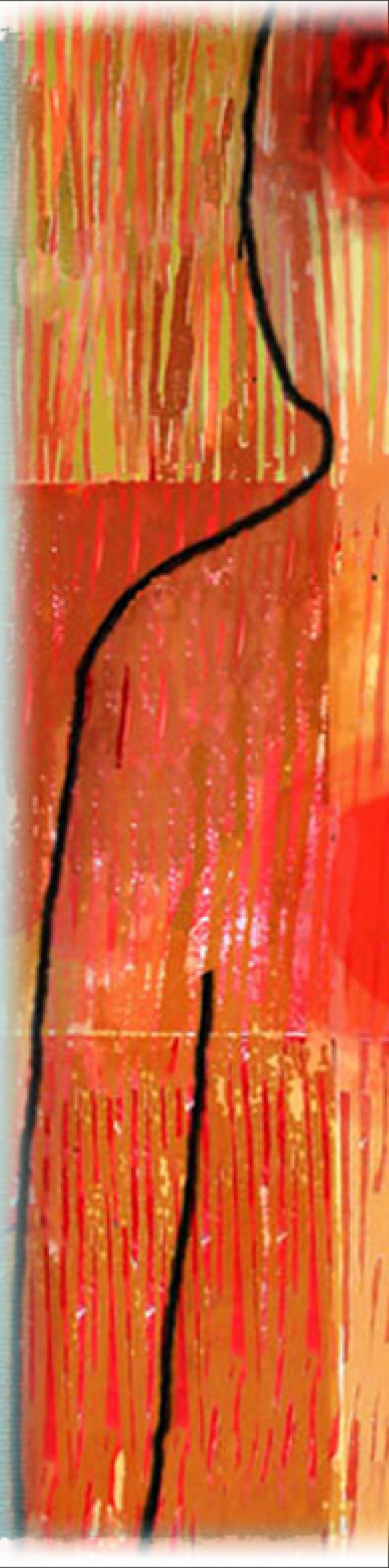
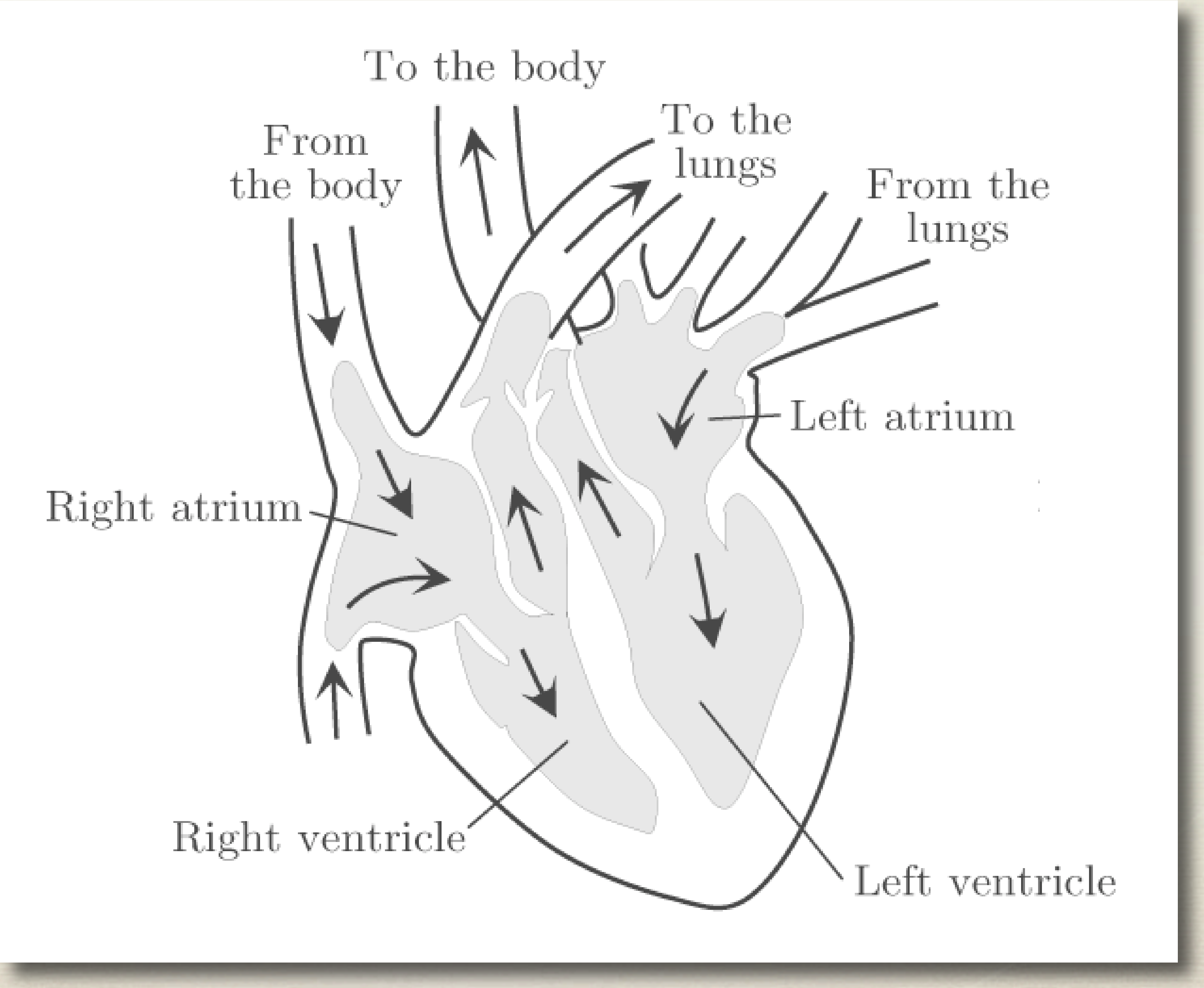
THE ELECTRICAL ACTIVITY OF THE HEART



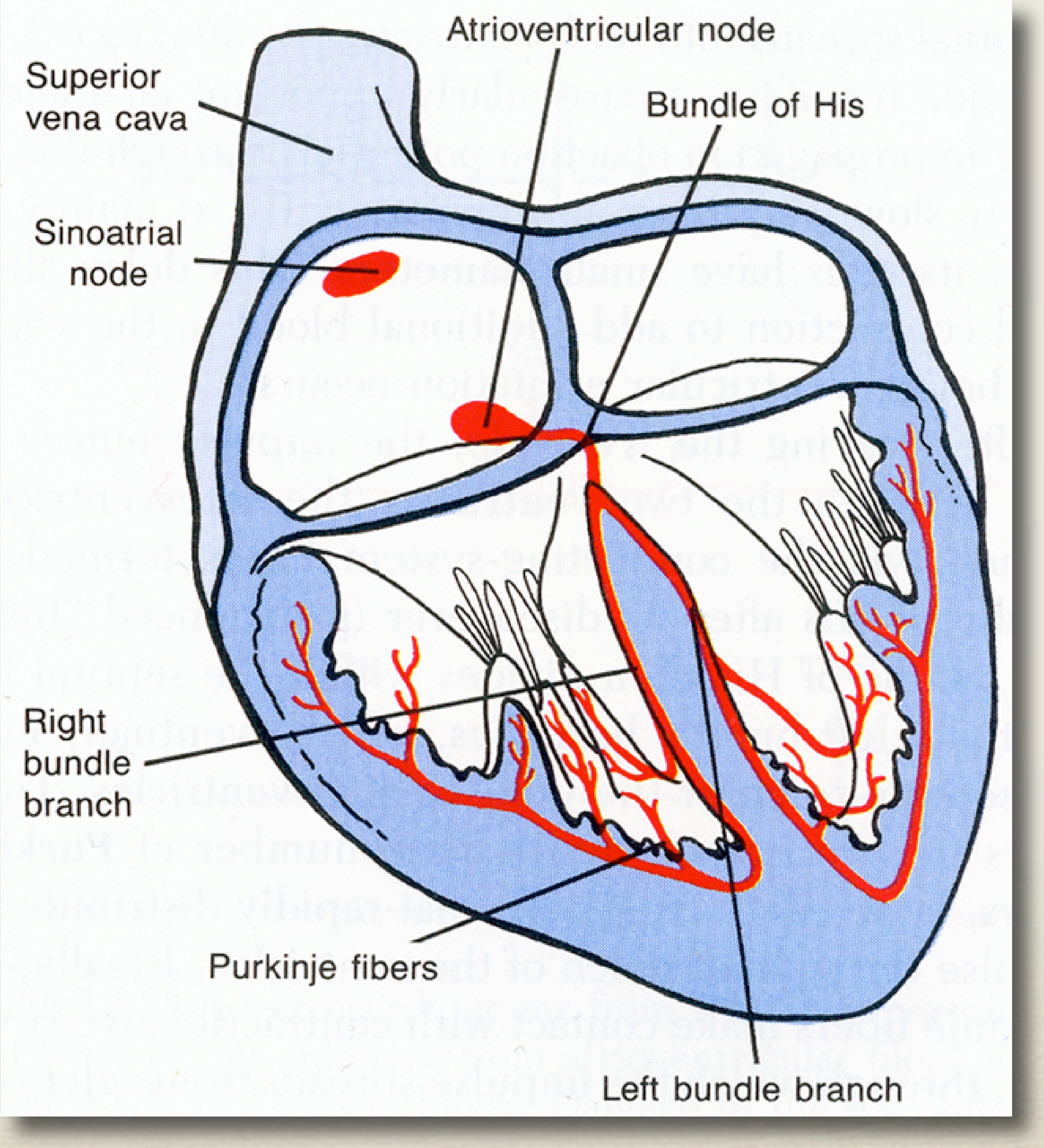
The Heart...

- is a muscle which is a pump with a capacity of ~7 liter/min.
- has 4 chambers: 2 atria and 2 ventricles.
- contracts thanks to electrical coordination of the muscle cells.
- has a conducting system for fast activation.
- is paced by the sinoatrial node, i.e., the natural pacemaker).

Blood Flow of the Heart



Conduction System of the Heart

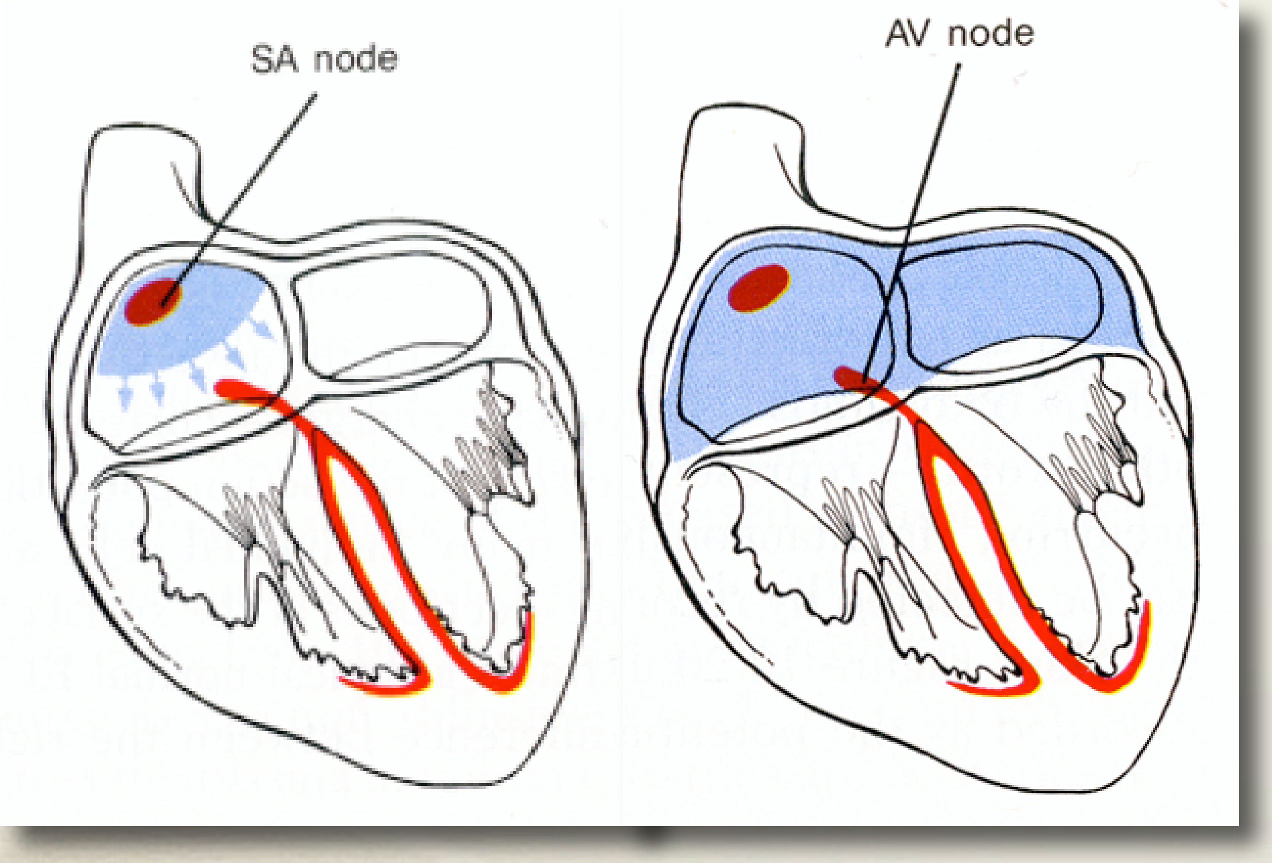


Cardiac Excitation

atrial excitation

begins

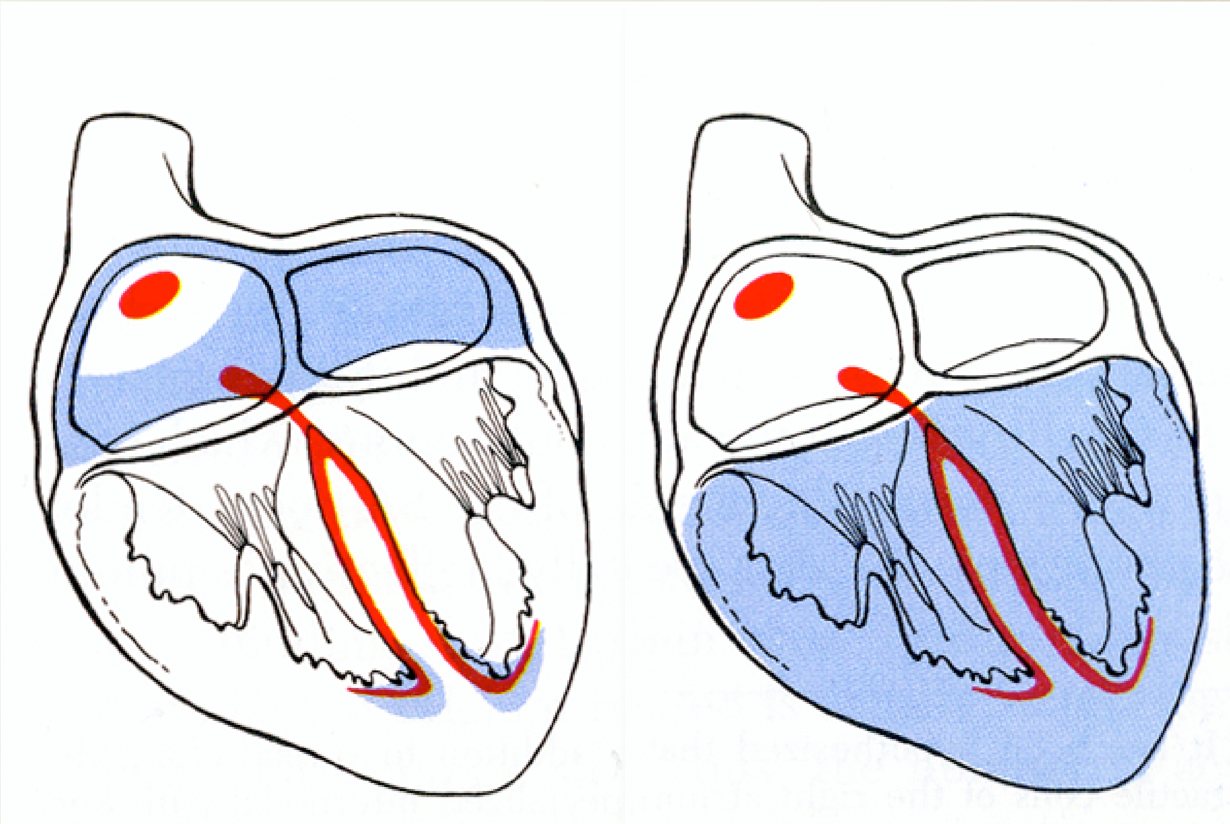
completes



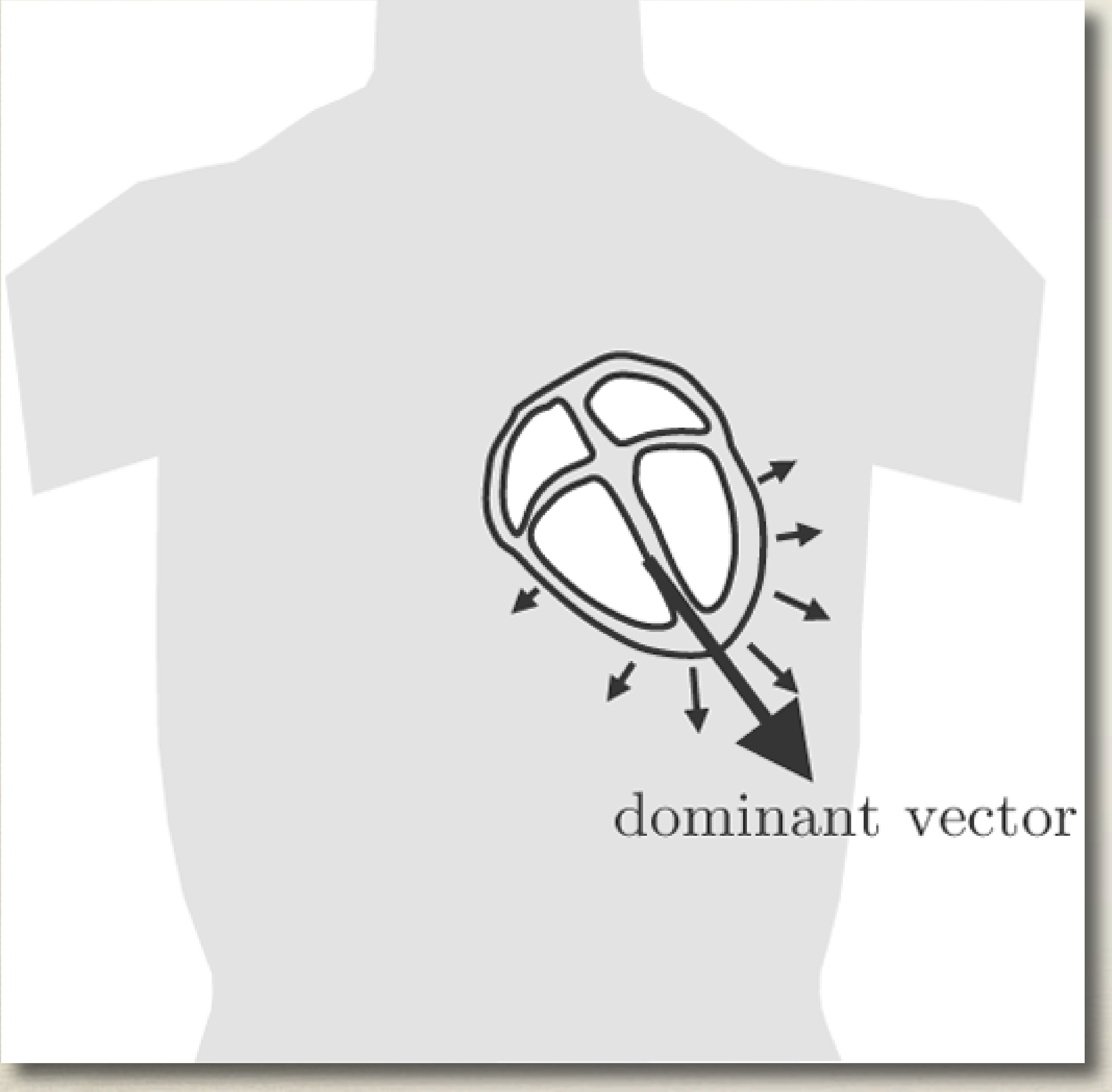
ventricular excitation

begins

completes

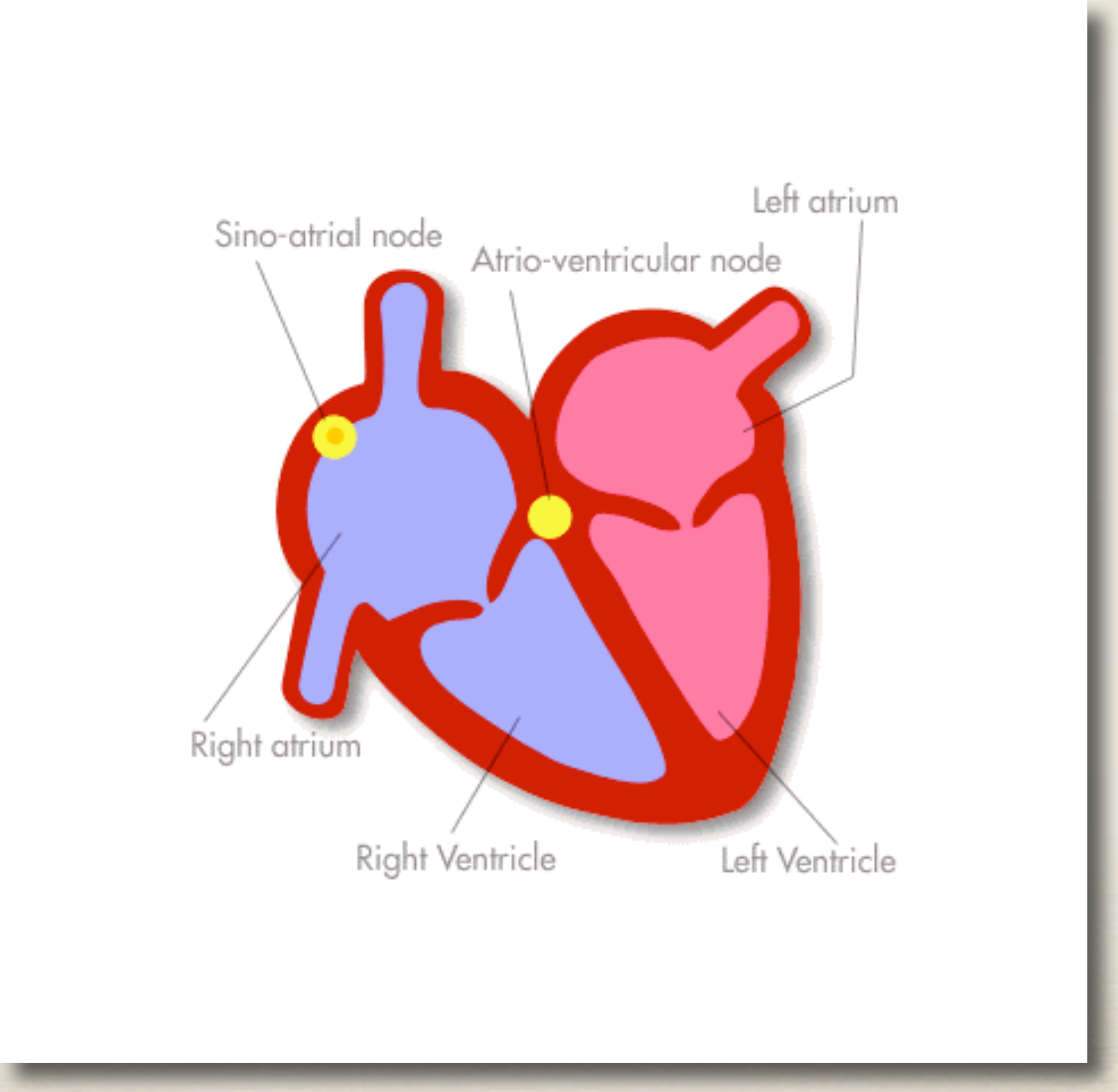


Electrical Vectors of the Heart

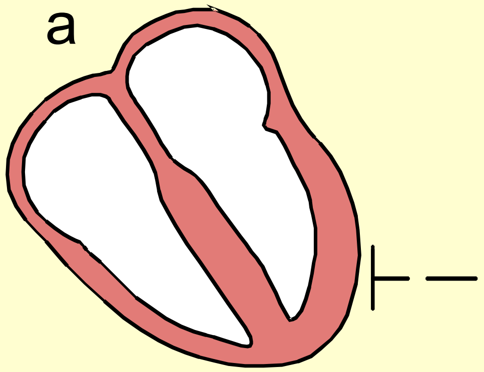


The vector associated with each group of cells in the myocardium is summed into a dominant vector describing the main direction of the electrical impulse.

Cardiac Excitation

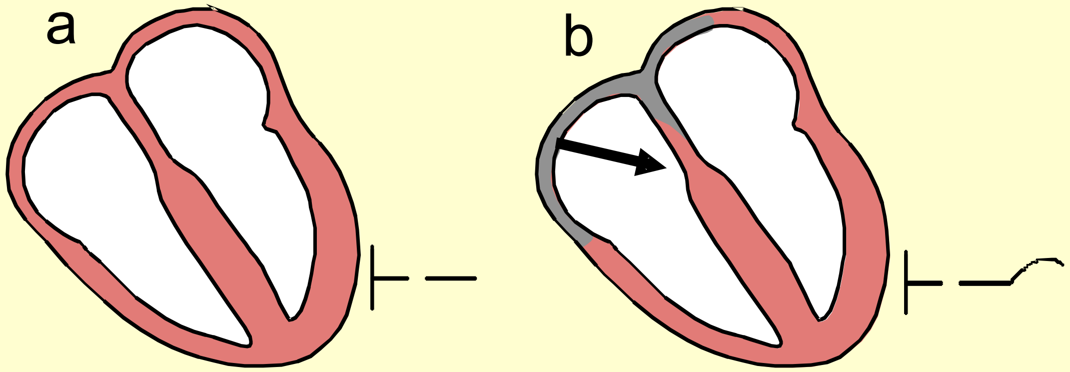


The Cardiac Cycle & Wave Shape



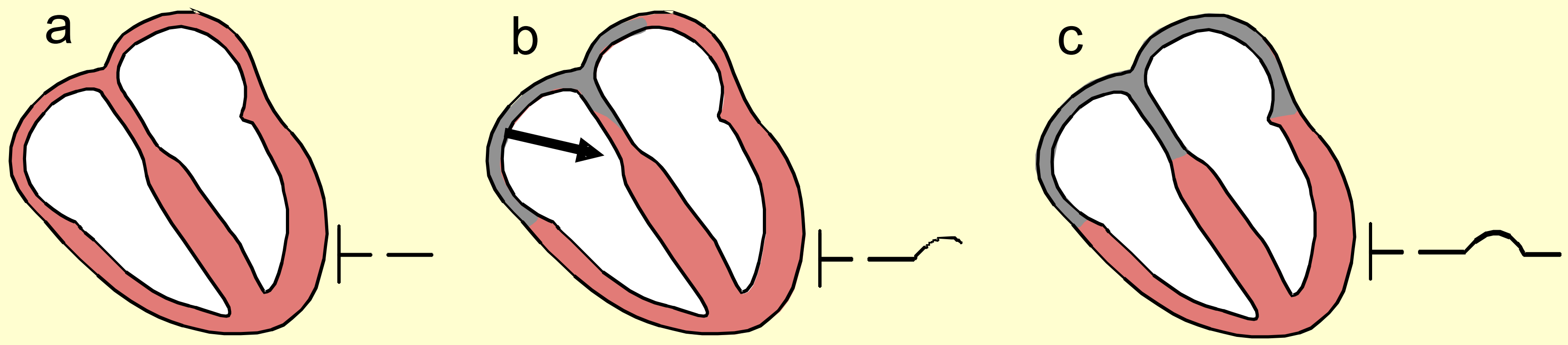
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape



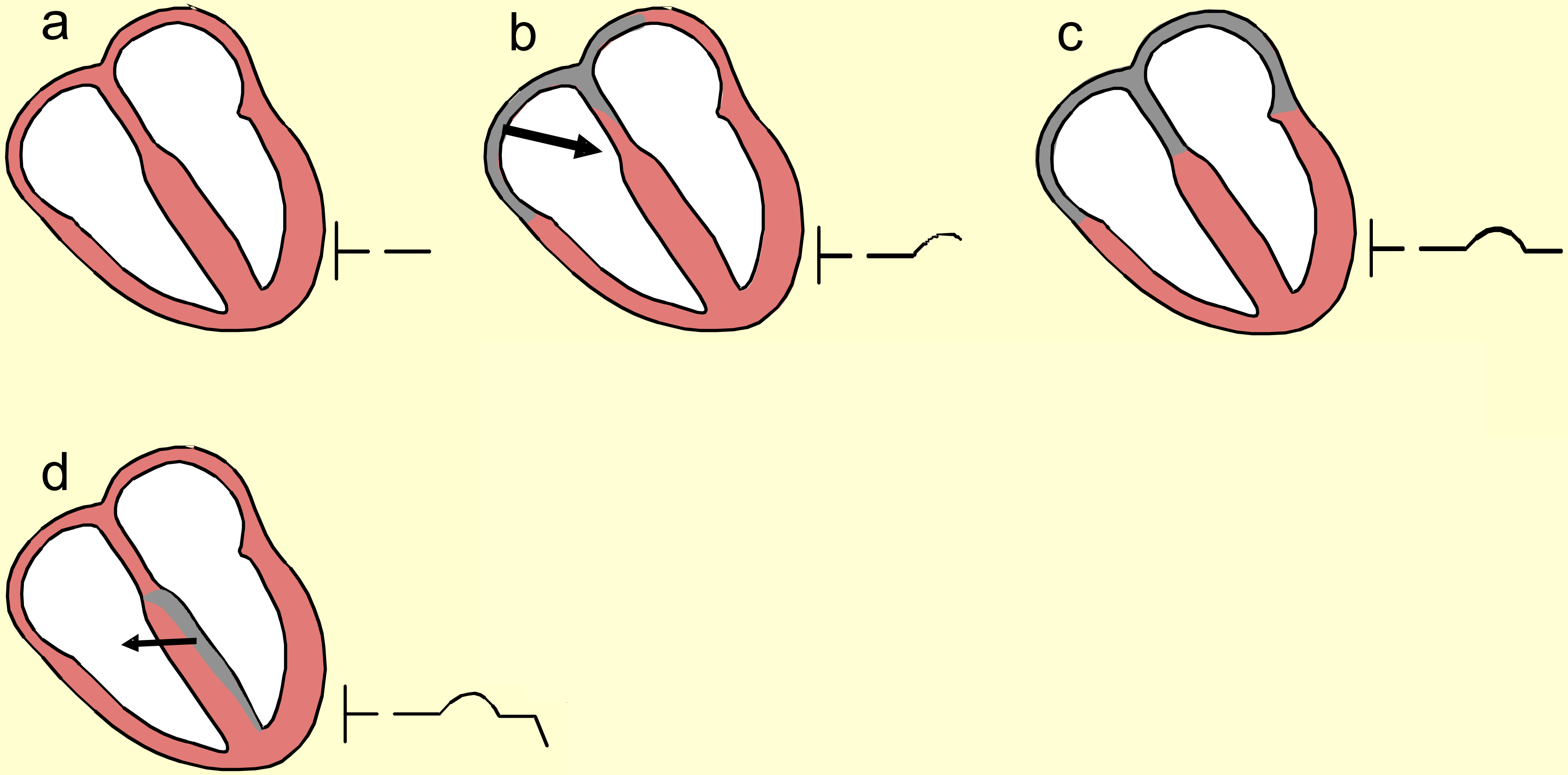
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape



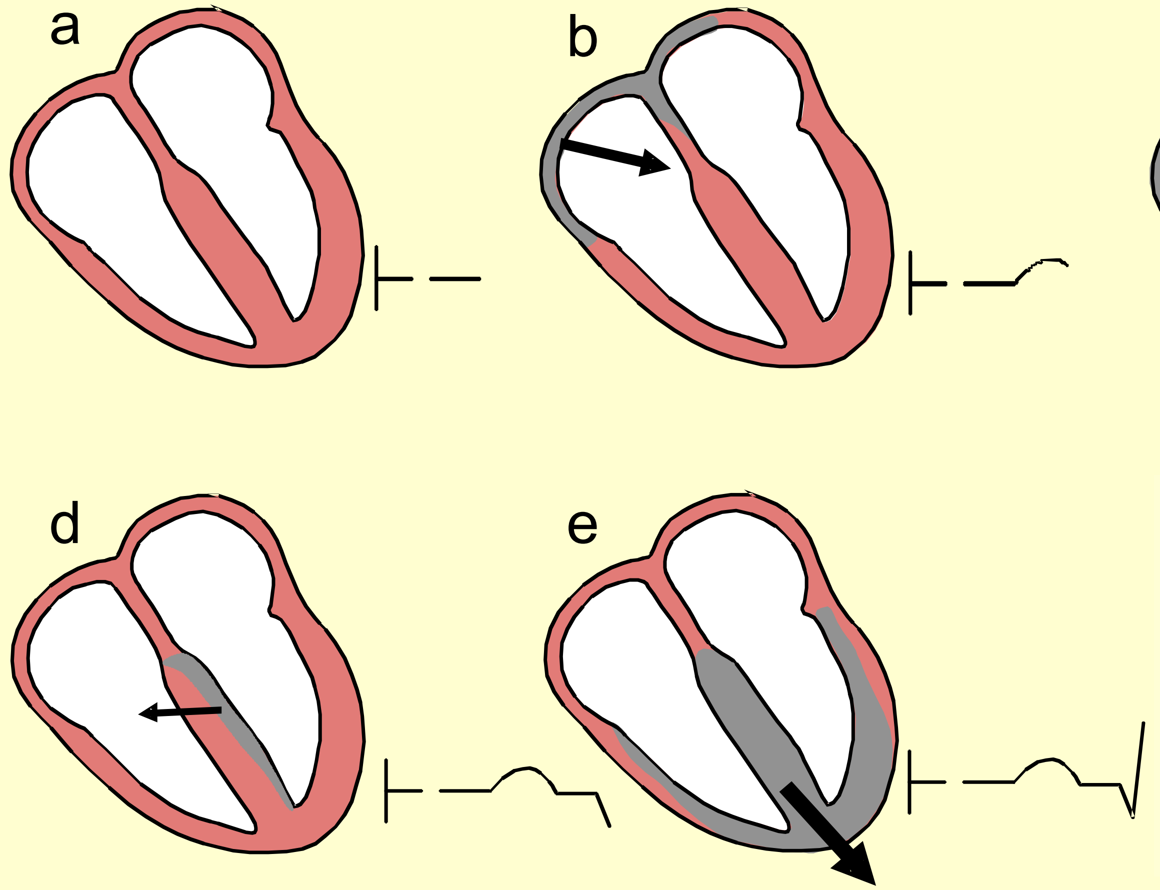
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape



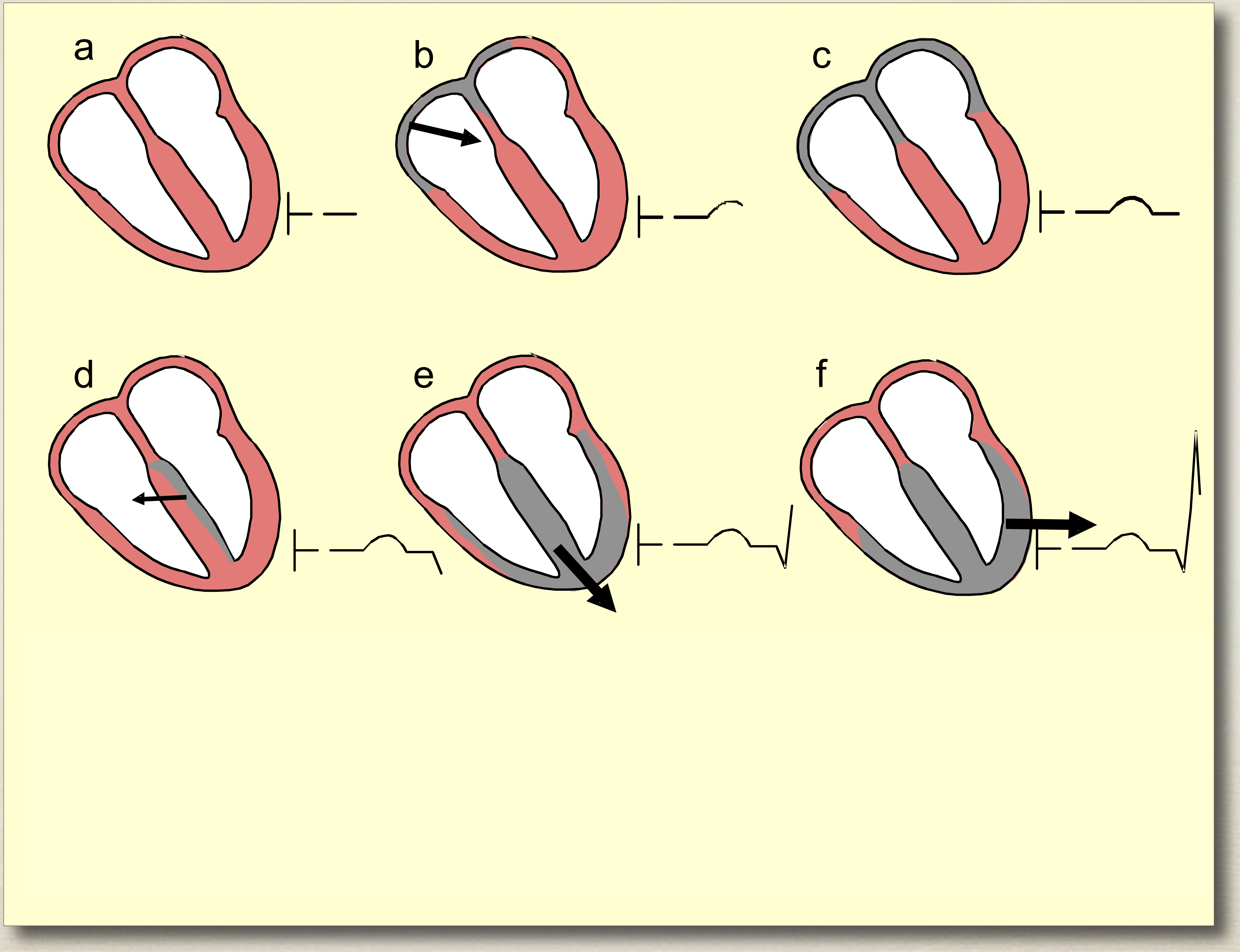
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape



