Advances in Electrocardiogram Signal Processing and Analysis

A model-based perspective

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Overview

- Introduction
- Overview of Model-Based ECG Analysis
- Recent Developments and Trends

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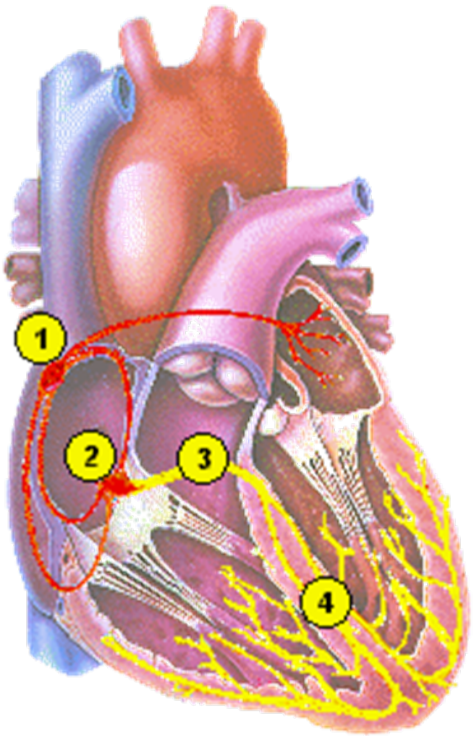
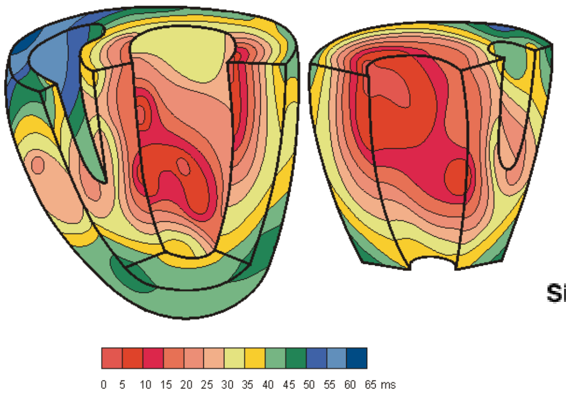
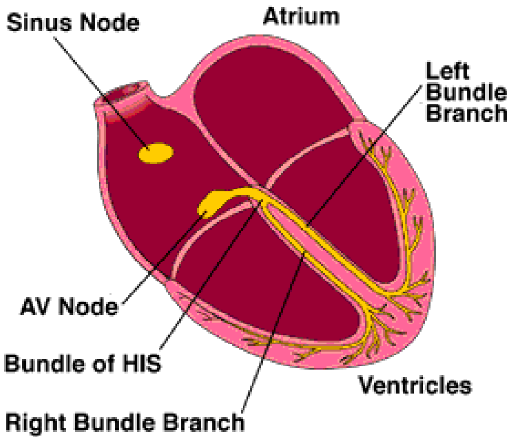
The Myocardium



