Chapter 3
Filtering for Removal of Artifacts

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Introduction

- Noise
  - Any signal that is not what we are interested in. (also termed as interference or artifact)

Problem statement

- Analyze various types of artifacts that corrupt biomedical signals and explore filtering techniques to remove them without degrading the signal of interest.
  - EMG during ECG acquisitions
  - Electronic noise from instruments
  - Power-line interference
  - EM waves in our environment

Deterministic vs. Random signal

- Deterministic signal
  - Whose value at a given instant of time may be computed
    - using a closed-form mathematical function of time
    - or predicted from a knowledge of a few past values of the signal
- Otherwise signal is a random signal

Random noise

- An interference that arises from a random process such as thermal noise in electronic devices
- A random process is characterized by the probability density function (PDF)
  - Probabilities of occurences of all possible values of a random variable

Random process

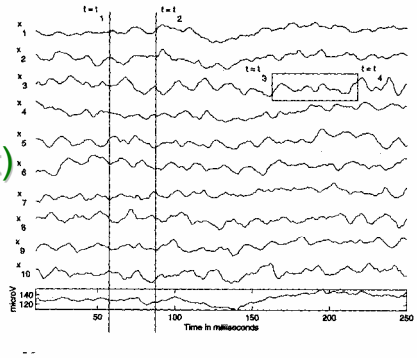
- x: a random process with pdf $p_x(x)$
  - Mean: $\mu_x = E[x] = \int x\, p_x(x)\, dx$
    - DC component of the signal
  - Mean-squared (MS): $E[x^2] = \int x^2\, p_x(x)\, dx$
    - Average power
  - Variance: $\sigma_x^2 = E[(x-\mu_x)^2] = \int (x-\mu_x)^2\, p_x(x)\, dx$
  - SNR: signal to noise ratio = average power of the signal to that of the noise
- PCG may be represented as a random process

Ensemble averages

- When the PDFs of random processes of concern are not known
  - Approximate the statistical expectation operation by averages computed using a collection or ensemble of sample observations of the random process
  - Such averages are called ensemble averages

Ensemble averages

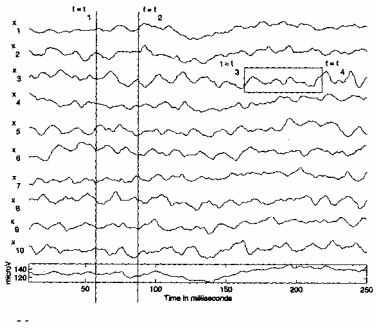
- M observations of random process x as functions of time
  - $x_1(t), x_2(t), x_3(t), \ldots, x_M(t)$
  - Estimate the mean of the process at t1
  - $\mu_x(t1)=\lim (1/M) \Sigma x_k(t_1)$



Flash visual ERP
10 realizations

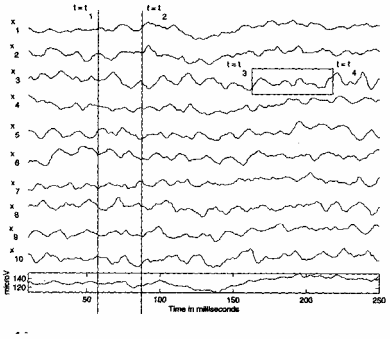
Ensemble averages

- Autocorrelation function ACF
  - shows how the values of a signal at a particular instant of time are statistically related to (or have characteristics in common) values of the same signal at another time instant
  - $\Phi_{xx}(t_1,t_1+\tau)=\lim (1/M) \Sigma x_k(t_1)\, x_k(t_1+\tau)$
    - τ is the delay parameter
- Average signal (as a function of time):
  - $\bar{x}(t) = \mu_x(t) = (1/M) \Sigma x_k(t)$



Time averages

- $\mu_x(k) = \lim (1/T) \int_{-T/2}^{T/2} x_k(t)$
- Time-averaged ACF
  - $\Phi_{xx}(\tau,k)=\lim (1/T) \int_{-T/2}^{T/2} x_k(t)\, x_k(t+\tau)$
- FT of the ACF is the power spectral density (PSD) function
  - Useful in spectral analysis and filter design