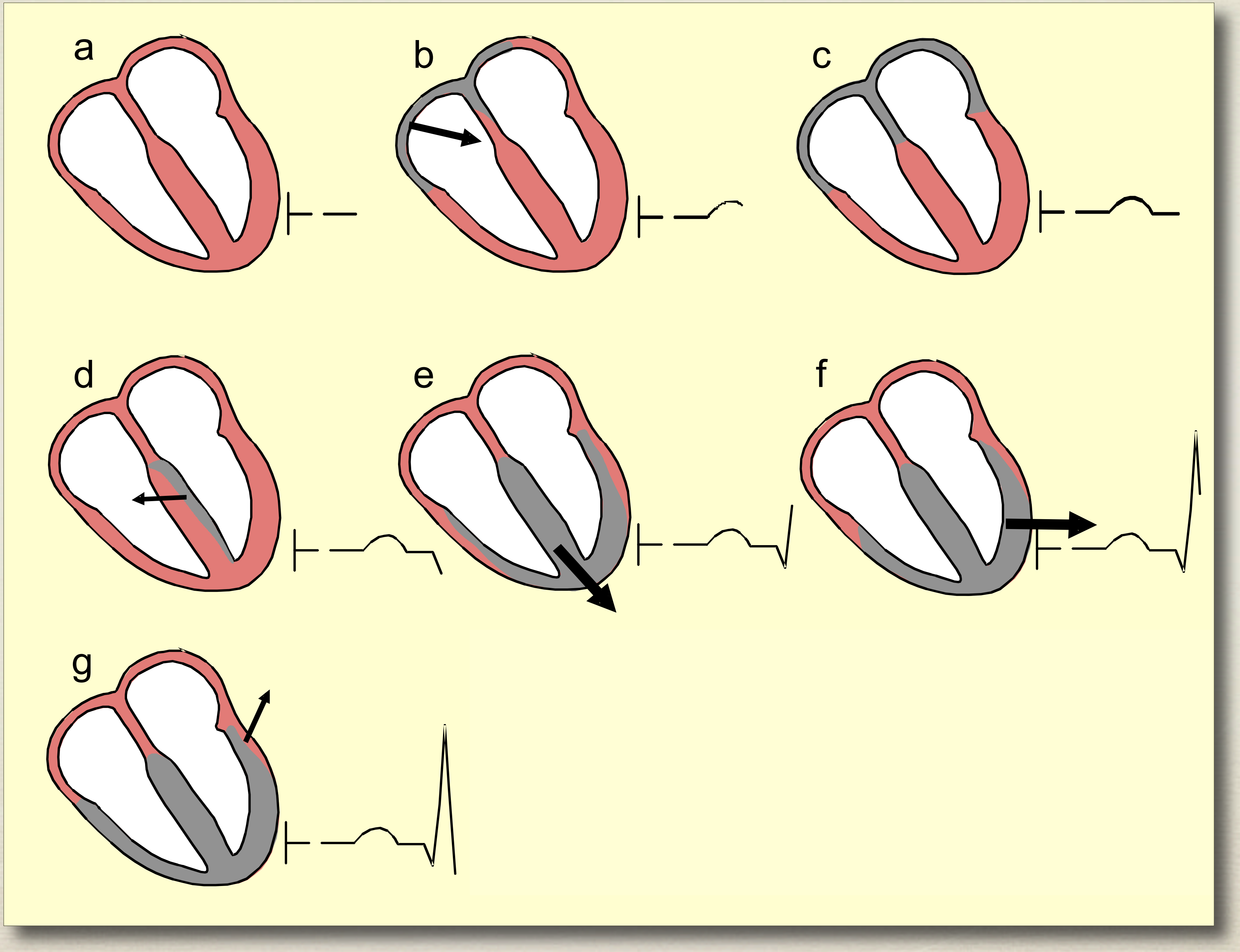
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape



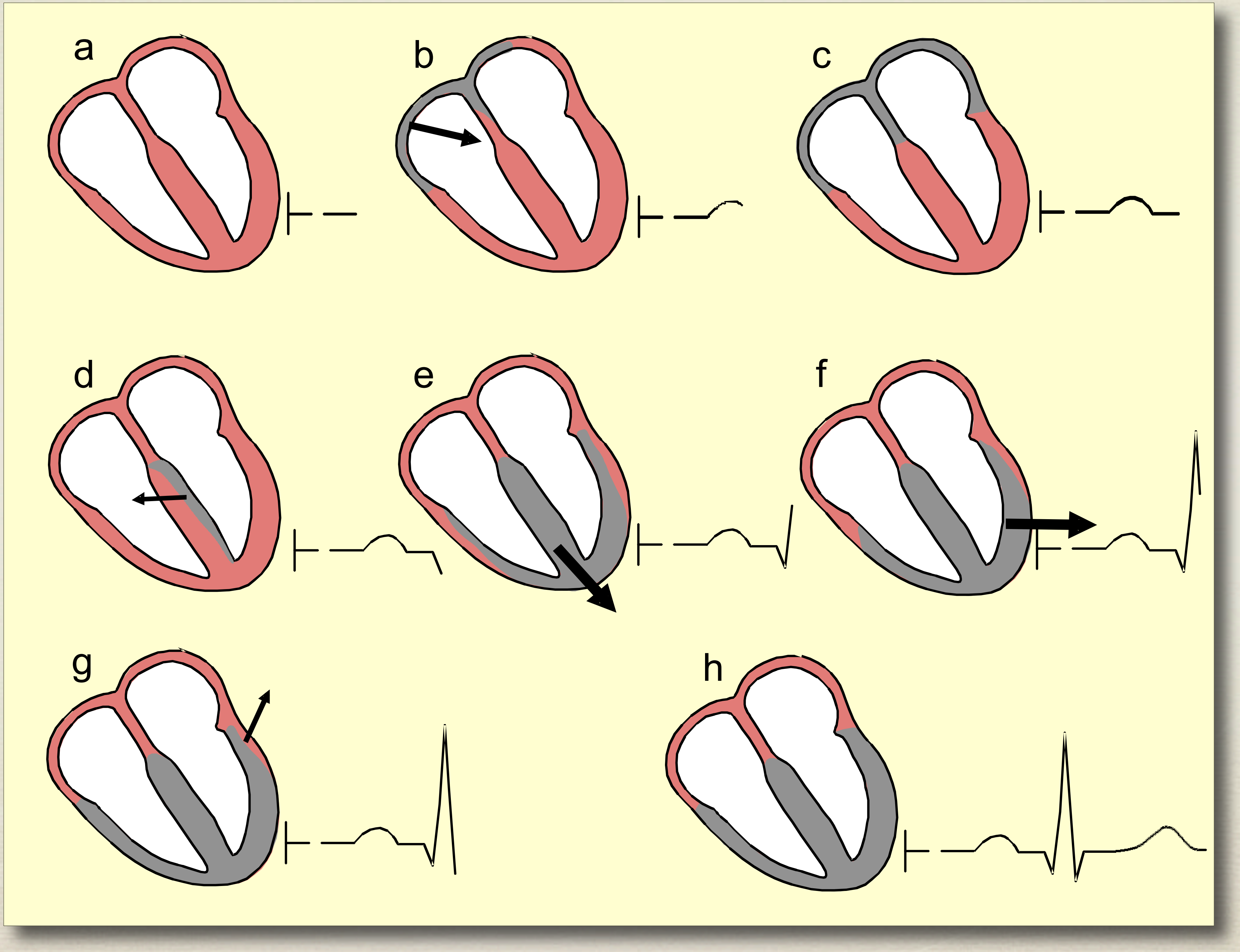
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape



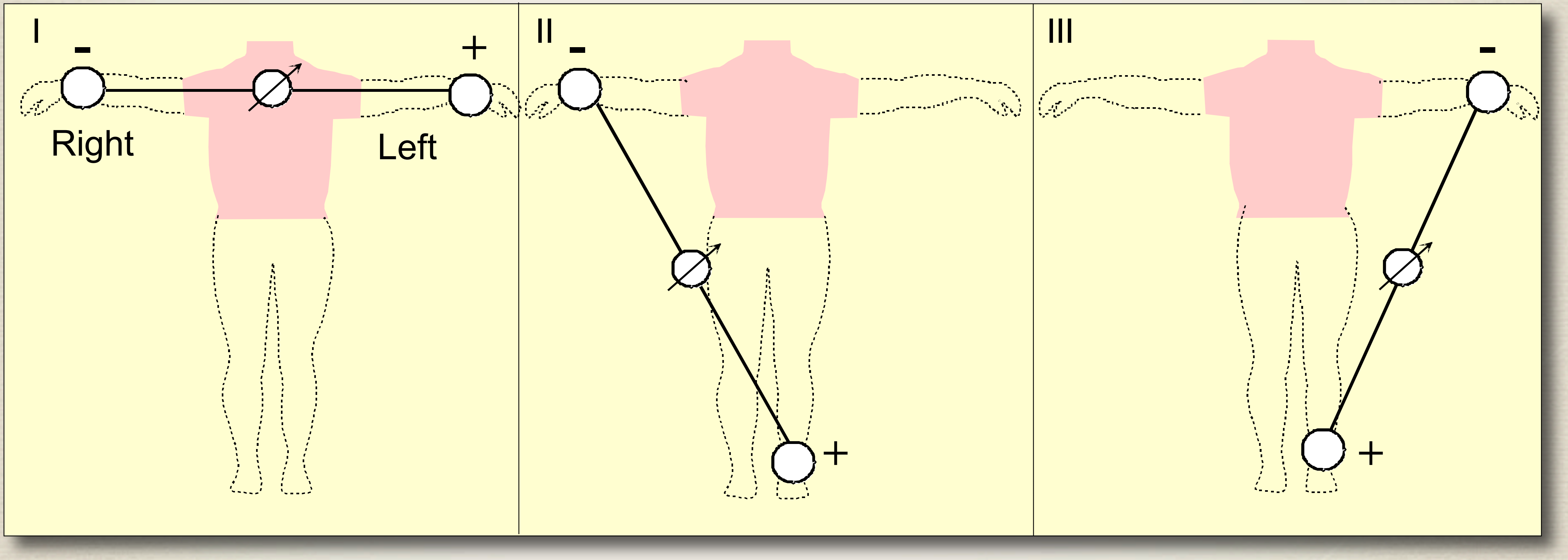
lead V5 "views" outer left ventricle

The Cardiac Cycle & Wave Shape

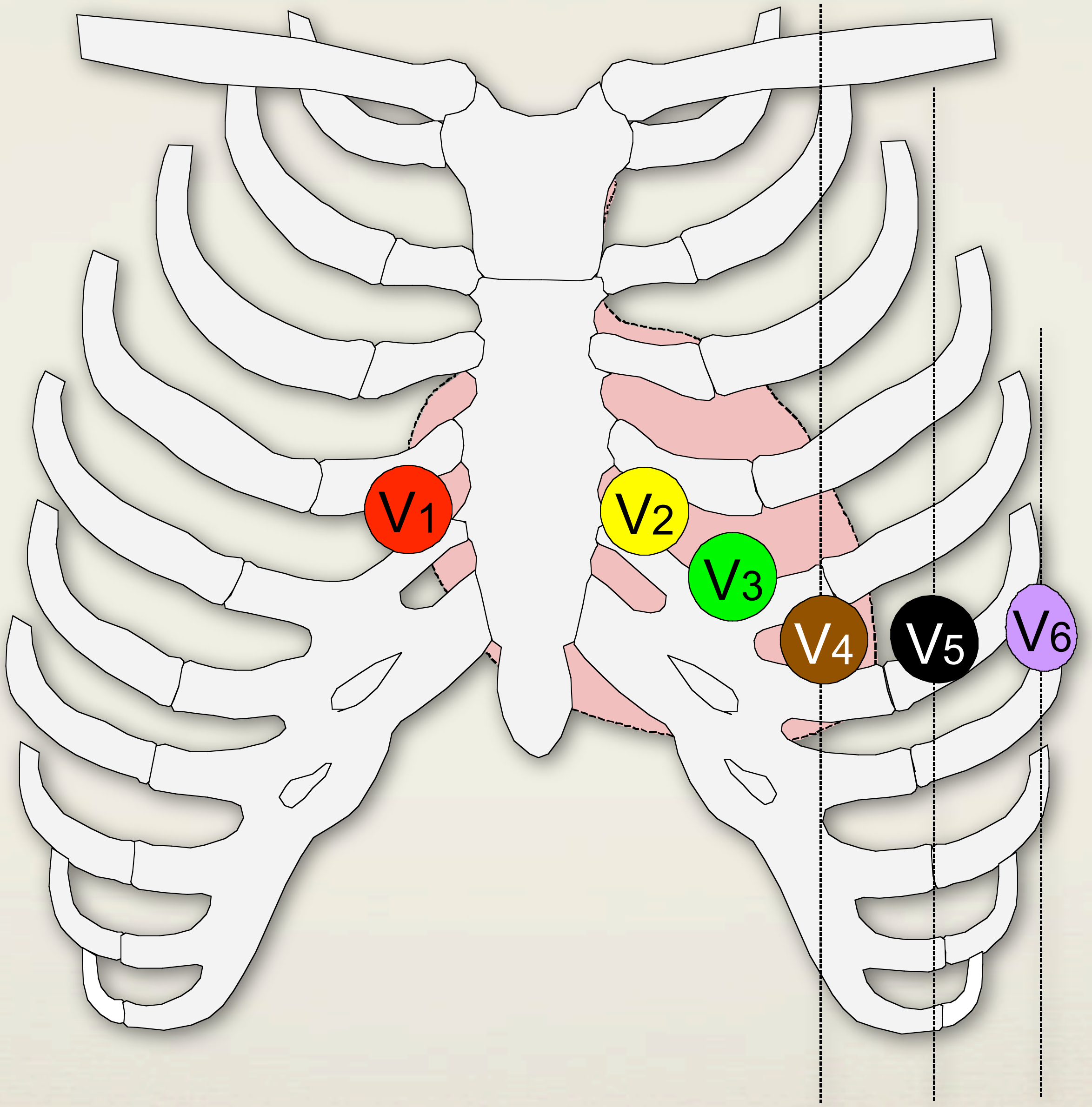


lead V5 "views" outer left ventricle

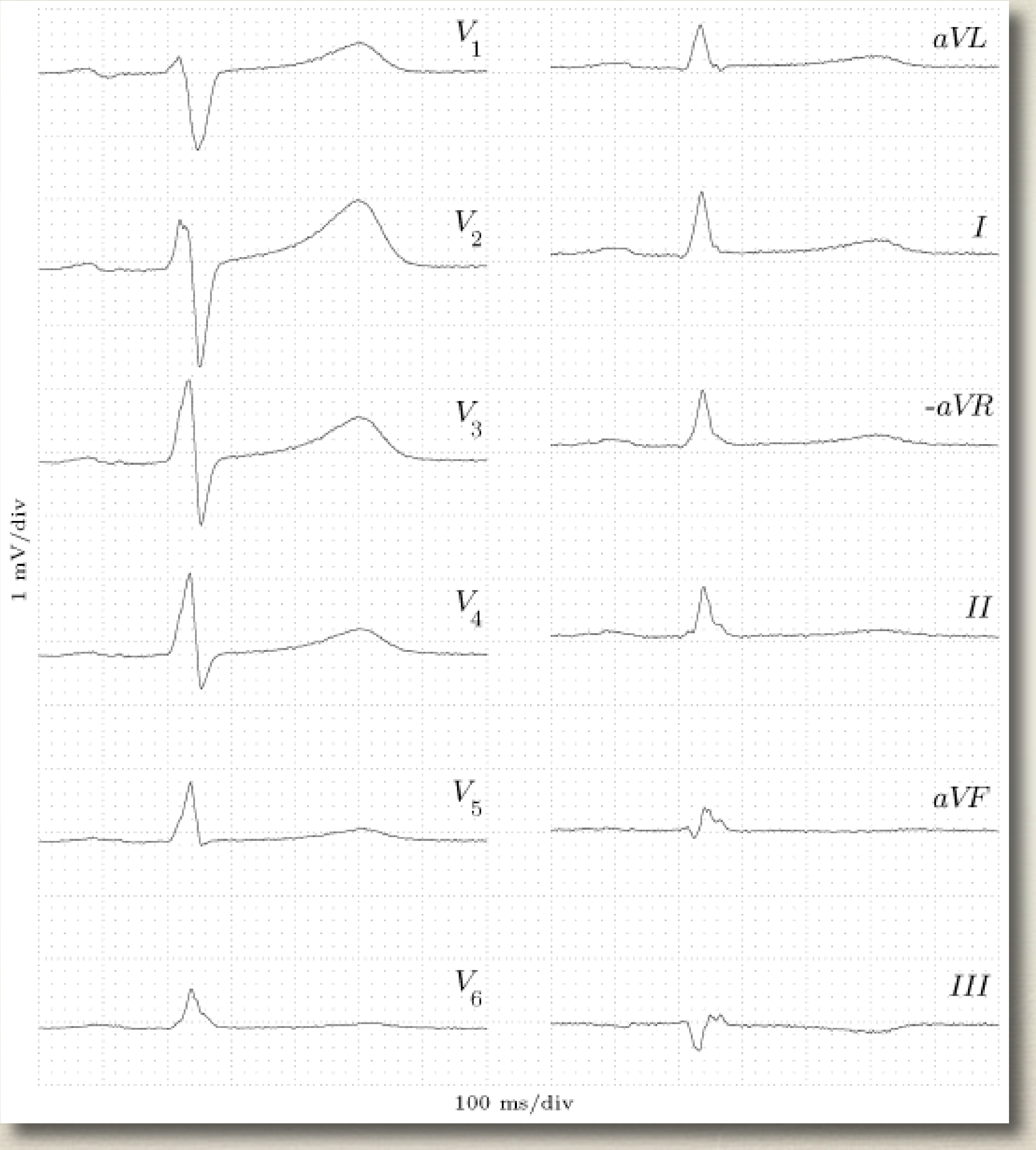
Extremity Leads – I, II, III



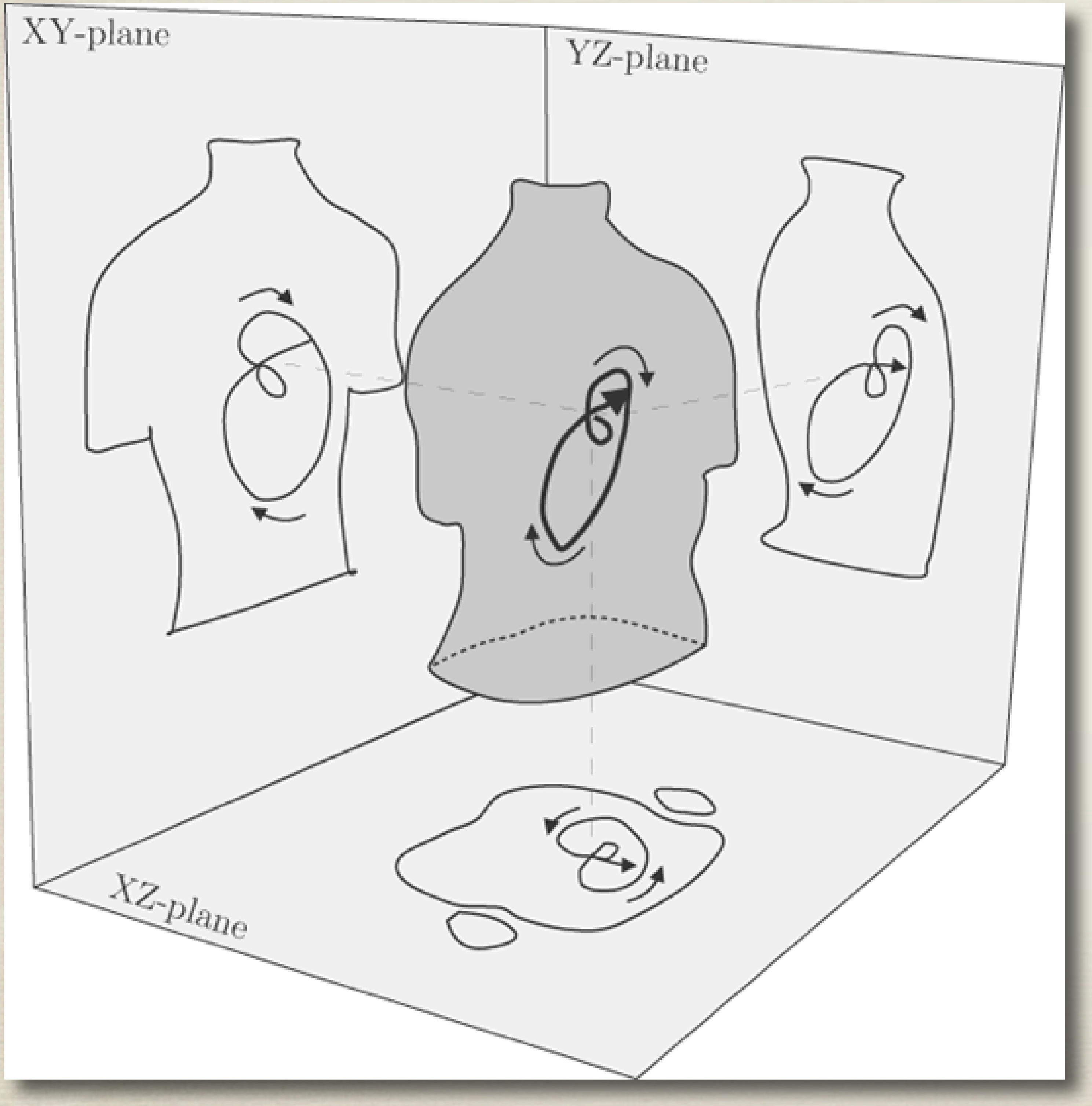
Precordial Leads – V_1 to V_6

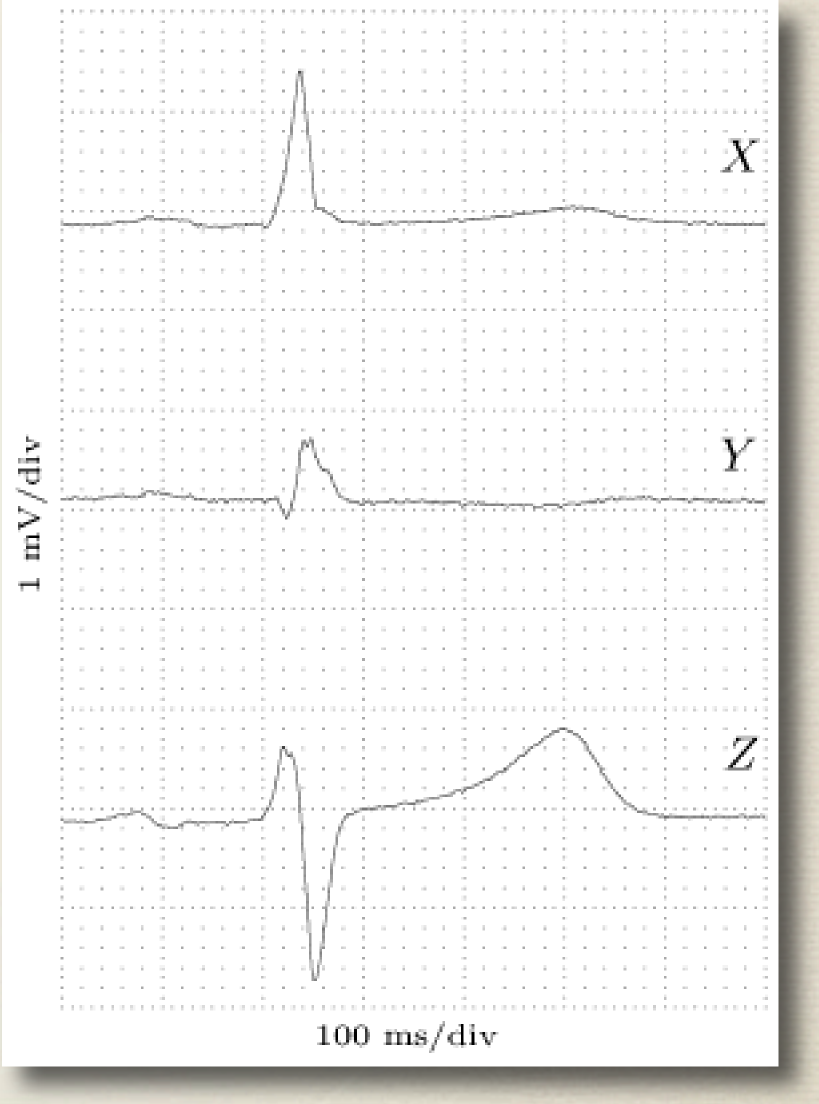


The Standard 12-lead ECG

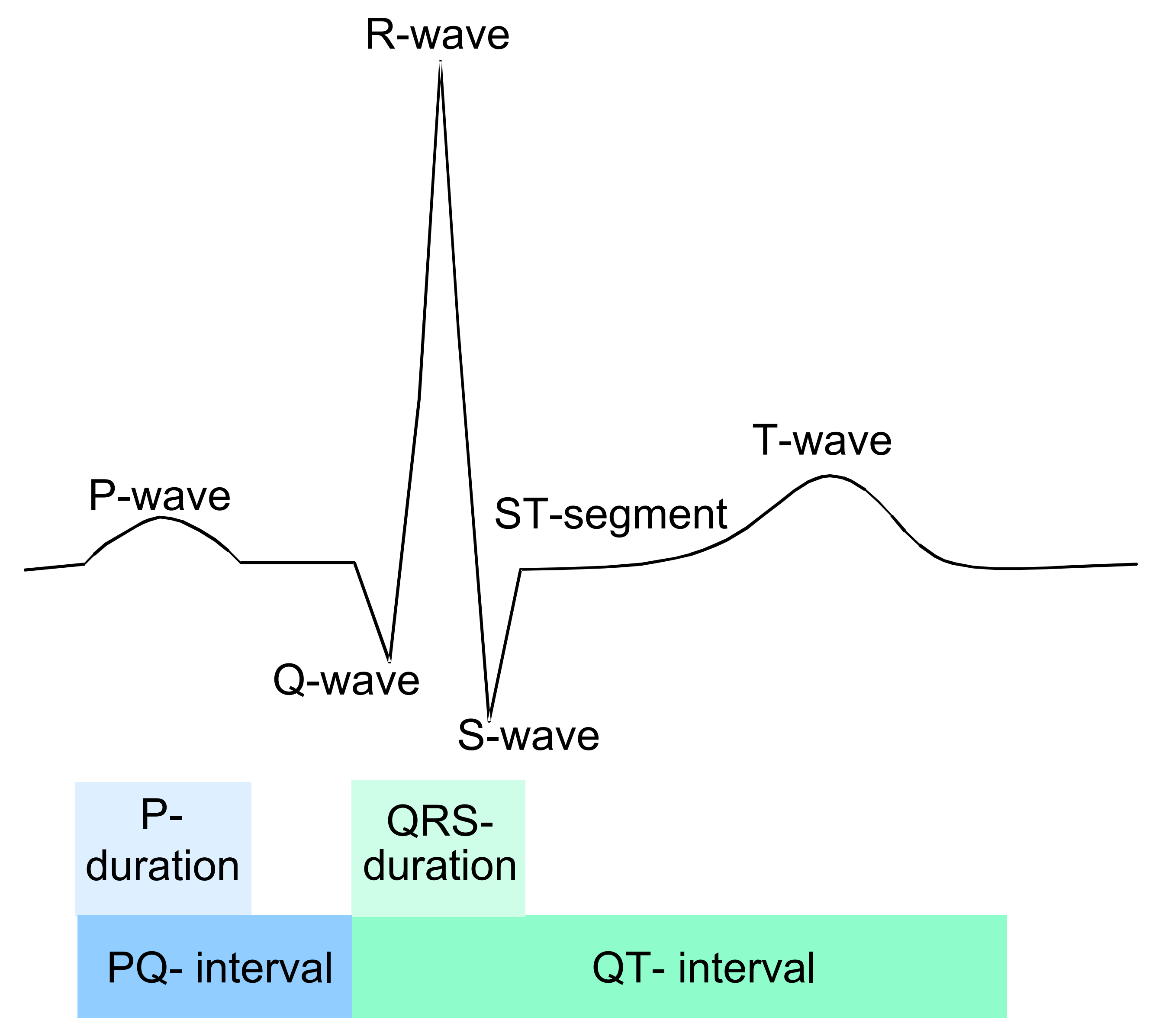


The Vectorcardiogram (VCG)