The heart as a muscle

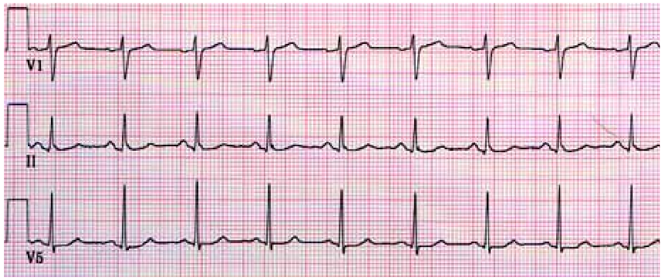


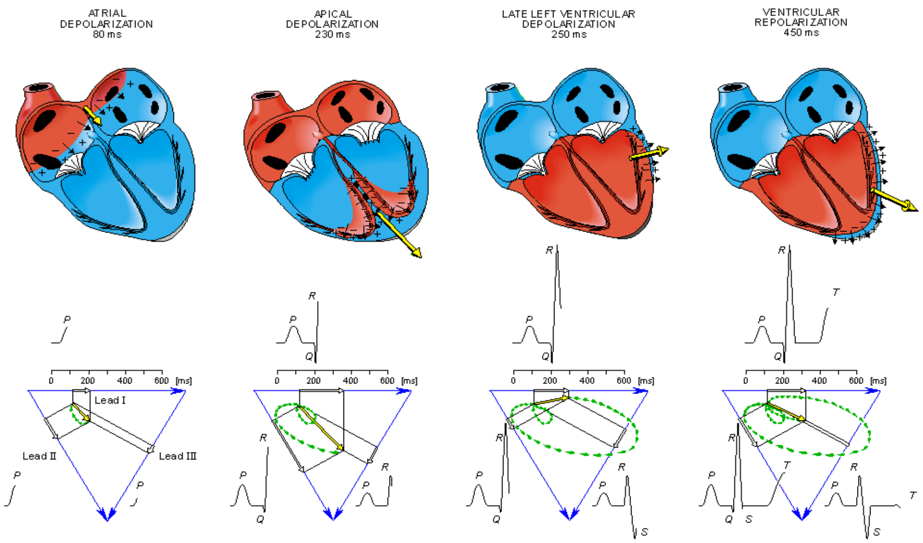


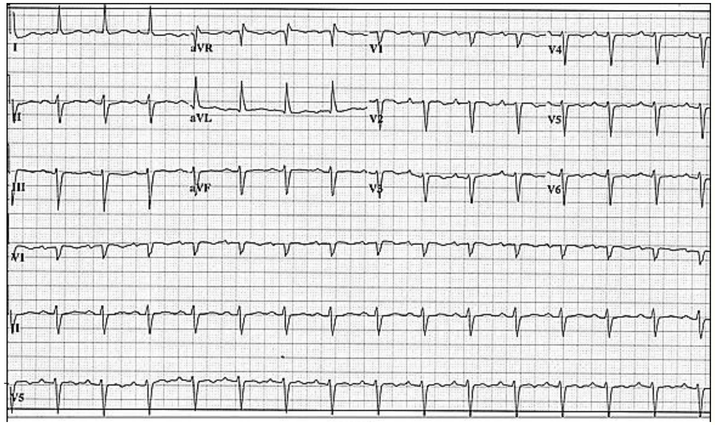
The heart as a surface of potentials

The Electrocardiogram (ECG)

- The Electrocardiogram (ECG) is the overall electrical activity of the heart recorded from the body surface