Covariance

- $C_{xy}=E[(x-\mu_x)(y-\mu_y)]=$
  $\iint(x-\mu_x)(y-\mu_y)\, p_{xy}(x,y)\, dx\, dy$
  - $p_{xy}(x,y)$: joint PDF
- Correlation coefficient
  - $\rho_{xy} = C_{xy}/\sigma_x\sigma_y$
- High covariance = two processes have "similar" variability or behaviour

Cross-correlation

- $\theta_{xy}(t1,t1+\tau) = E[x(t1)y(t1+\tau)]=$
  $\iint x(t_1)y(t_1+\tau)p_{xy}(x,y)\,dx\,dy$
- Correlation functions are useful
  - in analyzing the nature of variability and spectral bandwidth of signals
  - For event detection in template matching

Structured noise

- Typical waveform of the interference is known in advance
  - Example: power-line interference (50 or 60 Hz)
- Phase of the waveform may not be known
- Interfering waveform may not be exact sinusoid
  - Harmonics of the fundamental 50 or 60 Hz component may be present

Physiological Interference

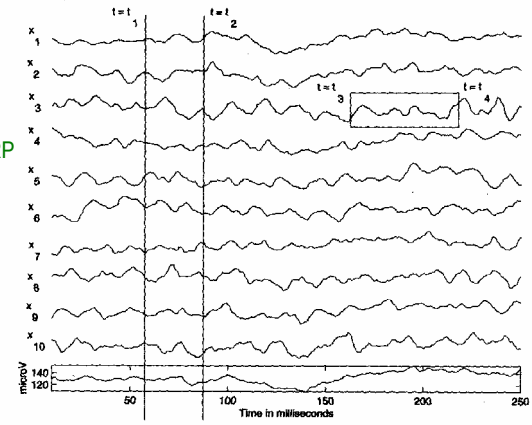
- EMG affecting ECG
- EGG interfering with precordial ECG
- Maternal ECG added to the fetal ECG of interest
- ECG interfering with the EEG
- Ongoing EEG in ERPs
- Breath, lung, or bowel sounds contaminating the heart sounds (PCG)

Illustration of the problem with case-studies

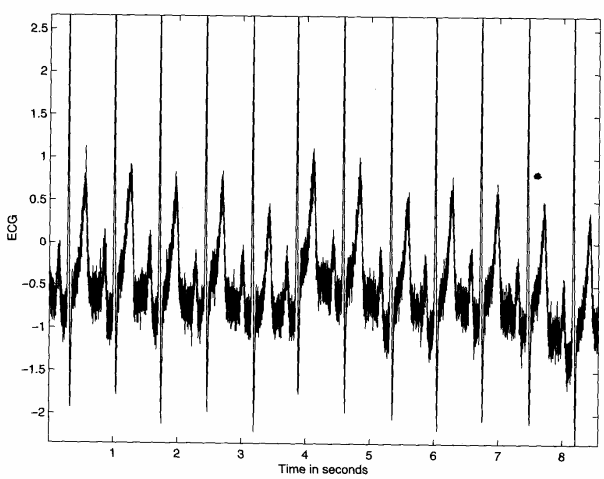
- ERP has a very small amplitude (10 microVolt)
- Due to the ongoing EEG and power-line interference ERP signals cannot be analyzed using the individual acquisitions