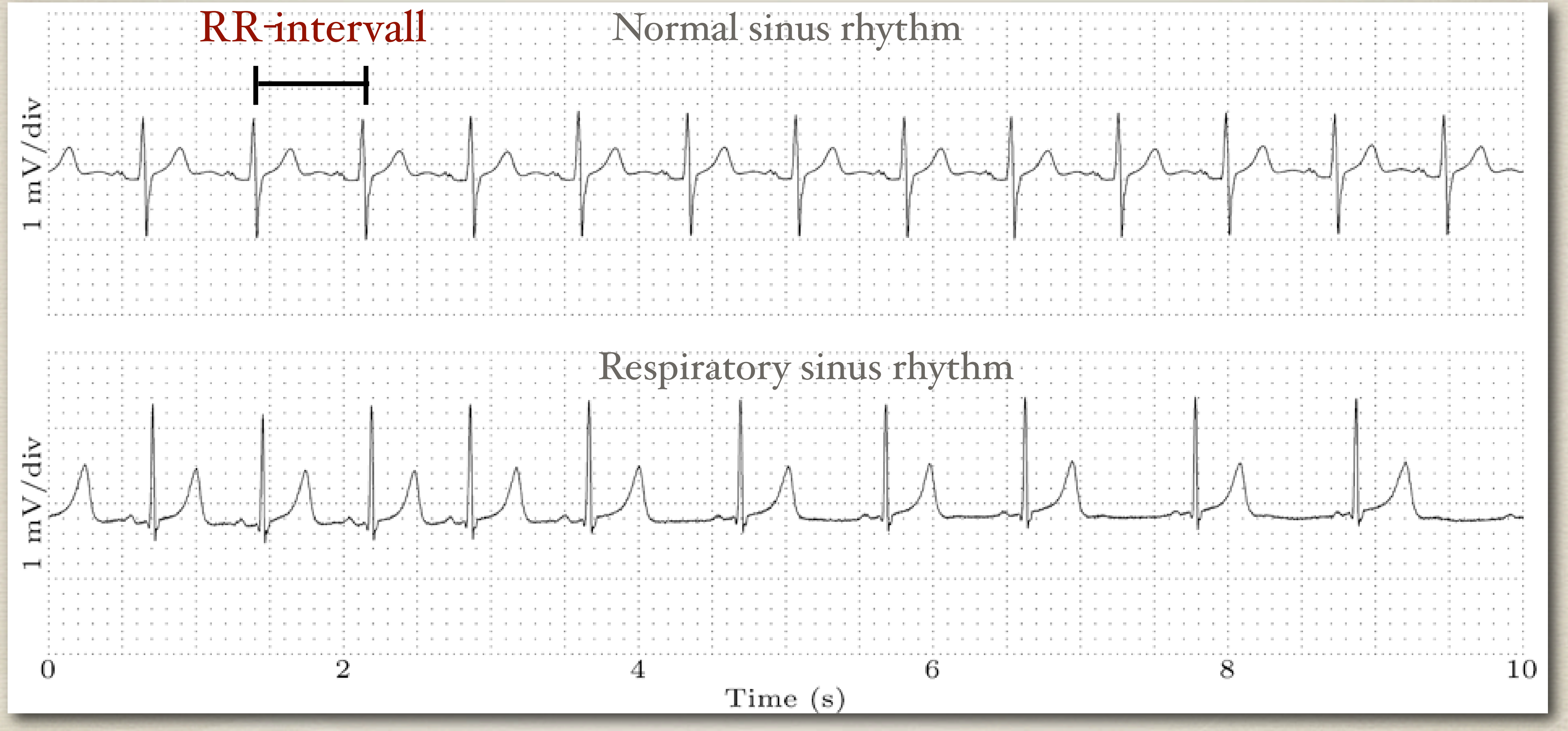


ECG Waves: P-QRS-T

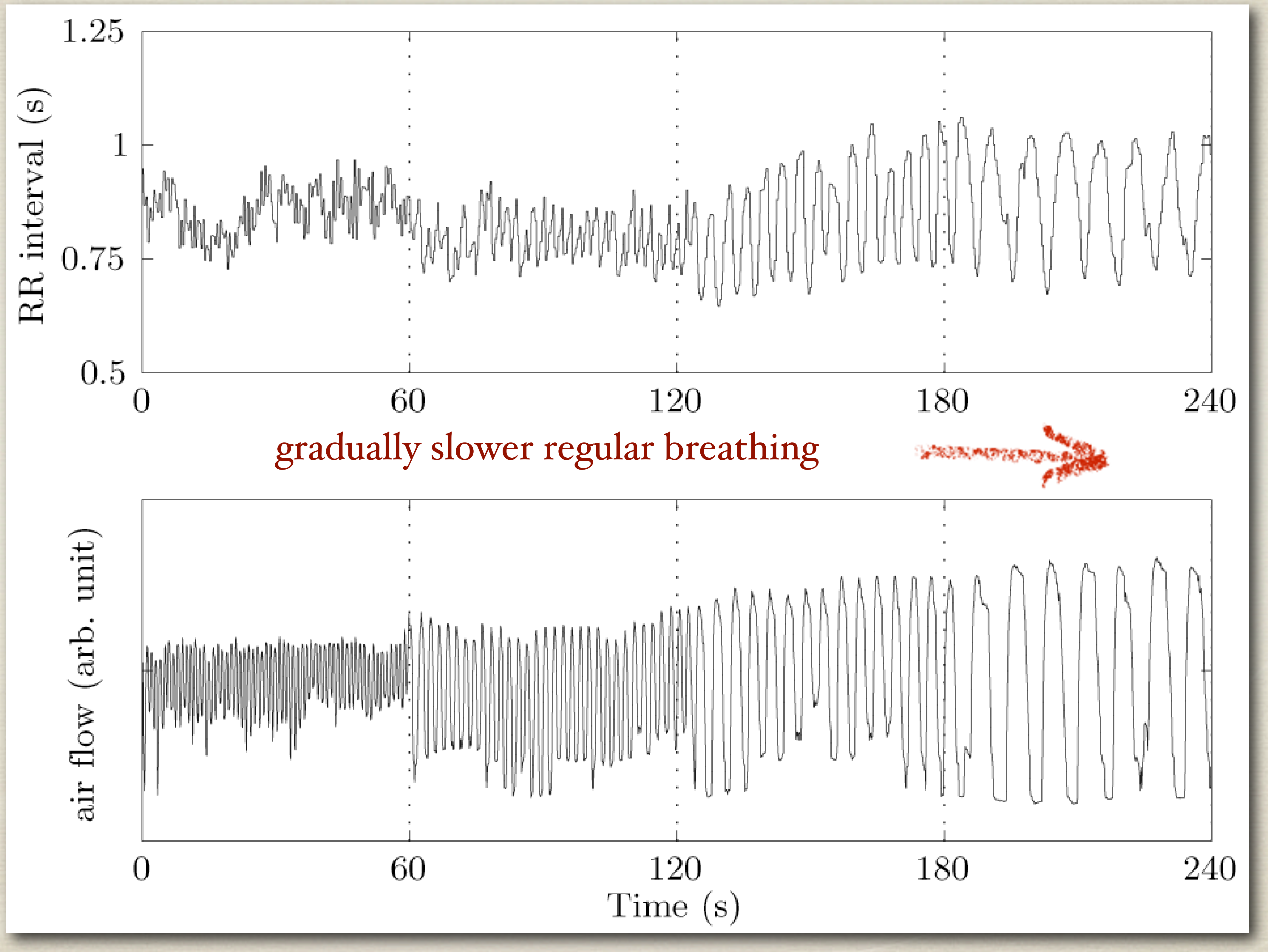


ECG normality is related to PQRST amplitudes and durations

Normal Sinus Rhythms



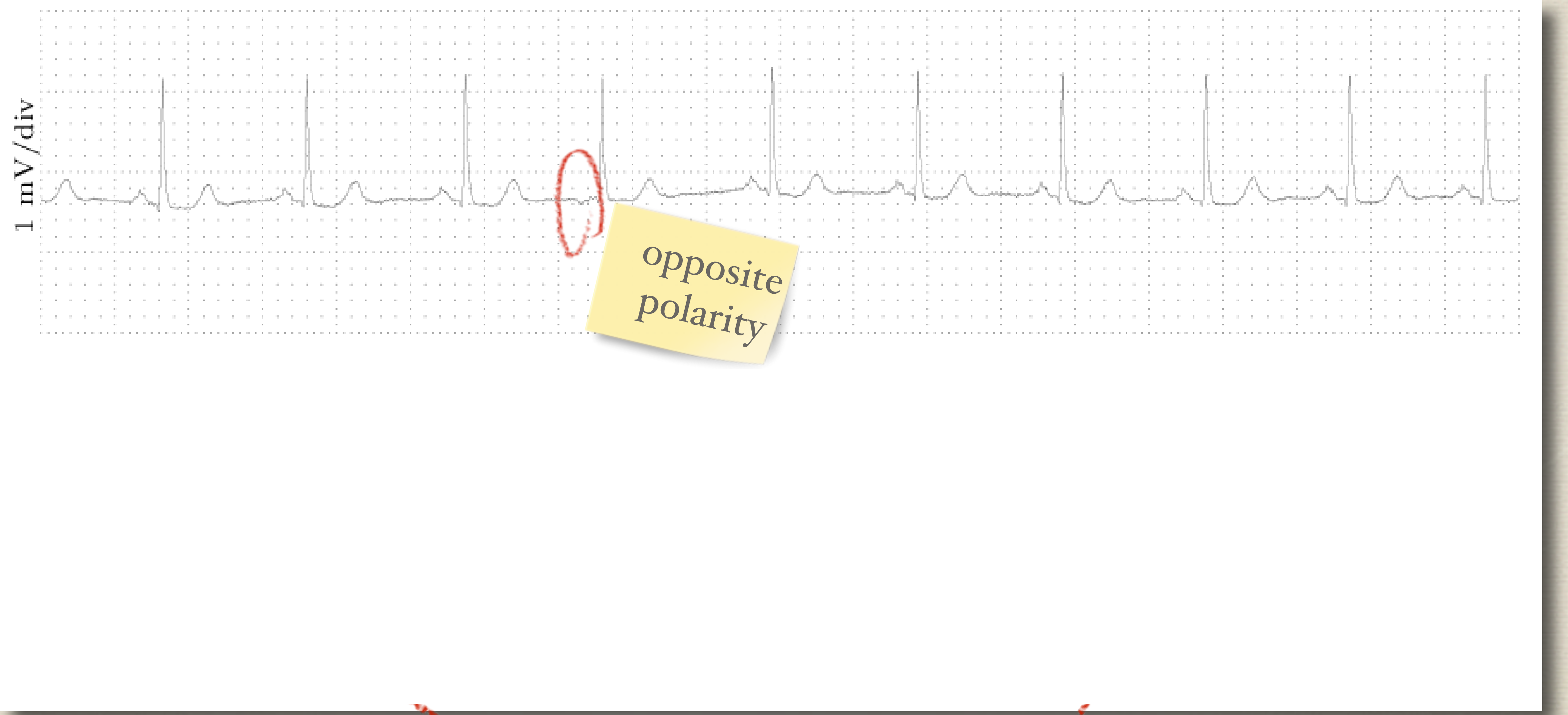
Heart Rate Variability



gradually slower regular breathing

Arrhythmias: Ectopic Beats

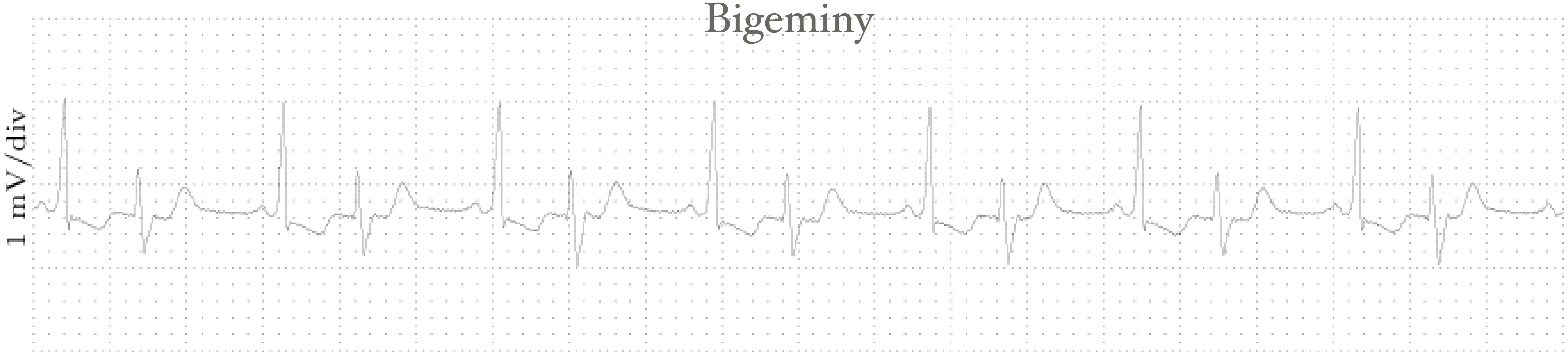
Supraventricular ectopic beat



opposite polarity

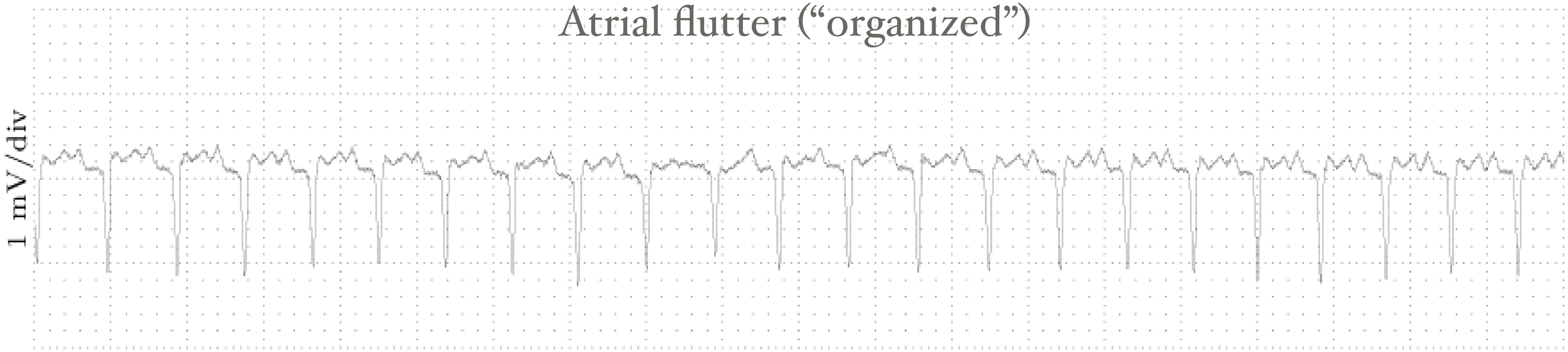
Ventricular ectopic beats

Arrhythmias: Bi- & Trigeminy

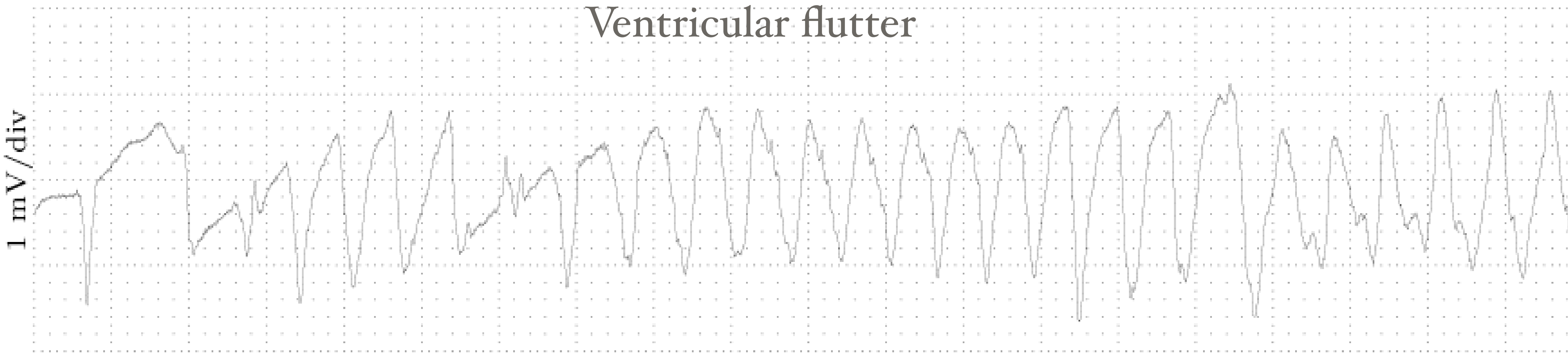


Arrhythmias:
Atrial Flutter/Fibrillation

Atrial flutter (“organized”)



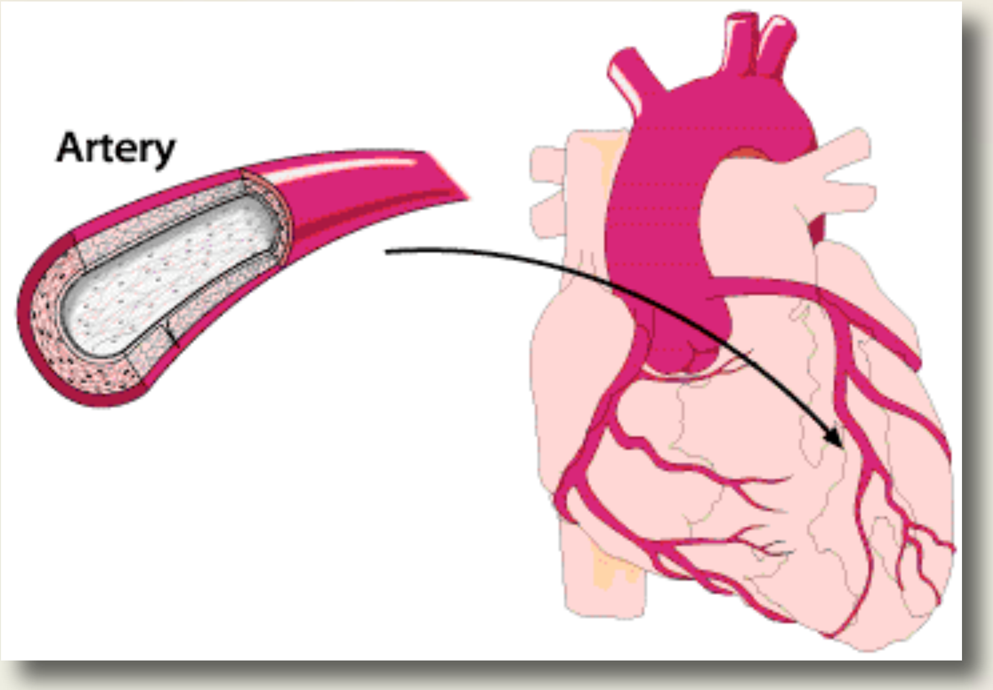
Arrhythmias: Ventricular Flutter/Fibrillation



Heart Attack (Myocardial Infarction)

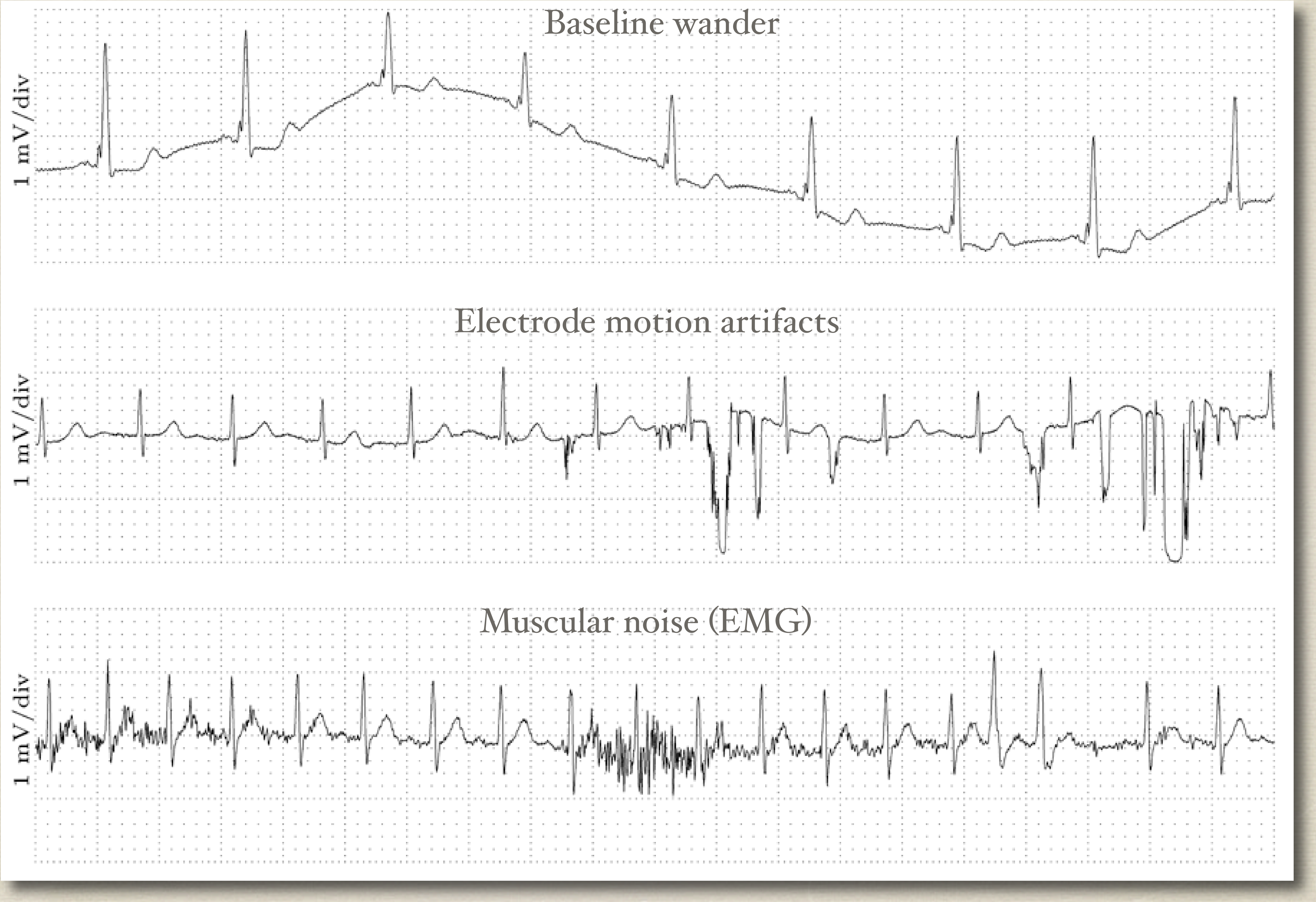
Infarction: tissue of the heart wall (myocardium) which has died

Myocardial Ischemia



Ischemia: insufficient supply of oxygenated blood to the heart.

Noise in the ECG



Baseline wander

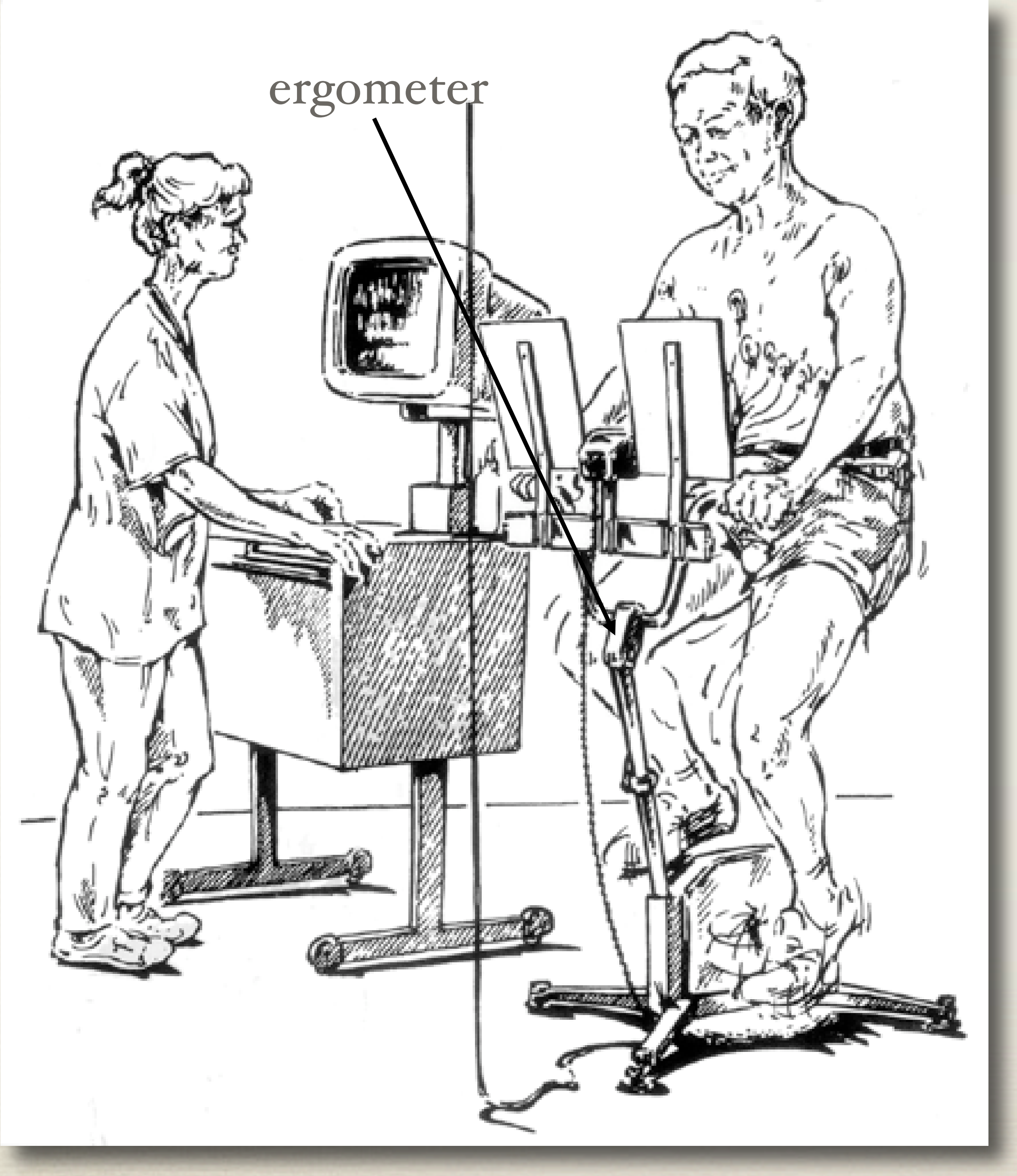
Electrode motion artifacts

Muscular noise (EMG)

Clinical ECG Applications

- Resting ECG
- Intensive care monitoring
- Ambulatory monitoring
- Exercise stress test
- High-resolution ECG
- Defibrillation

The Exercise Stress Test



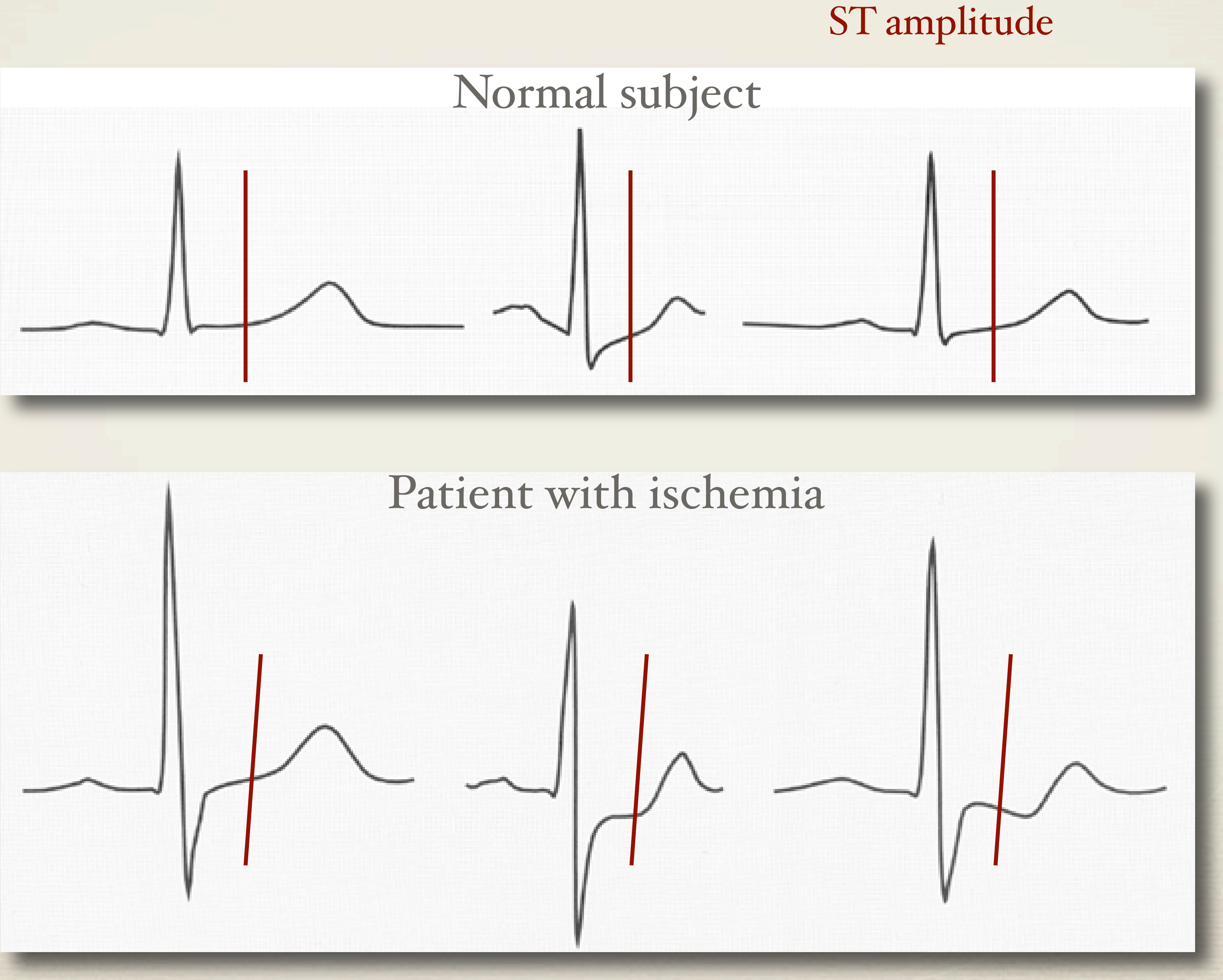
Exercise usually starts at a low workload.

The load is thereafter increased progressively.

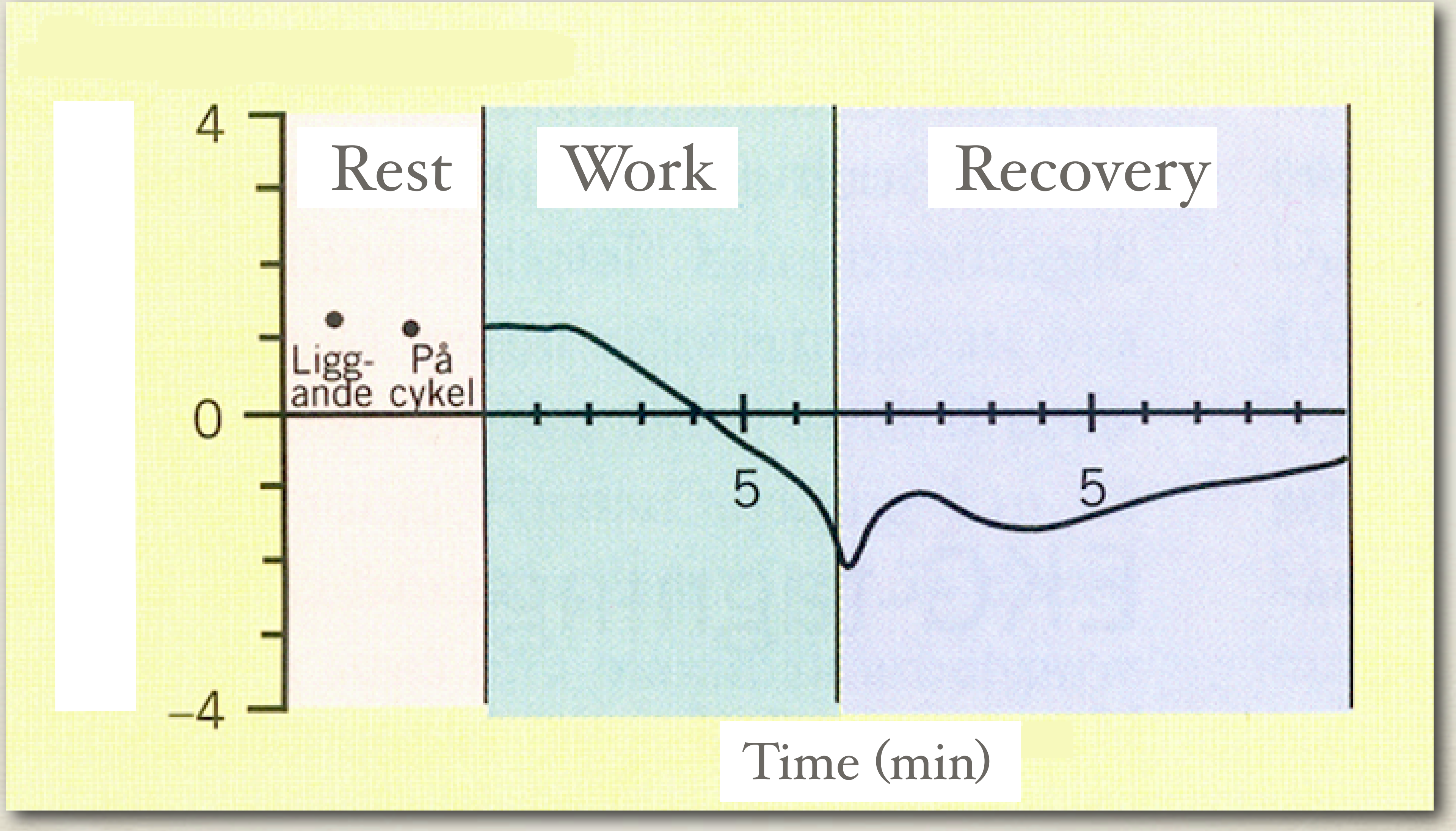
Exercise is terminated when the patient experiences fatigue or chest pain.

To be fighted: EMG noise and baseline wander

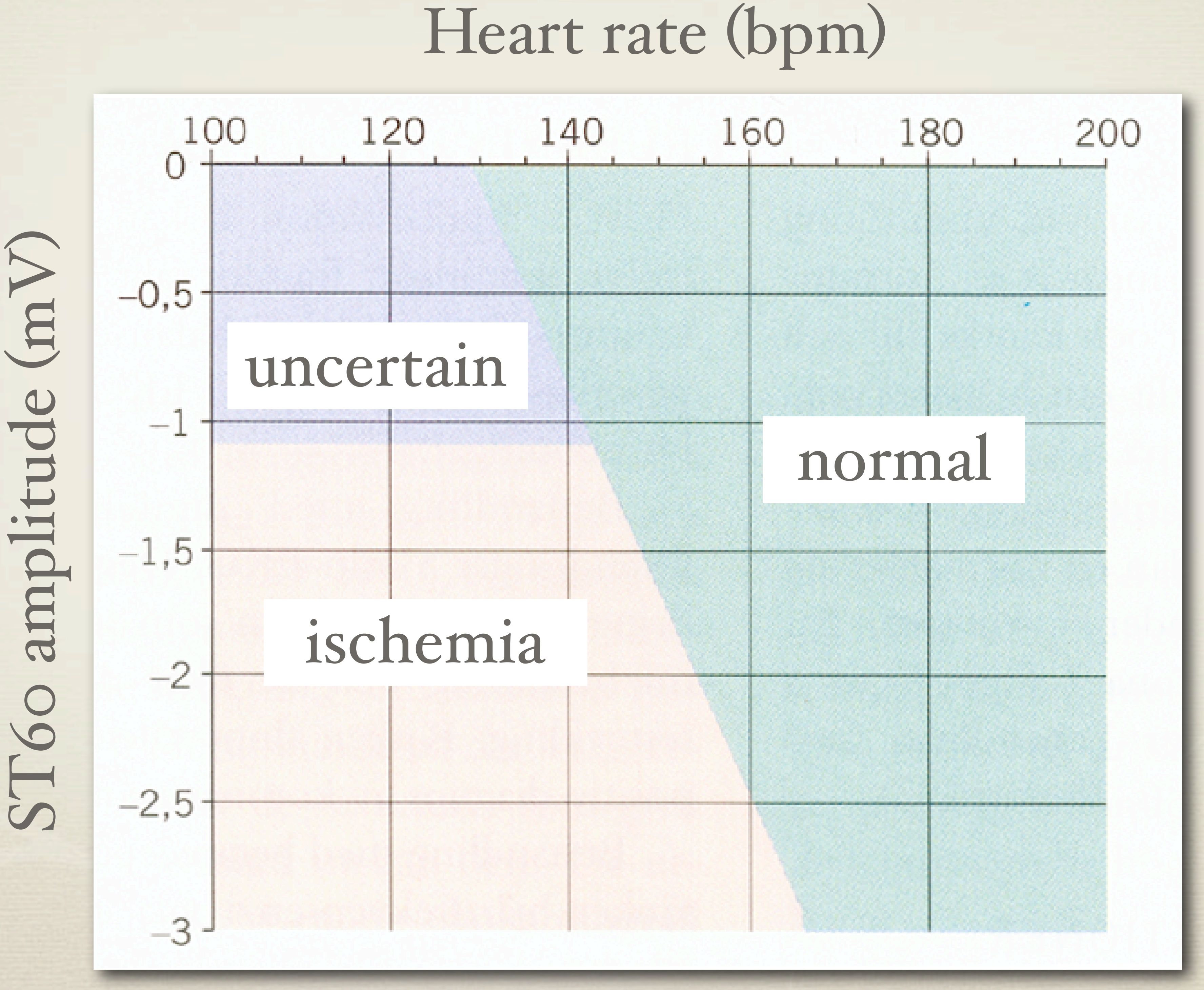
Stress Testing and Ischemia – ECG Reaction



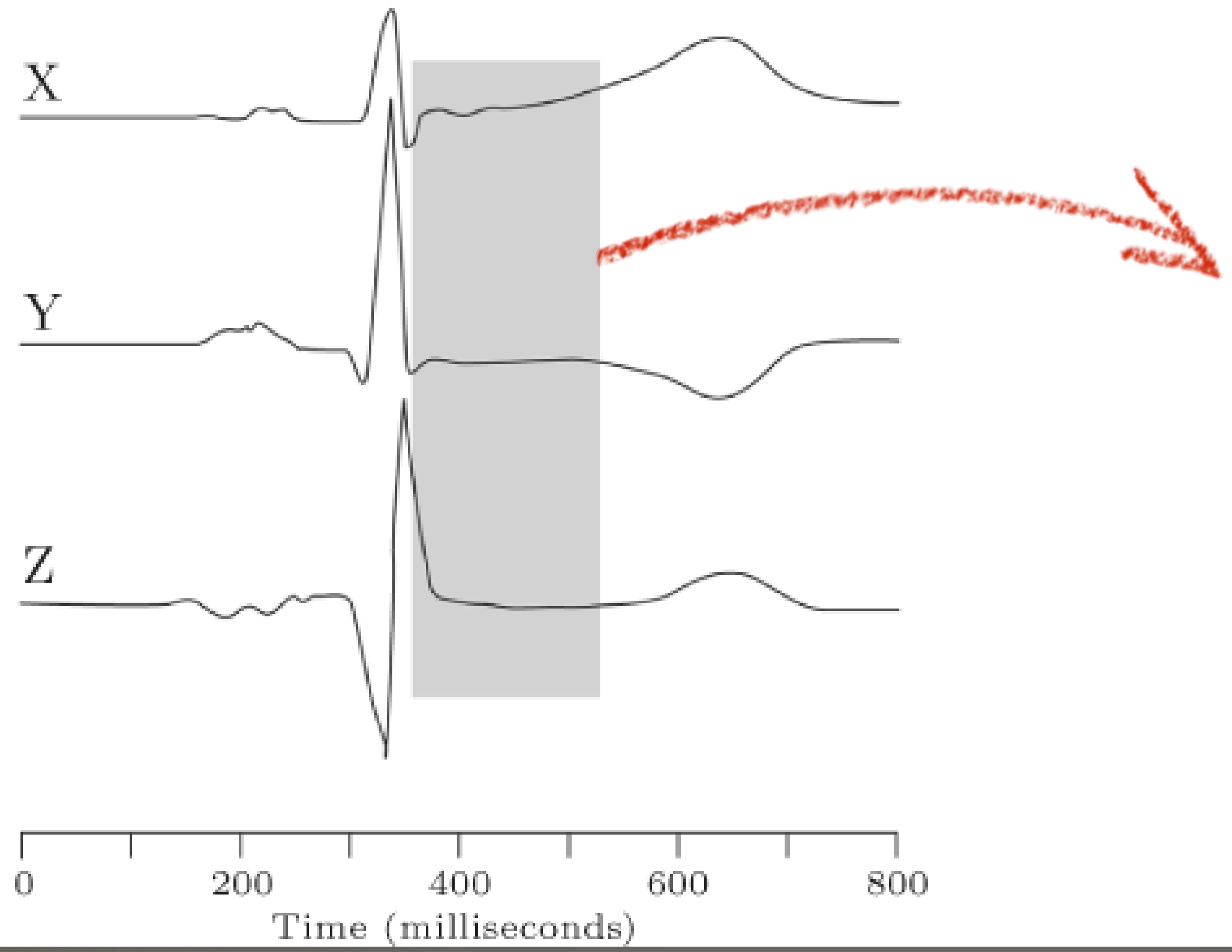
Stress Testing and Ischemia – ECG Reaction



ST Reaction Versus Heart Rate – Decision Regions

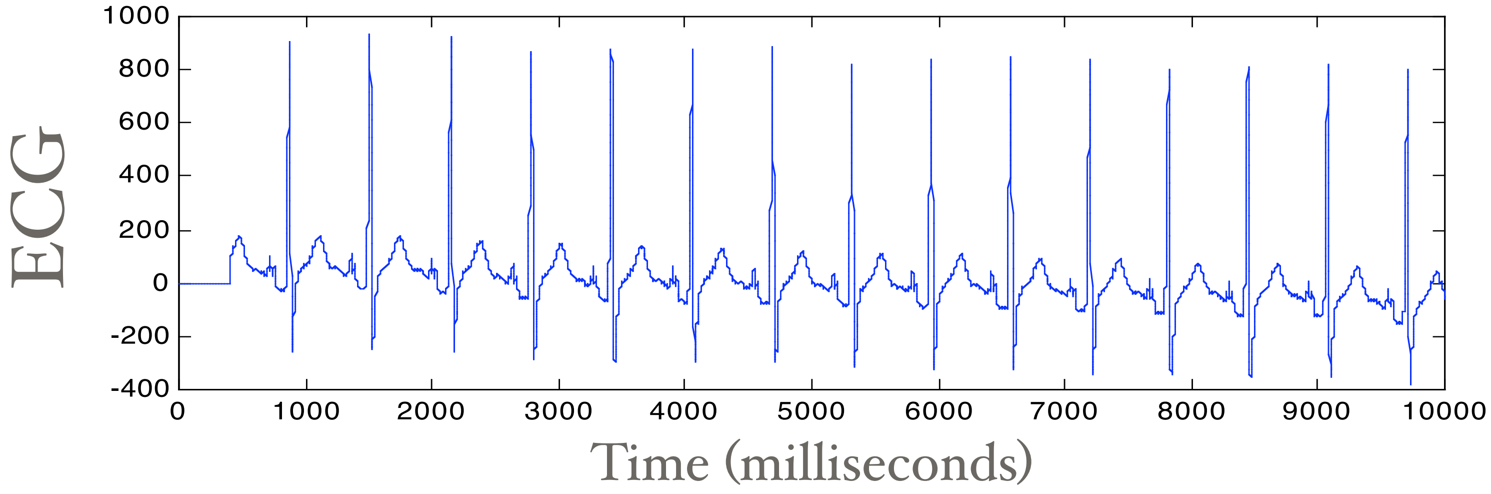


High-Resolution ECG and Cardiac Late Potentials

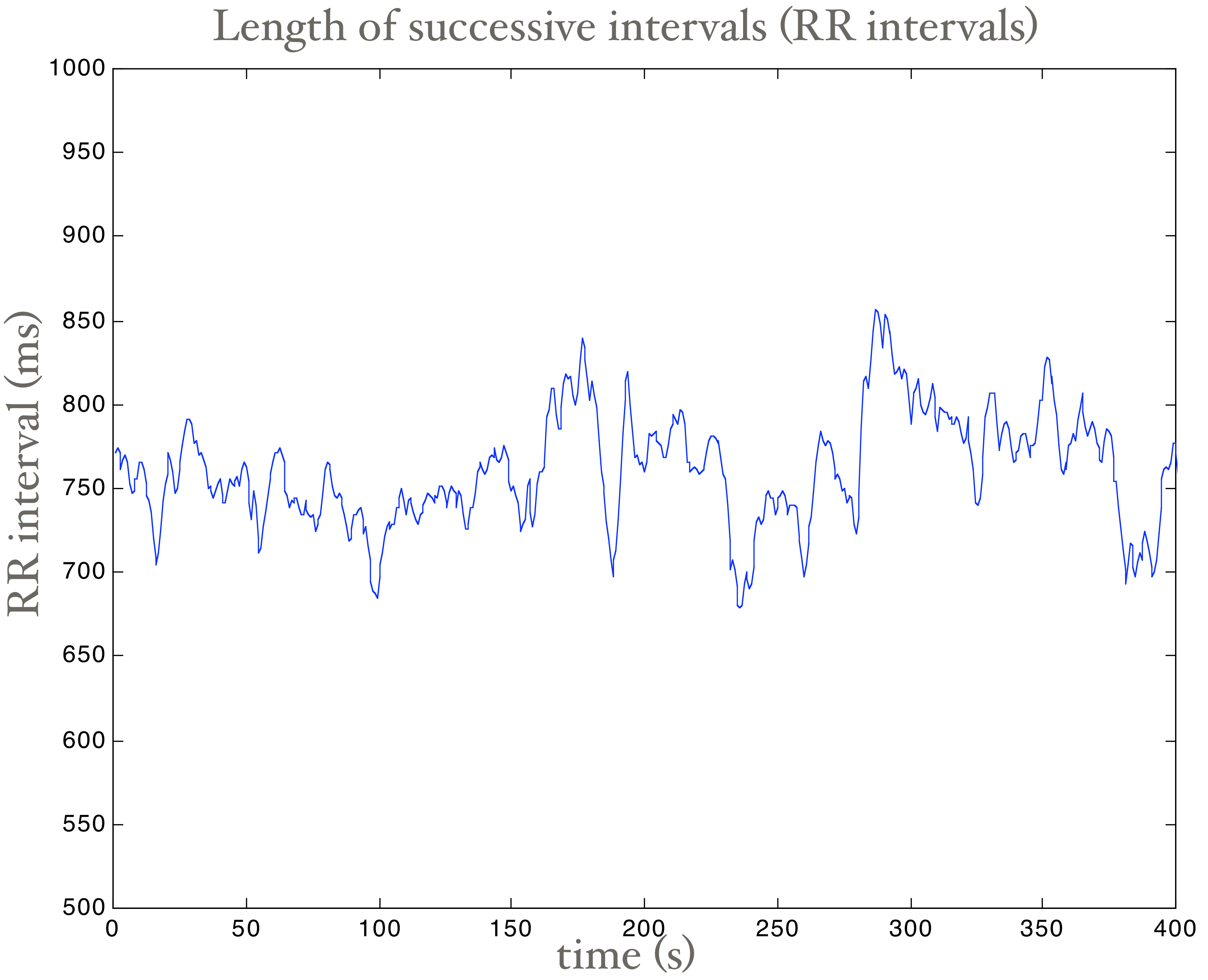


Ensemble averaging made the discovery of late potentials possible. Their presence is a risk factor in patients with heart attack.