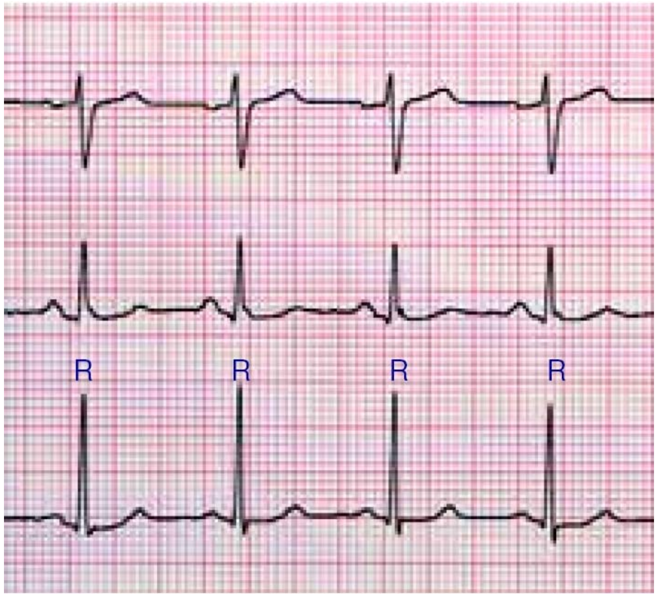




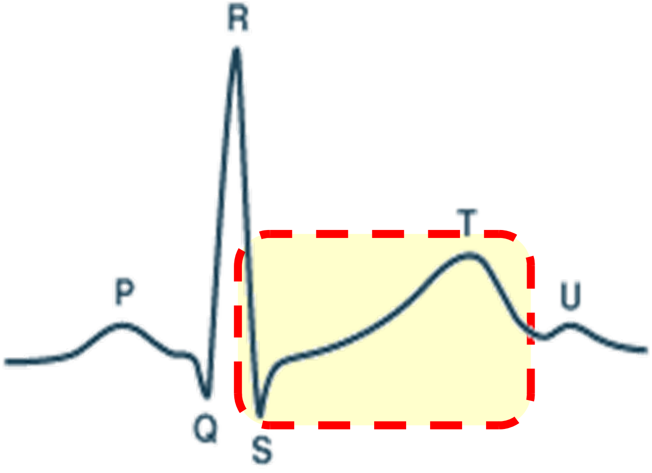


The Electrocardiogram (ECG)

- The major ECG information are embedded in its RR-interval time-series and beat-wise morphology



RR-Intervals



Morphology

Signal Processing Aspects of the Heart

- A distributed source, which can only be approximated by a dipole in the far-field

  → Multichannel Analysis issues

- A random electrical field (SA-node pacemaker cells)

  → Stochastic processes

- Variable waveforms ranging from cyclostationary to chaotic and fully random waveform

  → Nonlinear dynamics & chaos

- A mixture of discrete-time and continuous-time dynamical system

  → Markov chains versus continuous-time cyclostationary dynamic systems

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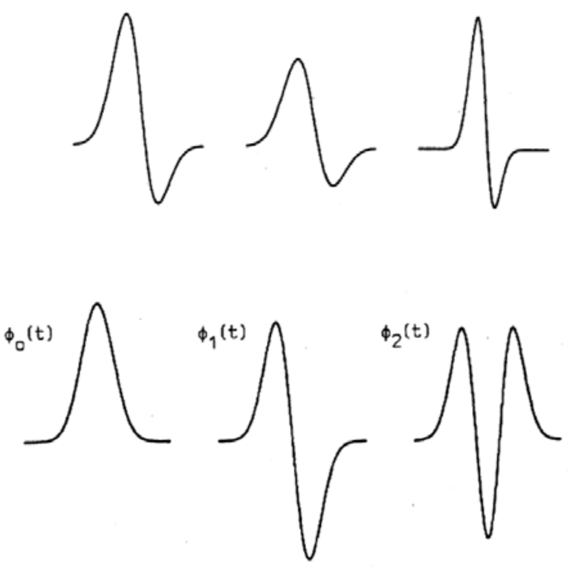
Cardiac Modeling

- Model-based ECG signal processing is currently a prominent branch in ECG analysis

- As with all biological systems, the heart can be modeled at different "levels of abstraction":
    - A mechanical pump with electro-mechanical analogy
    - An electro-chemical system
    - A massive ensemble of numerous action potentials (AP)
    - ✓ A signal source

ECG Signal Modeling

- Scher et al. (1960) → Factor Analysis
- Sornmo et al. (1981)→ Bessel Functions
- Laguna et al. (1996) → Hermite polynomials
- McSharry et al. (2003)→ Gaussian kernels in a dynamical form



✓ The latter became a turning point in ECG modeling and analysis; due to its dynamic representation

McSharry-Clifford's Synthetic ECG Generator and its polar extension

$$\dot{x} = \alpha x - \omega y \qquad \alpha = 1 - \sqrt{x^2 + y^2}$$

$$\dot{y} = \alpha y + \omega x \qquad \Delta\theta_i = (\theta - \theta_i) \bmod (2\pi)$$

$$\dot{z} = -\sum_{i \in \{P,Q,R,S,T\}} a_i \Delta\theta_i \exp\left(-\frac{\Delta\theta_i^2}{2b_i^2}\right) - (z - z_0) \qquad \theta = \mathrm{atan2}(y, x)$$

