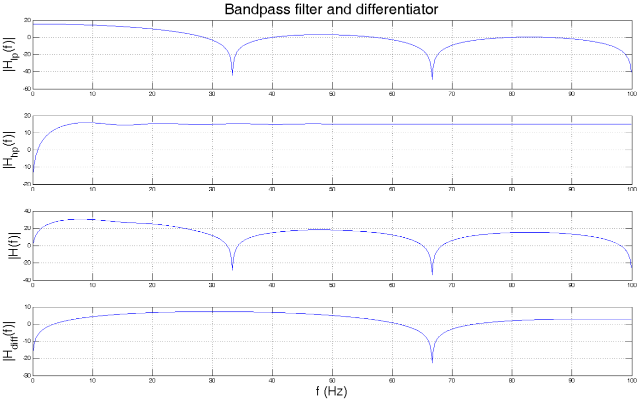
  - High-pass filter (cutoff at $f_c = 5$ Hz):

$$y[n] = -y[n-1] - x[n] + 32x[n-16] - x[n-32].$$

- **Second stage:** Differentiation:

$$y[n] = \frac{1}{8T_s}(-x[n-2] - 2x[n-1] + 2x[n+1] + x[n+2])$$

Pan & Tompkins Algorithm: Bandpass Filter & Differentiator (II)



Pan & Tompkins Algorithm: Squaring & Integration

- **Third stage:** Point by point squaring:

$$y[n] = (x[n])^2$$

  Ensures positive output and emphasizes higher frequencies.

- **Fourth stage:** Moving window integration:

$$y[n] = \frac{1}{N} \sum_{k=0}^{N-1} x[n-k]$$

  The choice of N is critical:
  - N too large $\Rightarrow$ Integration merges QRS and T waves.
  - N too small $\Rightarrow$ Several peaks at the output.

  N chosen s.t. the length of the window equals the maximum length of a QRS complex: $N = 30$ (150 ms).

Pan & Tompkins Algorithm: Decision Rule

- Integration waveform:

SPKI = 0.125 PEAKI + 0.875 SPKI

(if PEAKI is the signal peak)

NPKI = 0.125 PEAKI + 0.875 NPKI

(if PEAKI is the noise peak)

THRESHOLD I1 = NPKI + 0.25 (SPKI − NPKI)

THRESHOLD I2 = 0.5 THRESHOLD I1

PEAKI is the overall peak,
SPKI is the running estimate of the signal peak,
NPKI is the running estimate of the noise peak,
THRESHOLD I1 is the first threshold applied, and
THRESHOLD I2 is the second threshold applied.

- When QRS complex found:

SPKI = 0.25 PEAKI + 0.75 SPKI.

- Filtered waveform:

SPKF = 0.125 PEAKF + 0.875 SPKF

(if PEAKF is the signal peak)

NPKF = 0.125 PEAKF + 0.875 NPKF

(if PEAKF is the noise peak)

THRESHOLD F1 = NPKF + 0.25 (SPKF − NPKF)

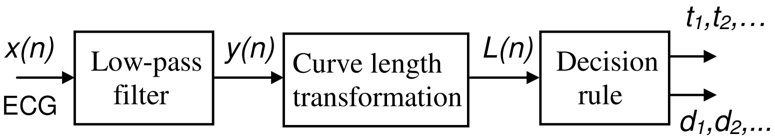
THRESHOLD F2 = 0.5 THRESHOLD F1

PEAKF is the overall peak,
SPKF is the running estimate of the signal peak,
NPKF is the running estimate of the noise peak,
THRESHOLD F1 is the first threshold applied, and
THRESHOLD F2 is the second threshold applied.

- When QRS complex found:

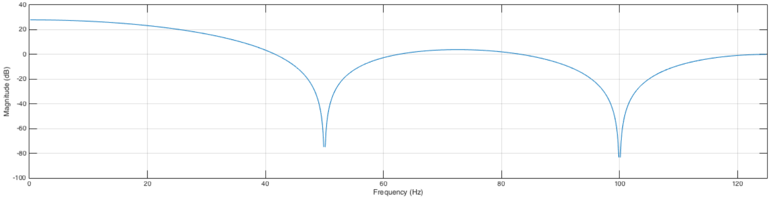
SPKF = 0.25 PEAKF + 0.75 SPKF.

Zong, Moody & Jiang Algorithm [WQRS]: Block diagram & Low-Pass Filter



- **Low Pass Filter:** $f_c = 16$ Hz when $f_s = 250$ Hz.

$$y[n] = 2y[n-1] - y[n-2] + x[n] - 2x[n-5] + x[n-10]$$



Zong, Moody & Jiang Algorithm [WQRS]: Curve length transformation

- **Length definition:**

$$L(w,t) = \int_{t-w}^{t} \sqrt{1 + \left(\frac{dy(t)}{dt}\right)^2} dt.$$

- **Single channel:**

$$L[M,n] = \sum_{k=n-M}^{n} \sqrt{T_s^2 + (y[k] - y[k-1])^2}.$$

M: width of the moving window $\Rightarrow$ 130 ms (max. width QRS complex: for $f_s = 250$ Hz, $M = 32.5$).