Spectral Analysis of the ECG?



Spectral Analysis of Heart Rate?



EEG, EP, and ECG: Time Base?

- EEG analysis resembles that of a ”stochastic process" and has no particular reference time.
- EP analysis starts from a known reference time of each stimulation.
- ECG analysis starts from an estimated reference time of each heart beat.

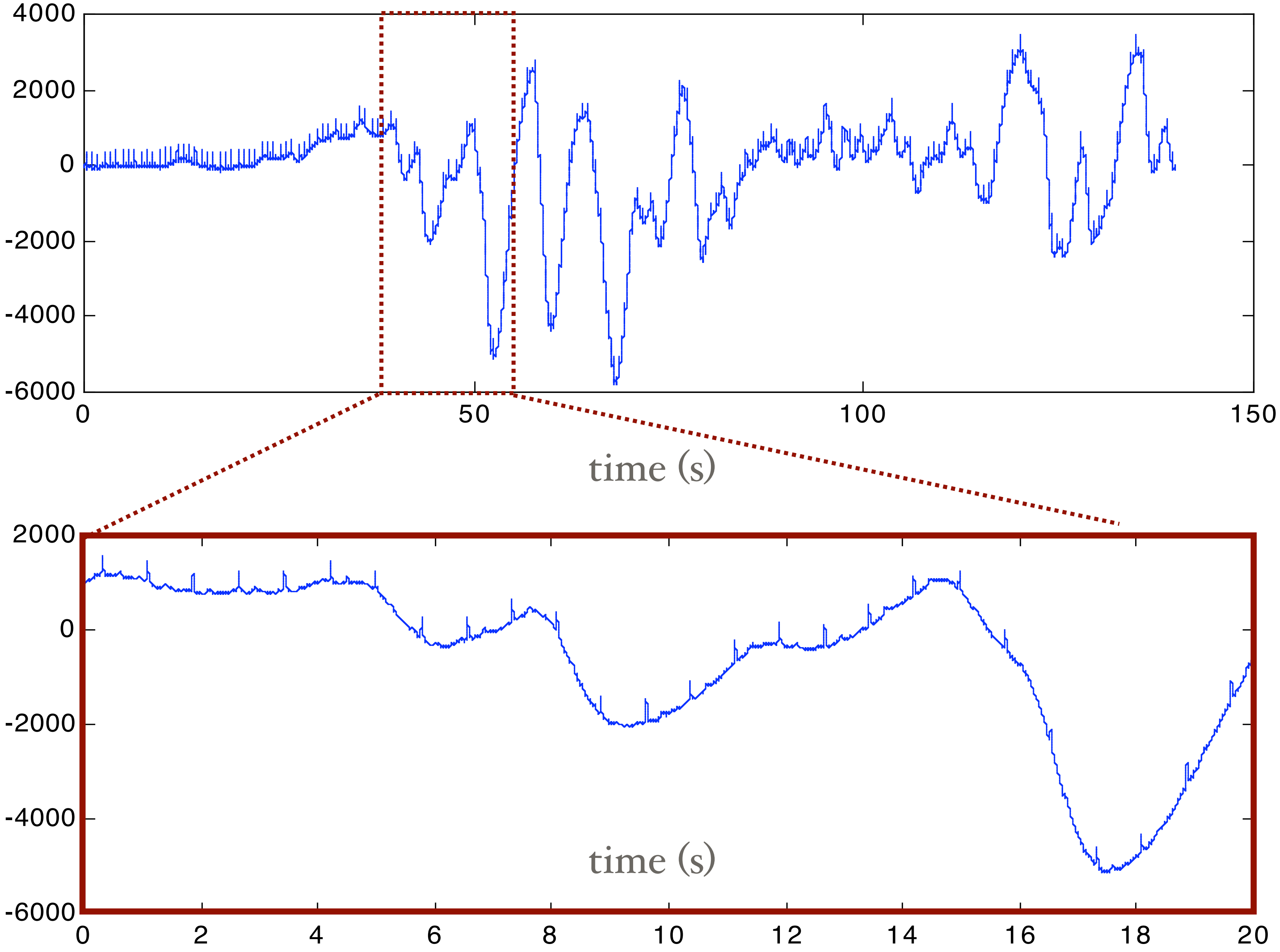
ECG Signal Processing

- Noise and artifact cancellation
- QRS detection
- Data compression
- Classification of QRS complex morphology
- Analysis of heart rate variability
- Detection of micropotentials
- And much more!

ECG Filtering Techniques...

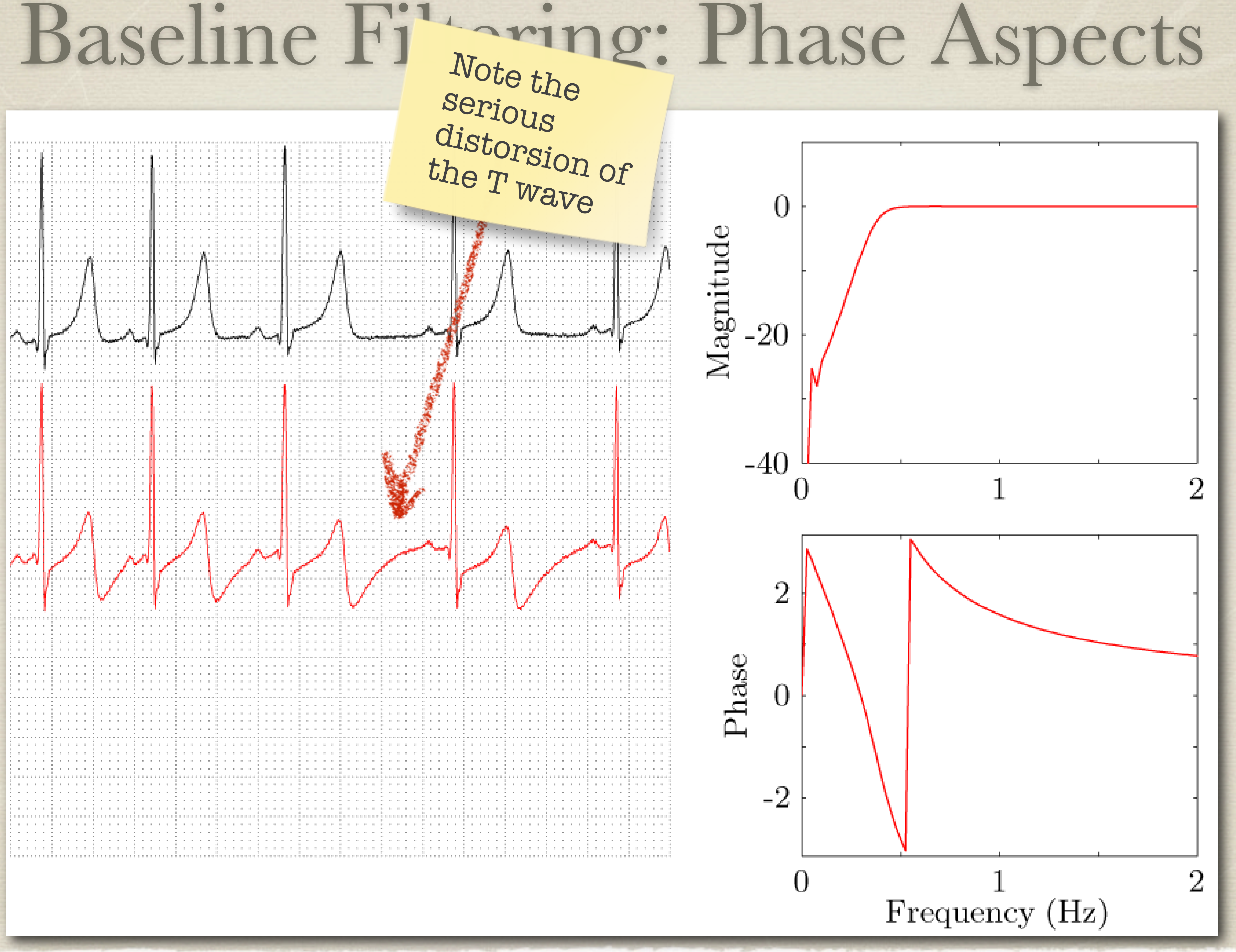
- **Baseline wander** is narrowband activity which is confined to frequencies below 1 Hz.
- **50/60 Hz interference** is common in environments with electrical devices. Shielded recording equipment is important.
- EMG noise overlaps with the spectral content of the ECG, notably the QRS complex.

ECG Baseline Wander

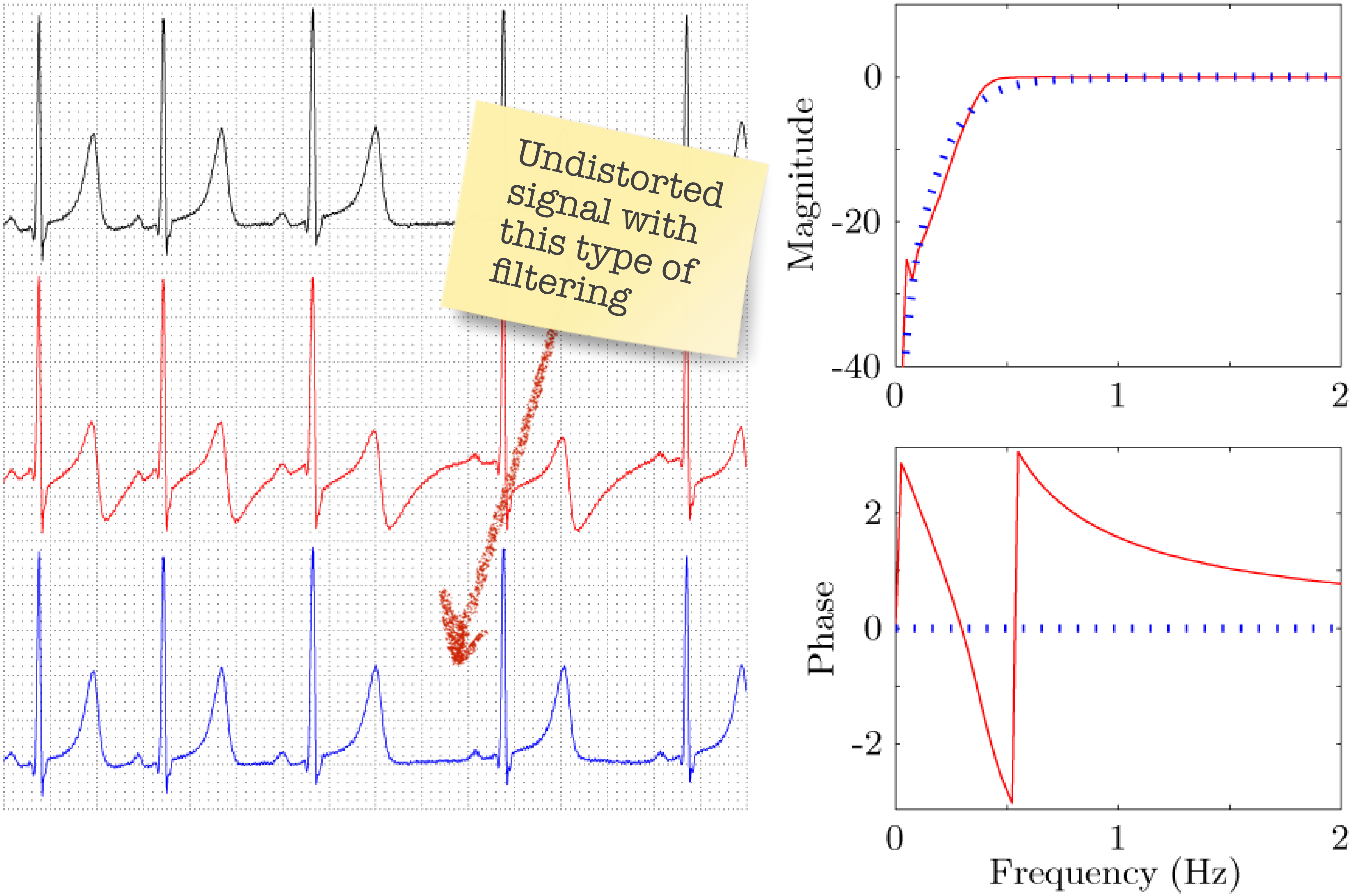


Baseline Filtering: Phase Aspects

Baseline Filtering: Phase Aspects


Note the serious distorsion of the T wave

Baseline Filtering: Phase Aspects



Undistorted signal with this type of filtering

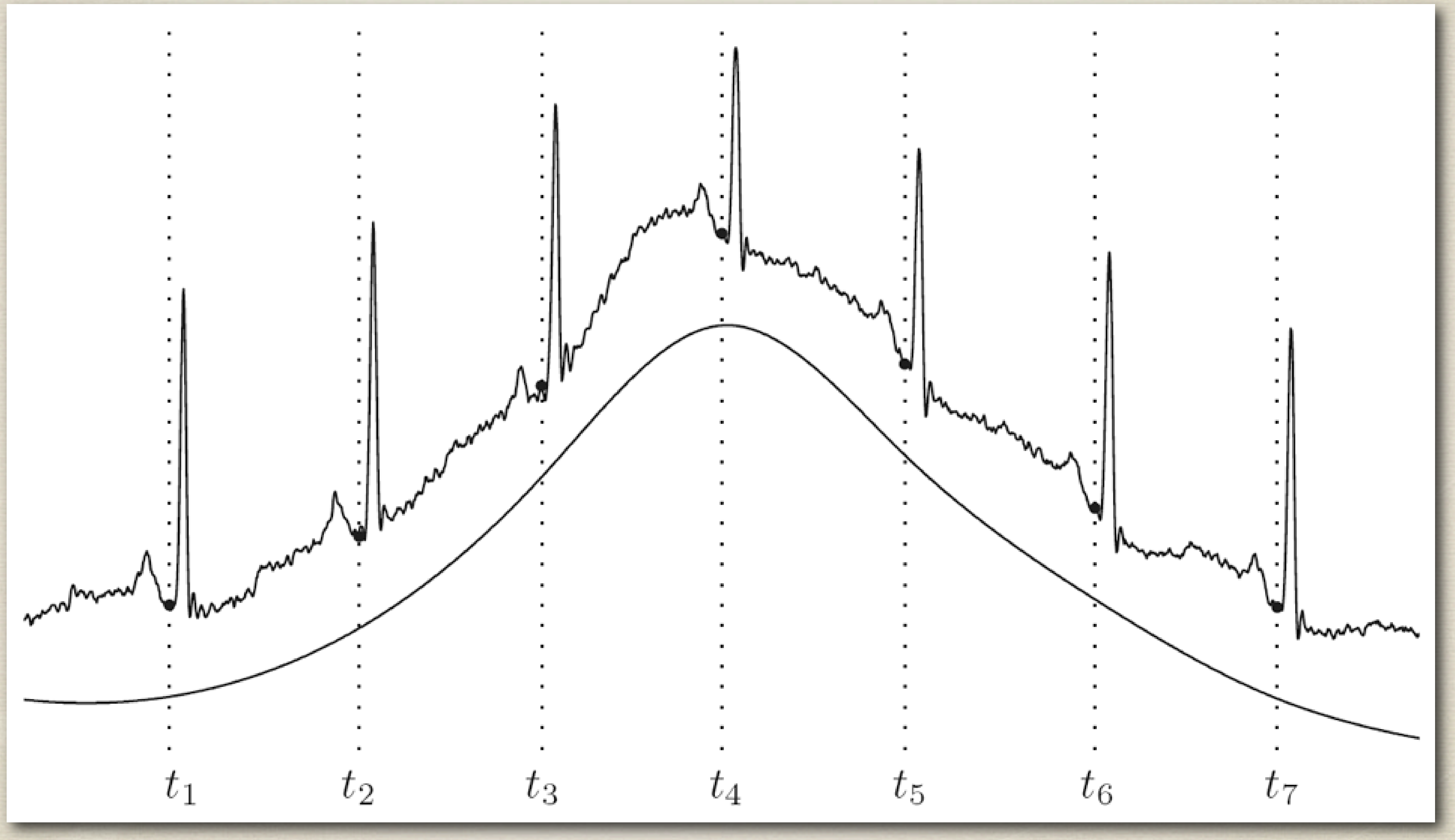
Baseline Filtering: An Example

Original
ECG

Linear
time-
invariant
filtering

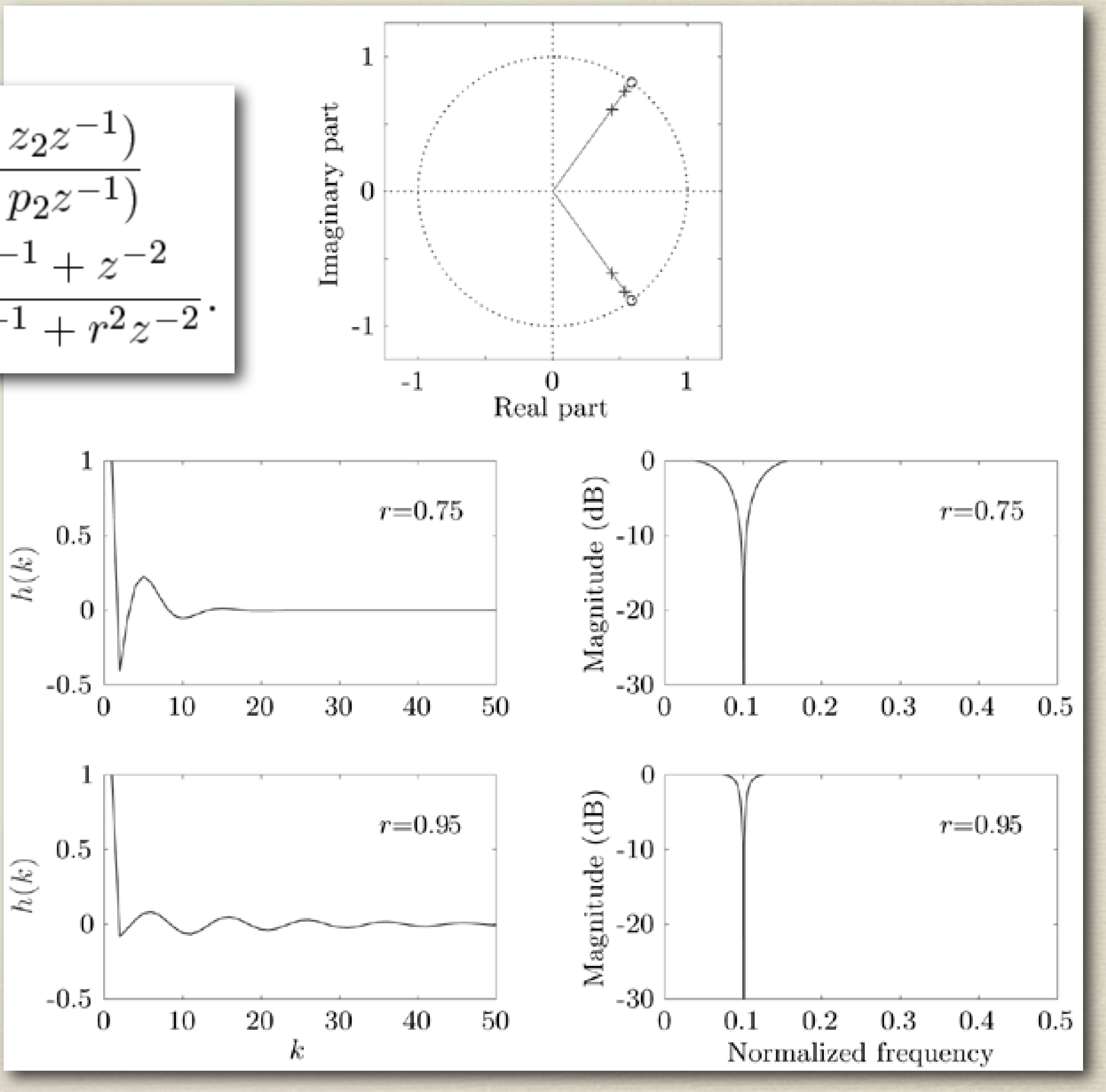
Linear
time-variant
filtering
(heart rate
dependent)

Cubic Spline Interpolation



50/60 Hz LTI Notch Filter

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



Nonlinear 50-Hz Filtering

- The nonlinear filter is based on the idea of subtracting a sinusoid, generated internally by the filter, from the observed signal.
- The amplitude of the internal sinusoid is adapted to the powerline interference present in the observed signal x(n).
- The adaptation process is the key to making the filter less sensitive to transients and avoiding related filter ringing.

Nonlinear 50-Hz Filtering, cont’

The transfer function for the internal oscillator is

$$H(z) = \frac{V(z)}{U(z)} = \frac{1}{1 - 2\cos\omega_0 z^{-1} + z^{-2}},$$

and thus the sinusoid results from the difference equationn

$$v(n) = 2\cos\omega_0 v(n-1) - v(n-2) + u(n),$$

A new estimate of the 50-Hz component is obtained by

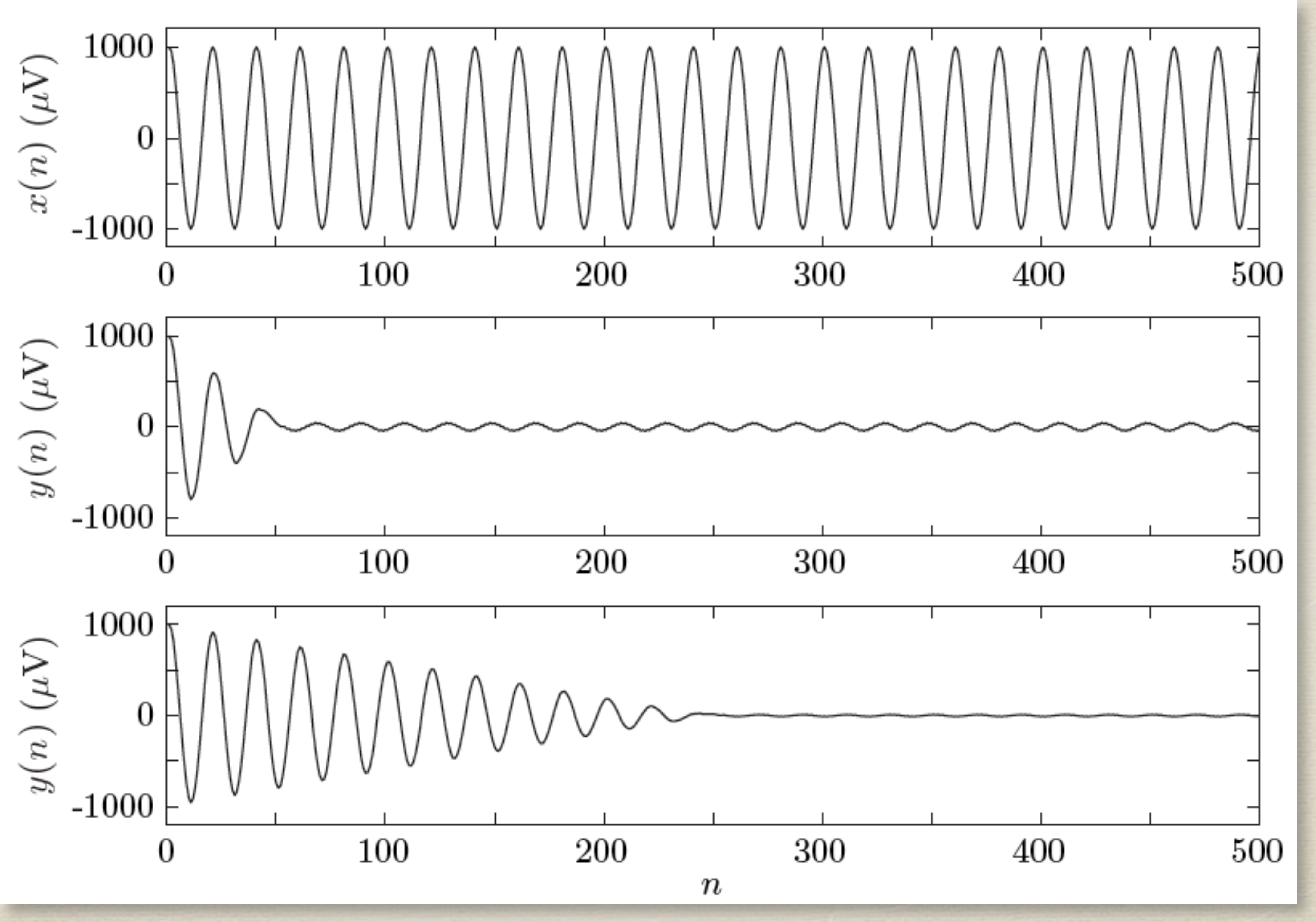
$$\hat{v}(n) = v(n) + \alpha\ \mathrm{sgn}(e\ (n)),$$

$$e(n) = x(n) - v(n).$$

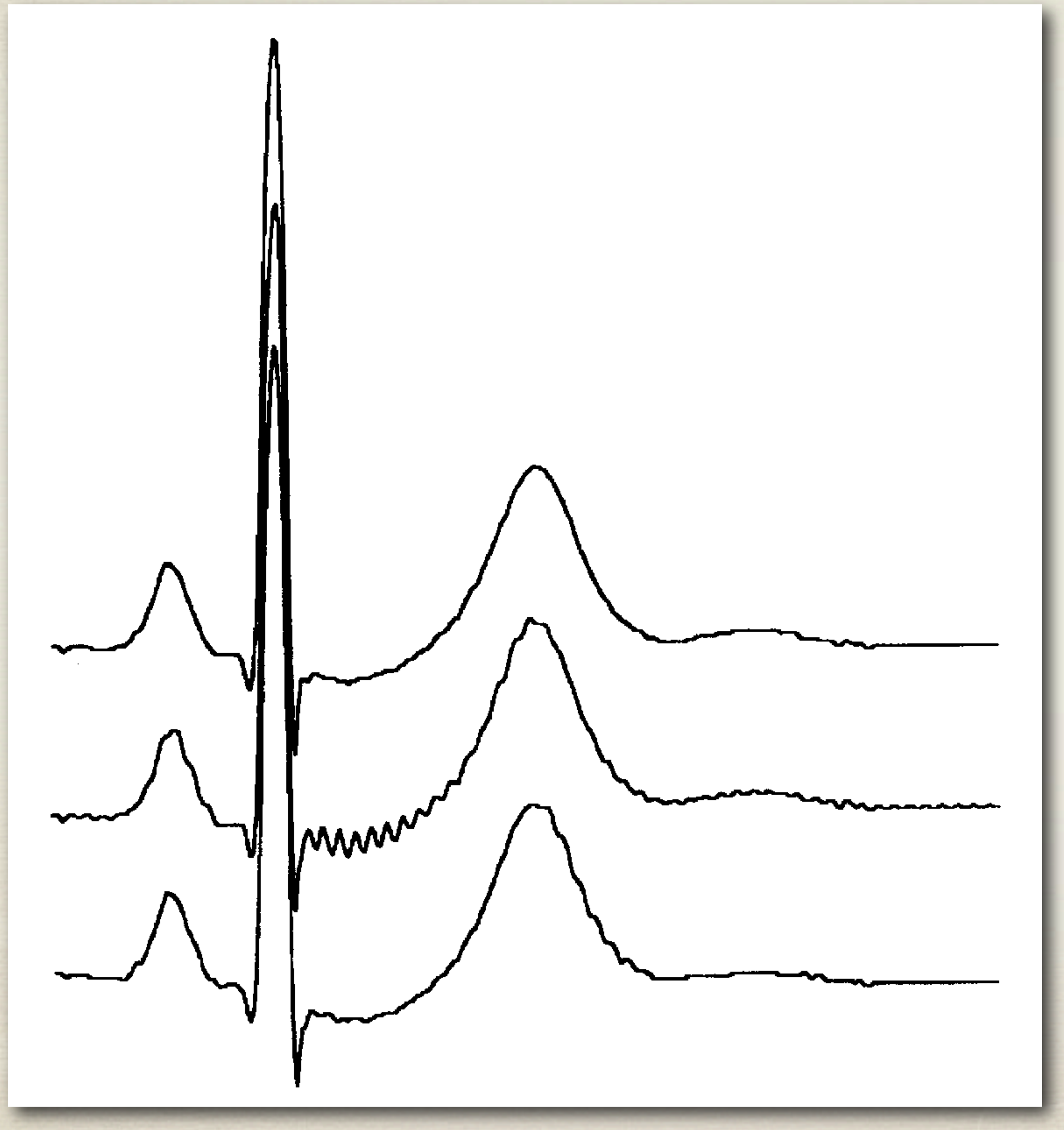
which then is subtracted from the ECG

$$y(n) = x(n) - \hat{v}(n).$$

Nonlinear Filtering Exemplified



50/60 Hz Filtering

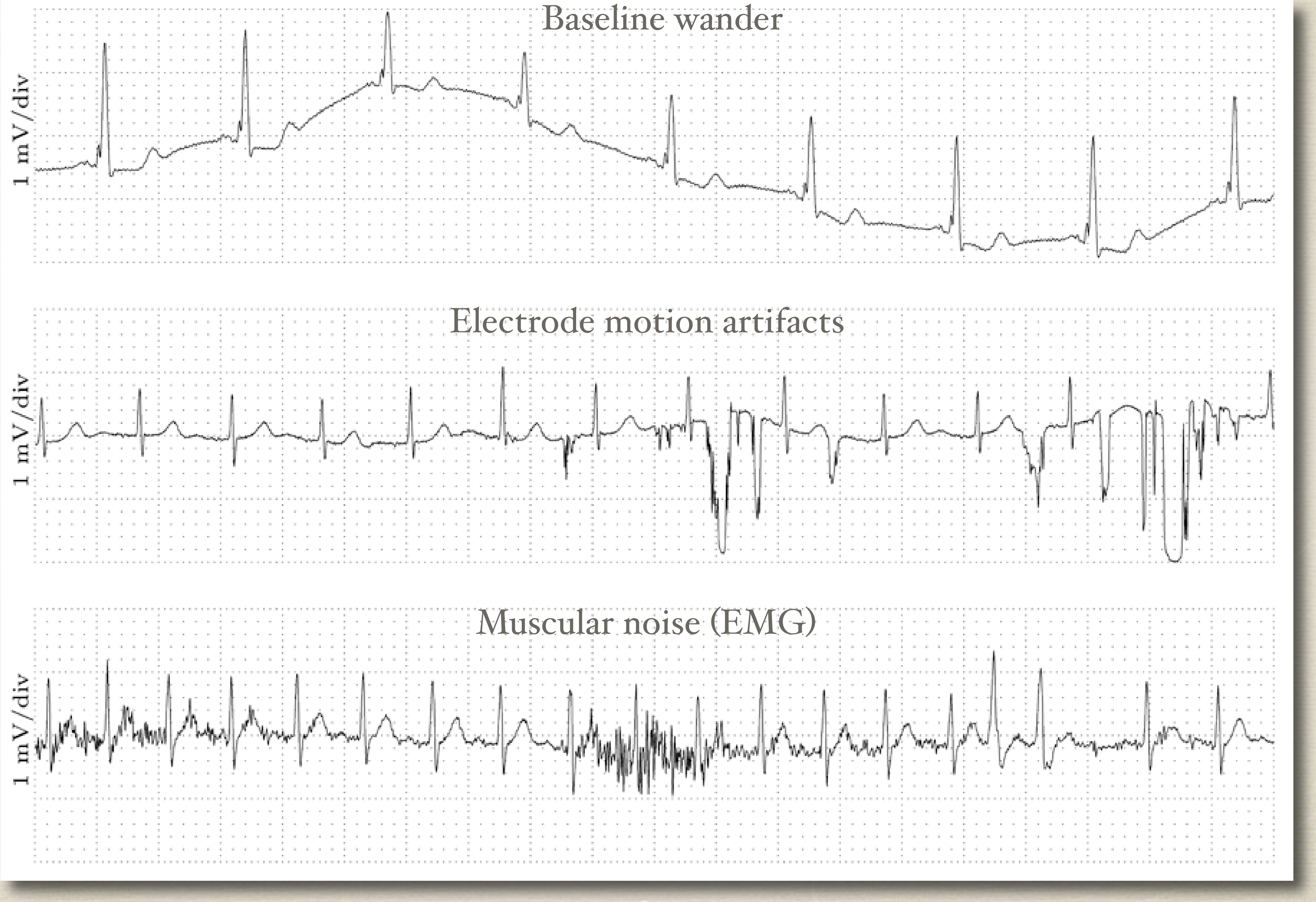


Original signal

Notch filtering

Nonlinear filtering

QRS Detection Problems



Baseline wander

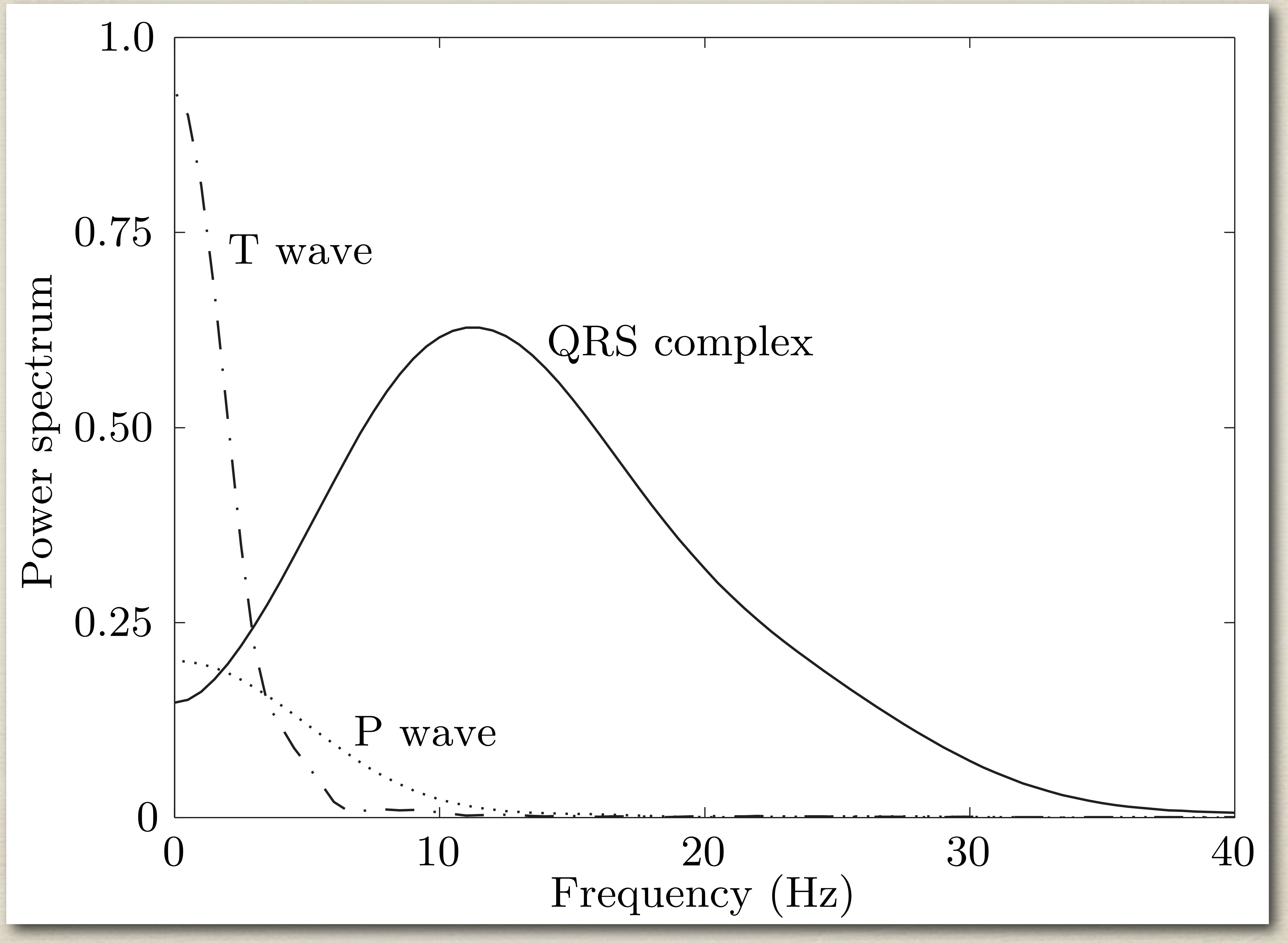
Electrode motion artifacts

Muscular noise (EMG)

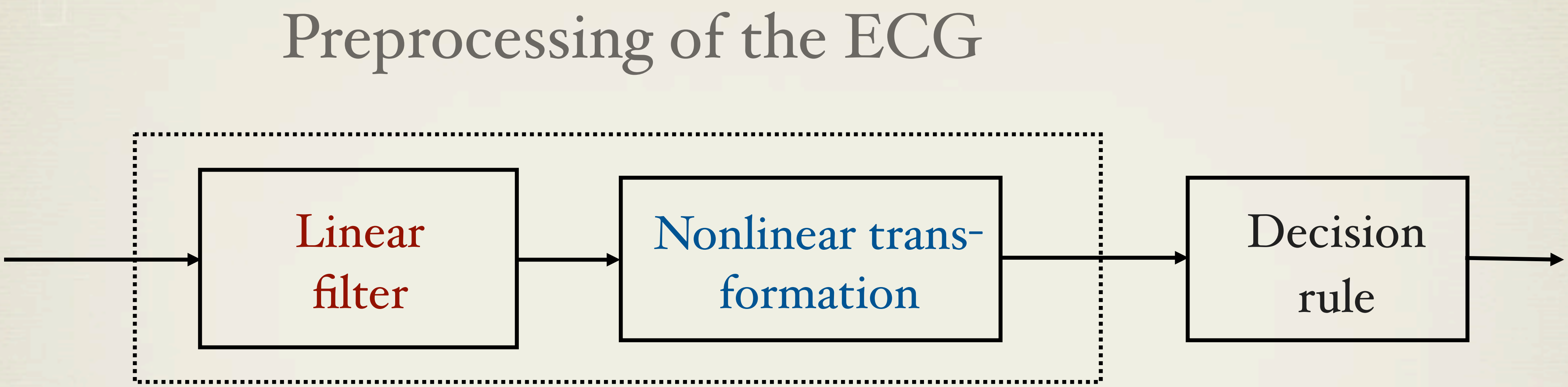
QRS Detection Problems, cont'd

Technical artifact

Spectral ECG properties



QRS Detection



Preprocessing of the ECG

Linear filter

Nonlinear transformation

Decision rule

How to decide the frequency response of the filter?