Multiple Realizations in ERP Acquisition

Flash visual ERP
10 realizations

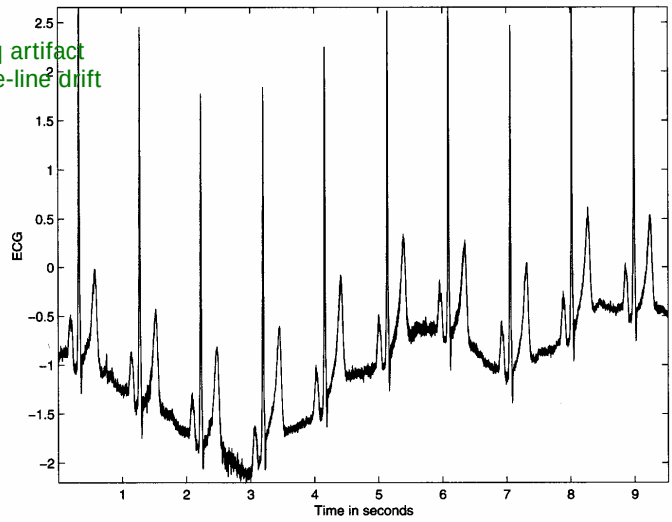


HF noise in the ECG

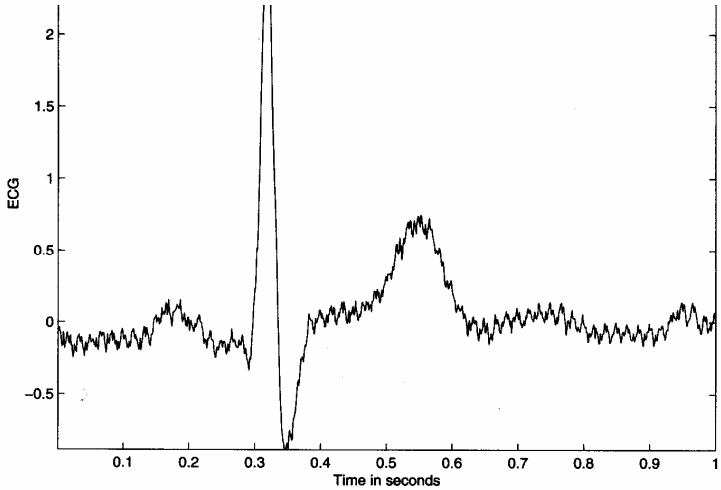


Motion artifact in the ECG

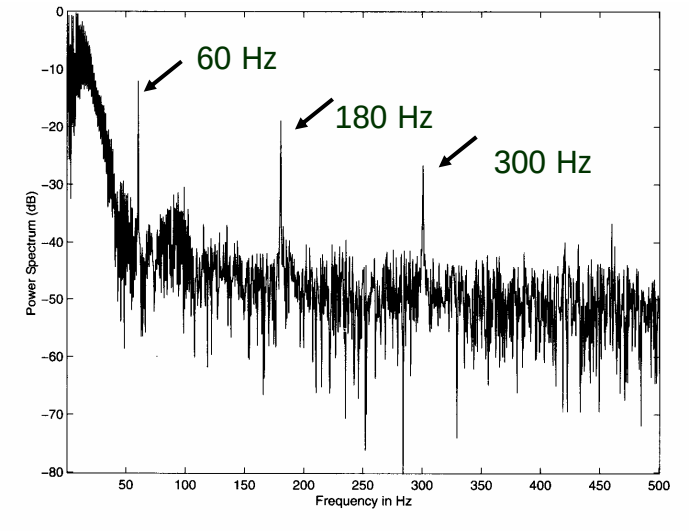
Low-freq artifact
and base-line drift



Power-line interference in ECG signals



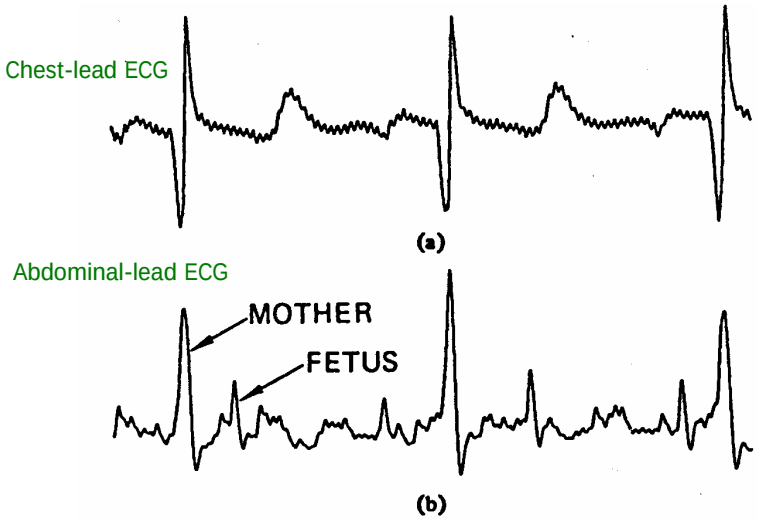
Power spectrum of the ECG signal



Low-pass filtering

- The bandwidth of ECG signal = 0.05-100 Hz which includes the 60 Hz component
- Low-pass filtering will work?
- LPFing
  - Causes smoothing and blurring in the QRS complex,
  - Affects the PQ and ST segments
- Solution
  - remove 60 Hz without sacrificing any other component

Maternal interferences in fetal ECG



Potential solutions to the problem

- Investigate various types of artifacts
- Demonstrate increasingly complex techniques to remove them
  - Time-domain filters
  - Frequency-domain filters