- **Multi-channel:**

$$L[M,n] = \sum_{k=n-M}^{n} \sqrt{\sum_{q=1}^{Q} T_s^2 + (y_q[k] - y_q[k-1])^2}.$$

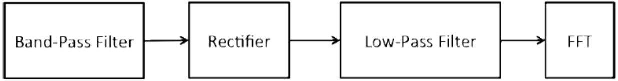
Zong, Moody & Jiang Algorithm [WQRS]: Decision rule

- **Adaptive thresholding:**
  - Set a threshold base equal to three times the mean value of the LT signal for the initial 10-second period.
  - Set actual threshold = 1/3 $\times$ threshold base.
  - Adapt the threshold base value based on the maximum LT value of each detected QRS complex.
- **Local search strategy:**
  - When the LT signal crosses the threshold $\Rightarrow$ probable QRS.
  - From the threshold-crossing point, t_{ci}, search backward for 125ms to get a min. value, L_{mini}, and forward for 125ms to get a max. value, L_{maxi}.
  - Obtain the difference, $LA_i = L_{maxk} - L_{mini}$.
  - From t_{ci}, search backward to find, Q_{bi}, where the LT drops monotonically to $L_{mini} + LA_i/100$, and forward to find, S_{bi}, where the LT increases to $L_{maxi} - LA_i/20$.
  - Set QRS onset to $Q_{bi} - 5$ and end to $S_{bi} + 5$ (i.e., $\pm$ 20 ms).
  - Apply a 250ms eye-closing period is applied after each detected QRS to avoid double detections.

Atrial Fibrillation (AF)

- Family of common heart disorders characterized by fast and uncoordinated activations in the atrium.
- Epidemic nature of AF:
  - 25 % of people > 40 will suffer AF during their lifetime.
  - 15.9M people foreseen to suffer AF in the US by 2050 (2M in Spain).
- Several causes for AF initiation and maintenance: re-entrant spiral waves, ectopic focal beats, other cardiac disorders, electrical remodeling, etc.
- Precise role of each factor is not well known.
- **In ECGs:** spiky signal with irregular inter-spike times and average atrial rates of 400–600 bpm.

Dominant Frequency (DF) Analysis (I)



- Band-Pass Filter (40 – 250 Hz).
- Rectification: $y[n] = |x[n]|$.
- Low-Pass Filter ($f_c = 20$ Hz).
- Fast Fourier Transform (FFT) for Spectral Estimation:
  - Dominant frequency (DF): Frequency associated to largest peak in the spectrum.
  - Organization index (OI).
  - Regularity index (RI).

Dominant Frequency (DF) Analysis (II)

- Dominant frequency (DF):

$$X(f) = \mathcal{F}\{x(t)\}$$
$$f_D = \mathrm{argmax}_f |X(f)|$$

- Regularity Index (RI):

$$\mathrm{RI} = \frac{P_{bw}(f_D)}{P_B},$$

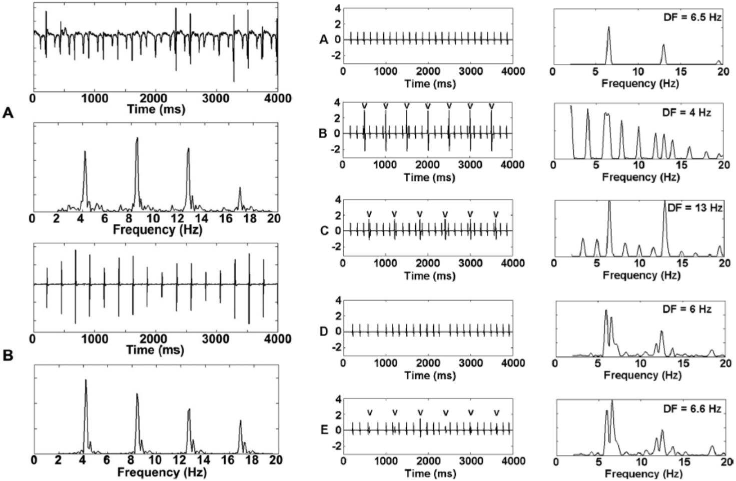
where $P_{bw}(f_D)$ is the power around f_D and P_B is the power in the whole band (usually 2–15 Hz or 2–30 Hz).

- Organization Index (OI):

$$\mathrm{OI} = \frac{\sum_{k=1}^{K} P_{bw}(kf_D)}{P_B},$$

- Signals only used if RI large enough (e.g., RI > 0.2).

Dangers of DF Analysis



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