PROCESSING, FEATURE EXTRACTION AND SHAPE REPRESENTATION OF THE ECG, I

- Basic stages of ECG signal processing
- ECG filtering
- Basic stages of ECG signal processing
- QRS complex detection
- The principles of QRS complex detection
- QRS complex detection
- QRS complex detection, performance evaluation
- Heart beat detection in multimodal data
- (Challenges in ECG signal processing today)
- (ECG filtering)
- (ECG filtering, power line interference)
- (Wave delineation)
- (Sophisticated QRS complex detection)
- (QRS complex detection, performance evaluation)

Basic stages of ECG signal processing

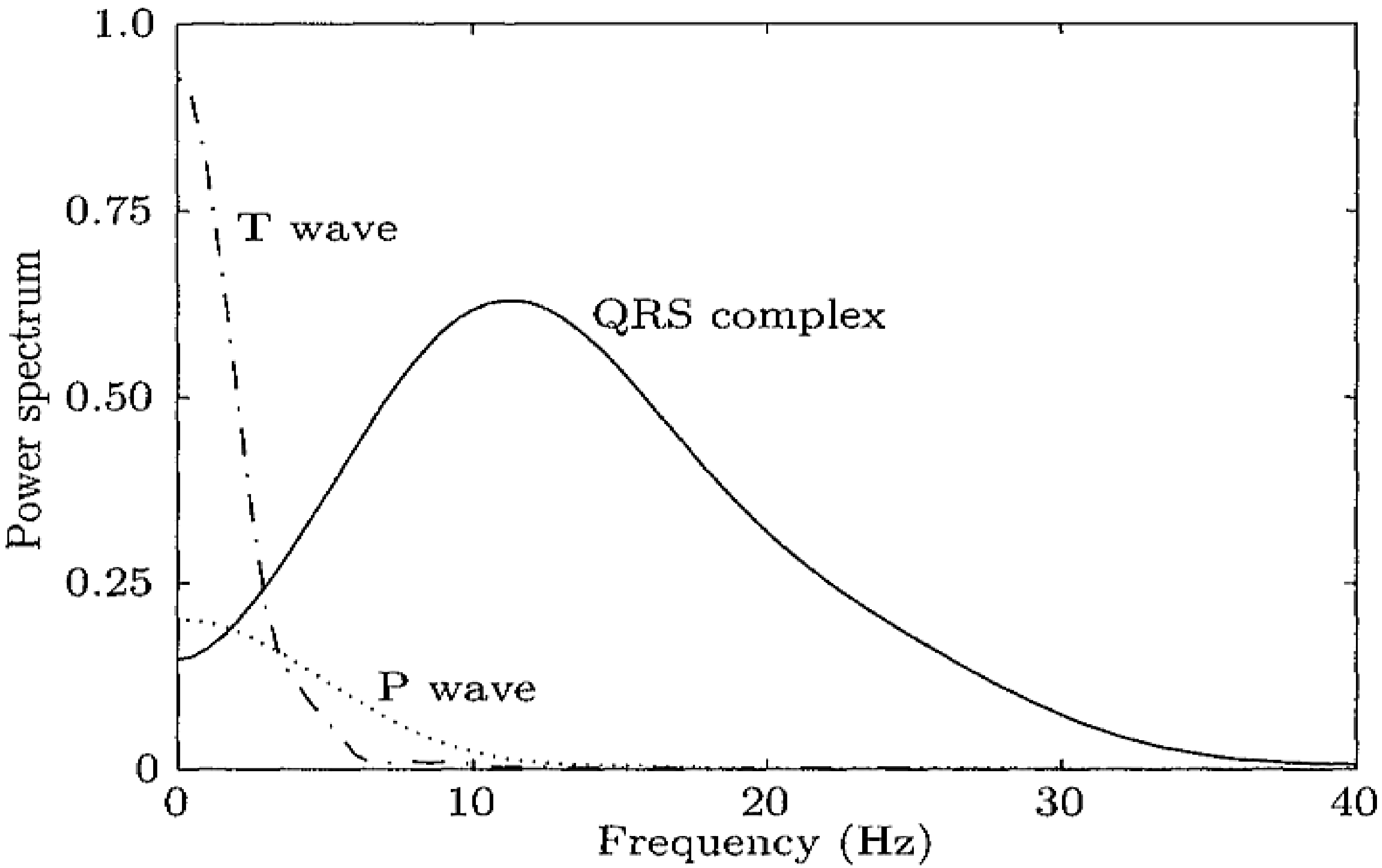
- *ECG filtering*
- *QRS complex detection*
  → (Wave delineation)
- *QRS complex classification*
  → (Rhythm classification)
  → *Ischaemia detection* (*classifying ischaemic events*, detecting transient ischaemic episodes, and their precise beginnings, extrema and ends)

ECG filtering

- (a) Baseline wander, (b) electrode motion artifacts, (c) electromyogram noise

(Sornmo, Laguna)

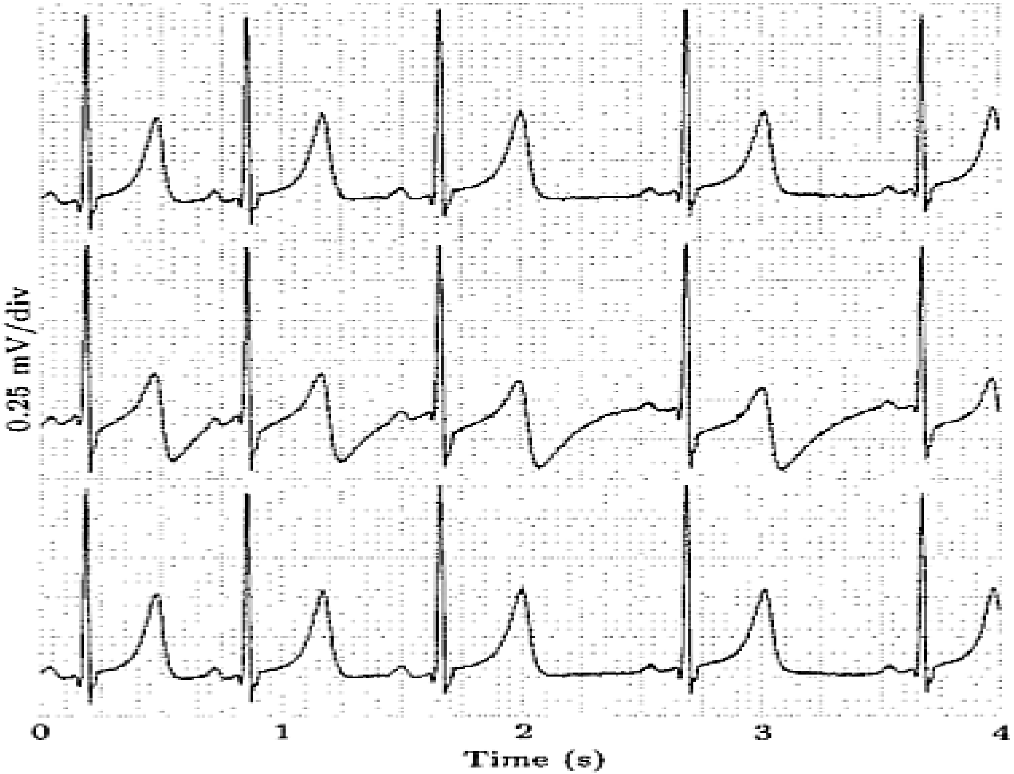
ECG filtering



(Sornmo, Laguna)

ECG filtering

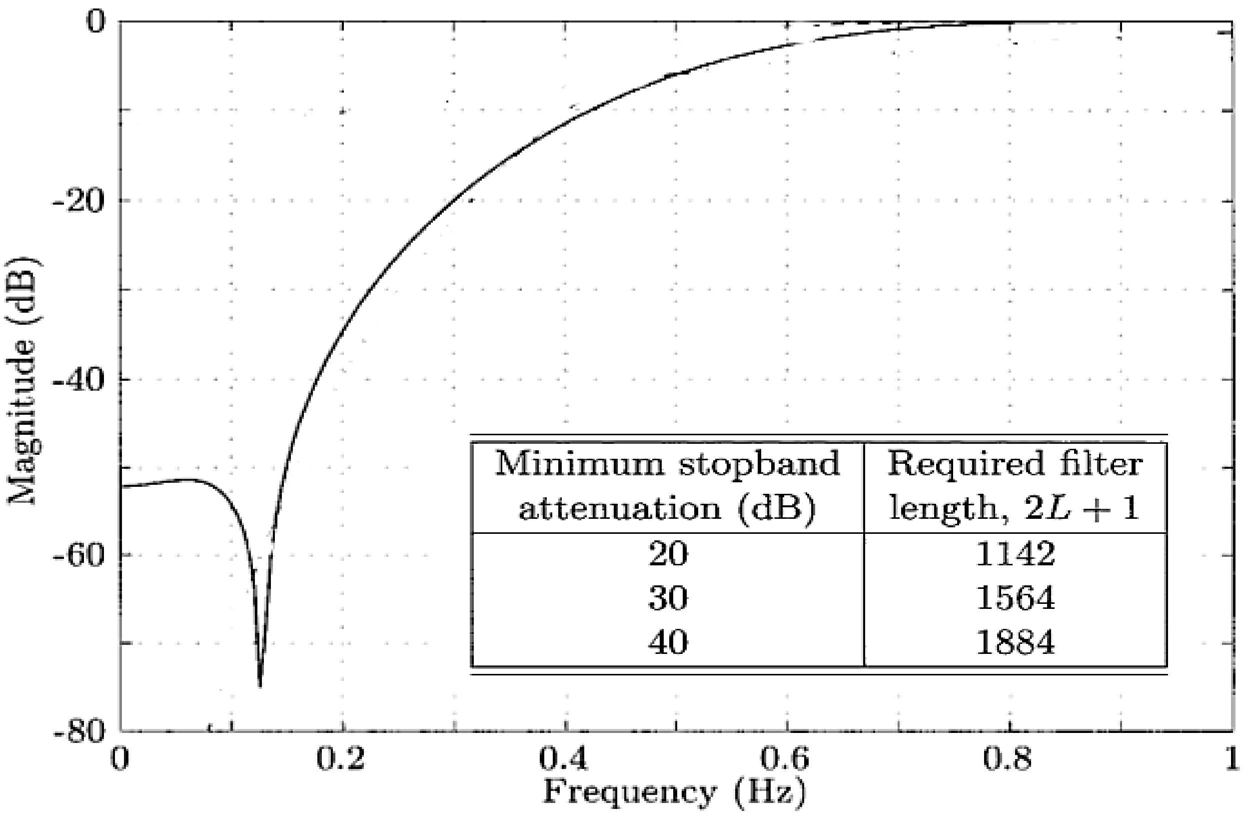
- Linear time-invariant filtering (middle → IIR filter, bottom → FIR filter)



(Sornmo, Laguna)

ECG filtering

- FIR filter (1142 coefficients), linear time-invariant filtering (cutoff at *Fc* = 0.6 *Hz*, *Fs* = 250 *smp/sec*)

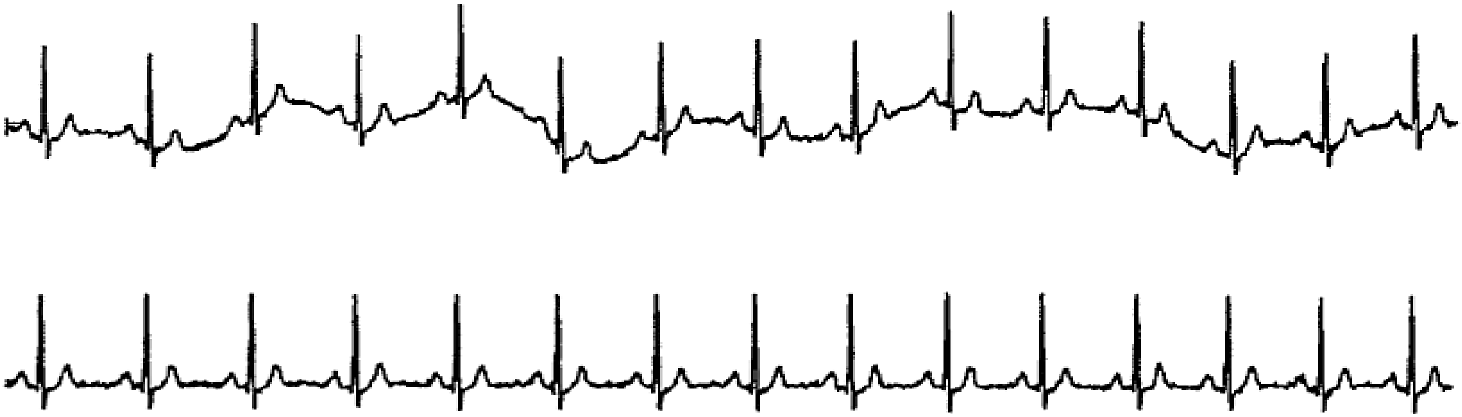


Minimum stopband attenuation (dB)	Required filter length, $2L+1$
20	1142
30	1564
40	1884

(Sornmo, Laguna)

ECG filtering

- The original ECG signal, linear FIR filtering



(Sornmo, Laguna)