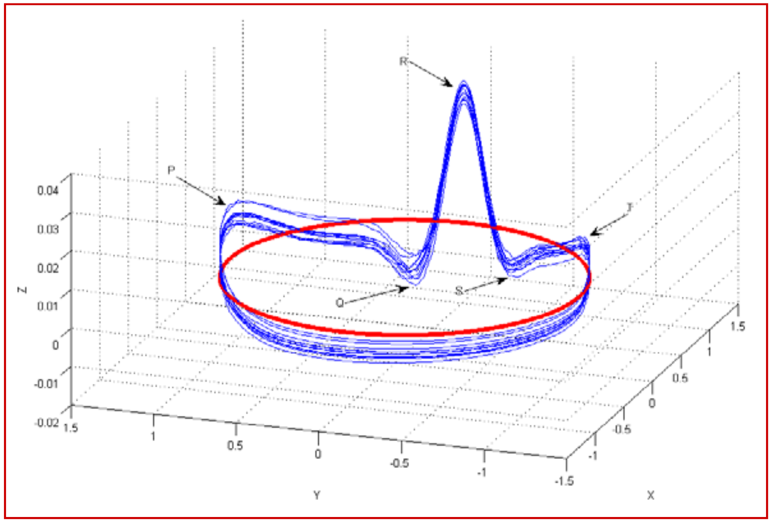
(McSharry et al. 2003)

$$\theta_{k+1} = (\theta_k + \omega\delta) mod(2\pi)$$

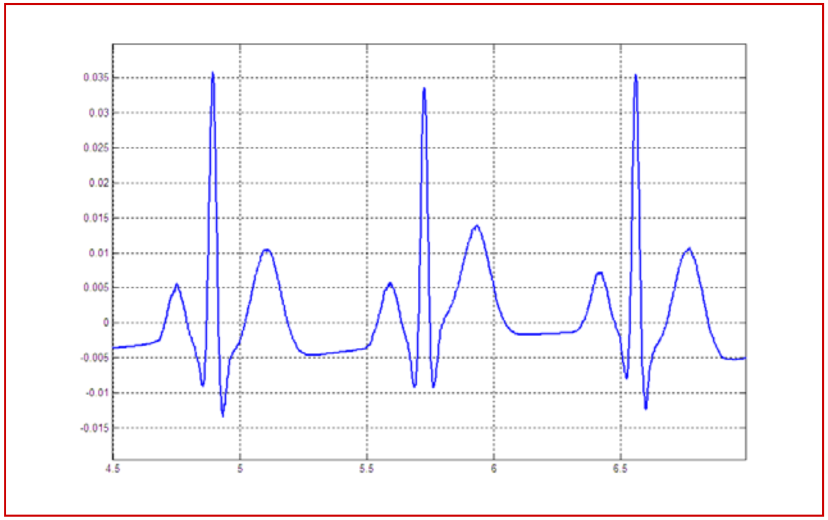
$$z_{k+1} = -\sum_i \delta \frac{\alpha_i \omega}{b_i^2} \Delta\theta_i exp\left(-\frac{\Delta\theta_i^2}{2b_i^2}\right) + z_k + \eta$$

(SAmeni et al. 2006)