Which type: Squarer, rectifier,...

Choice of thresholds:
Only amplitude threshold?
Fixed or adaptive?

Models for QRS Detection

$x(n) = s(n) + v(n)$	signal in noise
$x(n) = s(n-\theta) + v(n)$	unknown occurrence time
$x(n) = As(n-\theta) + v(n)$	unknown occurrence time and amplitude
$x(n) = \sum_{i=1}^{q} A_i s(n-\theta_i) + v(n)$	unknown number of QRS's, occurrence time, and amplitude

$$\vdots$$

Design of Linear Detection Filter

Our approach: find the maximum likelihood (ML) estimate for the unknown occurrence time in the model:

$$x(n) = s(n-\theta) + v(n)$$

ML estimator:

$$y(\theta) = \sum_{n=0}^{N-1} h(n)x(\theta - n)$$

$$\hat{\theta} = \arg\max_{\theta} y(\theta)$$

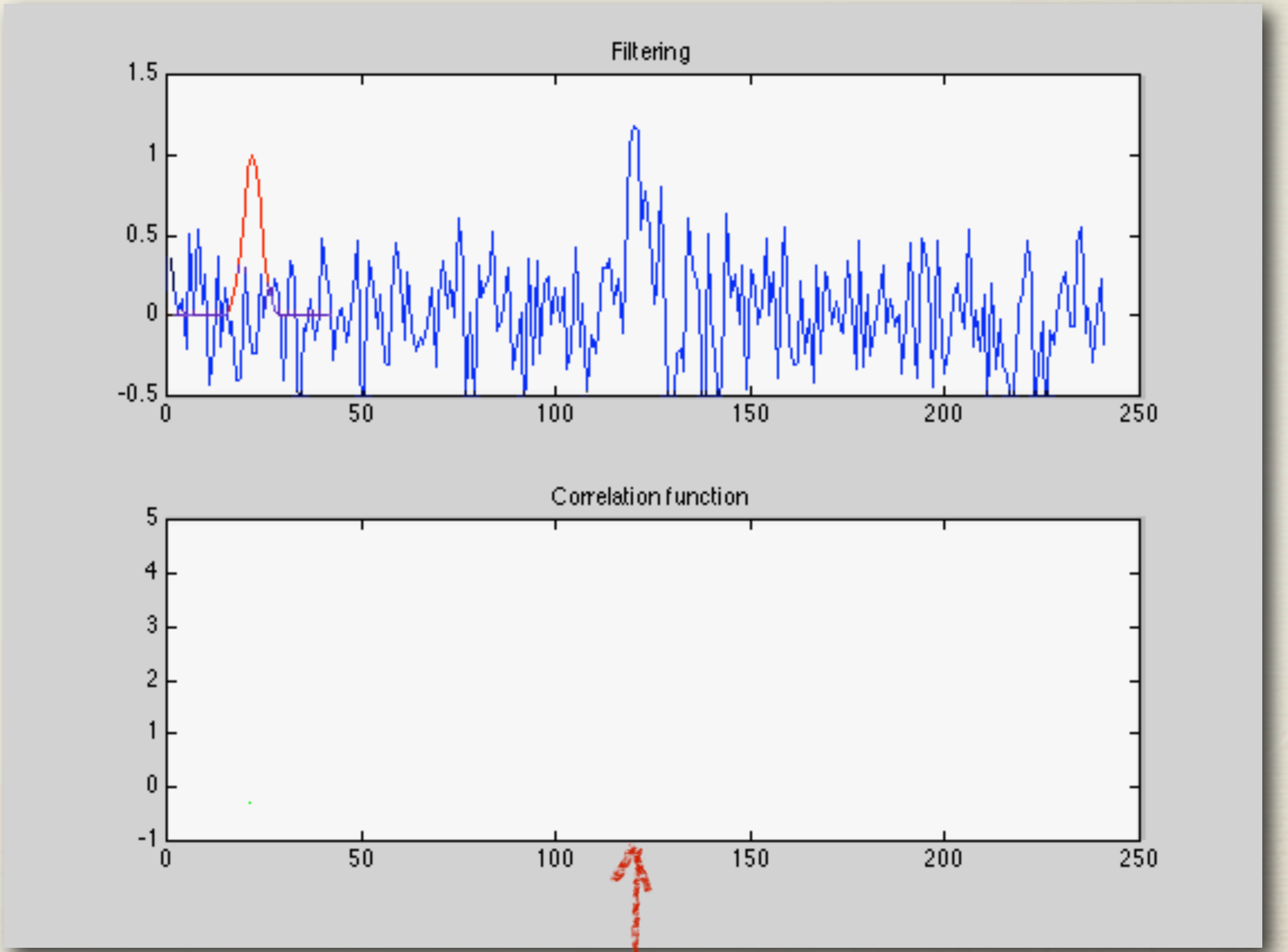
where $h(n) = s(N-1-n)$ is the matched filter!

Matched Filtering

Input signal

Reference signal

Convolution



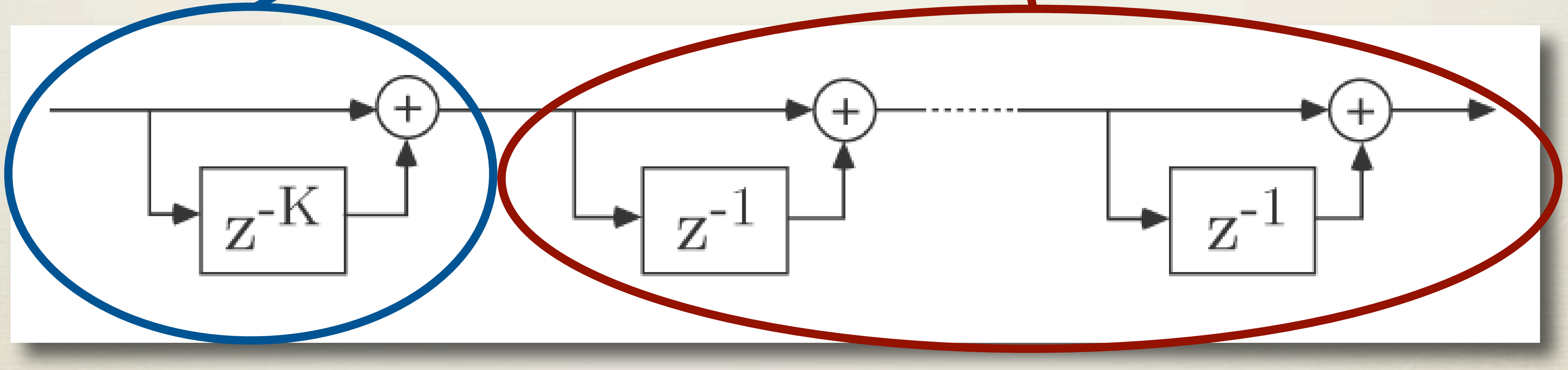
detection

Simple Detector Filter Structures

A useful class of filter system functions is defined by:

$$H(z) = (1 - z^{-K})(1 + z^{-1})^{L}$$

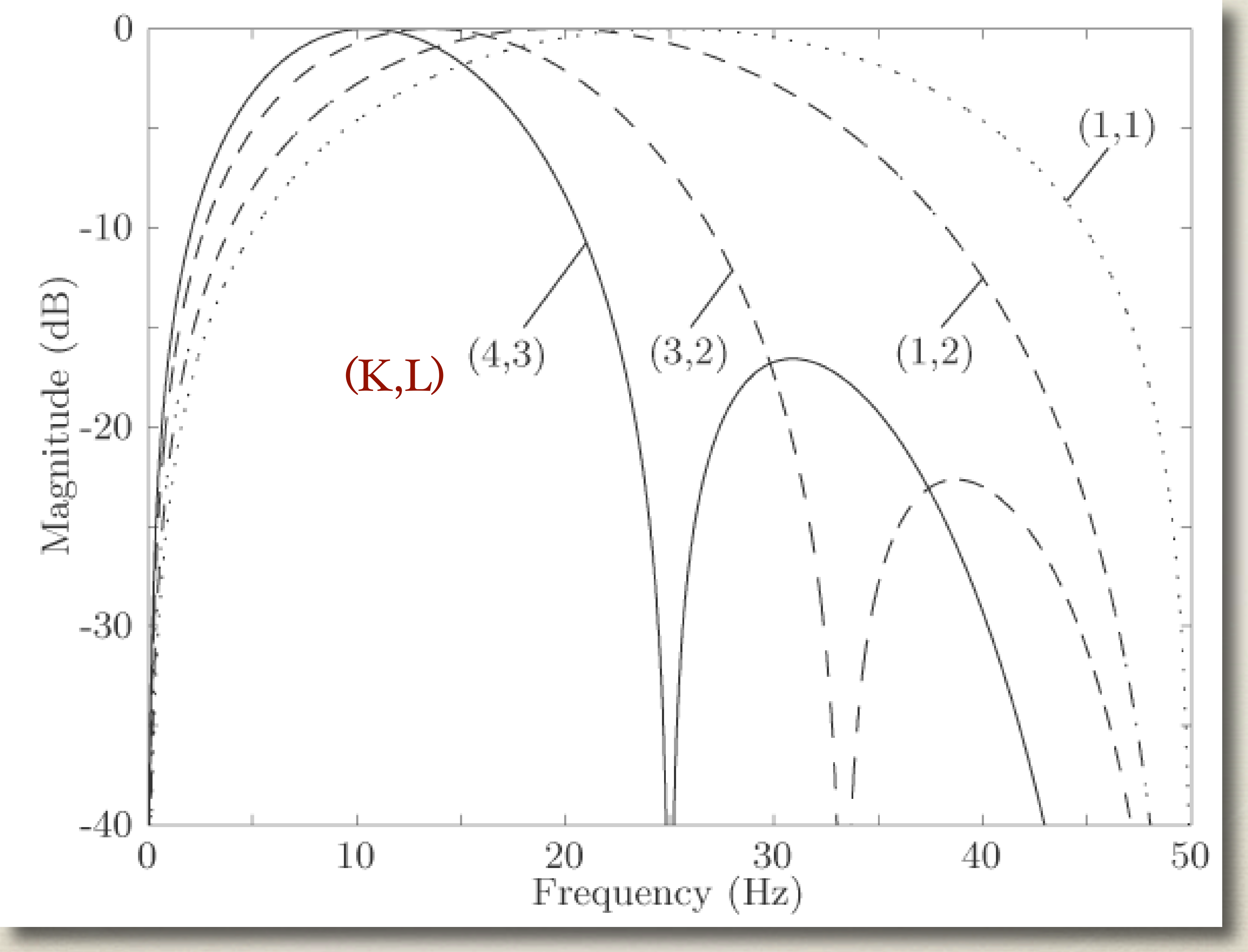
only for certain sampling rates



K:th difference
bandpass

L cascaded blocks
lowpass

Simple Filters for QRS Detection – Frequency Response



$$H(z) = (1 - z^{-K})(1 + z^{-1})^{L}$$

Design of Nonlinear Transformation

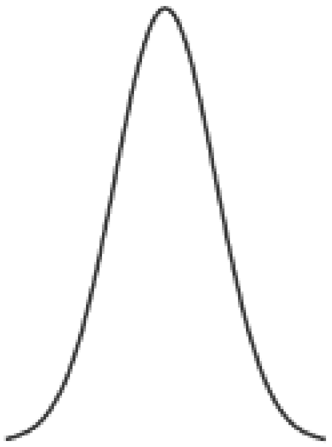
- Formal design may be based on a statistical assumption on the amplitude A in the model

  $$x(n) = As(n - \theta) + v(n)$$

  leading to complicated calculations in most cases.

- The rectifier or squarer is often used. In fact, the squarer is optimal for the ML approach (see the textbook).

Envelope-based Detection



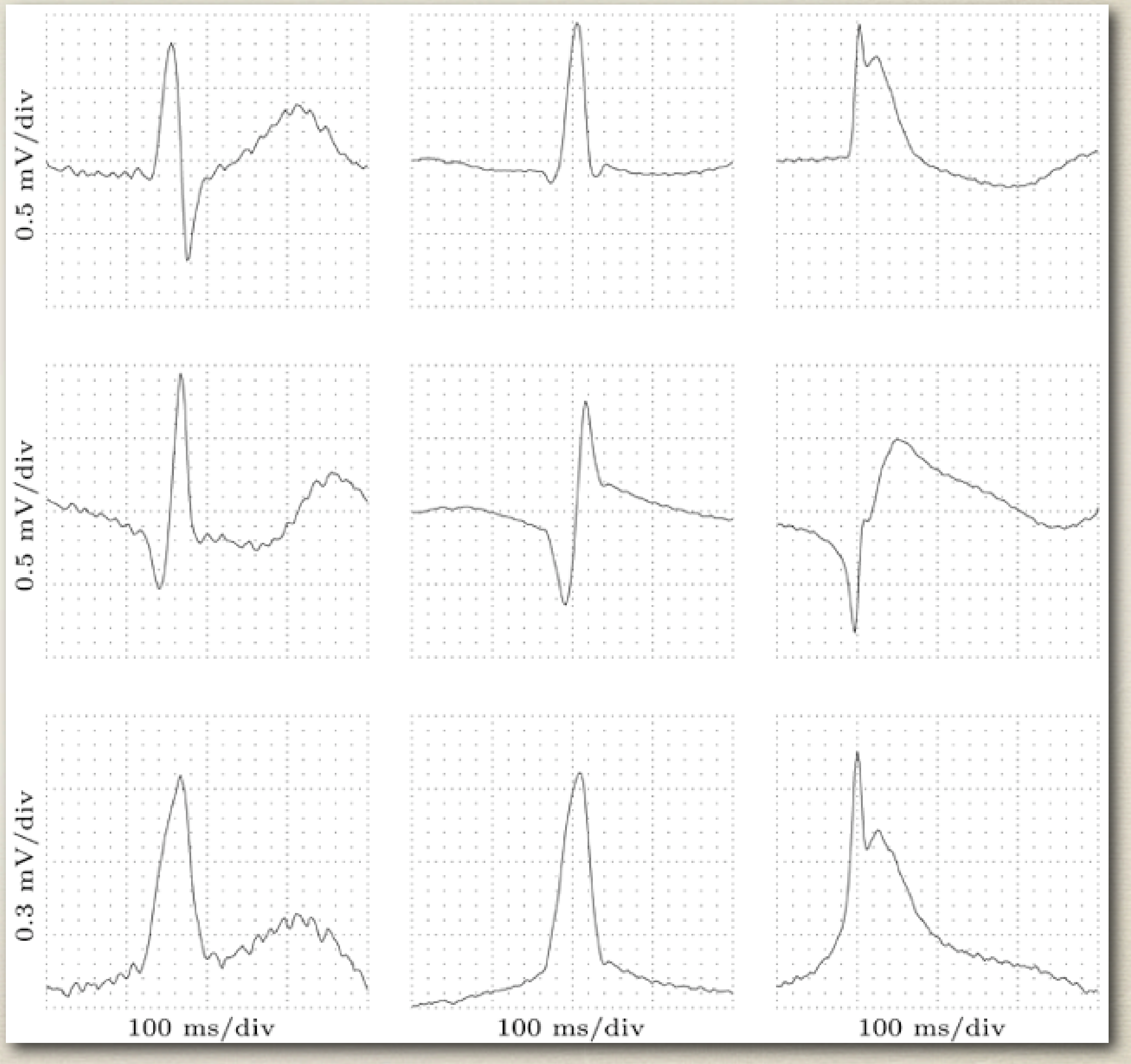
$b(n)$

Envelope Examples

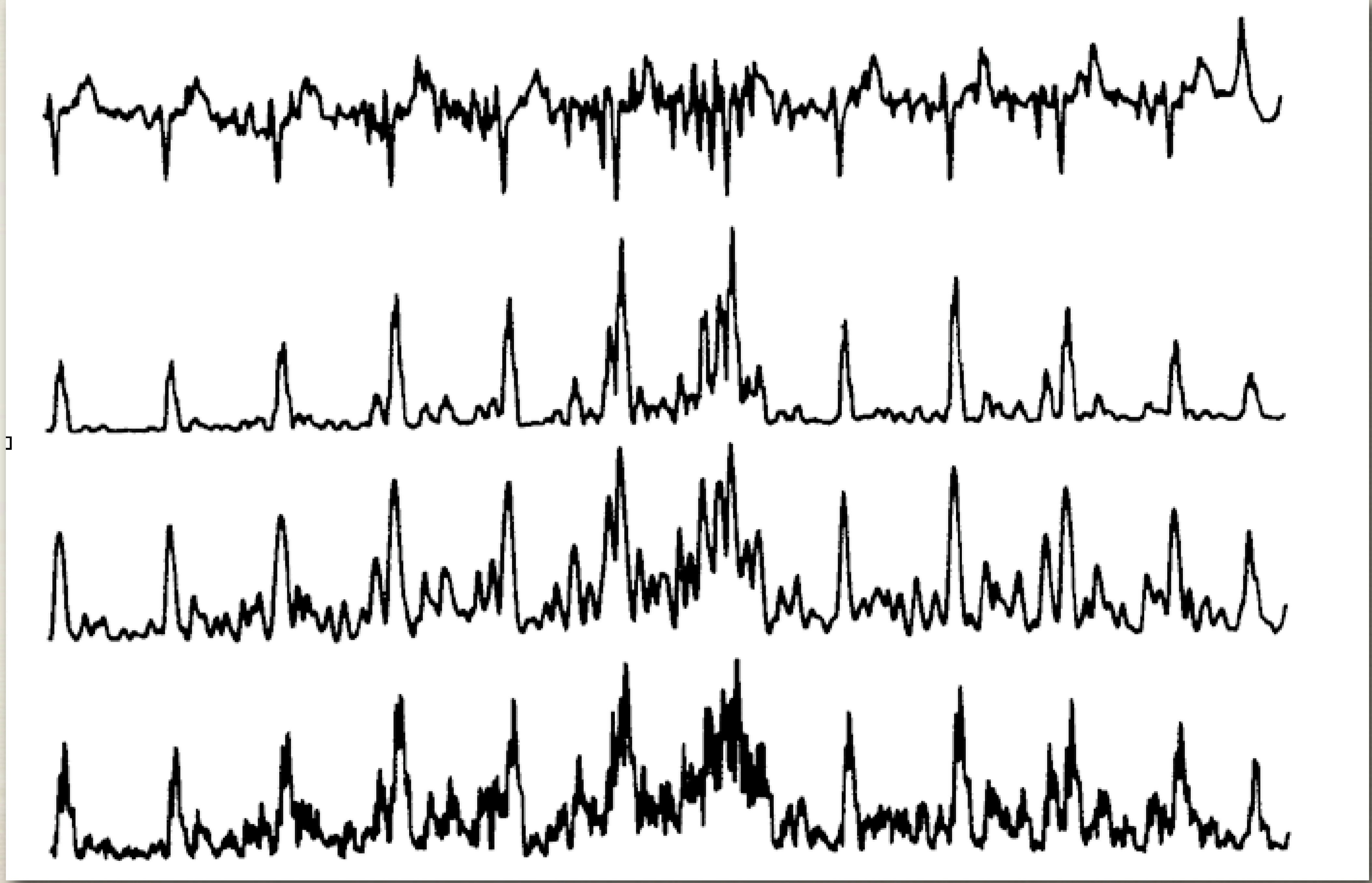
ECG

Hilbert-transformed ECG

Envelope



Preprocessor Output



ECG

Squarer

Envelope

Rectifier

Preprocessor Output

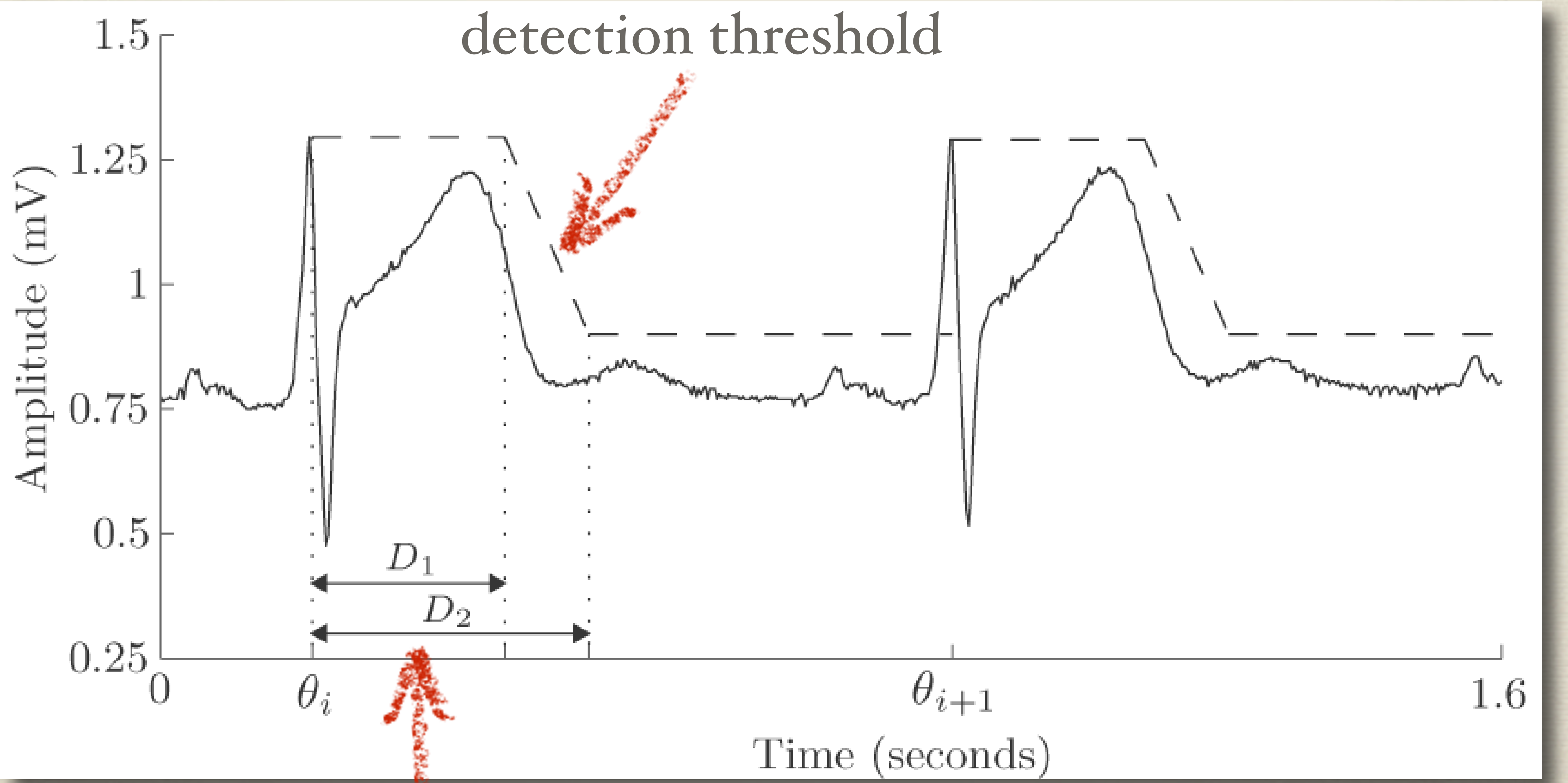
ECG

Squarer

Envelope

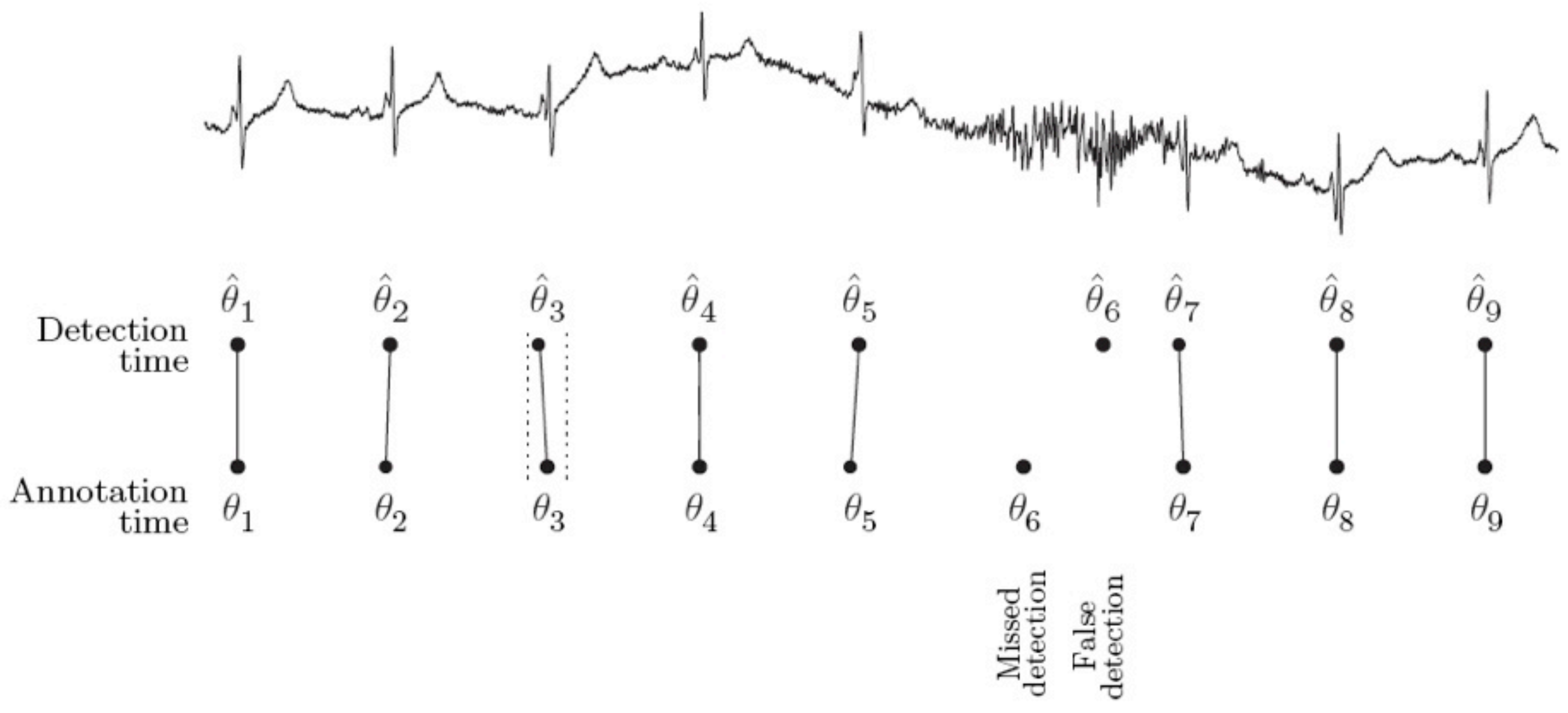
Rectifier

QRS Detection: Decision Rule



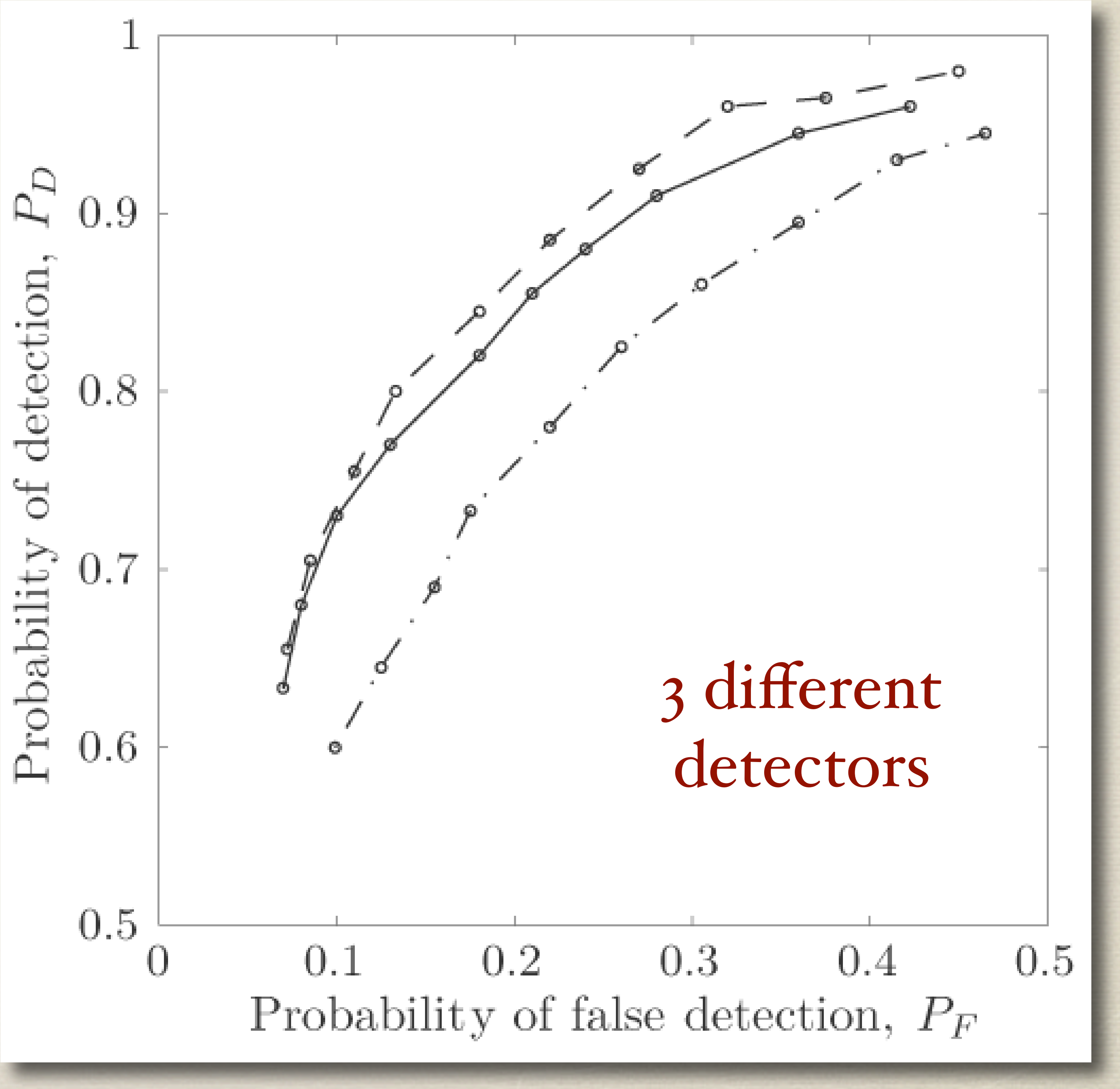
detection threshold

Refractory period


$\hat{\theta}_1$ $\hat{\theta}_2$ $\hat{\theta}_3$ $\hat{\theta}_4$ $\hat{\theta}_5$ $\hat{\theta}_6$ $\hat{\theta}_7$ $\hat{\theta}_8$ $\hat{\theta}_9$
Detection time
Annotation time
θ_1 θ_2 θ_3 θ_4 θ_5 θ_6 θ_7 θ_8 θ_9
Missed detection
False detection

QRS Detector Performance

Receiver
operating
characteristic
(ROC)



3 different
detectors

QRS End Delineation

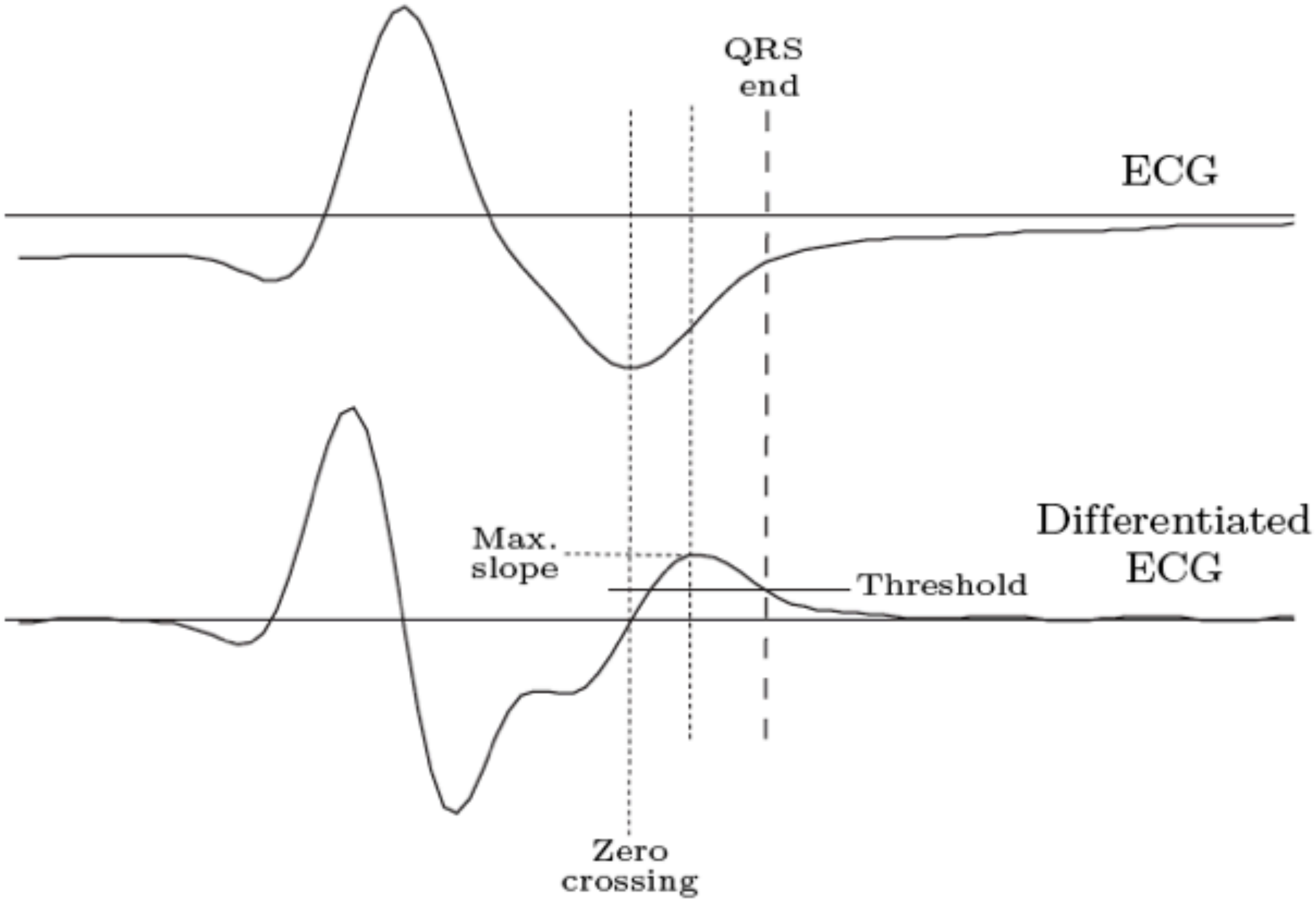
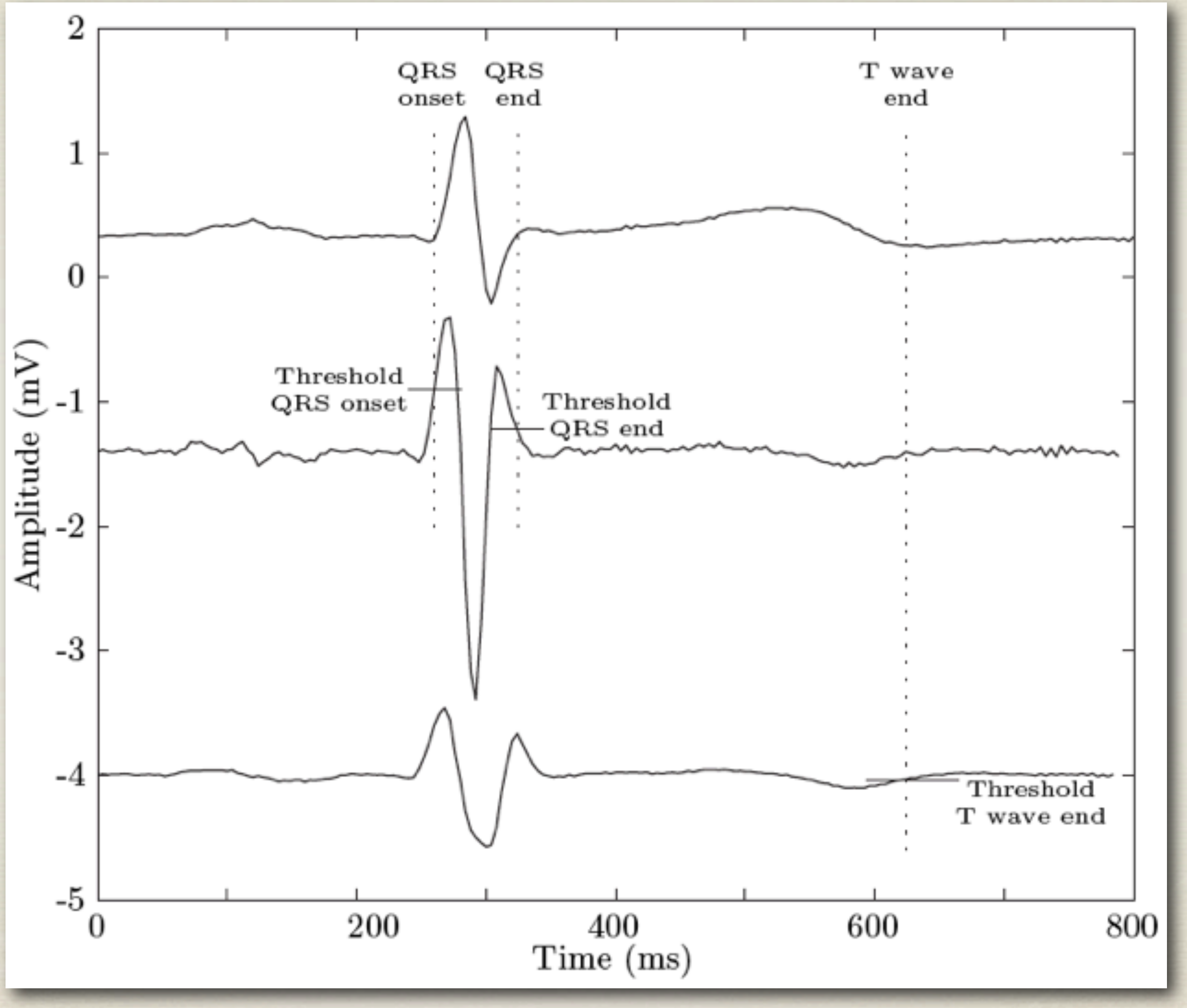


Figure 7.27: Determination of the QRS end using slope information. The QRS end is the time at which the differentiated signal crosses a threshold after the maximum slope has occurred. The threshold level is usually expressed as a percentage of the maximum slope.