Basic stages of ECG signal processing

- ECG filtering
- *QRS complex detection*

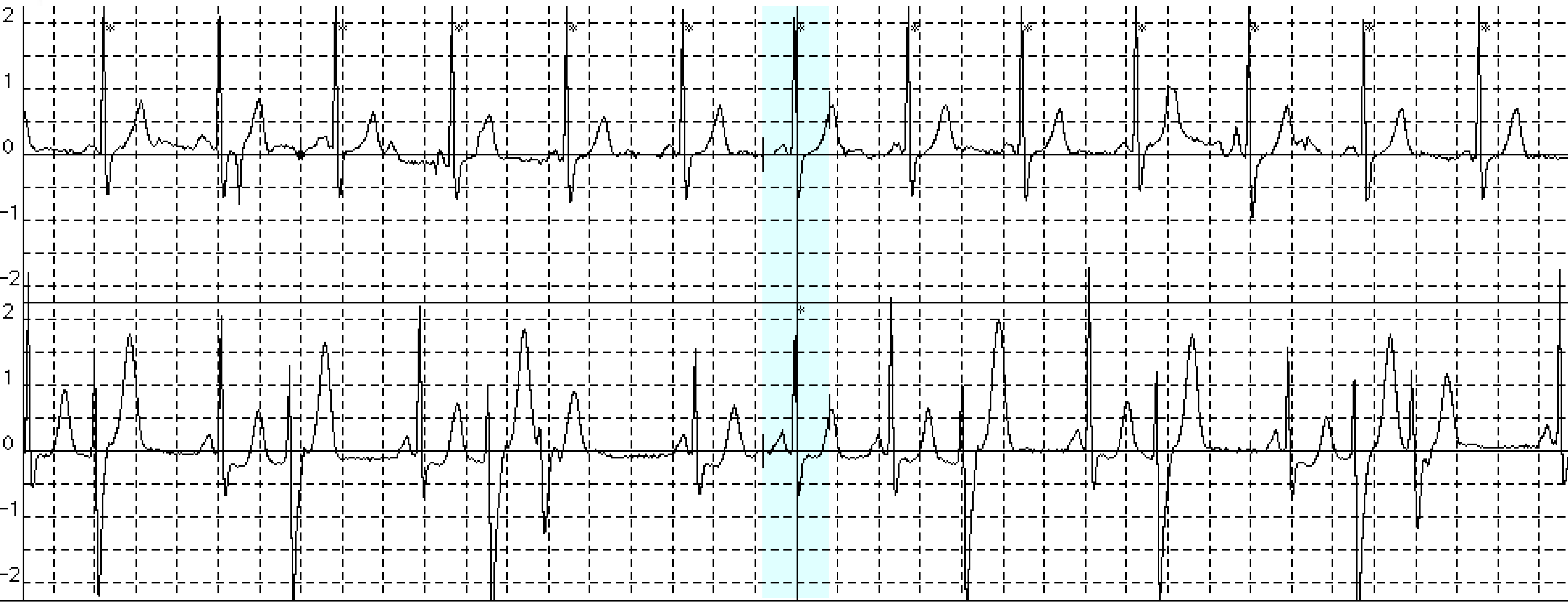
  → (Wave delineation)
- *QRS complex classification*

  → (Rhythm classification)

  → *Ischaemia detection* (*classifying ischaemic events*, detecting transient ischaemic episodes, and their precise beginnings, extrema and ends)

QRS complex detection

- Exercises 1.a – 1.e: QRS complex detection (detecting heart beats)
- Each heartbeat has QRS complex (a region within heartbeat with highest dynamic)

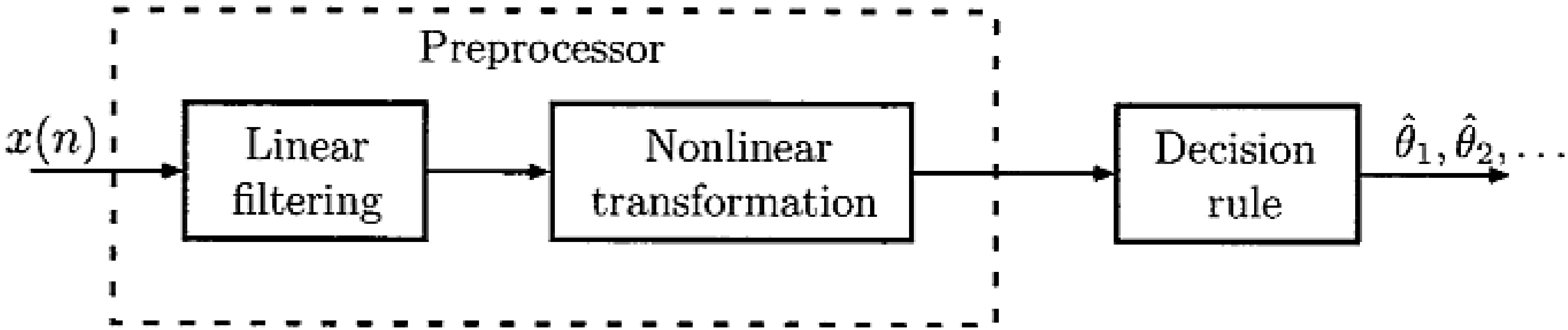


The principles of QRS complex detection

- Approaches based on signal derivatives or digital filters
- Wavelet-based QRS detection approaches
- Approaches based on matched filters
- Other approaches (adaptive filters, hidden Markov models, mathematical morphology, length transform, neural networks, ...)

QRS complex detection

- Block diagram of a QRS complex detector based on signal derivatives or digital filters



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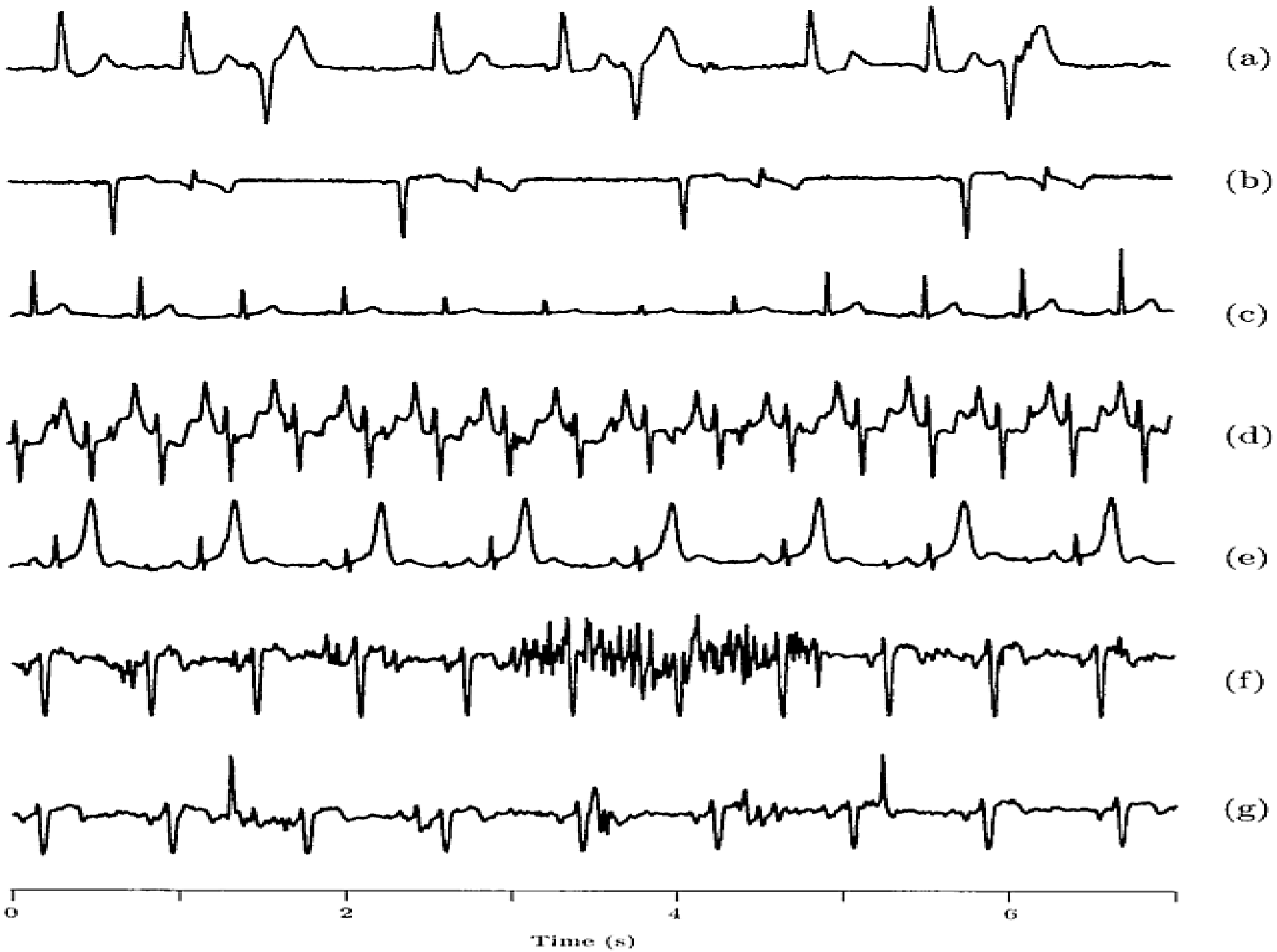
QRS complex detection

- Why QRS complex detection is problematic?



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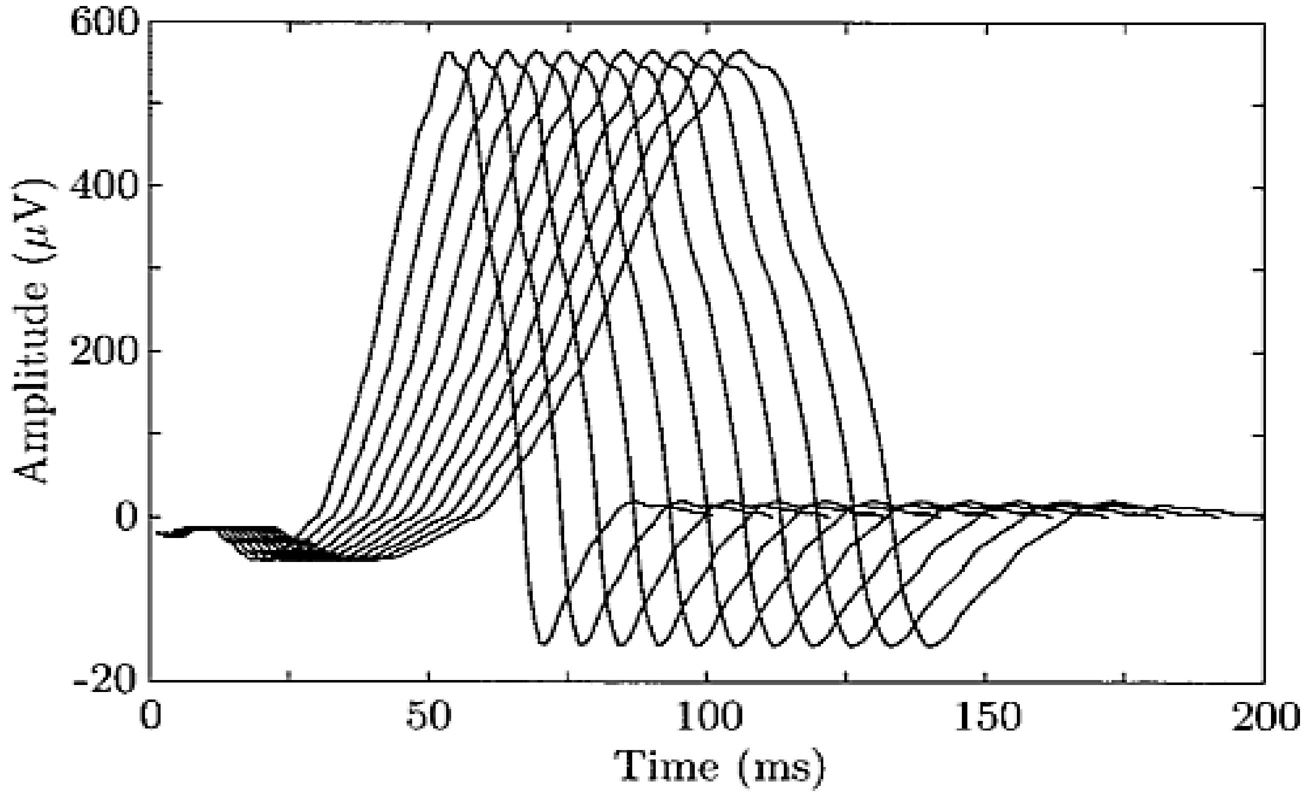
QRS complex detection

- Why QRS complex detection is problematic?
  (identical morphology but different durations)