McSharry-Clifford's Synthetic ECG Generator



3D trajectory of McSharry's model

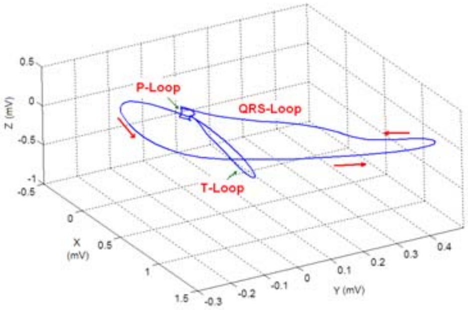


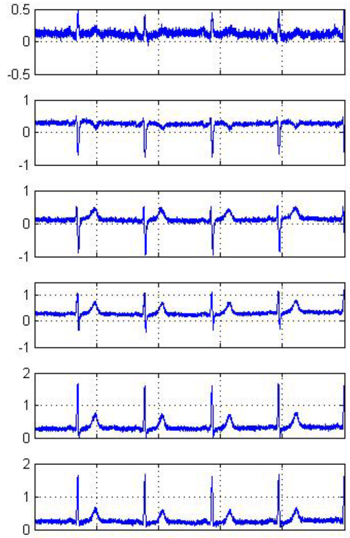
A sample synthetic ECG

Further Extensions of Morphological ECG Modeling

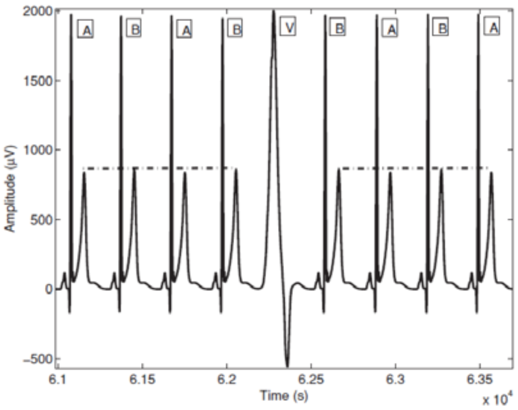
- McSharry-Clifford's ECG model was further extended to
  - o Multichannel Adult and Fetal VCG and ECG
  - o Normal versus Abnormal ECG with Ectopic Beats

$$
\begin{aligned}
\dot{\theta} &= \omega \\
\dot{x} &= -\sum_i \frac{\alpha_i^x \omega}{(b_i^x)^2} \Delta\theta_i^x \, exp[-\frac{(\Delta\theta_i^x)^2}{2(b_i^x)^2}] \\
\dot{y} &= -\sum_i \frac{\alpha_i^y \omega}{(b_i^y)^2} \Delta\theta_i^y \, exp[-\frac{(\Delta\theta_i^y)^2}{2(b_i^y)^2}] \\
\dot{z} &= -\sum_i \frac{\alpha_i^z \omega}{(b_i^z)^2} \Delta\theta_i^z \, exp[-\frac{(\Delta\theta_i^z)^2}{2(b_i^z)^2}]
\end{aligned}
$$





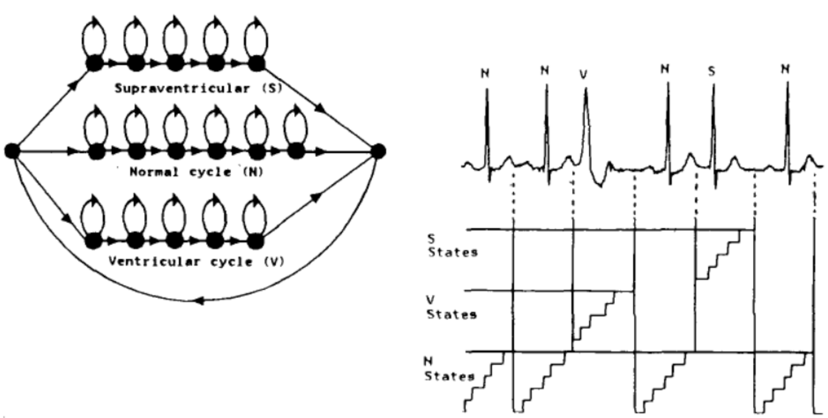
(Sameni et al. 2007)