LPD-based Delineation



LPD: Lowpass filtered differentiation

Data Compression

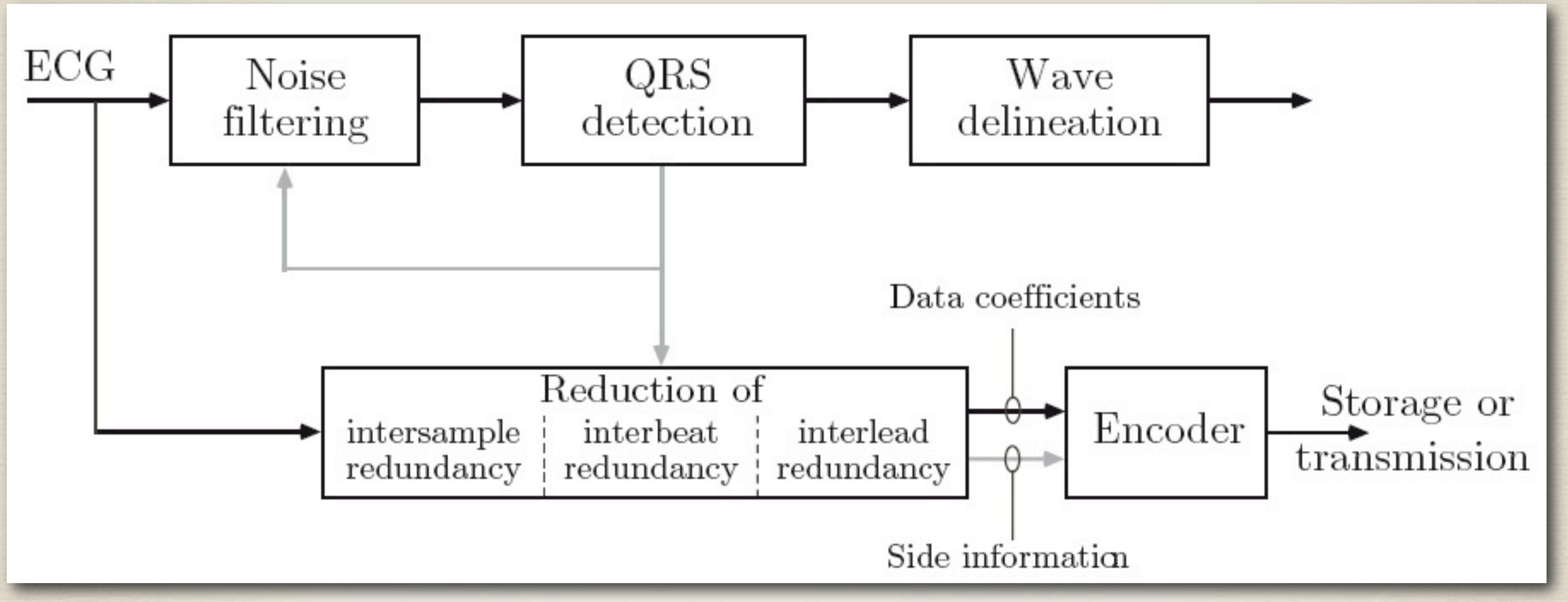
- The overall goal is to represent a signal as accurately as possible using the fewest number of bits.
- **Lossless compression**: the compressed/ reconstructed signal is an exact replica of the original signal.
- **Lossy compression**: the reconstructed signal is allowed to differ from the original signal.
- With lossy compression, a certain amount of distortion has to be accepted in the reconstructed signal, although the distortion must remain small enough not to modify or jeopardize the diagnostic content of the ECG.

ECG Data Redundancy

The three main types of data redundancy in the ECG signal are:

- Intersample (intrabeat) redundancy.
- Interbeat redundancy is manifested, within each lead, by successive, similar-looking heartbeats.
- Interlead redundancy is due to the fundamental fact that a heartbeat is “viewed” concurrently in different leads.

Data Compression of ECG Signals



ECG

Noise filtering

QRS detection

Wave delineation

Reduction of

intersample redundancy

interbeat redundancy

interlead redundancy

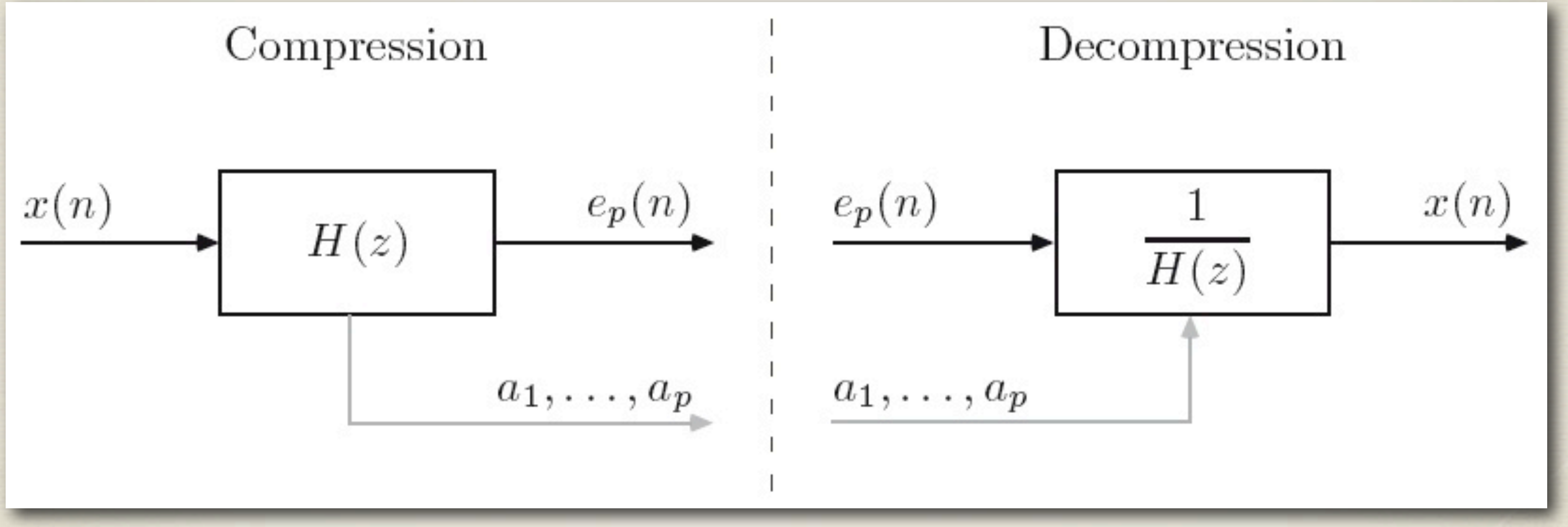
Data coefficients

Side information

Encoder

Storage or transmission

Lossless Data Compression based on Linear Prediction



Linear Prediction

ECG

1st difference

2nd difference

optimal 3rd order predictor

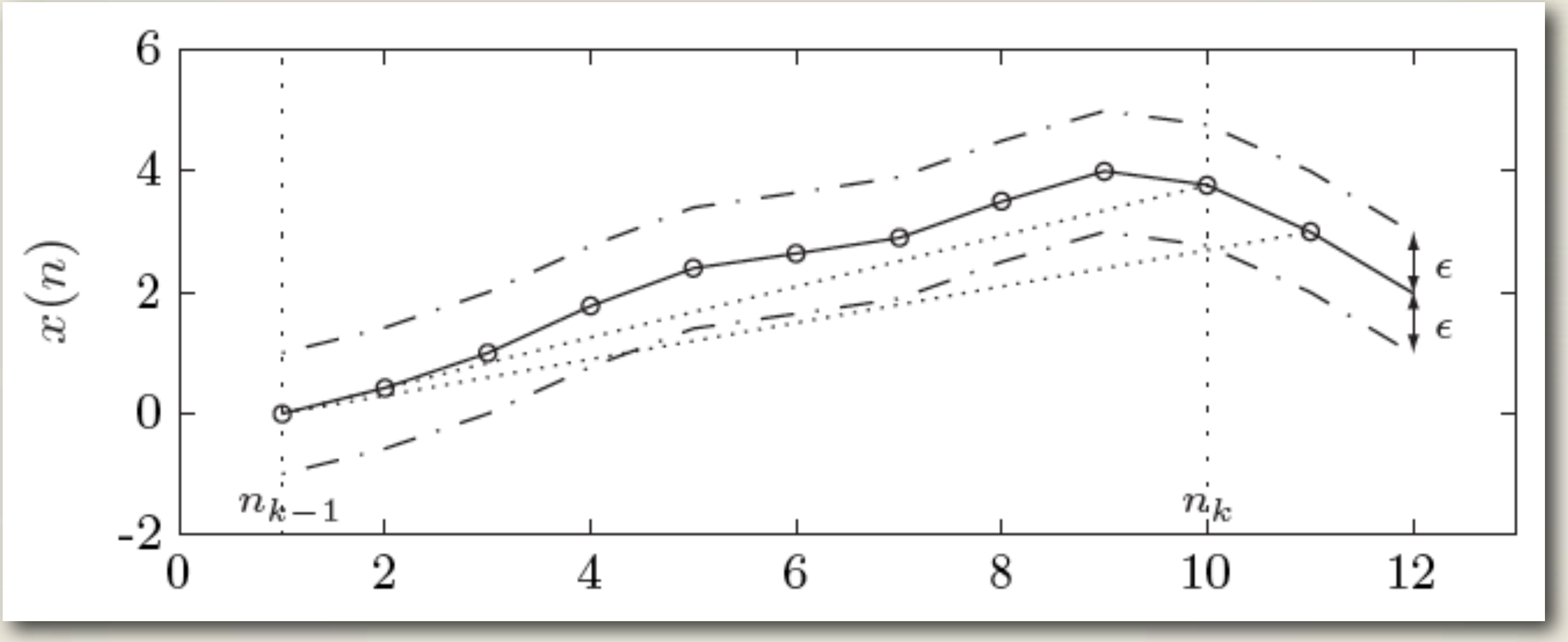
Lossy Data Compression

- Direct Methods
  - Amplitude zone time epoch coding (AZTEC)
  - Scan-along polygonal approximation (SAPA)
- Transform methods
  - Karhunen-Loève transform (KLT)
  - Wavelets and wavelet packets.

Example of AZTEC

ε: error tolerance

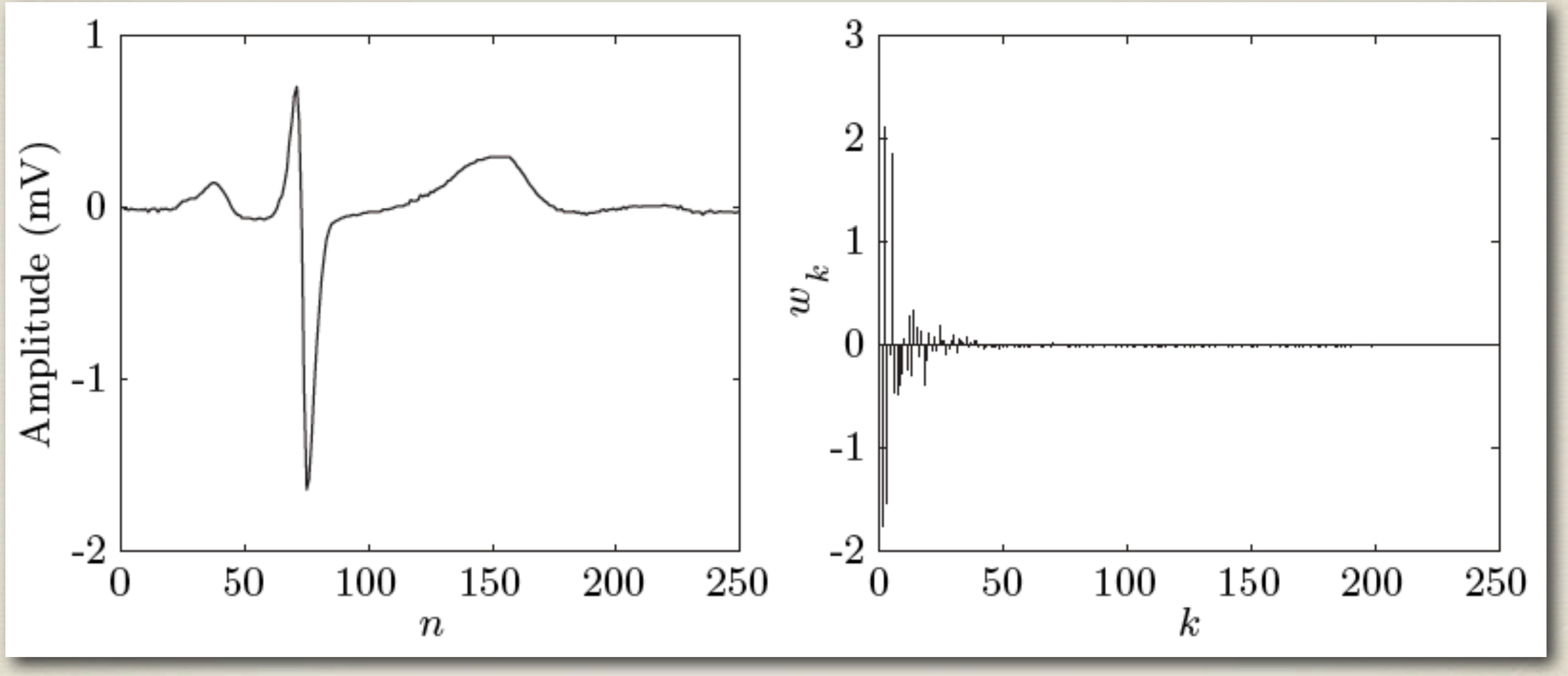
The SAPA Principle



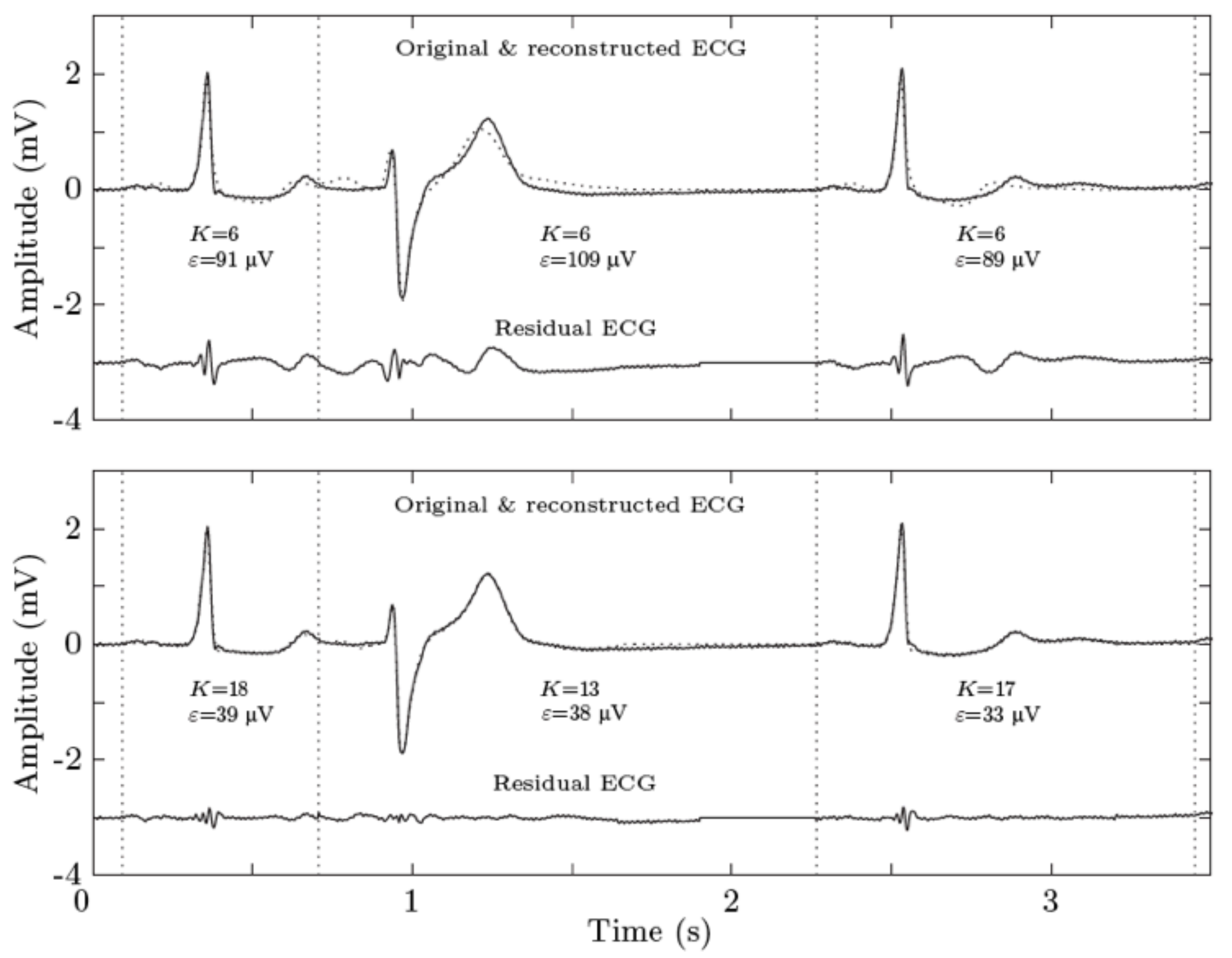
ε: error tolerance

Example of SAPA

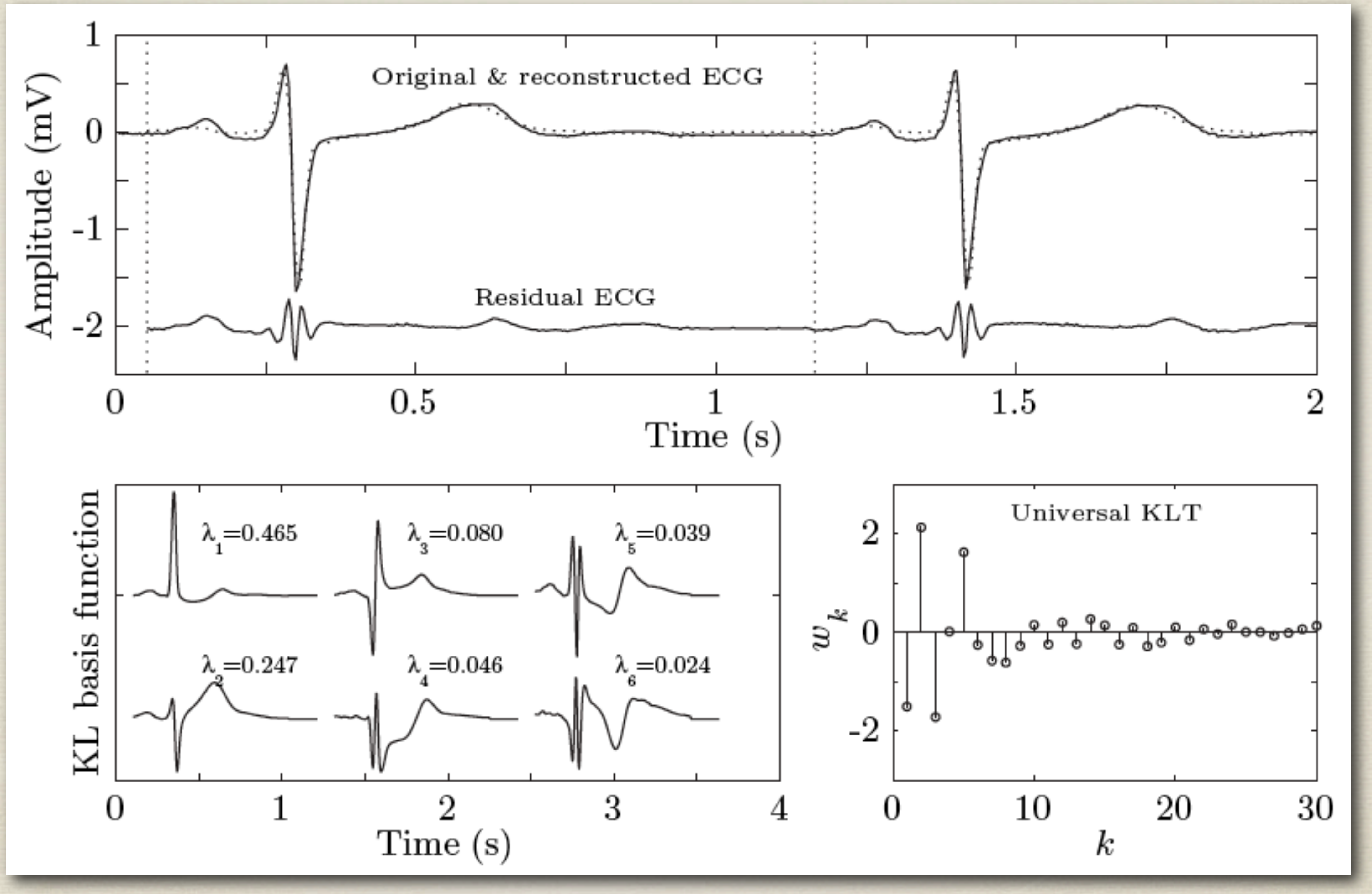
KLT-based Data Compression



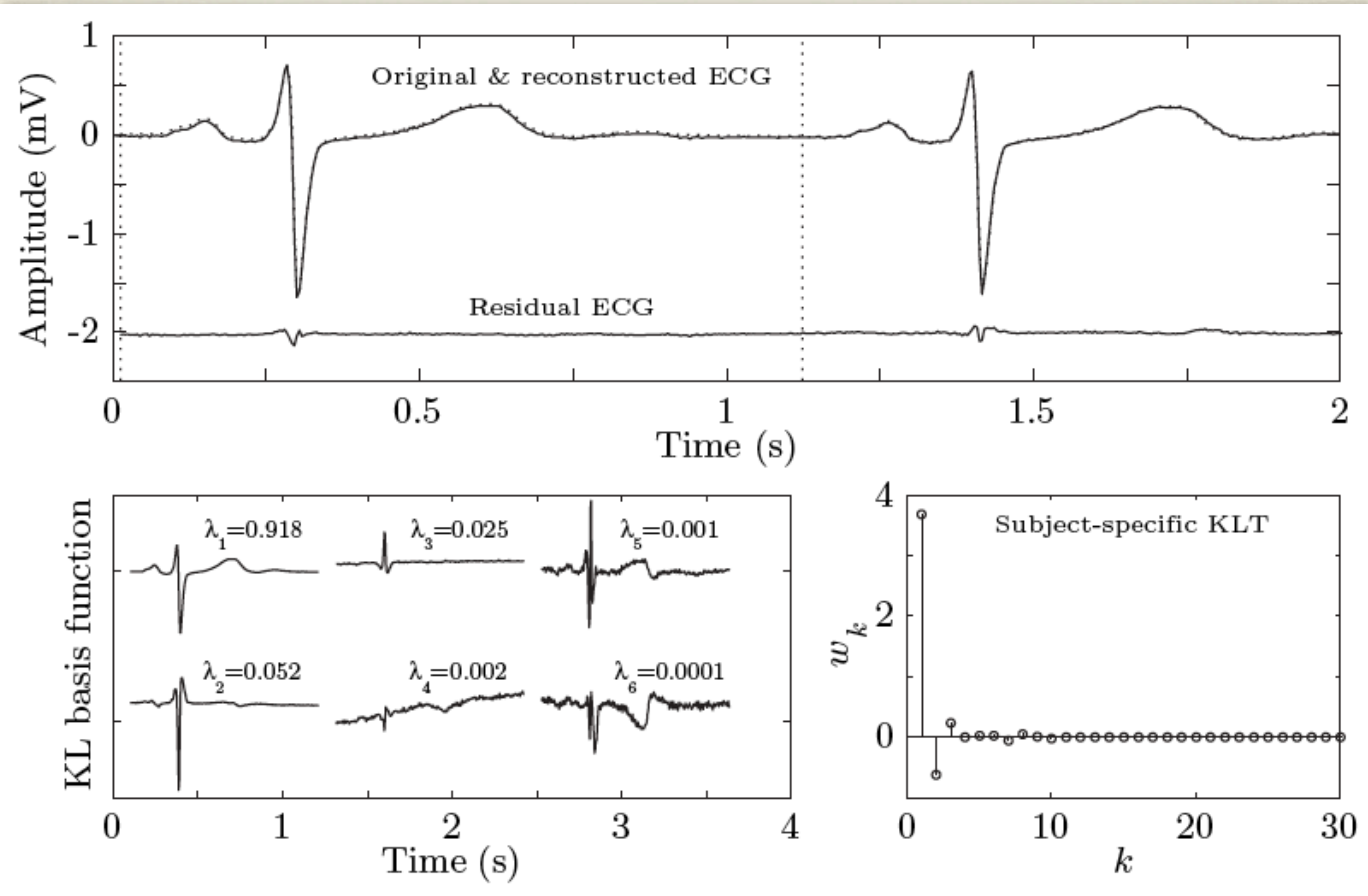
KLT Compression with Tolerance



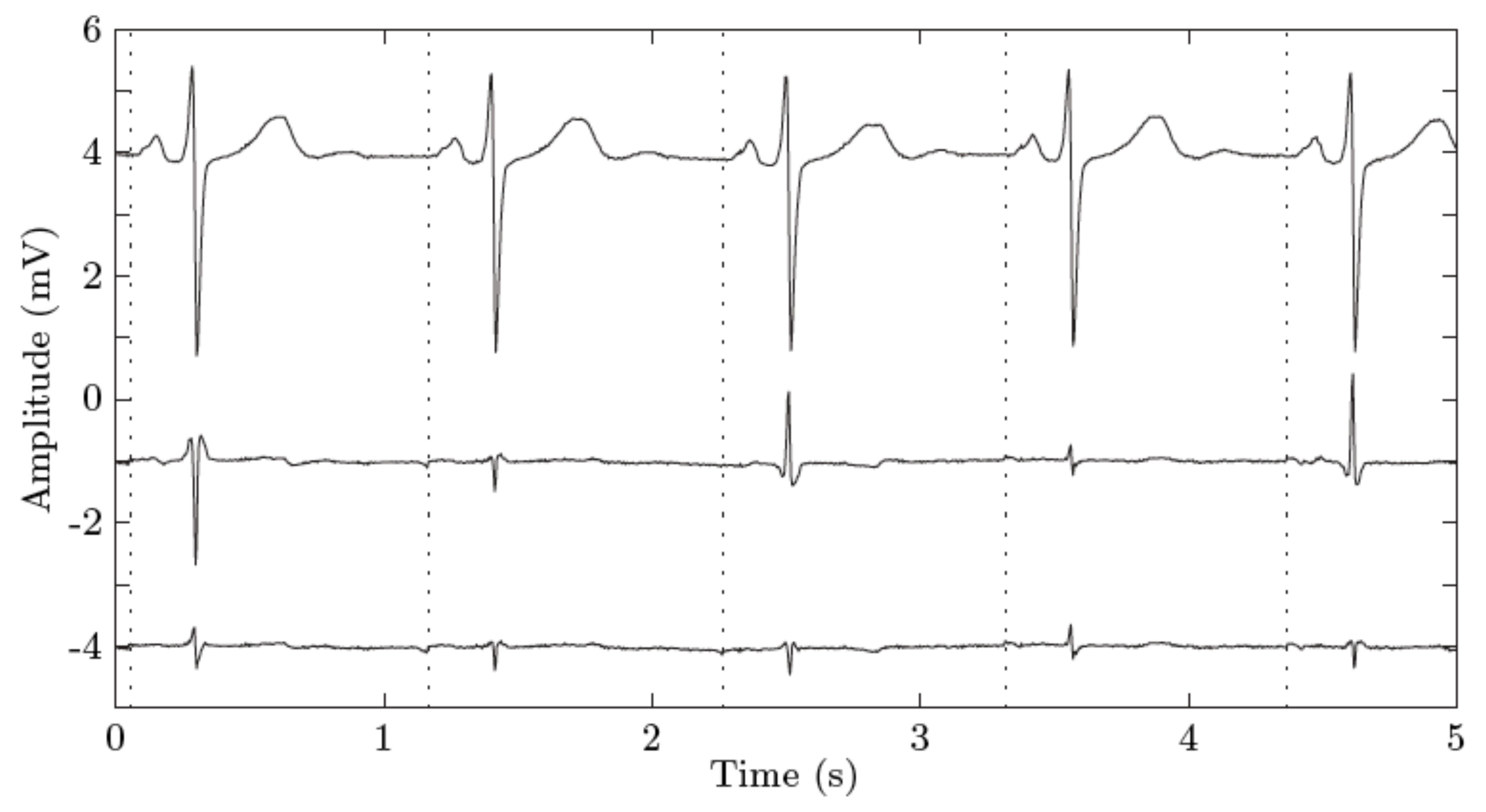
KLT Using Universal Data



KLT Using Subject-Specific Data

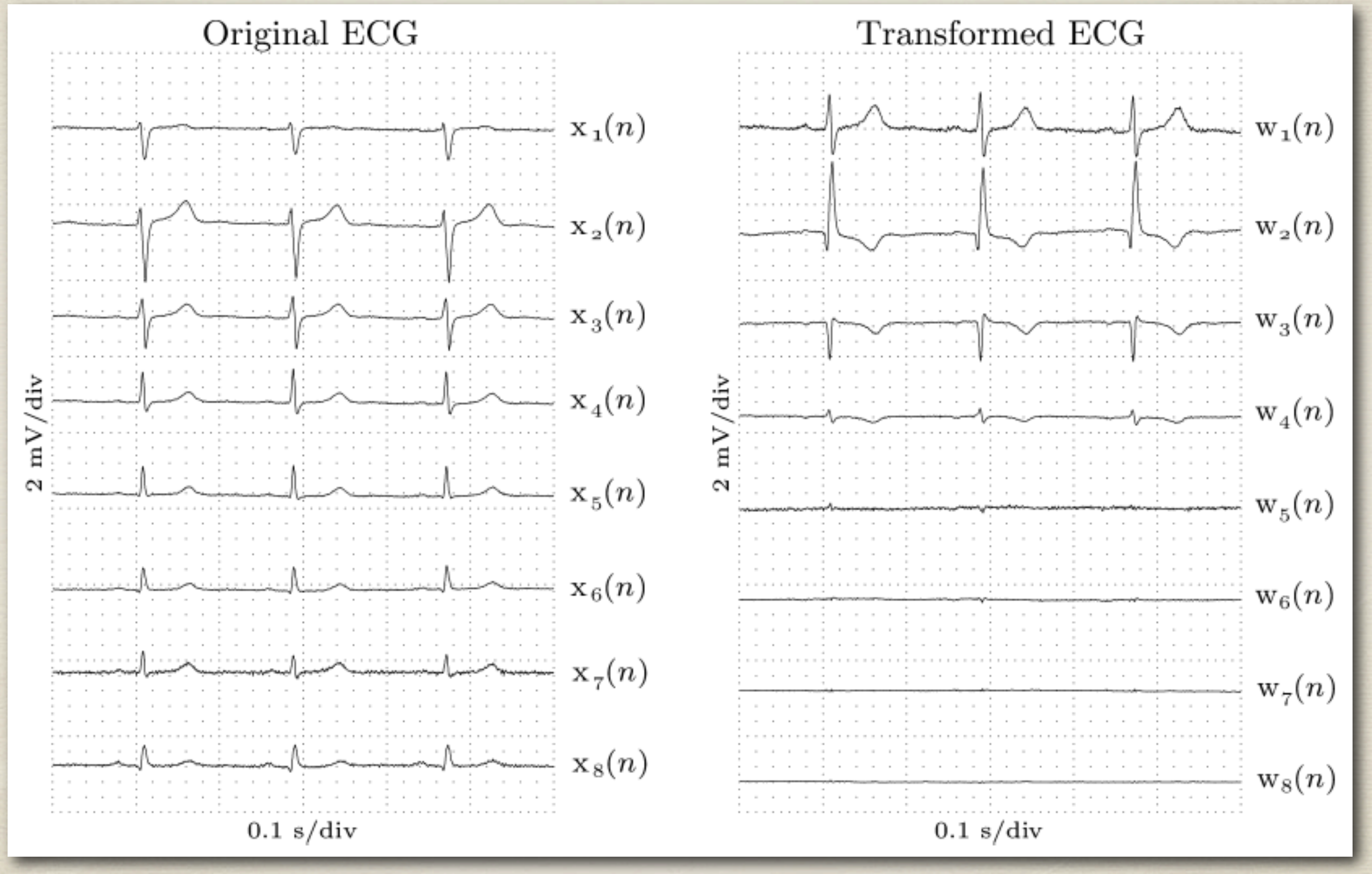


Handling Interbeat Redundancy



Average beat subtraction

Handling Interlead Redundancy



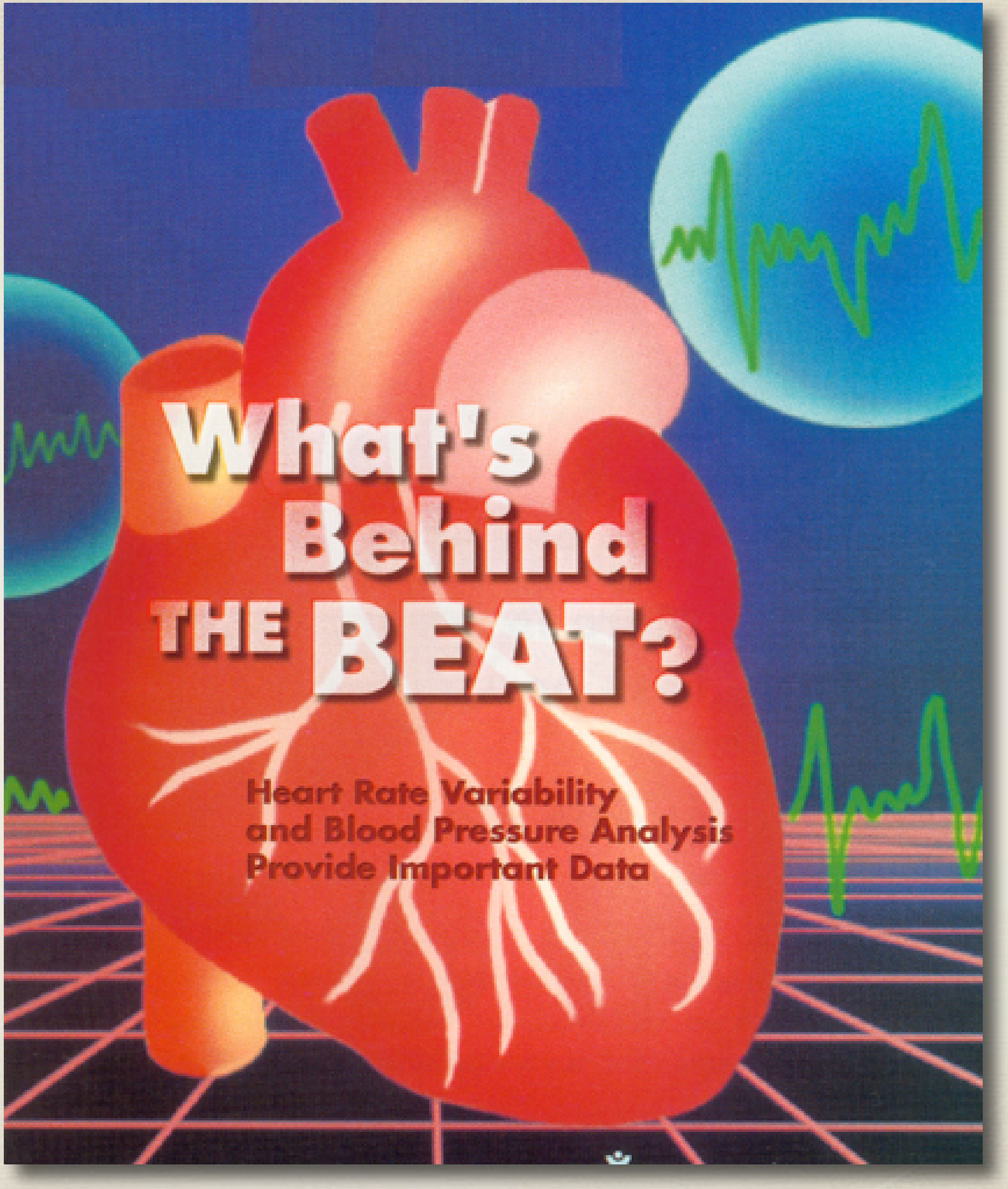
Performance Measures

Percentage root mean-square difference (PRD)

$$\mathcal{P}_{\text{PRD}} = \sqrt{\frac{\sum_{n=0}^{N-1} (x(n) - \tilde{x}(n))^2}{\sum_{n=0}^{N-1} x^2(n)}} \cdot 100,$$

Note: While the loss of a tiny Q wave in the reconstructed signal essentially goes unreflected in P_{PRD}, the absence of a Q wave represents an essential loss from a diagnostic point of view when, for example, diagnosing myocardial infarction.