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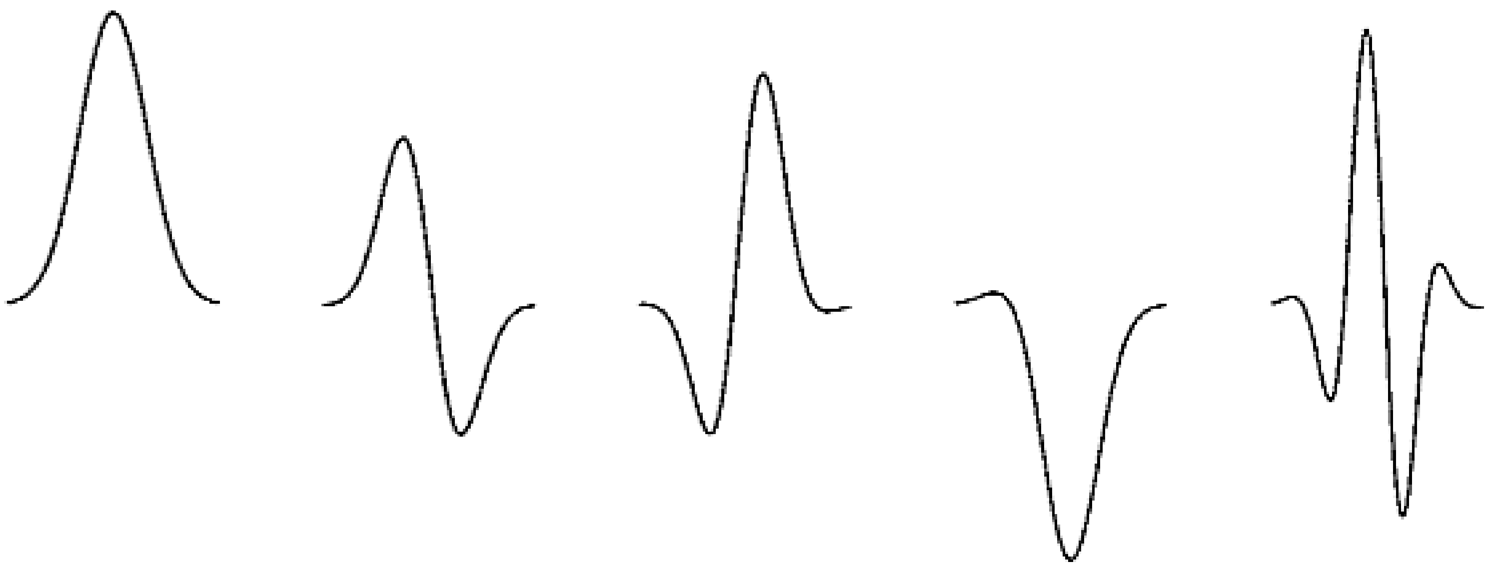
QRS complex detection

- Why QRS complex detection is problematic? (monophasic and biphasic waveshapes)



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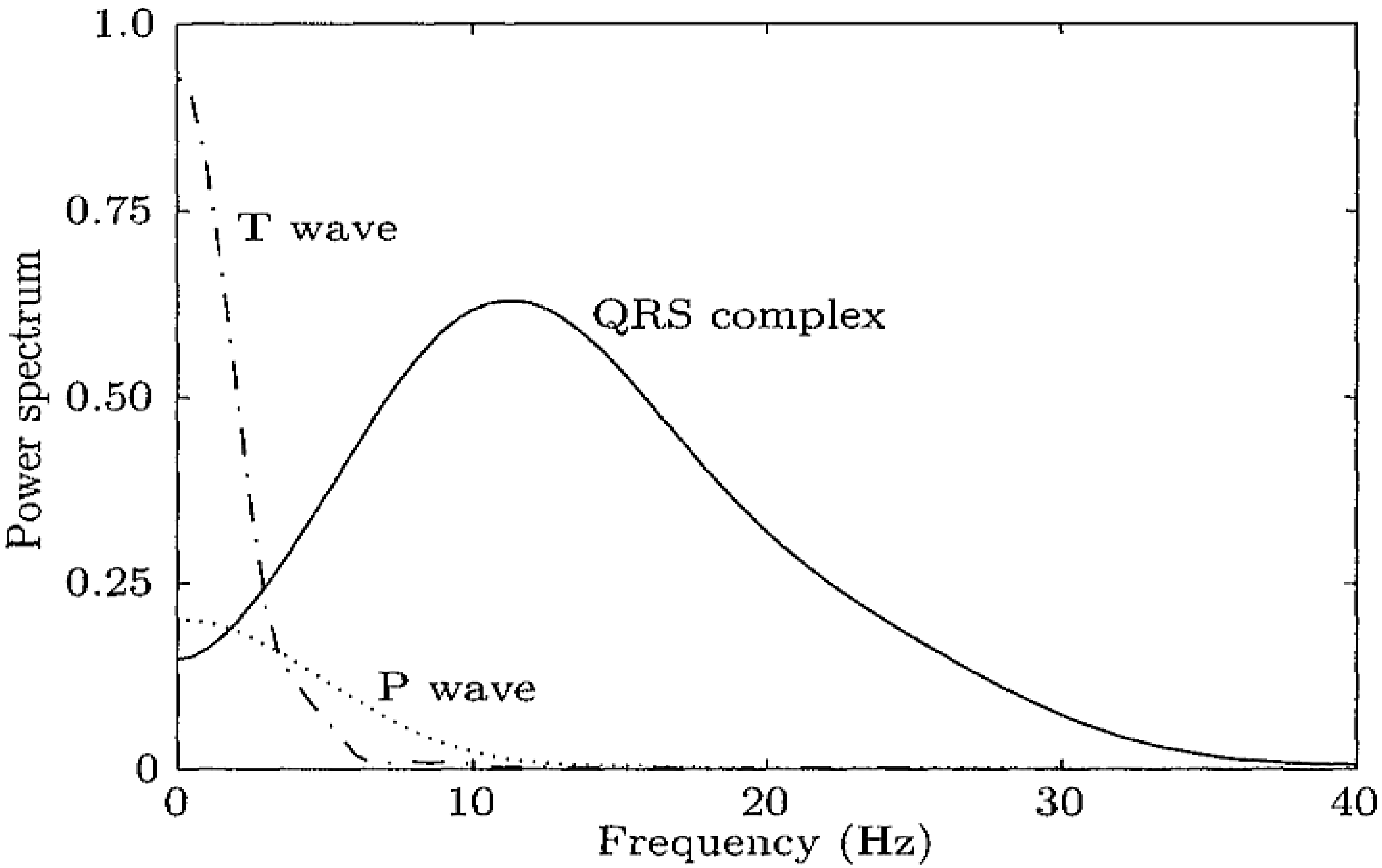
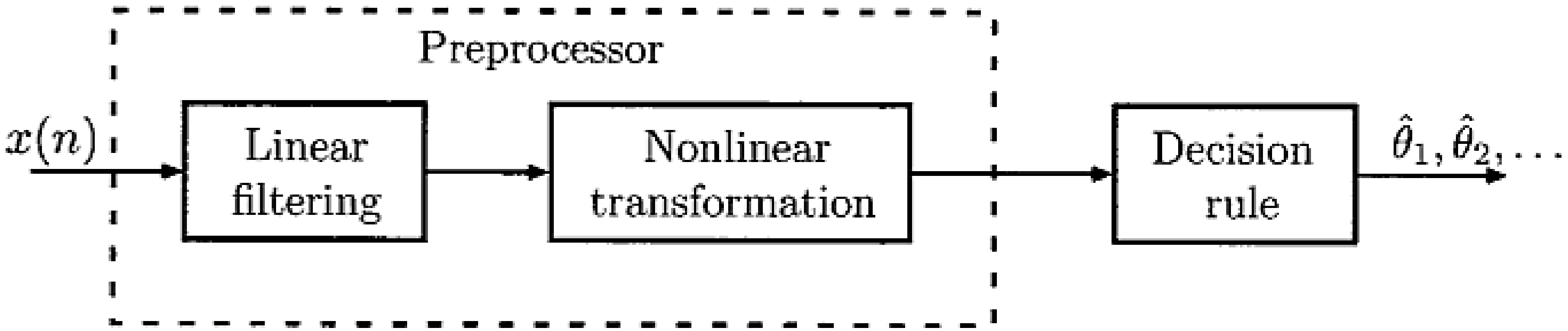
QRS complex detection



(Sornmo, Laguna)

QRS complex detection

- Phases of QRS complex detection
  - Linear filtering (extracting/emphasizing slopes and peaks of QRS complex)
  - Nonlinear transformation (energy collector) to get the detection function
  - Decision rule
  - Determining stable fiducial point (FP)



QRS complex detection

- Linear filtering and nonlinear transformation

d[n] - detection function

N - number of simultaneous ECG leads

H_1 - filter sensitive on slopes (Q-R and R-S) of QRS complex

H_2 - filter sensitive on peaks (Q, R, and S) of QRS complex

G - low-pass moving average filter

$$d[n] = G\left(\left(\sum_{i=1}^{N} \left(\left| H_1(x_i[n]) \right| + \left| H_2(x_i[n]) \right| \right) \right)^2 \right)$$

QRS complex detection

- Linear filtering

($H_1(z)$ - extracts slopes, $H_2(z)$ – extracts peaks, Fs = 500 *smp/sec*)

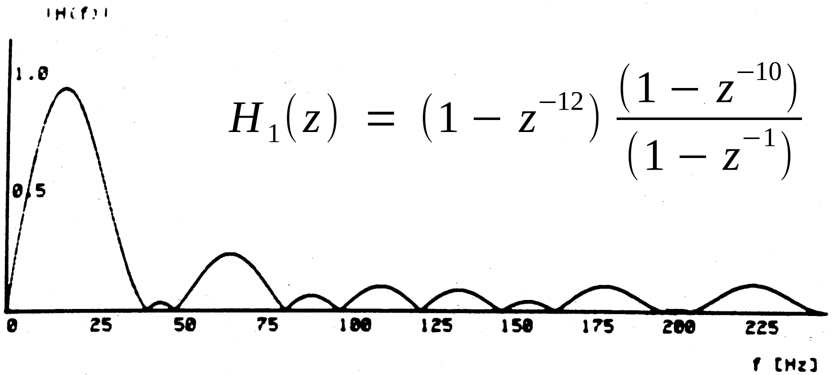
$$d[n] = G\left(\left(\sum_{i=1}^{N} \left(|H_1(x_i[n])| + |H_2(x_i[n])| \right) \right)^2 \right)$$

$$H_{1,2}(z) = \left(1 - z^{-m}\right)^M \frac{\left(1 - z^{-n}\right)}{\left(1 - z^{-1}\right)}$$

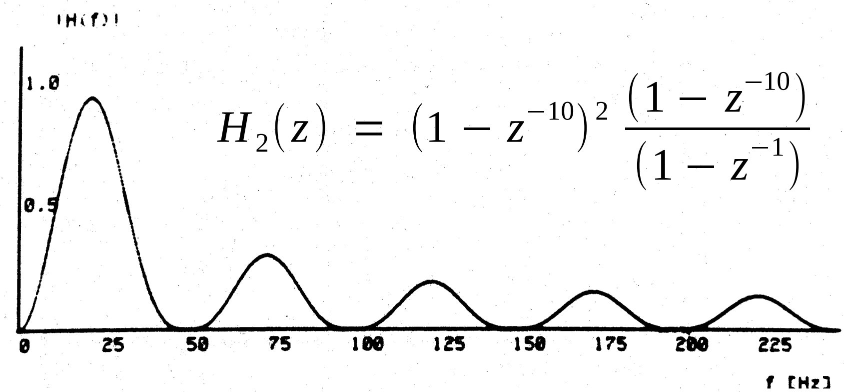
$$H_1(z) = \left(1 - z^{-12}\right) \frac{\left(1 - z^{-10}\right)}{\left(1 - z^{-1}\right)} \qquad H_2(z) = \left(1 - z^{-10}\right)^2 \frac{\left(1 - z^{-10}\right)}{\left(1 - z^{-1}\right)}$$

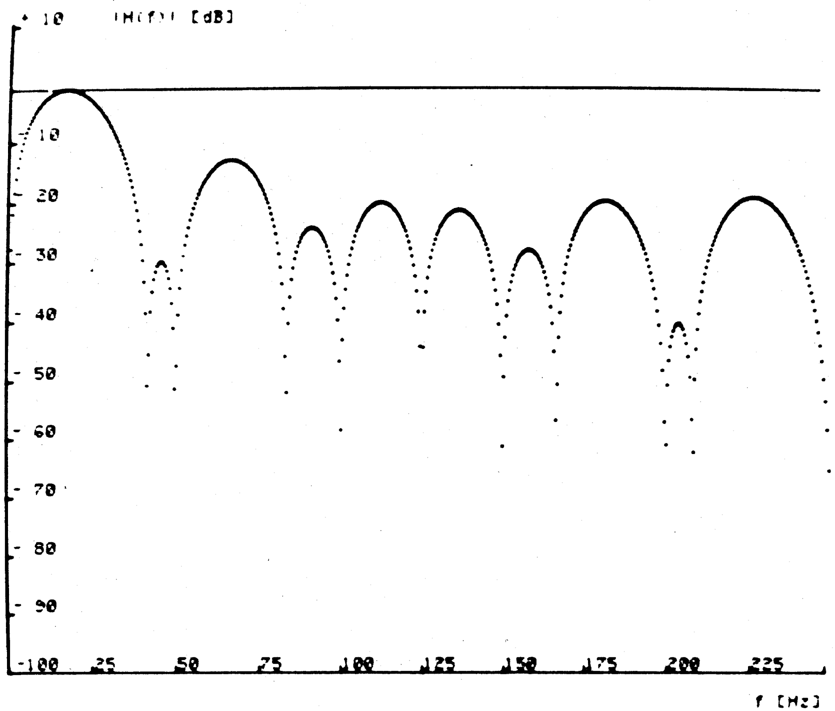
QRS complex detection

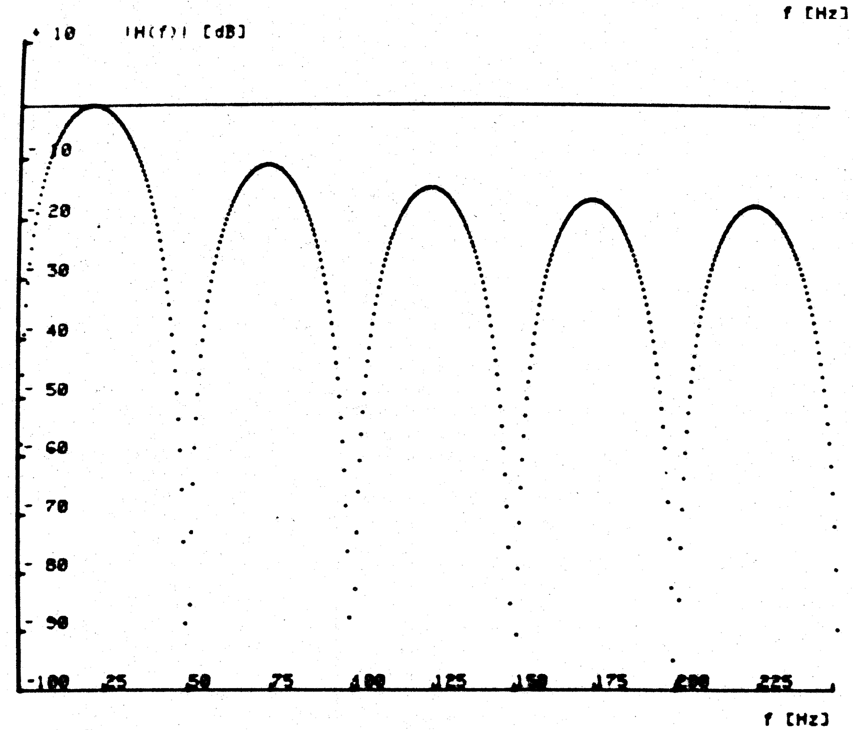
$$H_1(z) = (1 - z^{-12}) \frac{(1 - z^{-10})}{(1 - z^{-1})}$$