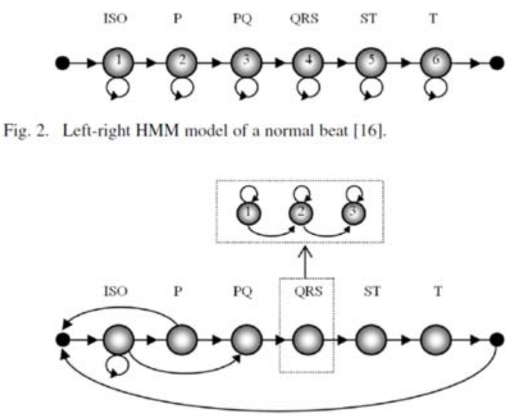
(Clifford et al. 2010)

Heart-Rate Dynamics

- The heart beat and its corresponding time-series are discrete by definition
- The procedure of model-based heart-rate analysis started with Markov chain modeling of the RR-interval and the intra-beat segments of the ECG (baseline, P, QRS, T, ...)



(Coast et al. 1990)



(Andreão et al. 2006)

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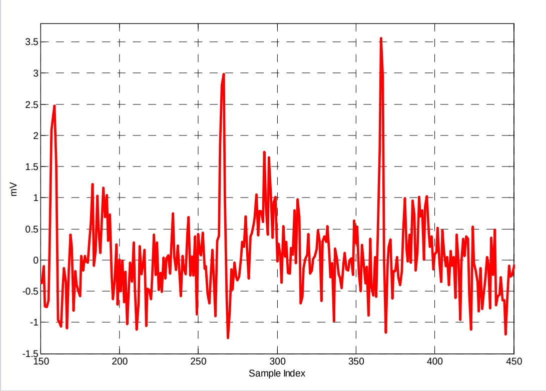
  - Model-based ECG signal processing
  - Statistical lower bounds for estimation errors
  - Multimodal analysis

Model-Based ECG Signal Processing

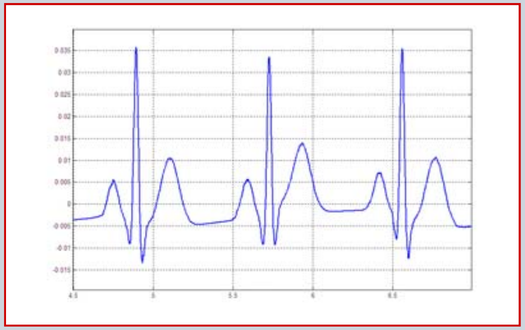
- The modified McSharry-Clifford's model set forth a notable body of research on model-based ECG processing and analysis, including:
  - Denoising
  - Segmentation
  - Compression
  - Parameter (Fiducial Point) Extraction

Model-Based ECG Signal Processing: Denoising

$$\begin{cases} \underline{x}_{k+1} = f(\underline{x}_k, \underline{w}_k, k) \\ \underline{y}_k = g(\underline{x}_k, \underline{v}_k, k) \end{cases}$$