Better performance measures need to be defined!

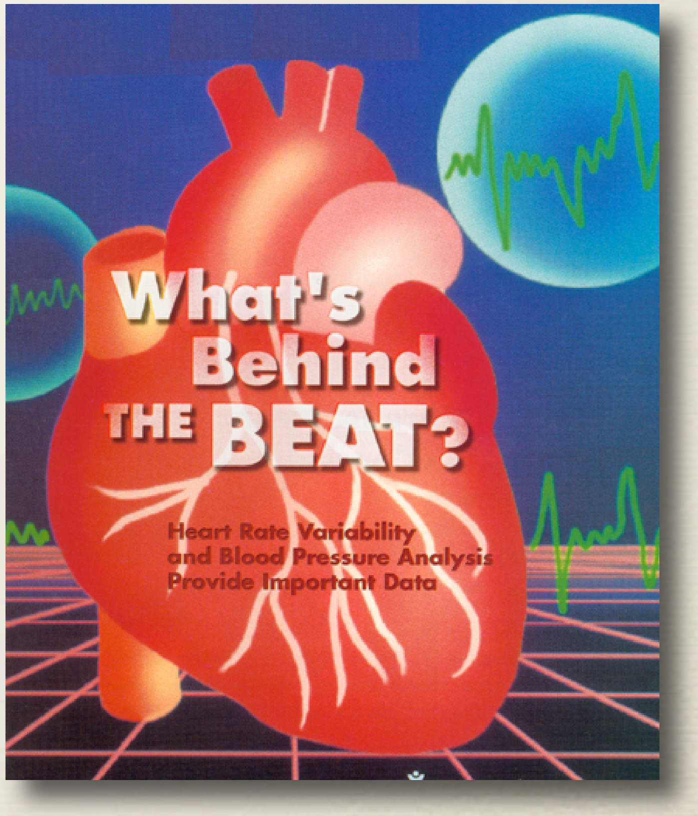


What's Behind THE BEAT?

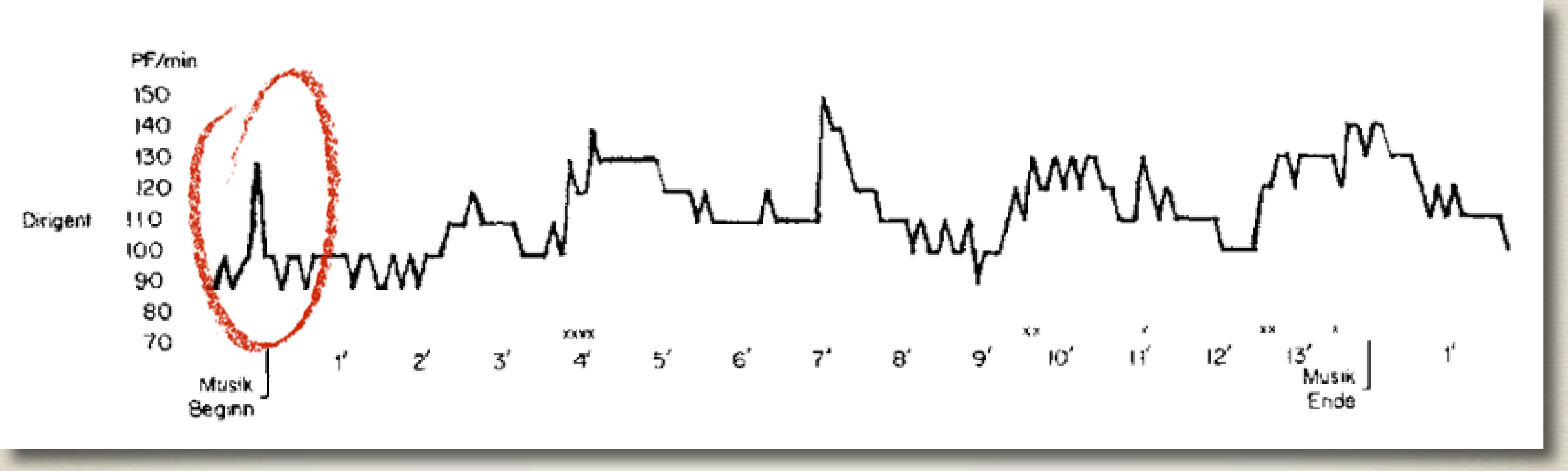
Heart Rate Variability
and Blood Pressure Analysis
Provide Important Data

Heart Rate Variability (HRV)

- indirect measure on autonomic nerve function,
- reflects interaction with:
  - cardiac activity
  - respiration
  - blood pressure
  - body temperature



Conductor’s Heart Rate



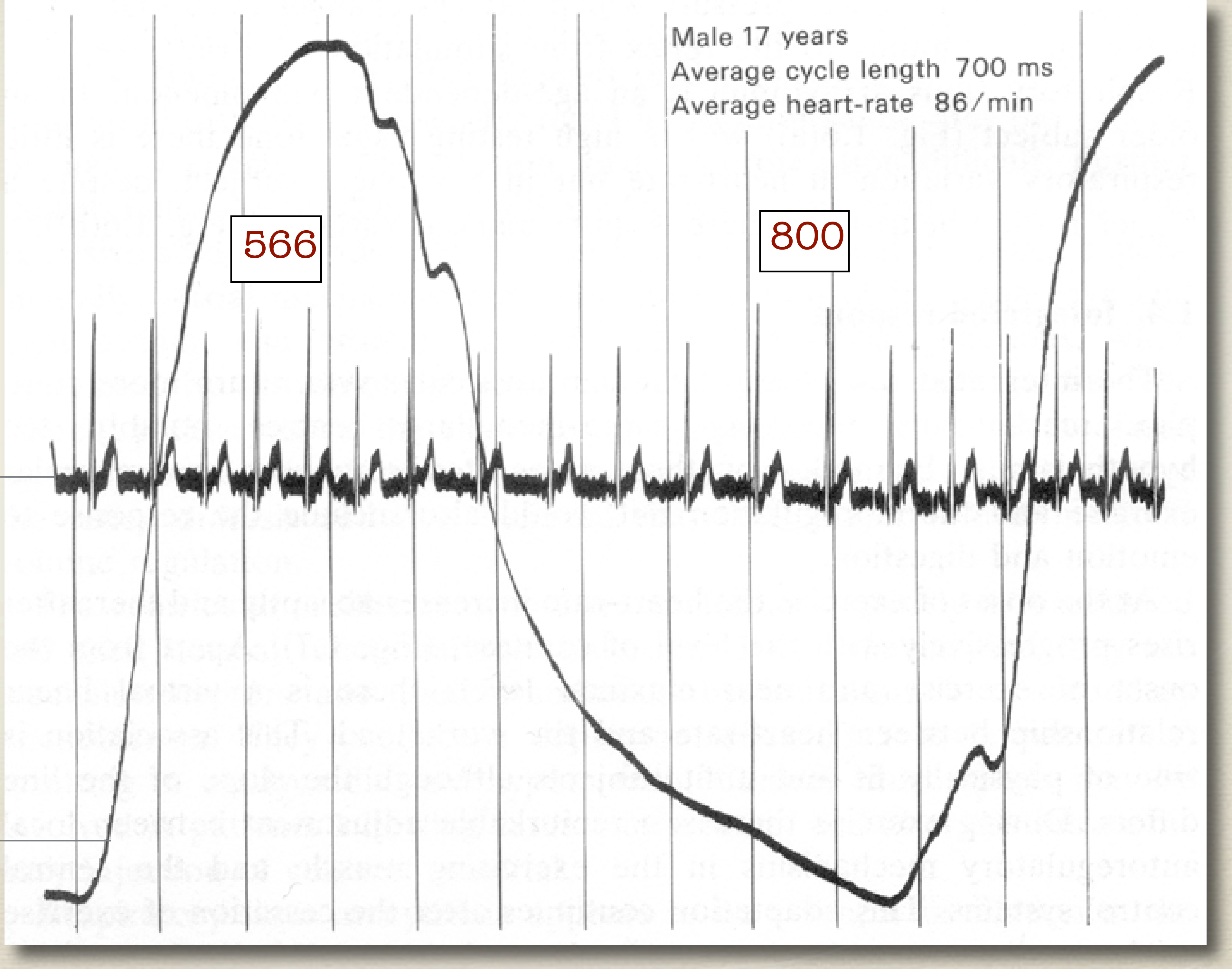
Herbert von Karajan conducting
the Leonora ouverture #3 by Beethoven

Heart Rate and Respiration

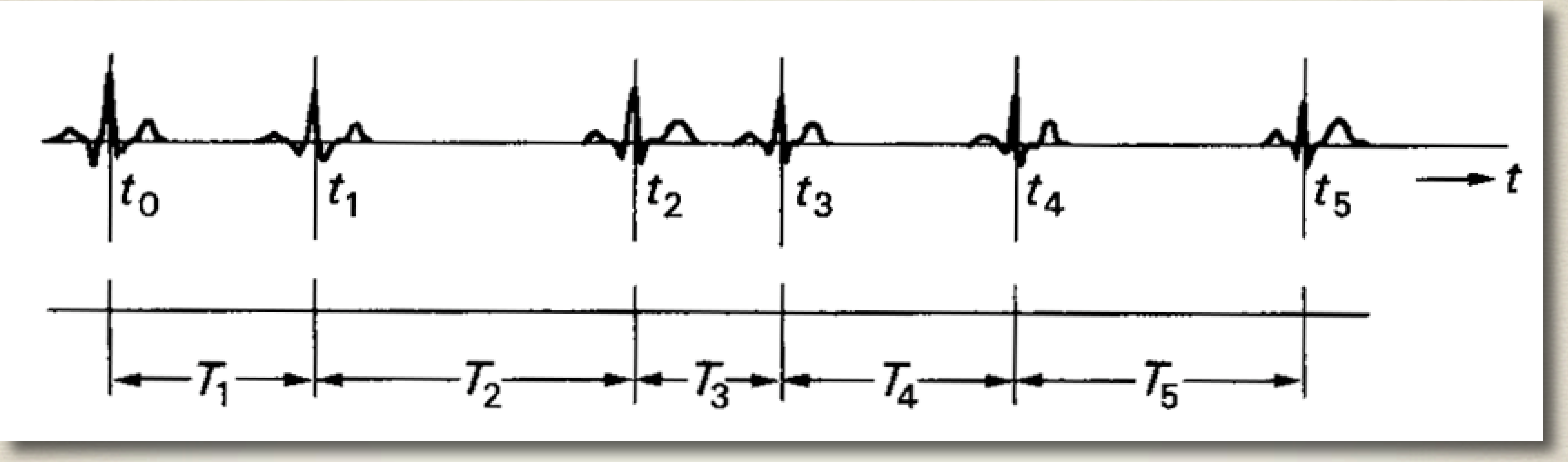
RR interval length (ms)

ECG

Lung volume



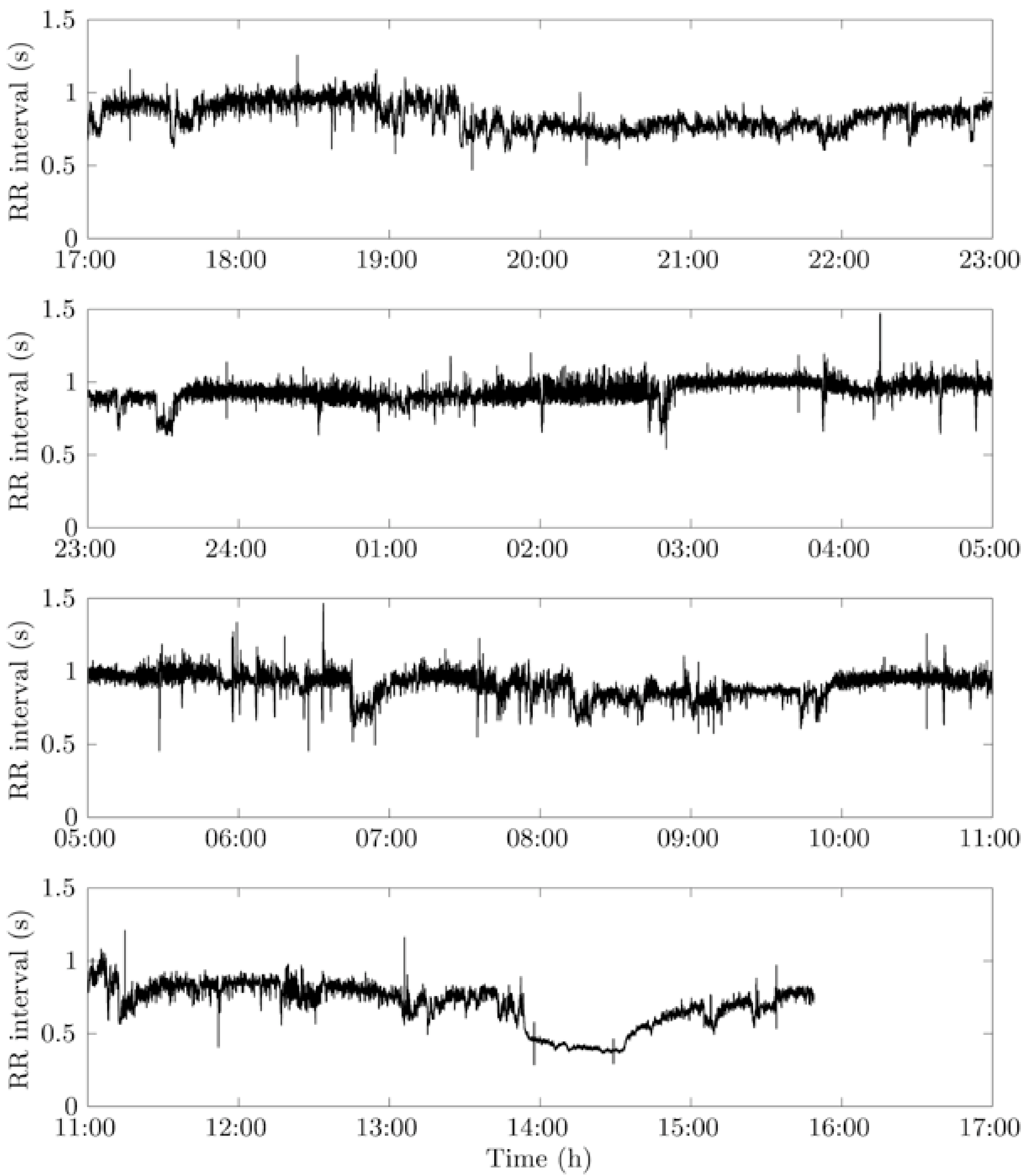
RR Interval Series



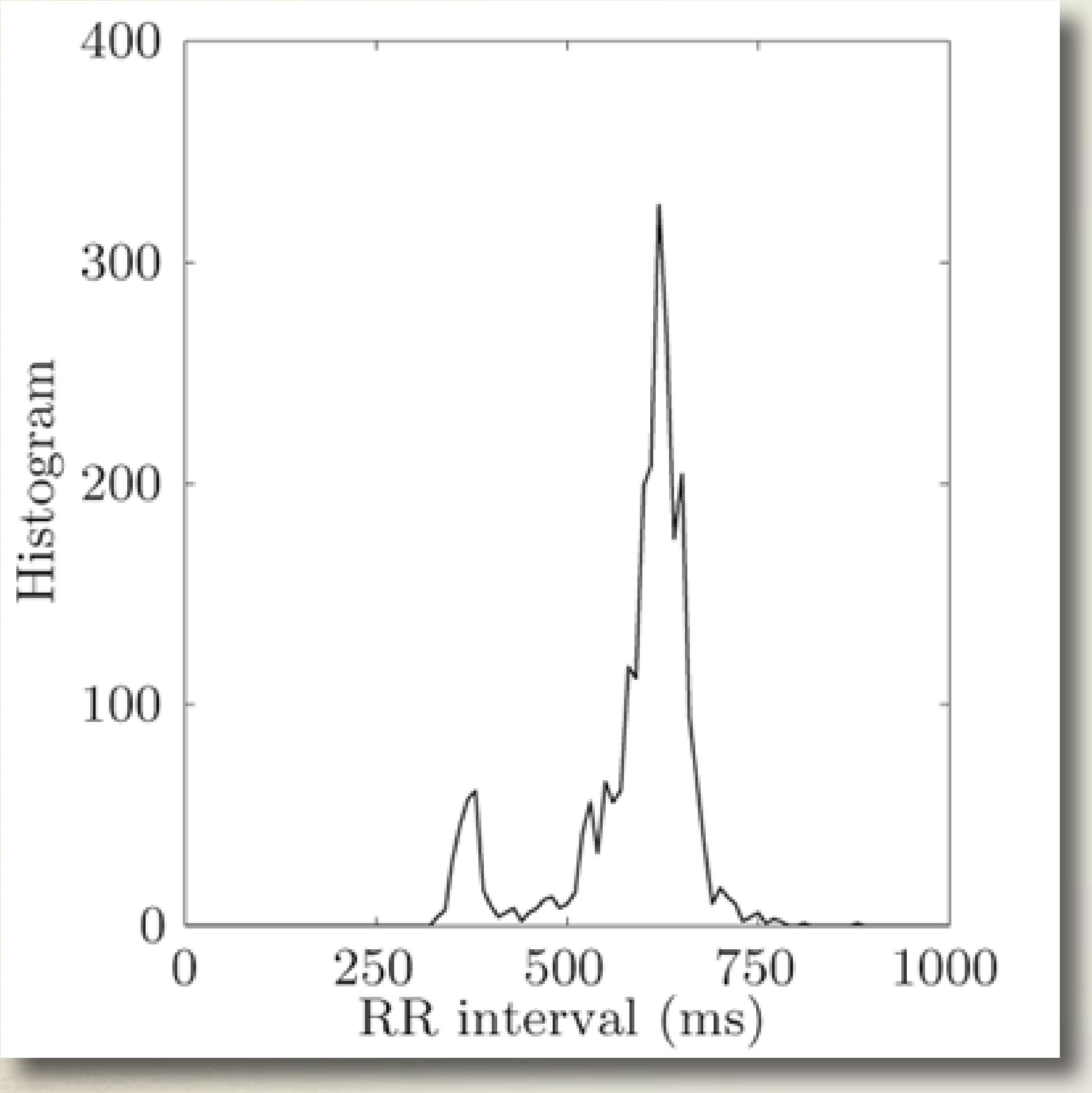
T_i = length of the i^{th} RR interval

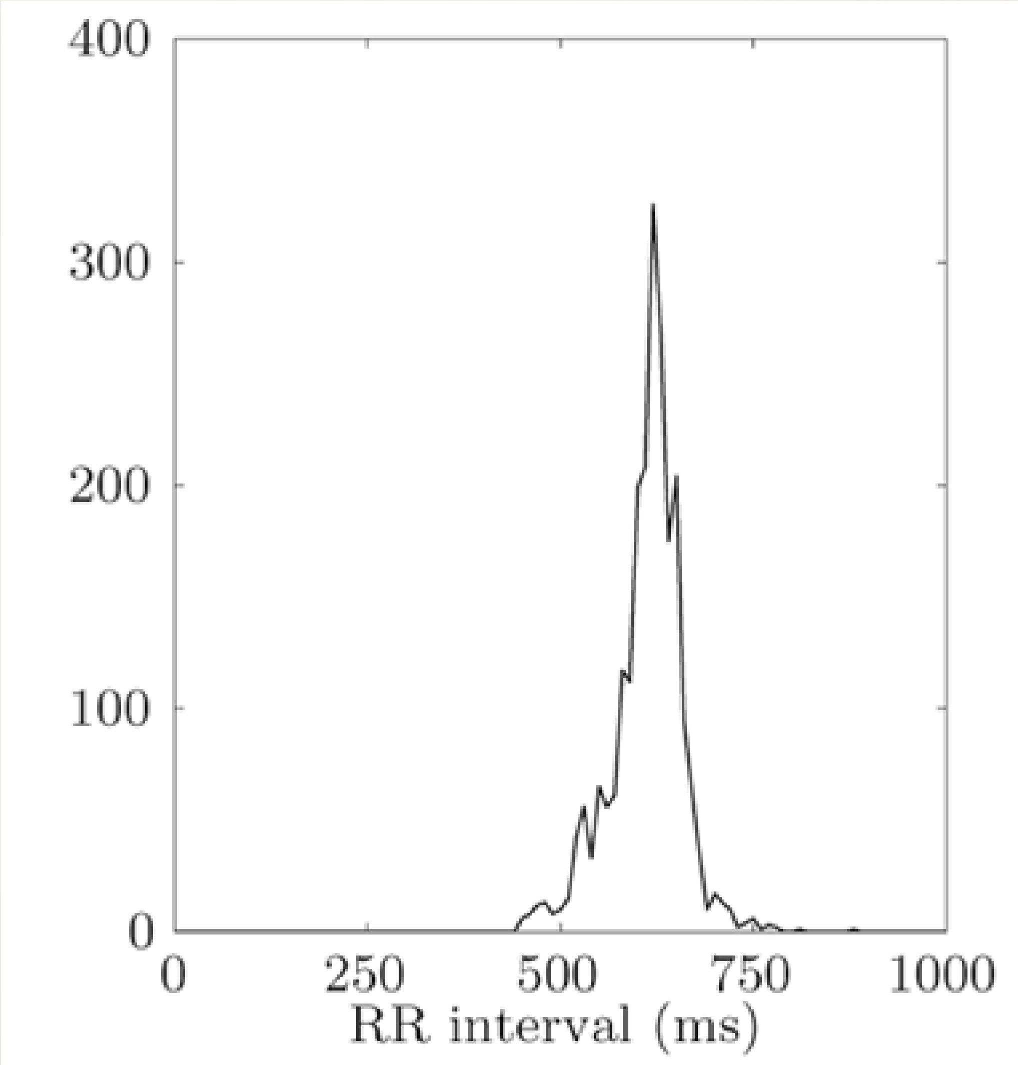
Note: the PP intervals better reflect the sinus node activity than do the RR intervals. However, the location of the P-wave is much more difficult to determine than that of the QRS complex.

24-hour RR interval trend



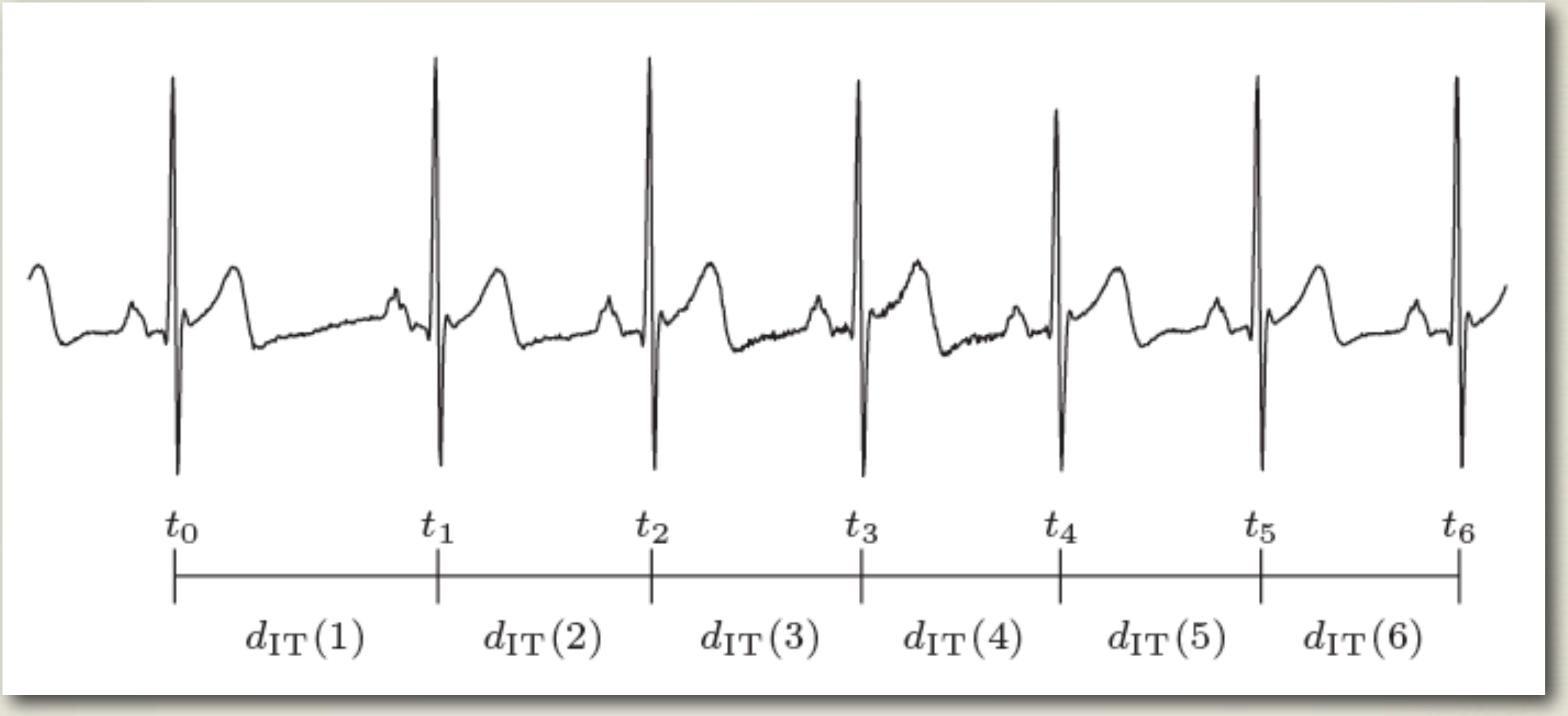
24h RR Interval Histograms





How to characterize the histogram?

The RR interval series – The Tachogram



Advantage: simple to compute
Disadvantage: spectrum is not in terms of Hz

Heart Rhythm Representations

The interval tachogram

$$d_{\mathrm{IT}}(k) = t_k - t_{k-1}, \quad k = 1, \ldots, M,$$

The inverse interval tachogram

$$d_{\mathrm{IIT}}(k) = \frac{1}{t_k - t_{k-1}}, \quad k = 1, \ldots, M,$$

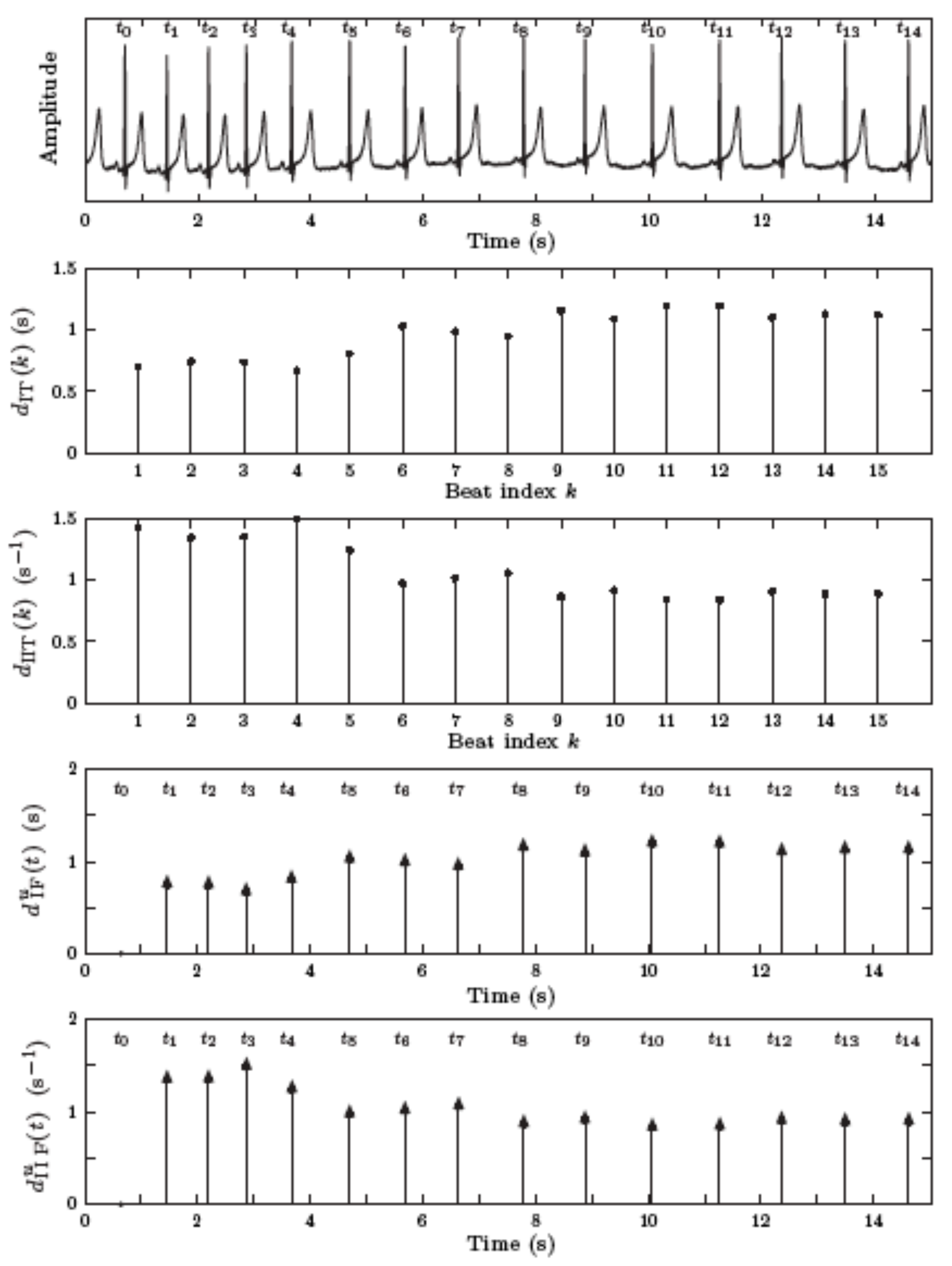
The inverse interval function

$$d^{u}_{\mathrm{IF}}(t) = \sum_{k=1}^{M} (t_k - t_{k-1})\, \delta(t - t_k)$$

The inverse interval function

$$d^{u}_{\mathrm{IIF}}(t) = \sum_{k=1}^{M} \left(\frac{1}{t_k - t_{k-1}} \right) \delta(t - t_k)$$