$$H_2(z) = (1 - z^{-10})^2 \frac{(1 - z^{-10})}{(1 - z^{-1})}$$







nd

QRS complex detection

- Linear filtering

  - Transfer functions
  - Difference equations
  - Impulse responses

$$H_1(z) = (1 - z^{-12}) \frac{(1 - z^{-10})}{(1 - z^{-1})}$$

$$H_2(z) = (1 - z^{-10})^2 \frac{(1 - z^{-10})}{(1 - z^{-1})}$$

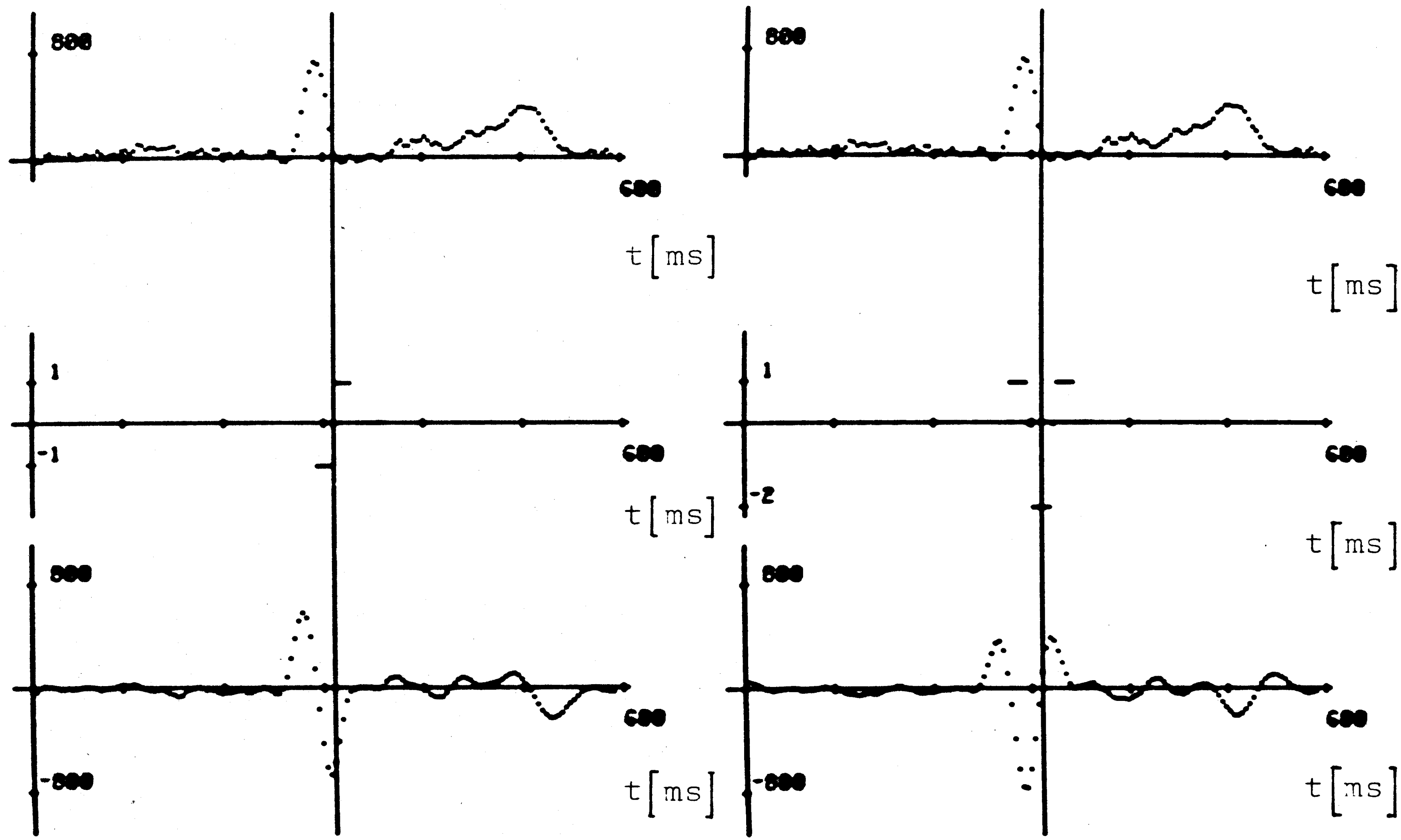
$$y_{1,i}[n] = y_{1,i}[n-1] + x_i[n] - x_i[n-10] - x_i[n-12] + x_i[n-22]$$

$$y_{2,i}[n] = y_{2,i}[n-1] + x_i[n] - 3x_i[n-10] + 3x_i[n-20] - x_i[n-30]$$

$$h_1[n] = \{\mathbf{1}, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1\}$$

$$h_2[n] = \{\mathbf{1}, 1, 1, 1, 1, 1, 1, 1, 1, 1, -2, -2, -2, -2, -2, -2, -2, -2, -2, -2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1\}$$

QRS complex detection



QRS complex detection

- Nonlinear transformation

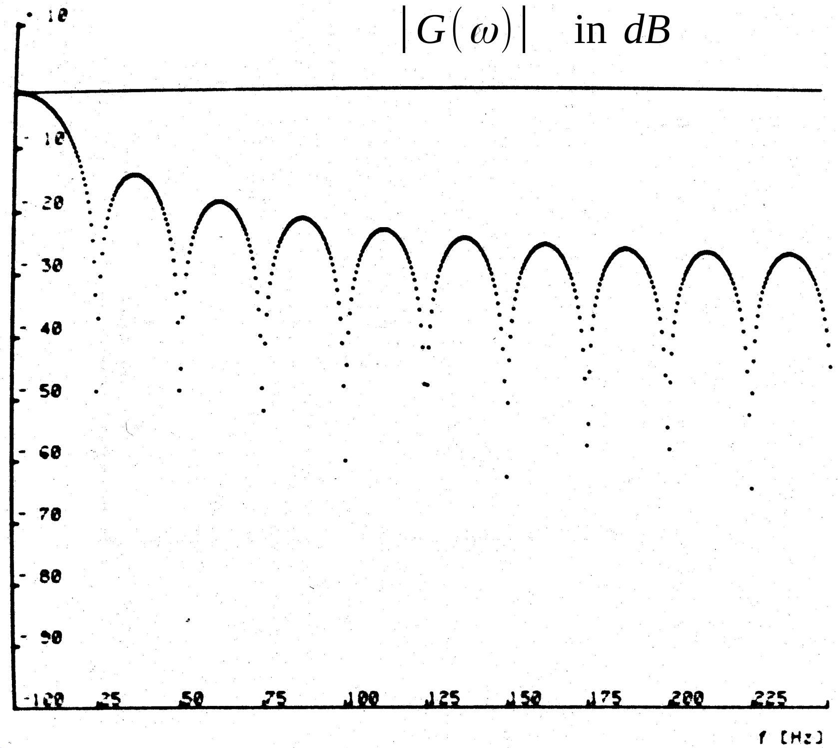
$$d[n] = G\left(\left(\sum_{i=1}^{N} \left(\left|H_1(x_i[n])\right| + \left|H_2(x_i[n])\right| \right) \right)^2 \right)$$

$$u[n] = \sum_{i=1}^{N} \left(\left|y_{1,i}[n-(T_2-T_1)]\right| + \left|y_{2,i}[n]\right| \right)$$

$$v[n] = (u[n])^2$$

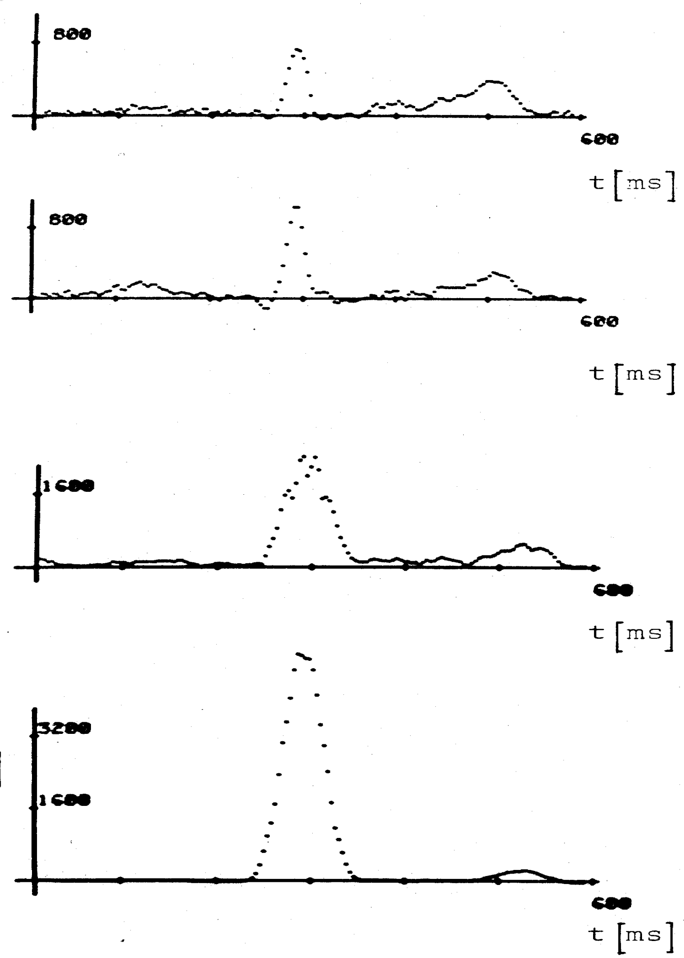
$$G(z) = \frac{(1 - z^{-20})}{(1 - z^{-1})}$$

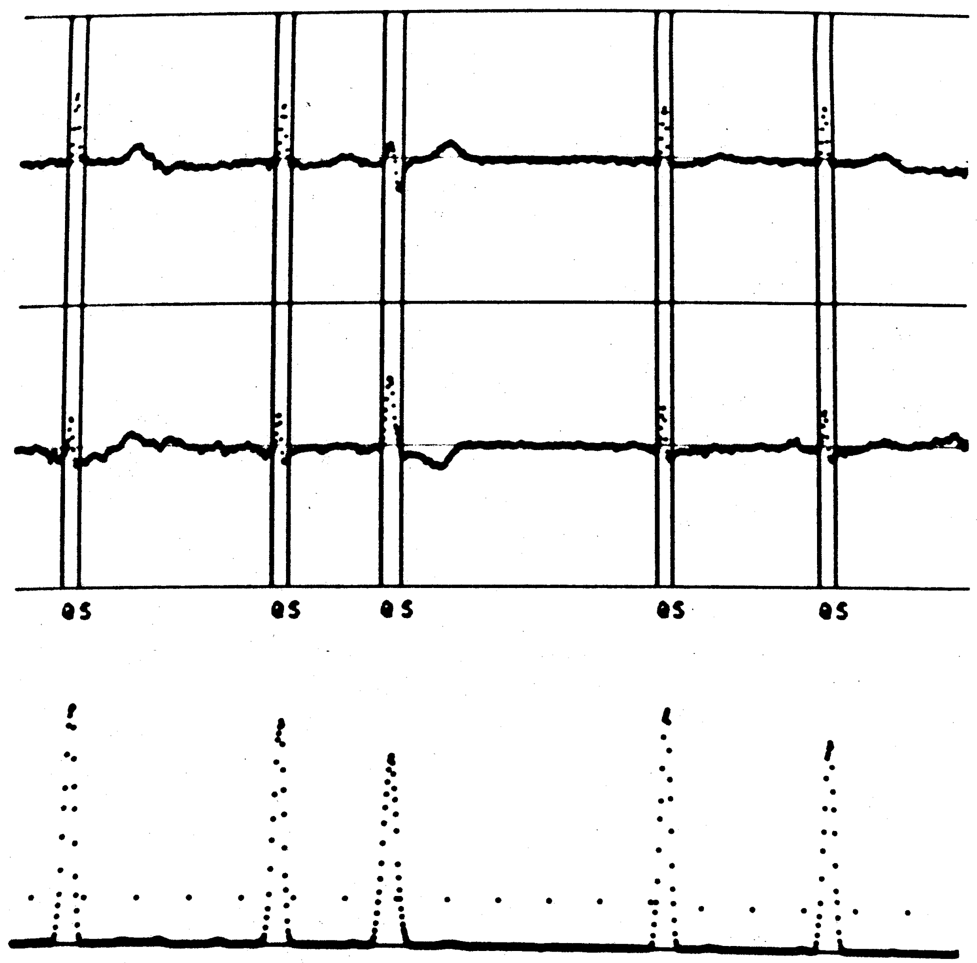
$$d[n] = d[n-1] + v[n] - v[n-20]$$



QRS complex detection

- Original signals, after filtering and summing, and the detection function, *d[n]*



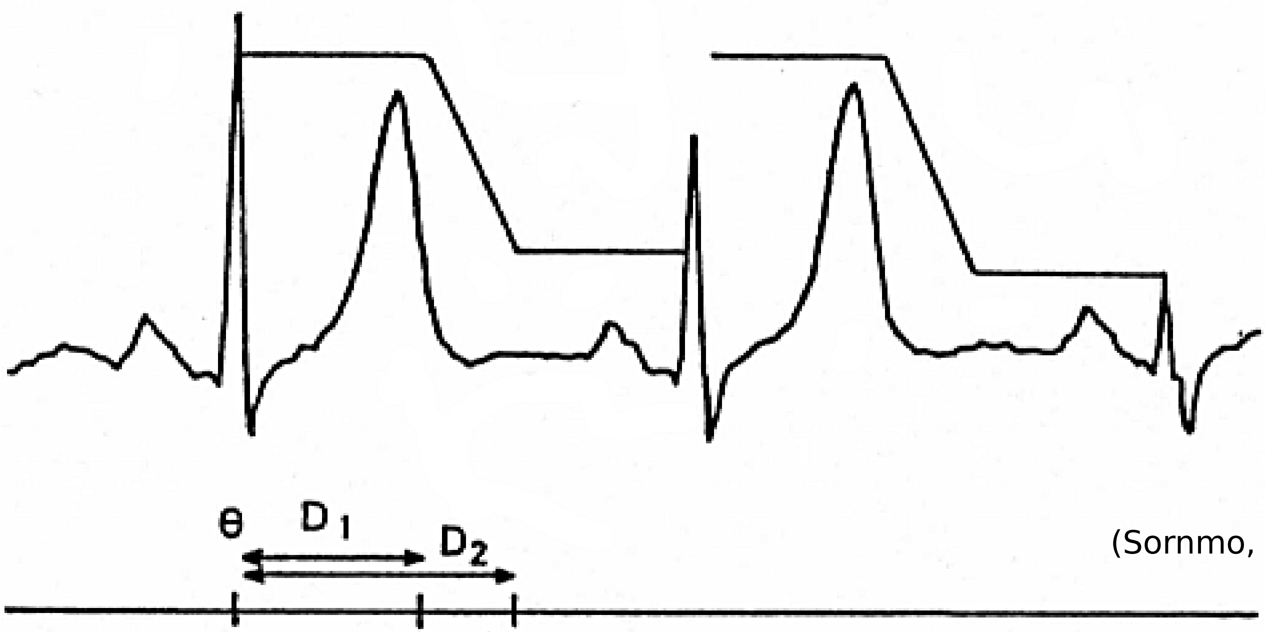


QRS complex detection

- Decision rule

$$\eta[n] = \begin{cases} \alpha_1, & n=\theta+1,\dots,\theta+D_1 \\ d[n], & n=\theta+D_1+1,\dots,\theta+D_2 \\ \alpha_2, & n=\theta+D_2,\dots \end{cases}$$

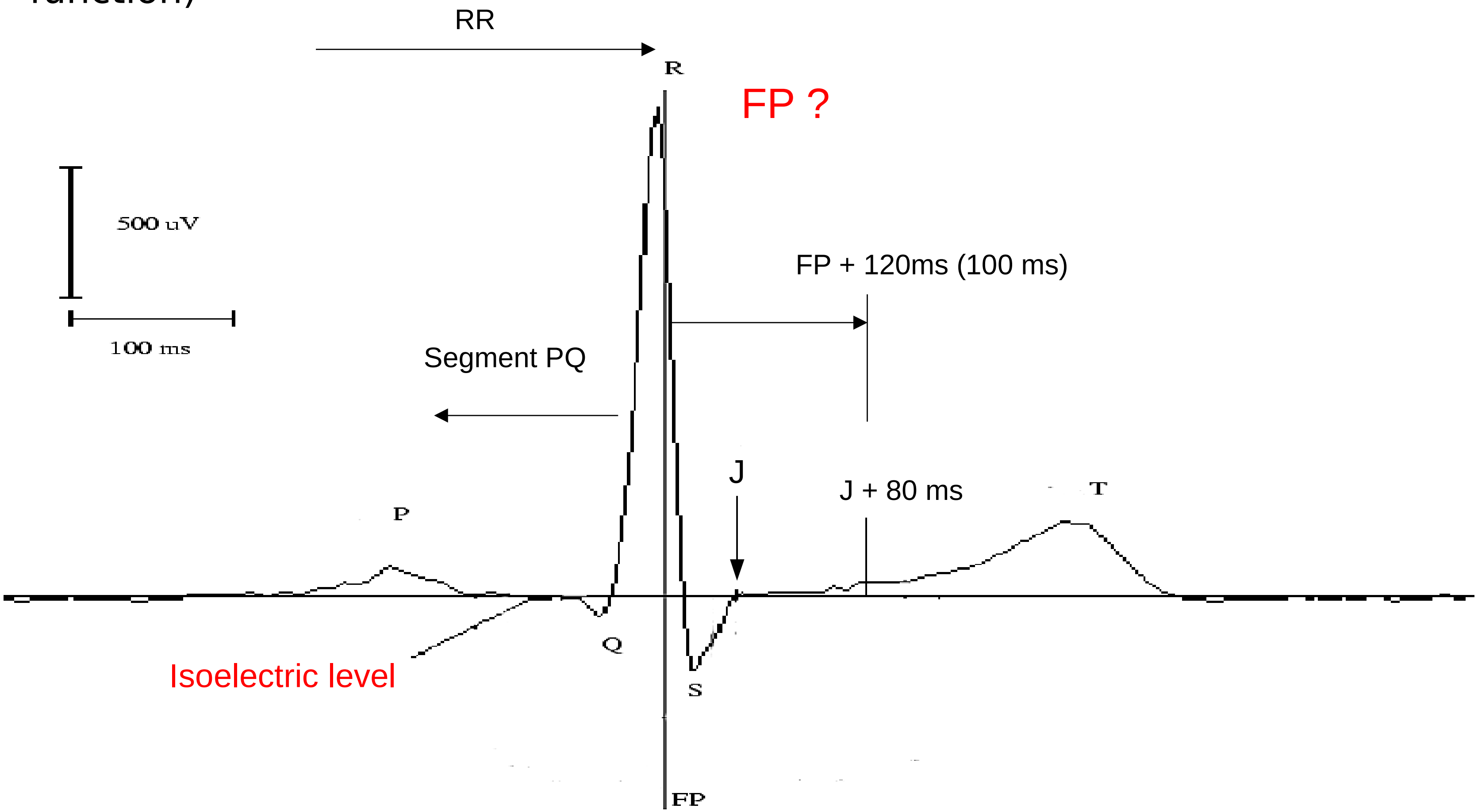
$$\alpha_1 \geq d[\theta + D_1 + 1] > \dots > d[\theta + D_2] = \alpha_2$$



(Sornmo, Laguna)

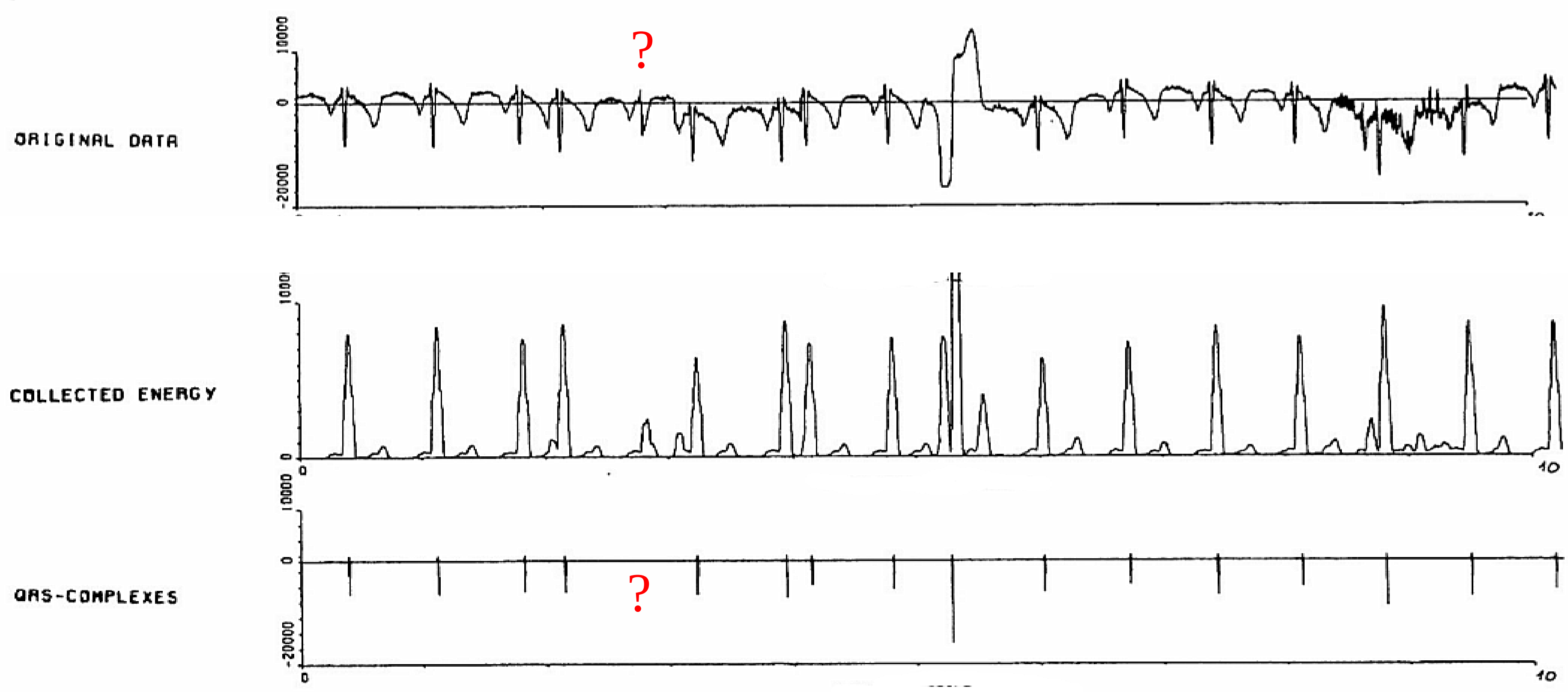
QRS complex detection

- What is Fiducial Point (FP), or reference point? (usually peak of the detection function)



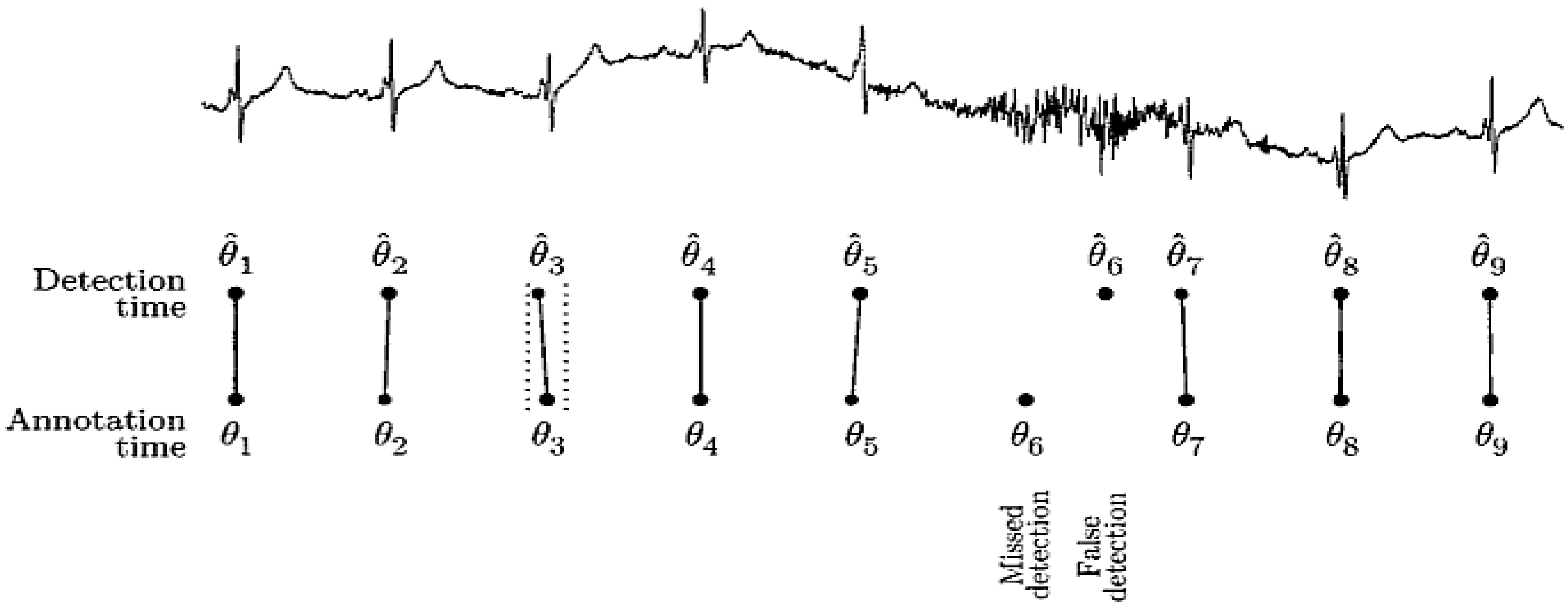
QRS complex detection

- Original ECG signal, detection function and detected QRS complexes



QRS complex detection, performance evaluation

- Example
  - True detection of an event – true positive (*tp*)
  - Missed detection of an event – false negative (*fn*)
  - False detection of an event – false positive (*fp*)
  - ? True rejection of a *non-event* ? – true negative (*tn*)



(Sornmo, Laguna)

QRS complex detection, performance evaluation

- Performance evaluation

Classic event oriented performance matrix

		Analyzer	Analyzer
		EVENT	NON-EVENT
Reference	event	*TP*	*FN*
Reference	non-event	*FP*	(*TN*)

TP – number of correctly detected events

FN – number of missed events

FP – number of falsely detected events

TN – number of correctly rejected non-events (undefined for detection task !)