Heart Rhythm Representations



The ECG

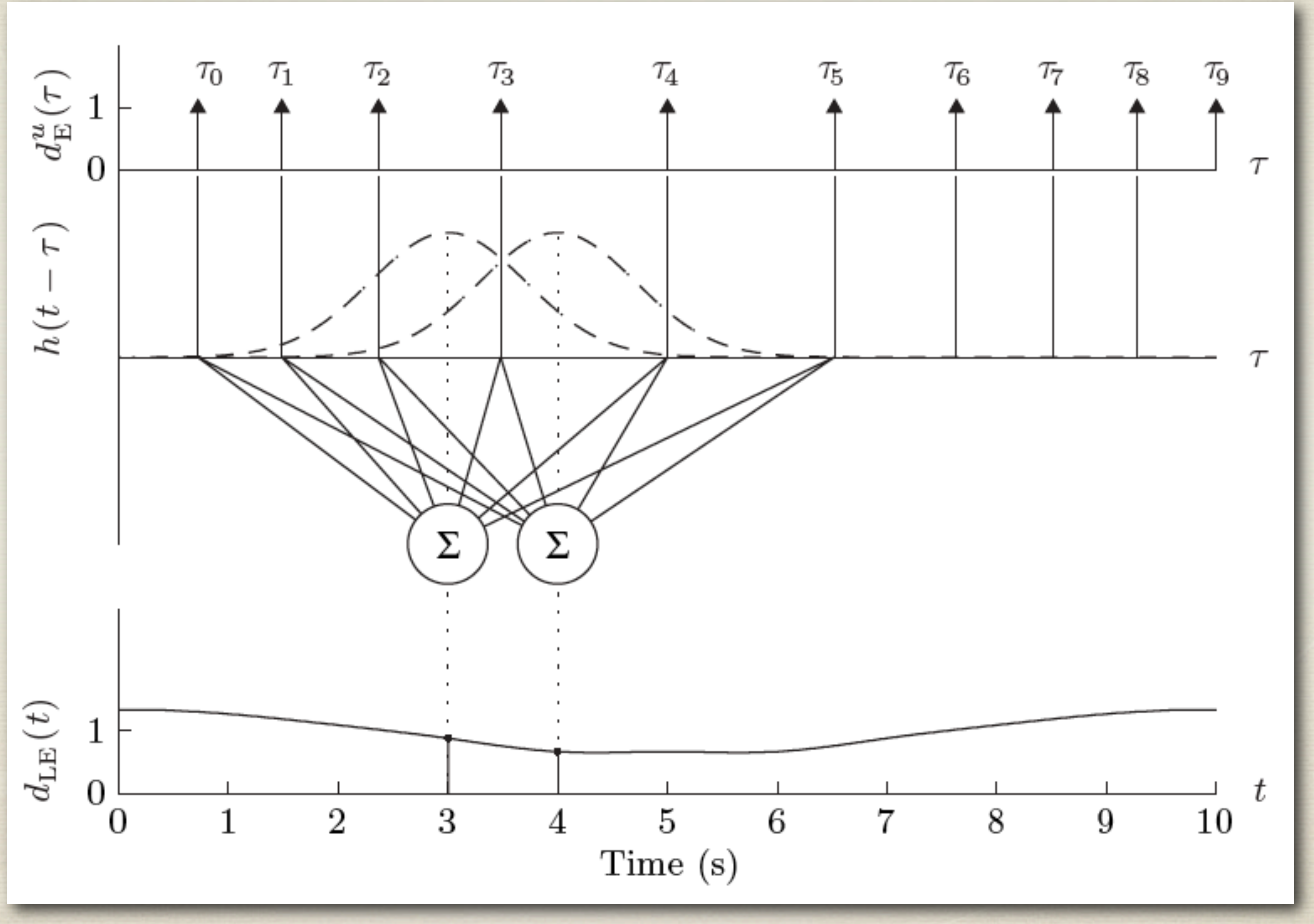
The interval tachogram

The inverse interval tachogram

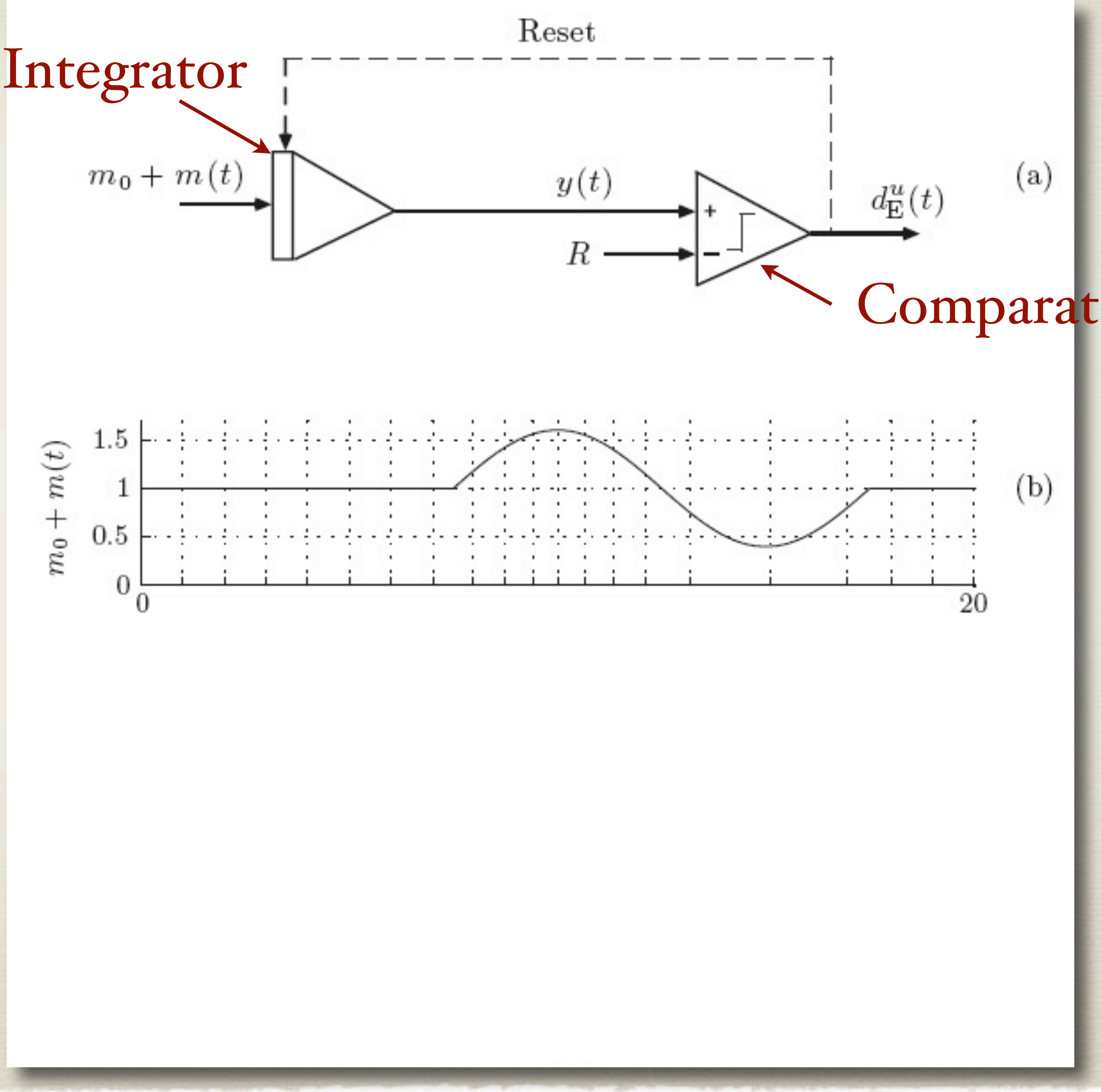
The inverse interval function

The inverse interval function

Lowpass Filtered Event Series



Integral Pulse Frequency Modulation (IPFM) Model



Integrator

Comparator

IPFM model

Modulation function

Integrator output

Event series

Output of the IPFM Model

IPFM model equation

$$\int_{t_{k-1}}^{t_k} (m_0 + m(\tau))d\tau = R, \quad k = 1, \ldots, M.$$

Event series as output

$$d_{\mathrm{E}}^{u}(t) = \sum_{k=0}^{M} \delta(t - t_k),$$

Heart Timing Signal

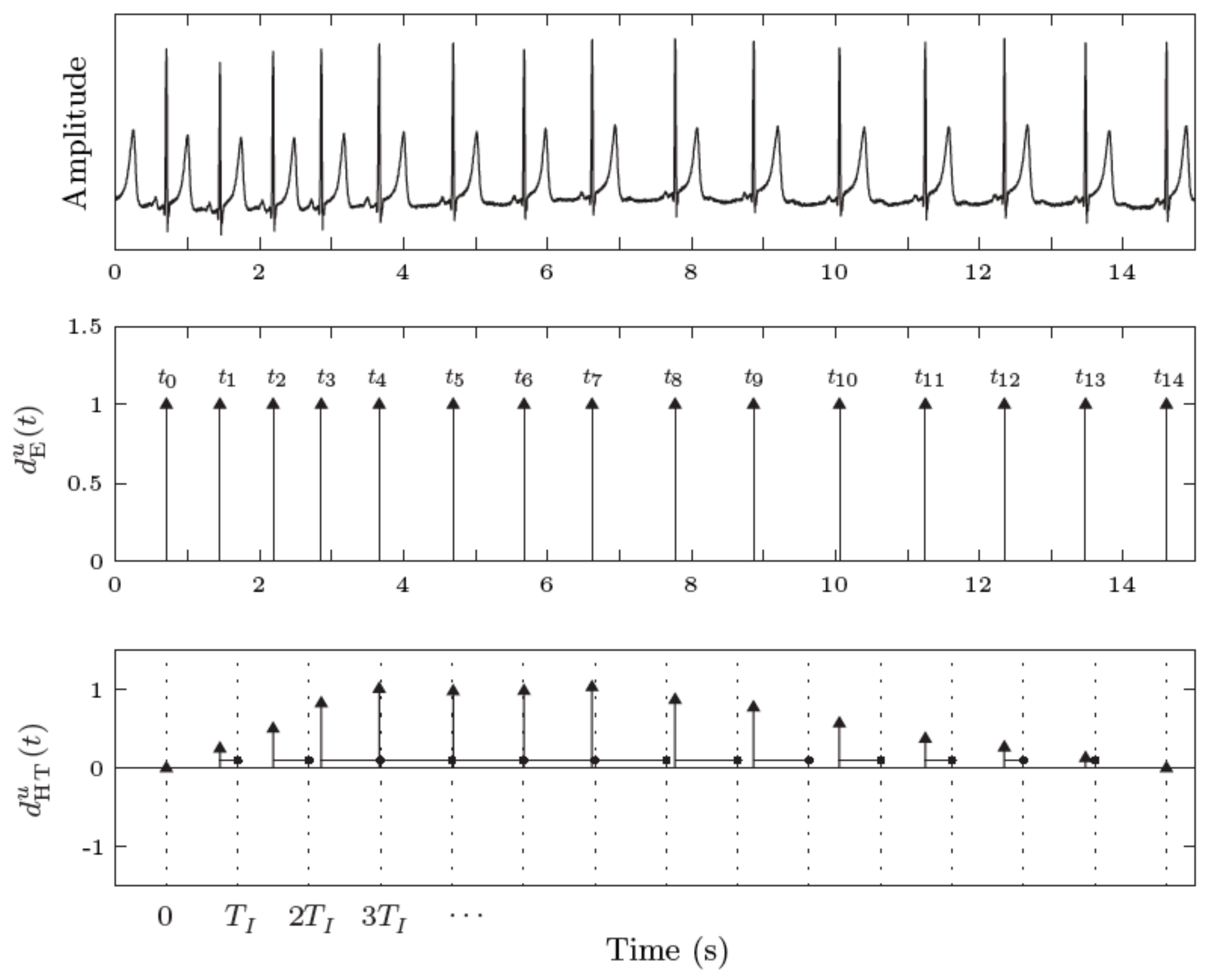
$$\begin{aligned} d^{u}_{\mathrm{HT}}(t) &= \sum_{k=0}^{M} (kT_I - t_k)\delta(t - t_k) \\ &= \sum_{k=0}^{M} d_{\mathrm{HT}}(t)\delta(t - t_k), \end{aligned}$$

i.e., defined as the deviation of the event time t_k from the expected occurrence time which is related to the mean RR interval length

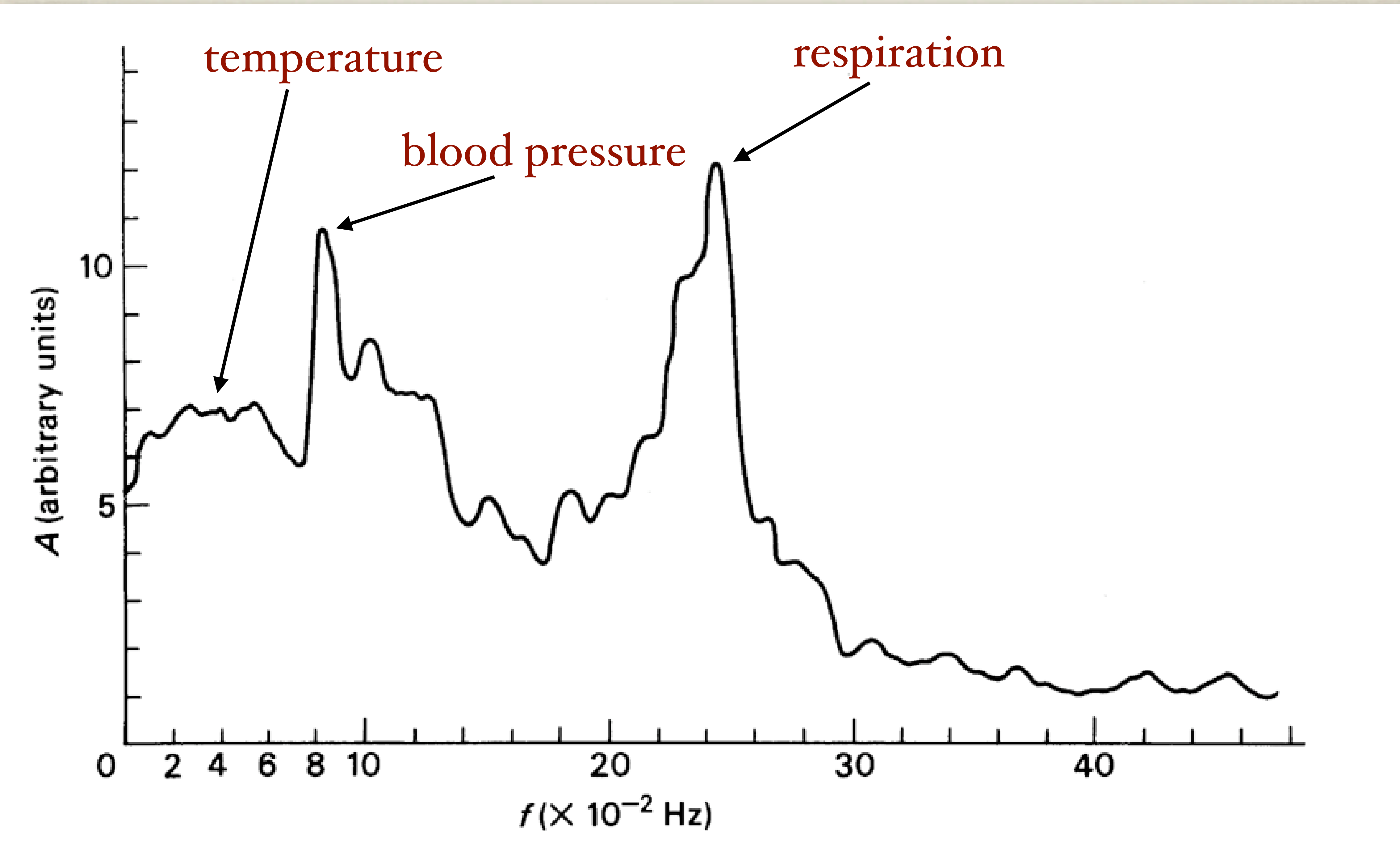
Compare this with the IPFM model:

$$\begin{aligned} \int_0^{t_k} m(\tau)d\tau &= kT_I - t_k \\ &= d_{\mathrm{HT}}(t_k). \end{aligned}$$

Heart Timing Signal: Example



Why Spectral Analysis of HRV?



Spectrum of Counts

Event series

$$x(t) = \sum_{k=1}^{N} \delta(t - t_k)$$

Fourier transform

$$X(\Omega) = \int_{-\infty}^{\infty} x(t) e^{-j\Omega t} dt$$

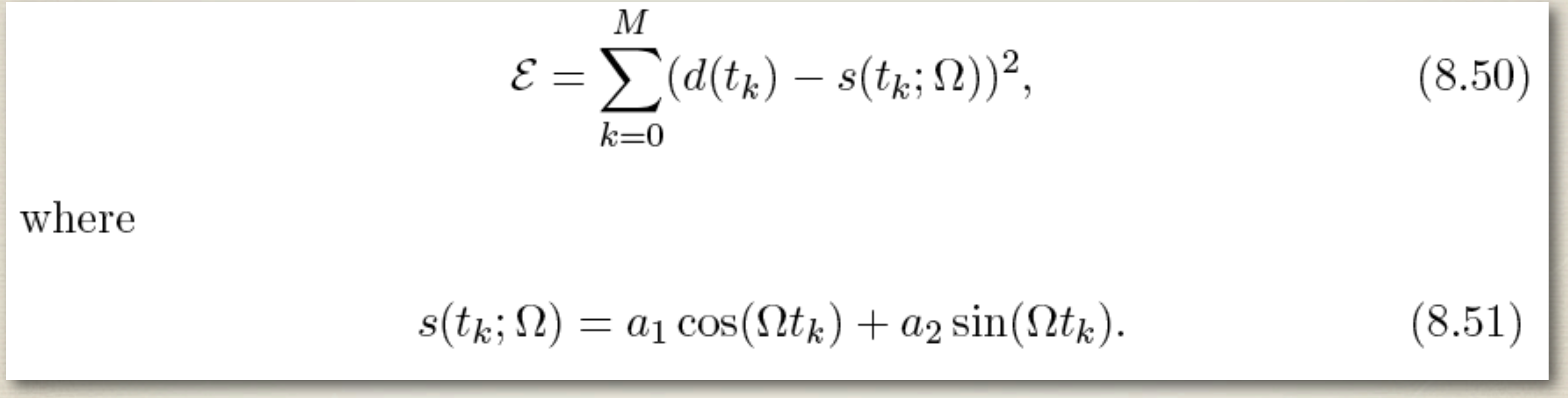
$$= \sum_{k=1}^{N} e^{-j\Omega t_k} = \sum_{k=1}^{N} (\cos \Omega t_k + j \sin \Omega t_k)$$

Power spectrum

$$S_x(\Omega) = \frac{1}{N} \left[\left(\sum_{k=1}^{N} \cos \Omega t_k \right)^2 + \left(\sum_{k=1}^{N} \sin \Omega t_k \right)^2 \right]$$

Lomb's Periodogram

The main idea behind Lomb's periodogram is the definition of a spectrum that results from minimization of the squared error between the observed data d(t_k) and a sinusoidal model signal s(t_k; Ω),

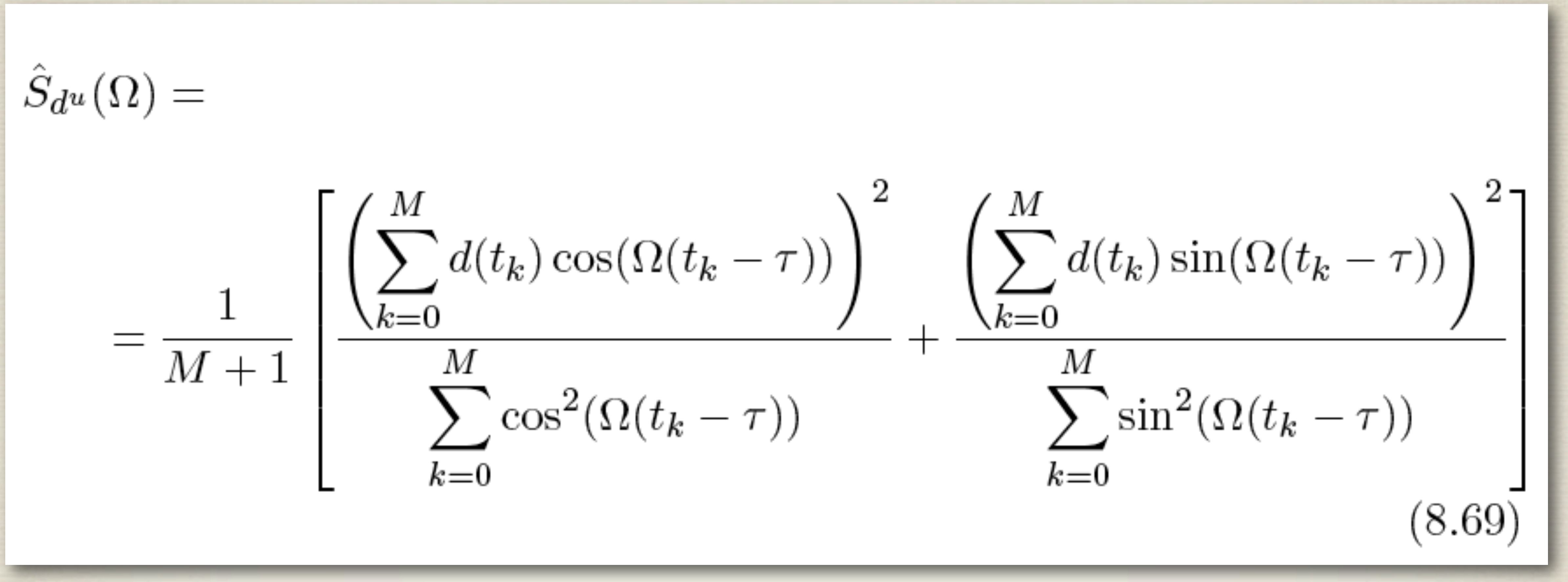


$$\mathcal{E} = \sum_{k=0}^{M} (d(t_k) - s(t_k; \Omega))^2, \tag{8.50}$$

where

$$s(t_k; \Omega) = a_1 \cos(\Omega t_k) + a_2 \sin(\Omega t_k). \tag{8.51}$$

Lomb's Periodogram, cont'



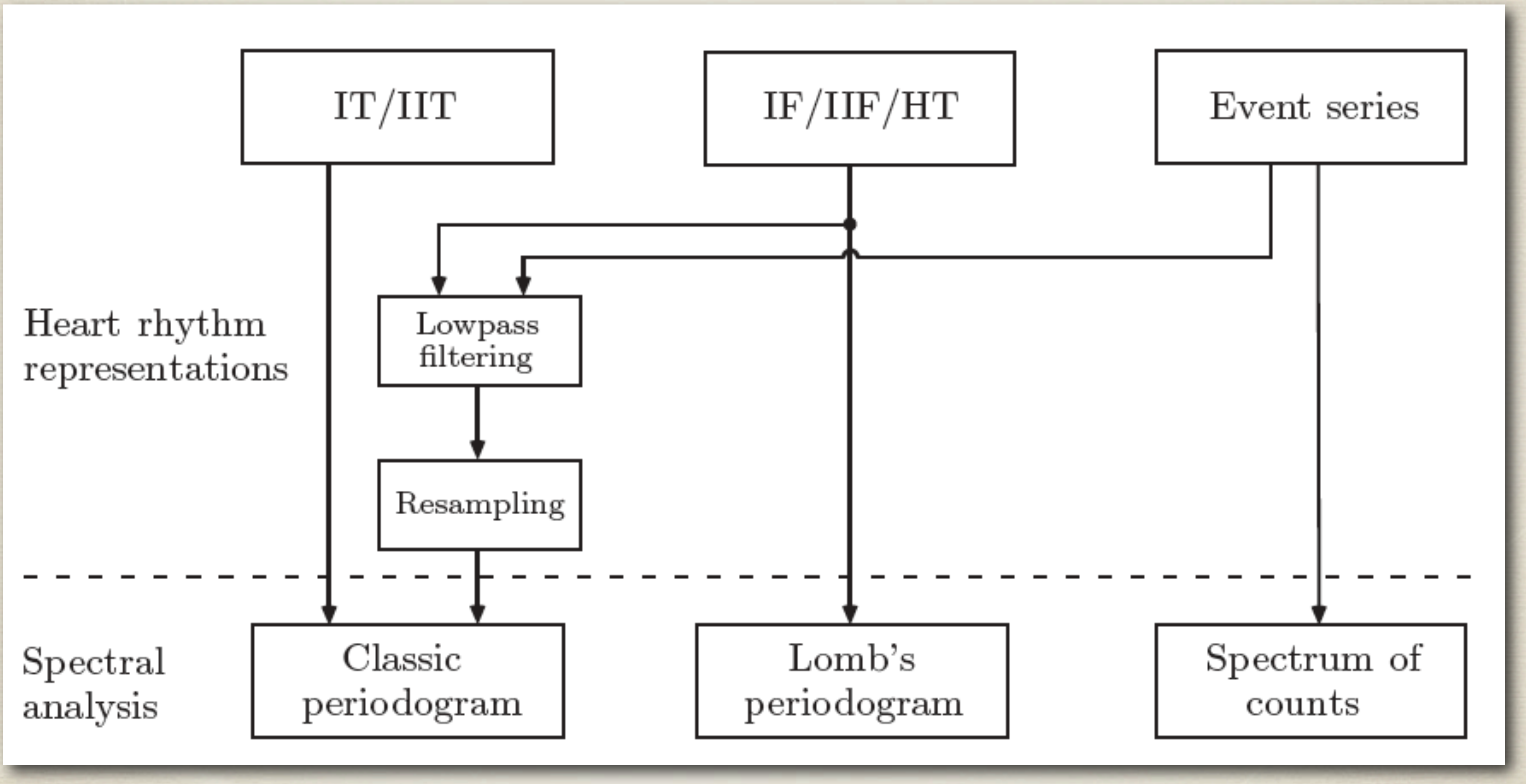
$$\hat{S}_{d^u}(\Omega) = \frac{1}{M+1}\left[\frac{\left(\sum_{k=0}^{M} d(t_k)\cos(\Omega(t_k-\tau))\right)^2}{\sum_{k=0}^{M}\cos^2(\Omega(t_k-\tau))} + \frac{\left(\sum_{k=0}^{M} d(t_k)\sin(\Omega(t_k-\tau))\right)^2}{\sum_{k=0}^{M}\sin^2(\Omega(t_k-\tau))}\right] \tag{8.69}$$

where τ is introduced to make Lomb's periodogram translation invariant in time, implying that identical periodograms are produced irrespective of where the observed samples are located in time.

Lomb's Periodogram and the Classical Periodogram

Lomb's periodogram reduces to the classical periodogram when the event times t_k are evenly sampled with the sampling interval T_I , i.e., $t_k = kT_I$, at the Nyquist rate or higher.

HRV Spectral Analysis



IT/IIT

IF/IIF/HT

Event series

Heart rhythm representations

Lowpass filtering

Resampling

Spectral analysis

Classic periodogram

Lomb's periodogram

Spectrum of counts

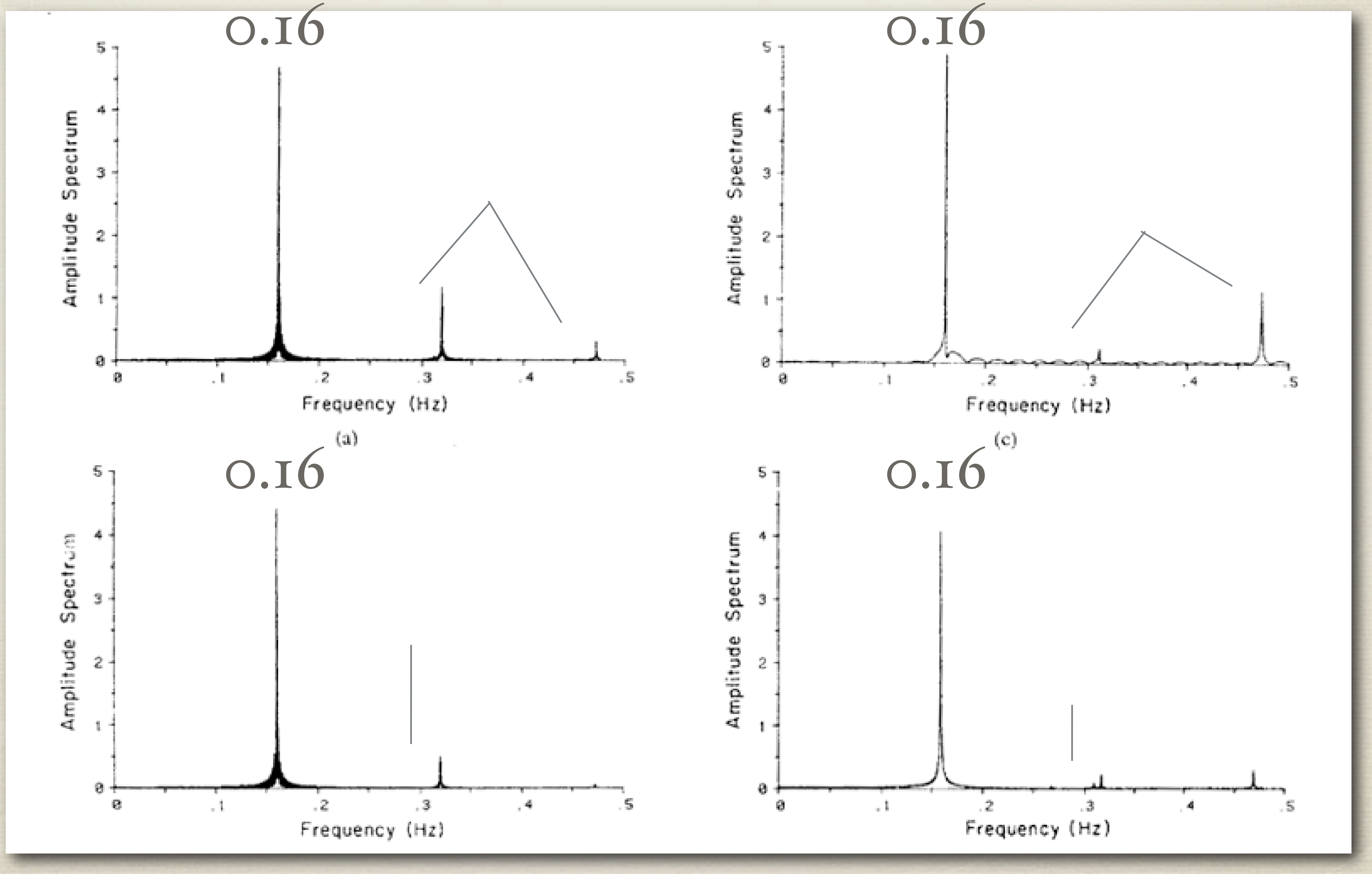
HRV Spectrum: A Comparison

- Spectrum of interval tachogram,
- spectrum of inverse interval function,
- spectrum of counts,
- spectrum of the lowpass filtered event series...
- ...are shown in the following slides!

Power Spectrum with One Modulation Frequency (0.16 Hz)

interval tachogram

inverse interval function



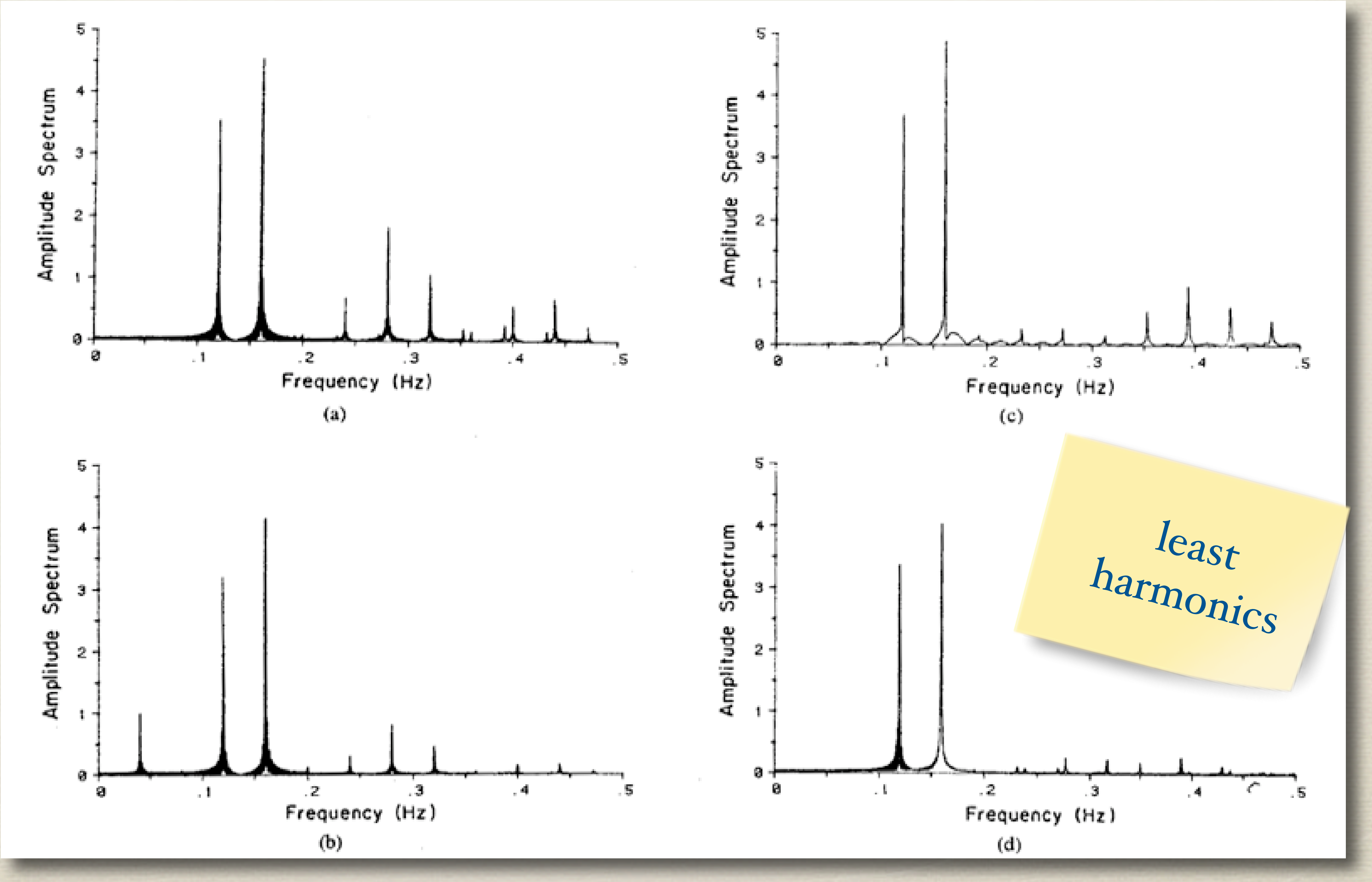
event series

LPFES

Power Spectrum with Two Modulation Frequencies (0.12, 0.16)

interval tachogram

inverse interval function



(a)

(b)

(c)

(d)

event series

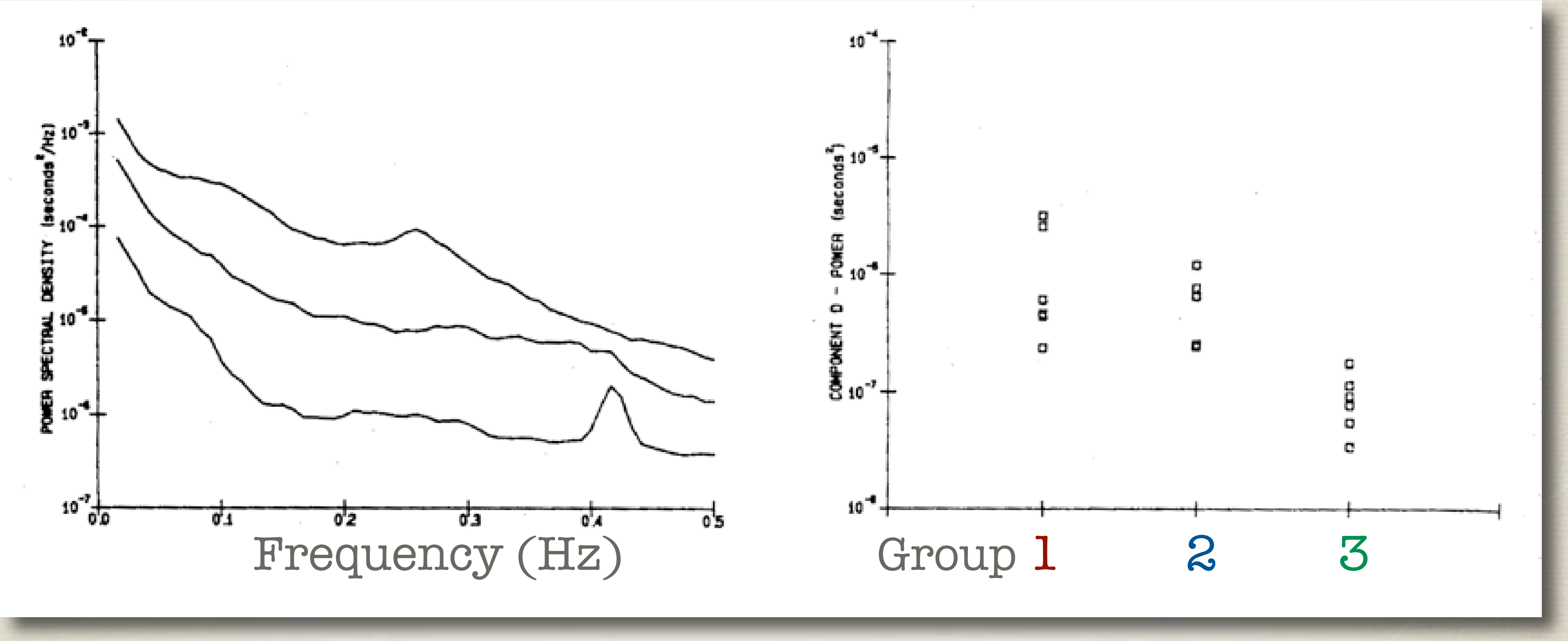
LPFES

least harmonics

HRV and Sudden Cardiac Death

Power spectrum (log scale)

Spectral power in 0.35–0.50 Hz

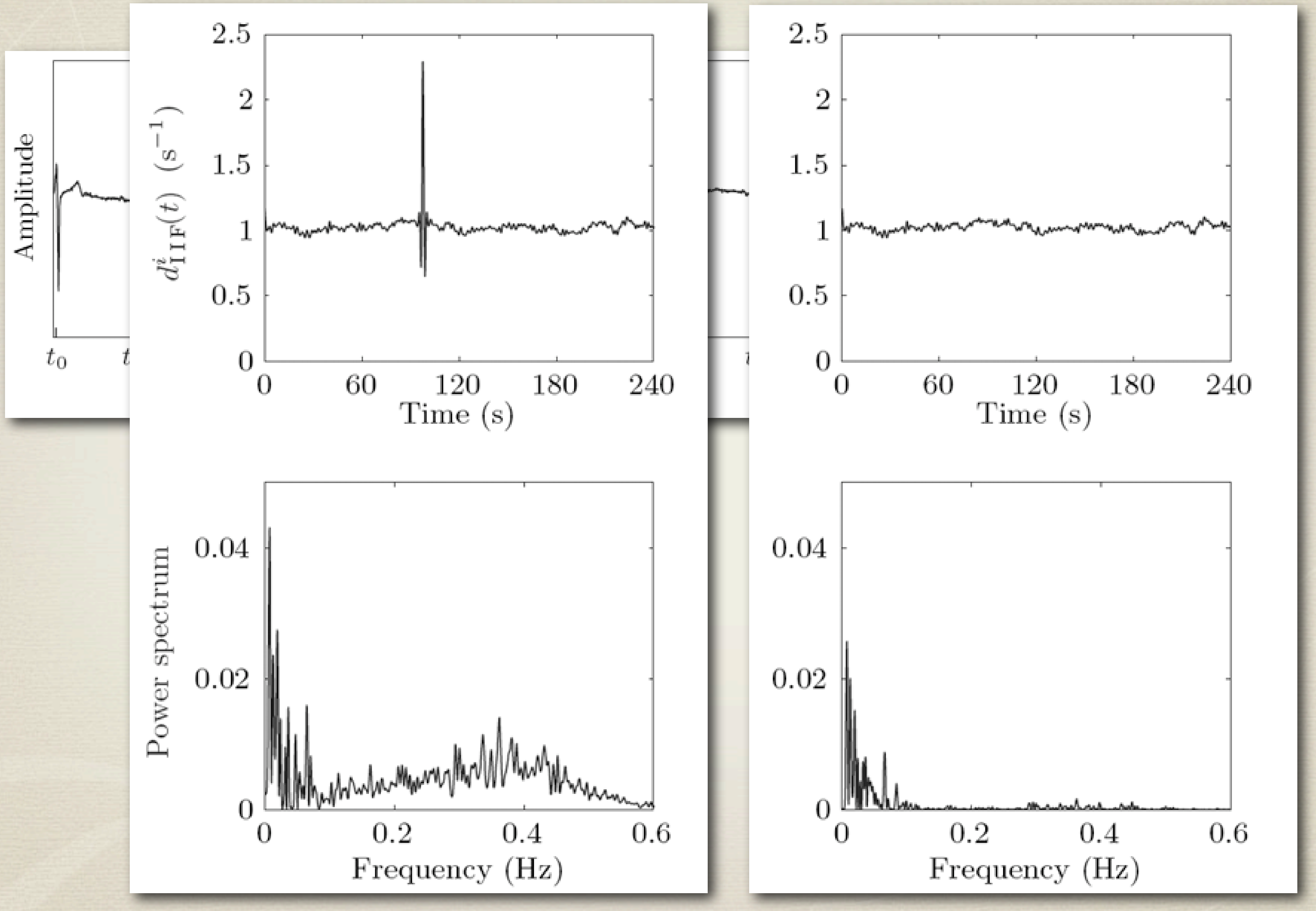


Group 1: normals

Group 2: diseased (many ectopics), low risk for SCD

Group 3: resuscitated from ventr. fibrillation, high risk for SCD

Ectopic Beat Correction



RR Interval or Heart Rate?

- Heart rate is inversely proportional to RR interval length.
- These two quantities appear to represent the same information, but the corresponding power spectra are obviously somewhat different.

Do not maltreat the signals...