QRS complex detection, performance evaluation

- Performance evaluation

		Analyzer	Analyzer
		EVENT	NON-EVENT
Reference	event	TP	FN
Reference	non-event	FP	(TN)

Sensitivity:

$$Se = \frac{TP}{TP + FN}$$

The proportion of events which were detected

Positive predictivity:

$$+P = \frac{TP}{TP + FP}$$

The proportion of detections which actually were events

QRS complex detection, performance evaluation

- Performance evaluation

		Analyzer	Analyzer
		EVENT	NON-EVENT
Reference	event	*TP*	*FN*
Reference	non-event	*FP*	(*TN*)

Sensitivity:

$$Se = \frac{TP}{TP + FN} \approx p\,(\text{EVENT} \mid \text{event})$$

An estimate of the likelihood of detecting an event

Positive predictivity:

$$+P = \frac{TP}{TP + FP} \approx p\,(\text{event} \mid \text{EVENT})$$

An estimate of the likelihood that a detection is an event

QRS complex detection, performance evaluation

- Approaches based on signal derivatives and digital filters (Pangerc Urška)
  (MIT BIH arrhythmia DB)
  $Se \approx 99.90\%$ $+P \approx 99.92\%$

- QRS detection based on matched filters (Haar-like filters) (Ding J J)
  (MIT BIH arrhythmia DB)
  $Se \approx 99.93\%$ $+P \approx 99.88\%$

Silva I, Moody B, Behar J, Johnson A, Oster J, Clifford G D ,and Moody G B, Editorial: Robust detection of heart beats in multimodal data, Physiological Measurement, Vol 36, pp. 1629-44, 2015

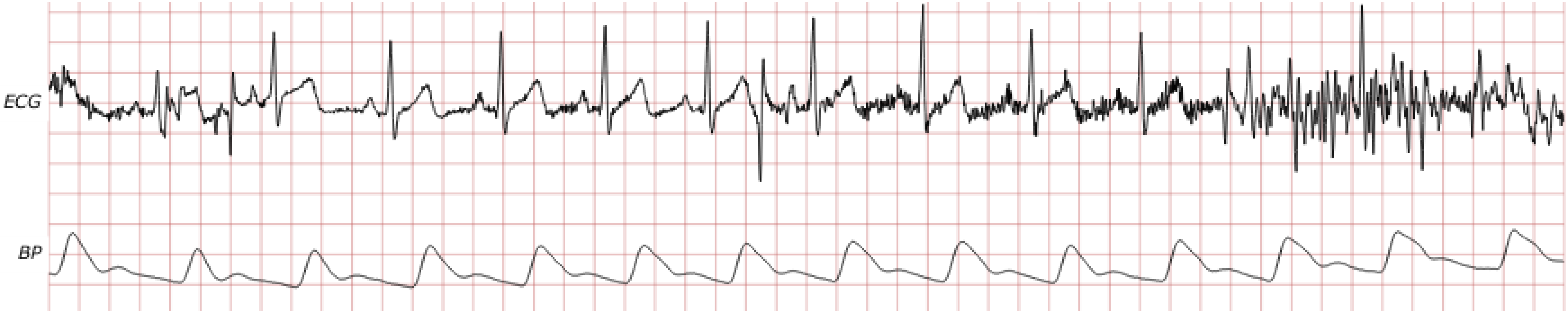
Pangerc U, and Jager F, Robust detection of heart beats in multimodal records using slope- and peak-sensitive band-pass filters, Physiological Measurement, Vol 36, pp. 1645-64, 2015

Ding J J, Huang C W, Ho Y L, Hung C S, Lin Y H, and Chen Y H, An efficient selection, scoring, and variation ratio test algorithm for ECG R-wave peak detection, Experimental & Clinical Cardiology Journal, Vol 20, pp. 4256–63, 2014

Elgendi, M, Eskofier B, Dokos S, and Abbot D, Revisiting QRS Detection Methodologies for Portable Wearable, Battery-Operated, and Wireless ECG Systems, PLoS One, Vol 9, e84018, 2014

Heart beat detection in multimodal data

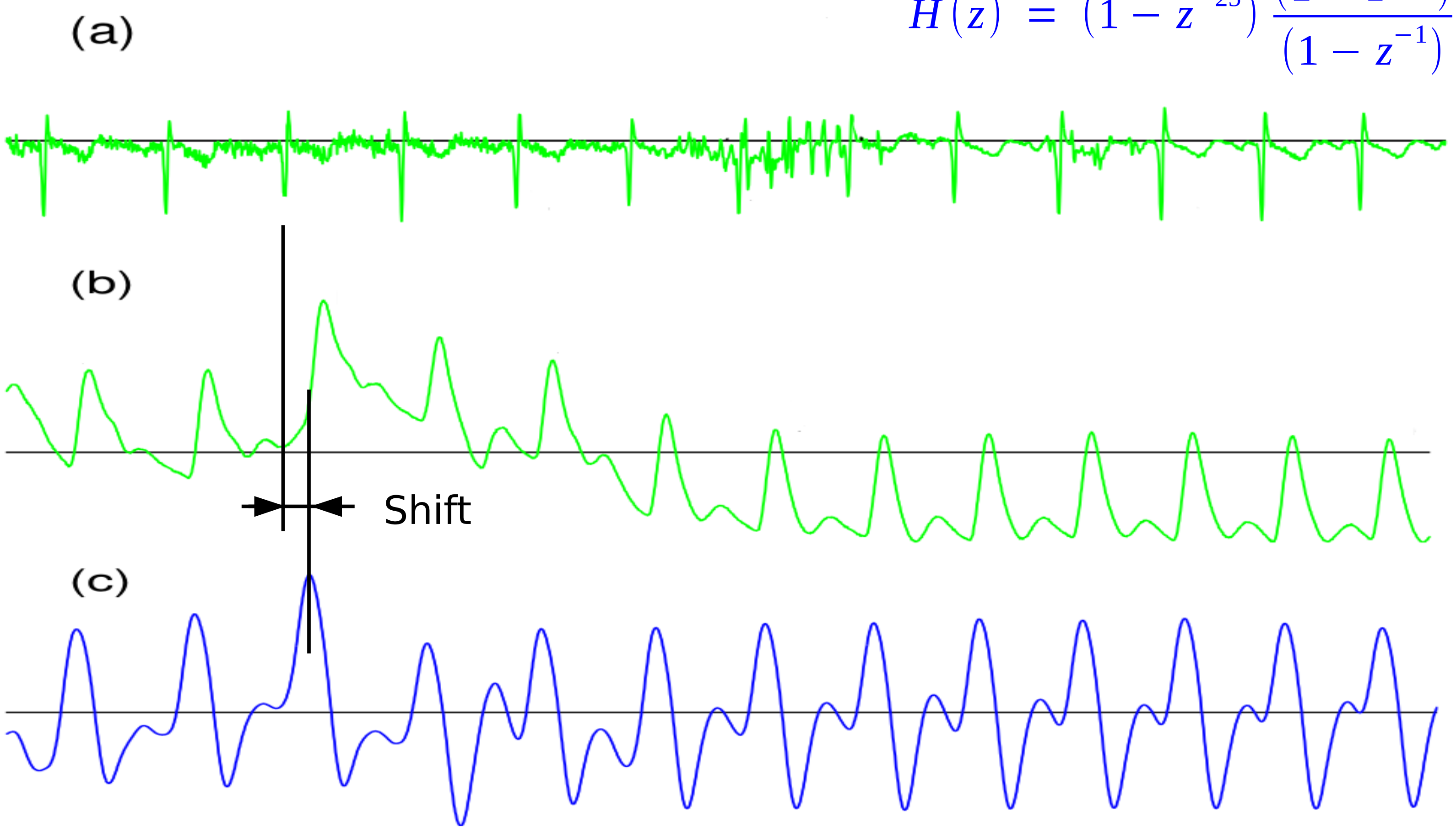
- Exercises 1.f – 1.g: Heart beat detection using ECG and pulsatile signals
- Use ECG signal and one of the pulsatile signals like: BP, ABP, PAP, PLETH



Heart beat detection in multimodal data

- a) ECG, b) BP, c) BP filtered by slope sensitive filter:

$$H(z) = \left(1 - z^{-25}\right) \frac{\left(1 - z^{-50}\right)}{\left(1 - z^{-1}\right)}$$



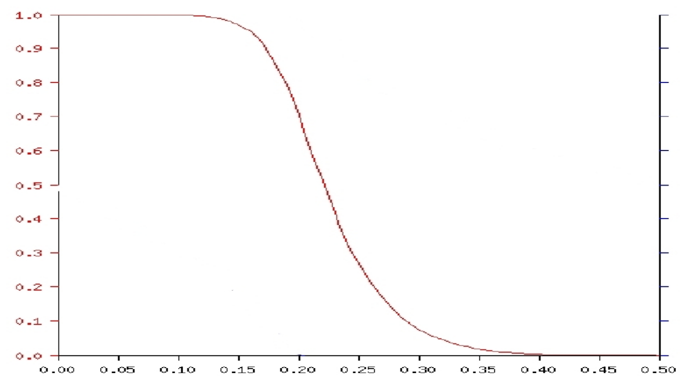
(Challenges in ECG signal processing today)

- Robust heart heat detection
- Signal quality estimation
- Reliable P wave identification
- Reliable QT interval estimation
- Distinguishing ischaemic from non-ischaemic ST changes
- Reliable heart beat classification
- Reliable rhythm analysis
- (Robust, reliable in-band signal filtering or source separation)
- (Identification of lead position misplacements or sensor shifts)
- (ECG modeling and parameter fitting)
- (The mapping of diagnostic ECG parameters to disease classifications or predictive metrics)
- (Global context pattern analysis)

(ECG filtering)

- Digital Butterworth filters have a smooth frequency response and are computationally non-intensive (linear time-invariant filtering)

$|H_L(\Omega)|$



- Low-pass $$|H_L(\Omega)|^2 = \frac{1}{1 + (\frac{\Omega}{\Omega_C})^{2N}}$$

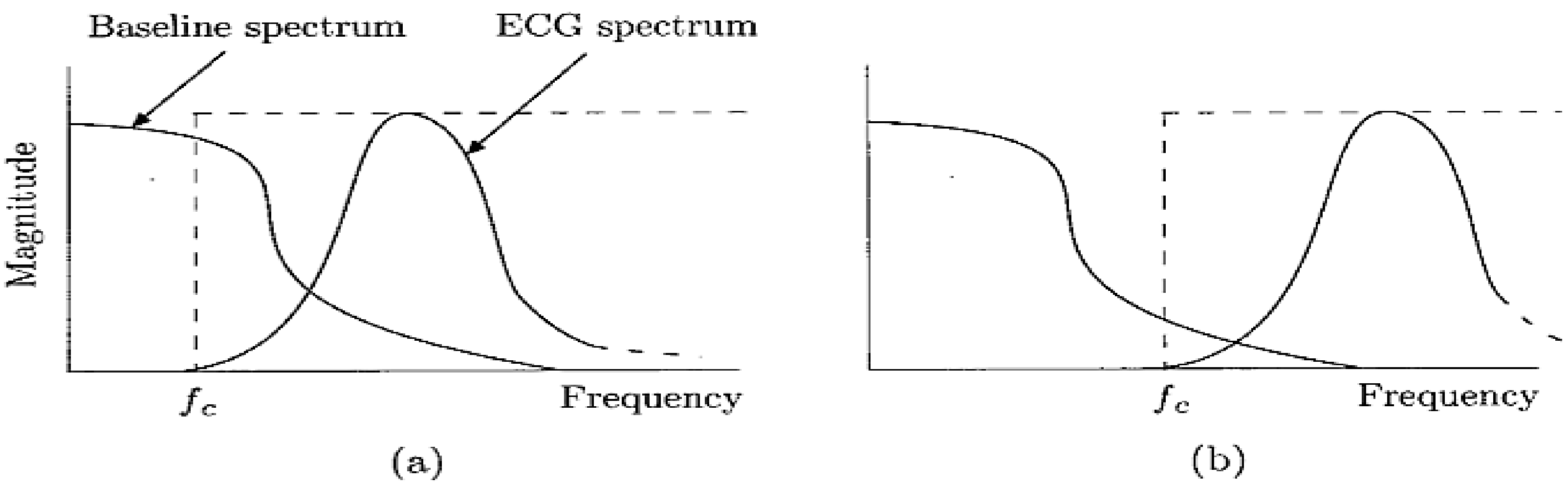
- (High-pass) $$|H_H(\Omega)|^2 = \frac{1}{1 + (\frac{\Omega_C}{\Omega})^{2N}}$$

- Their major drawback, the phase-shifting, is especially troublesome when using high-pass filtering (will discuss Butterworth high-pass filter for EMG analysis)

(ECG filtering)

- Linear time-variant filtering (heart rate dependent filtering)
- Cut-off frequency *$f_c(n)$* is inversely proportional to the instantaneous RR interval estimate *$RR(n)$*, $f_c(n) \sim 1 / RR(n)$
- The time-varying cut-off frequency *$f_c(n)$* is used to design a high-pass filter *$h(k,n)$* at every time instant *n*, where *k* denotes discrete time within the impulse response.

  (a) low heart rate, (b) high heart rate

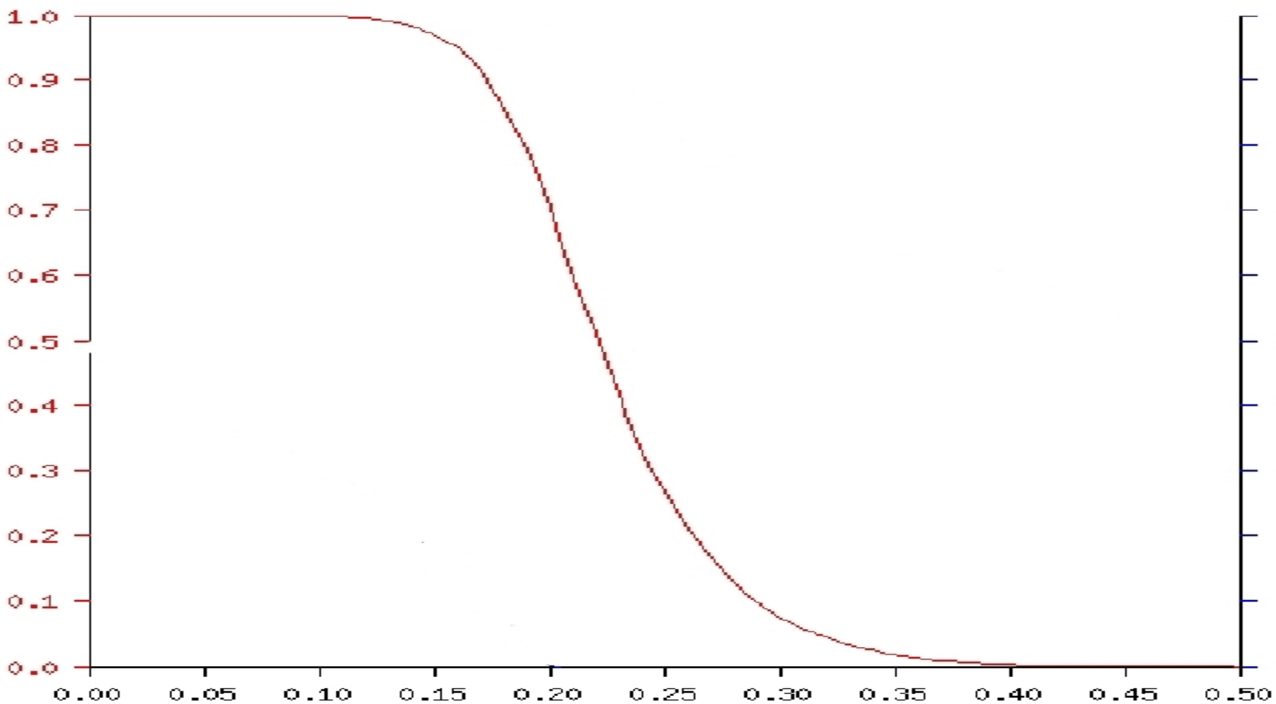


(Sornmo, Laguna)

ECG filtering

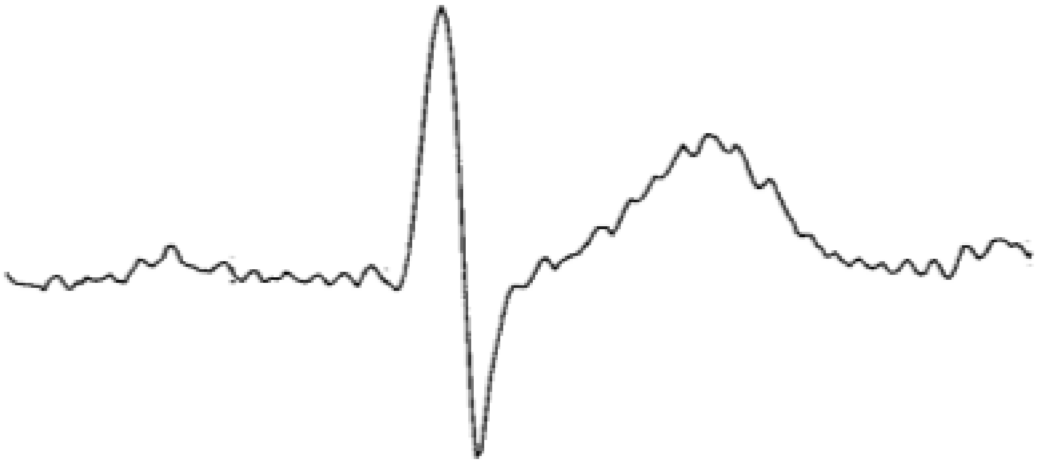
- Butterworth low-pass filtering
  $N = 2, \quad Fs = 200 \; smp/sec$
  Cut-off (-3dB) at 40 Hz

$$|H_L(\Omega)|^2 = \frac{1}{1 + \left(\frac{\Omega}{\Omega_C}\right)^{2N}}$$



(ECG filtering, power line interference)

- Power line interference (50/60 Hz)



(Sornmo, Laguna)

(ECG filtering, power line interference)

- Power line interference (50/60 Hz) (two zeros, two poles to make stop-band narrower)

$$z_{1,2} = e^{\pm j\omega_0}$$

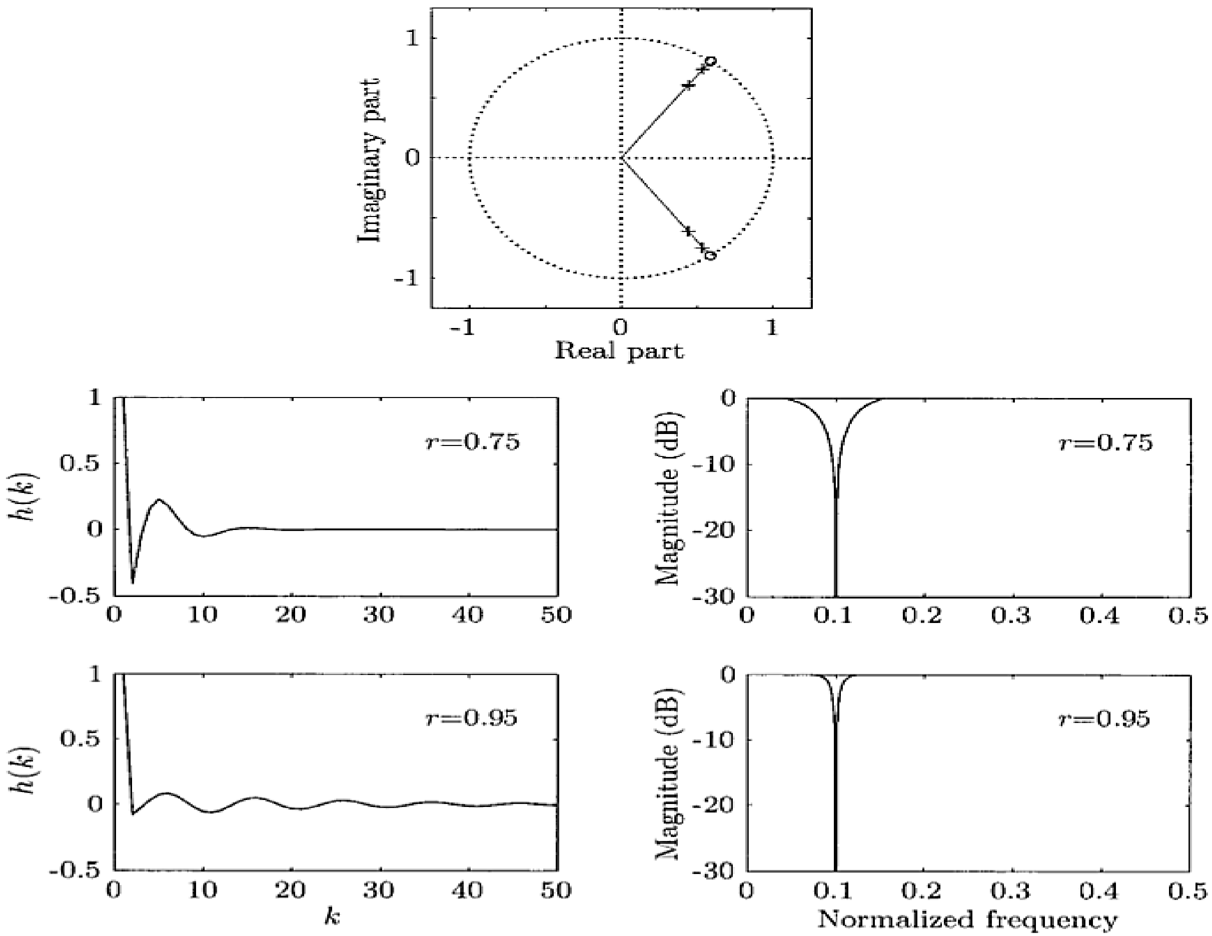
$$\begin{aligned} H(z) &= (1 - z_1 z^{-1})(1 - z_2 z^{-1}) \\ &= 1 - 2\cos(\omega_0) z^{-1} + z^{-2} \end{aligned}$$

$$p_{1,2} = r e^{\pm j\omega_0}$$

$$\begin{aligned} H(z) &= \frac{(1 - z_1 z^{-1})(1 - z_2 z^{-1})}{(1 - p_1 z^{-1})(1 - p_2 z^{-1})} \\ &= \frac{1 - 2\cos(\omega_0) z^{-1} + z^{-2}}{1 - 2r\cos(\omega_0) z^{-1} + r^2 z^{-2}} \end{aligned}$$

(ECG filtering, power line interference)

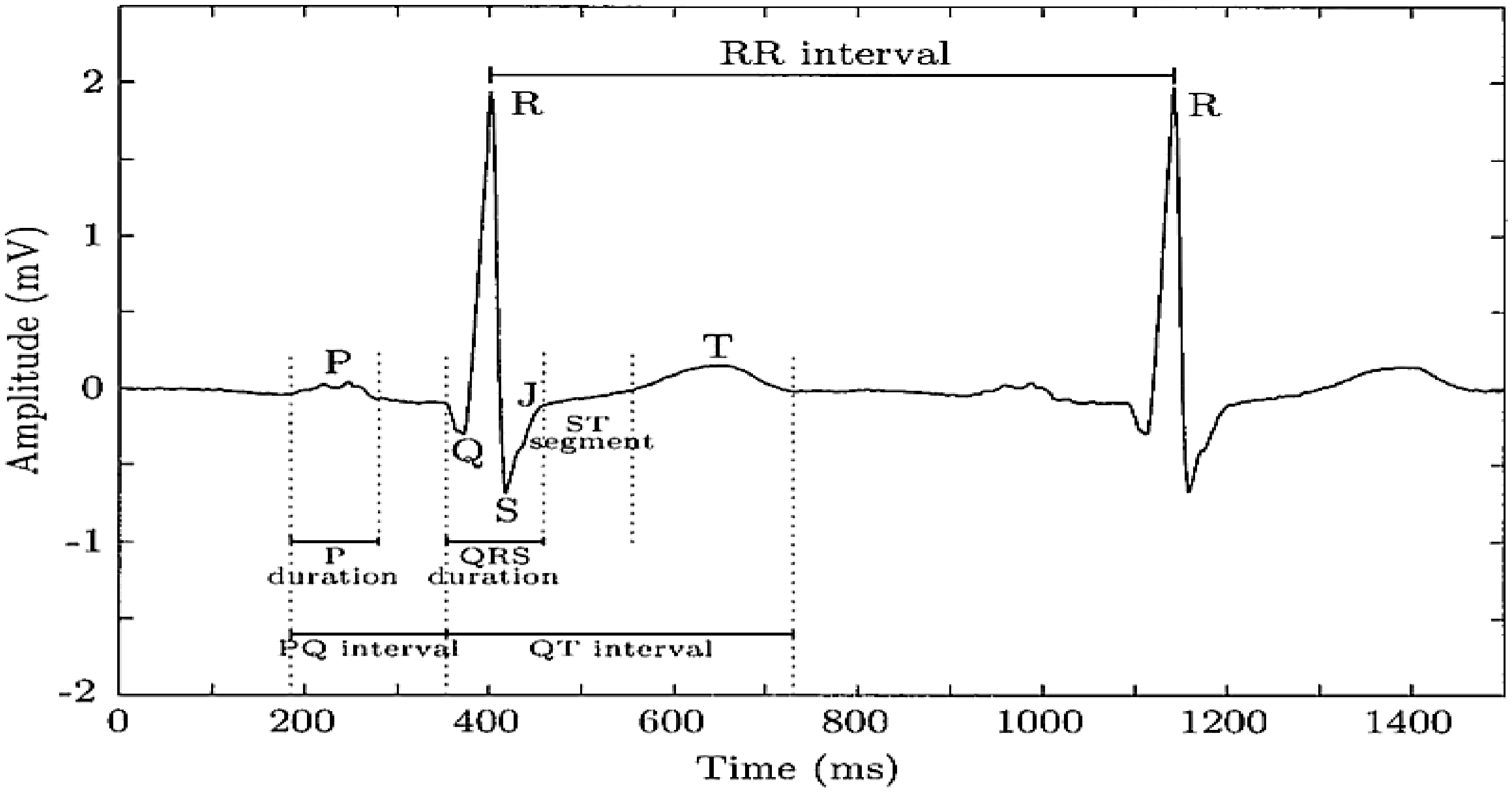
- Power line interference (50/60 Hz)



(Sornmo, Laguna)

(Wave delineation)

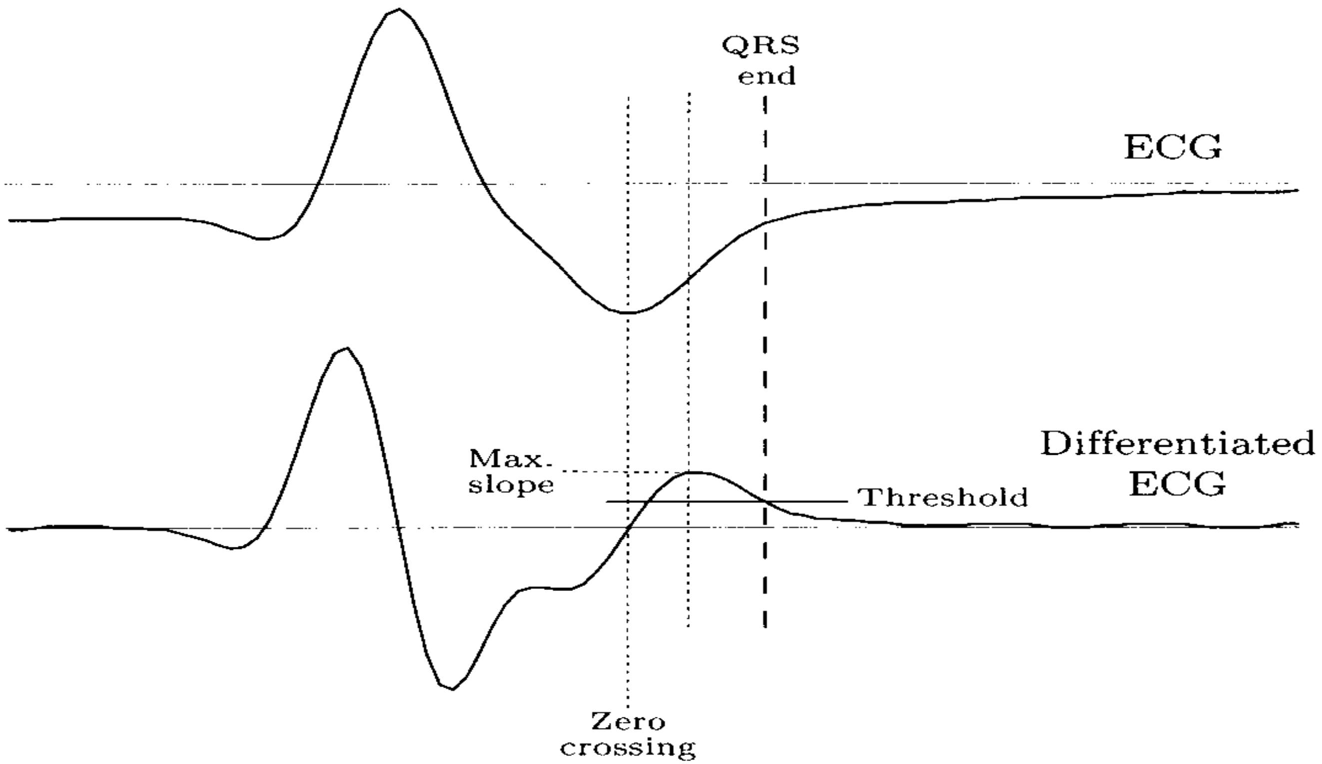
- P wave onset and offset, QRS complex onset and offset (J point), T wave onset and offset, PQ interval, QT interval



(Sornmo, Laguna)

(Wave delineation)

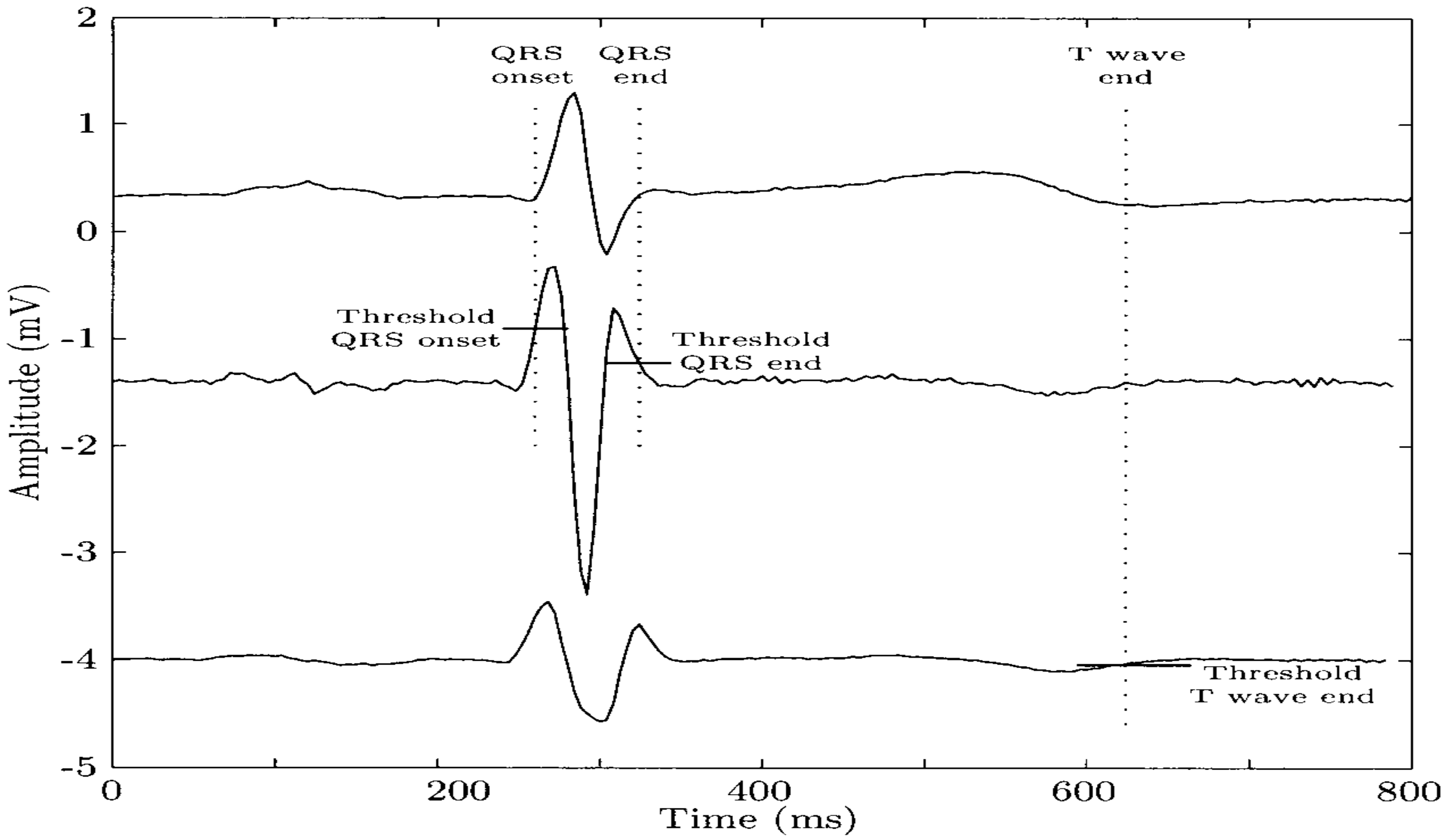
- Determining the position of QRS offset (end) (J point), the Threshold is expressed as a percentage of Maximum slope found



(Sornmo, Laguna)

(Wave delineation)

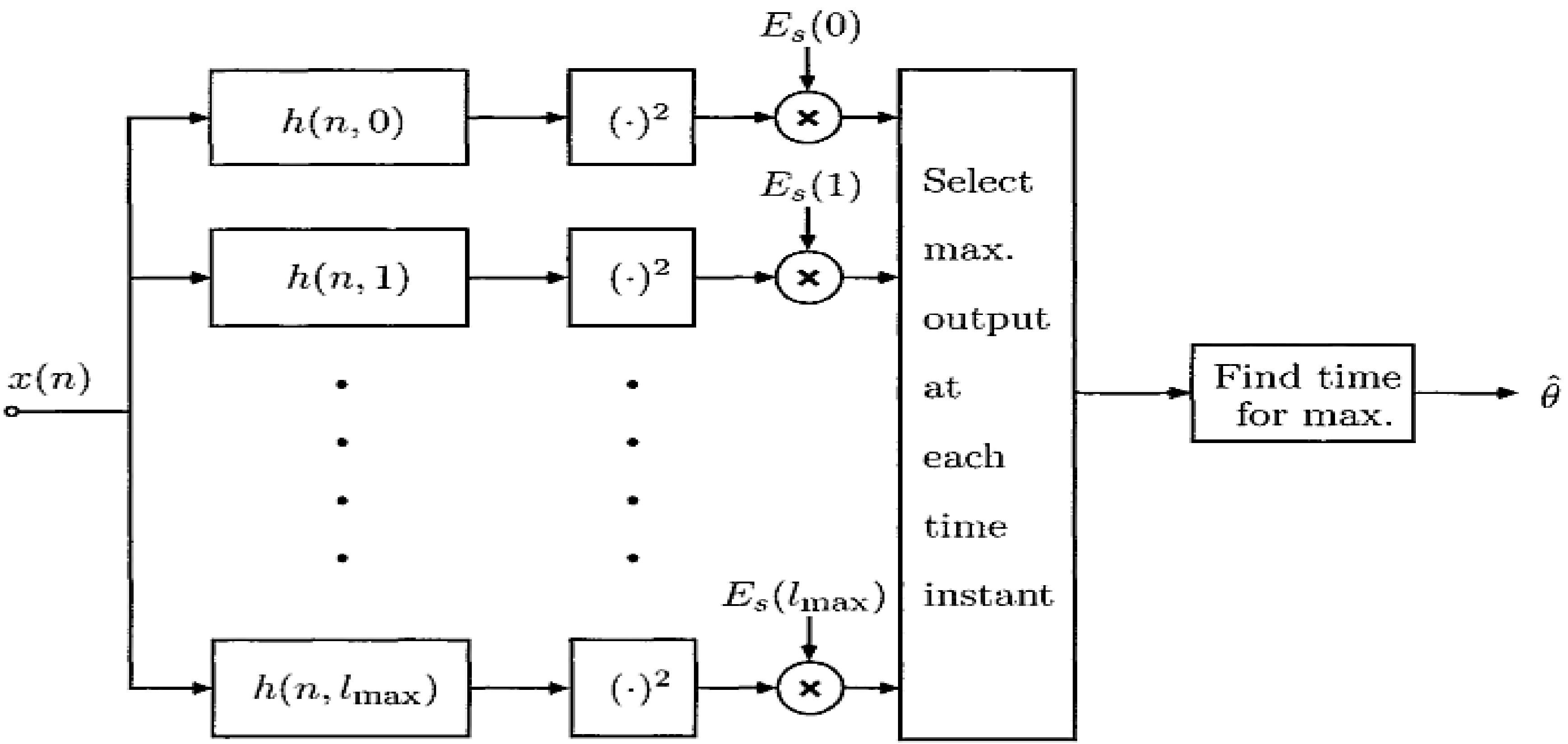
- Determining the position of QRS onset, QRS offset and T wave end



(Sornmo, Laguna)

(Sophisticated QRS complex detection)

- Block diagram of a sophisticated QRS complex detector

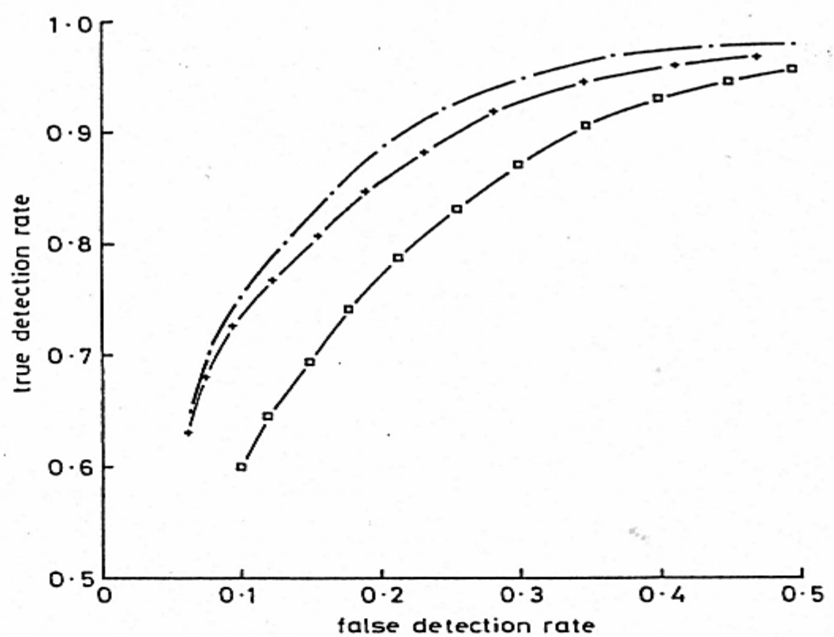


(Sornmo, Laguna)

(QRS complex detection, performance evaluation)

- Evaluation of three different QRS complex detectors
  (each symbol corresponds to a certain value of the detection threshold)
- Missed detections – False Negatives (*FN*), False detections – False Positives (*FP*)
  True detection rate (*Se*) Sensitivity (*Se*), $Se = TP / (TP + FN)$
  False detection rate ($1 - +P$) Positive predictivity ($+P$), $+P = TP / (TP + FP)$

- Correct detections:
  True positives (*TP*)
- Correct rejections?
  True Negatives (*TN*)
  are undefined for the detection task !



(Sornmo, Laguna)