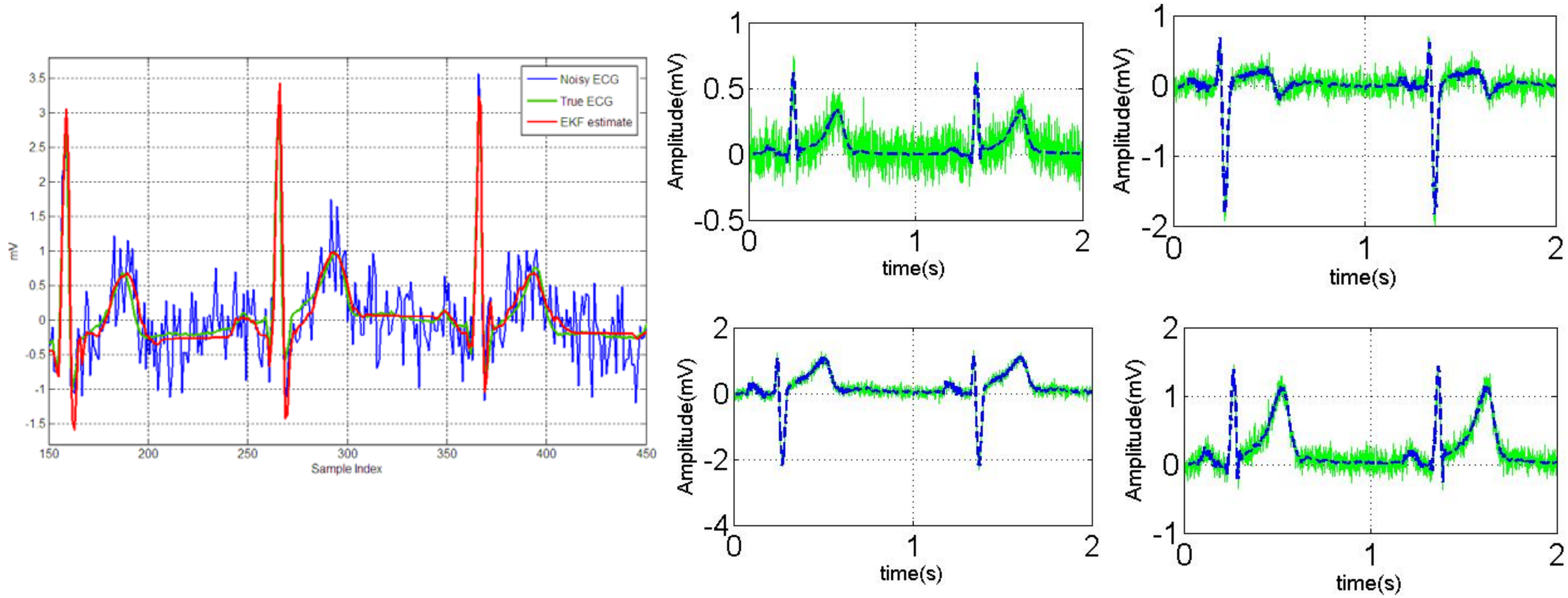


Noisy observations



Dynamical ECG model

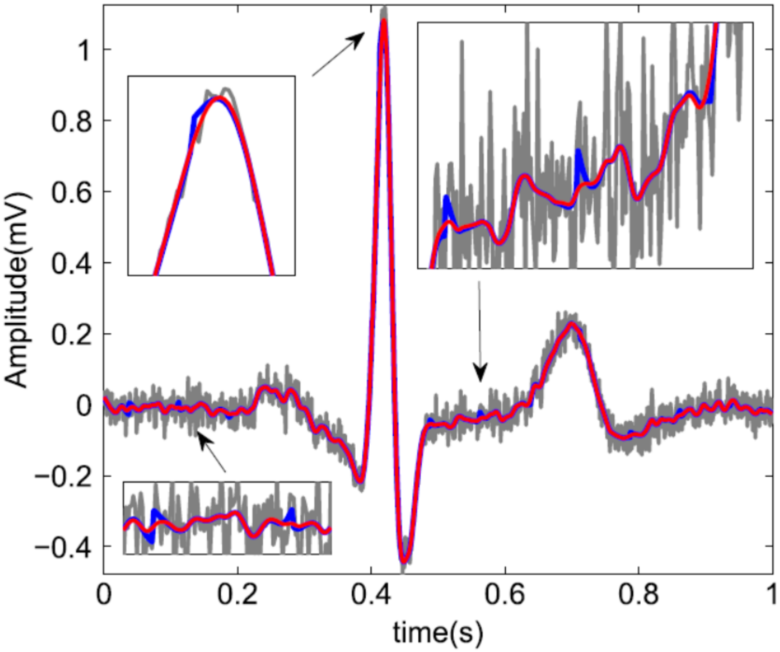
Typical denoising results



(Sameni et al. 2007)

ECG Denoising Using Smoothness Priors

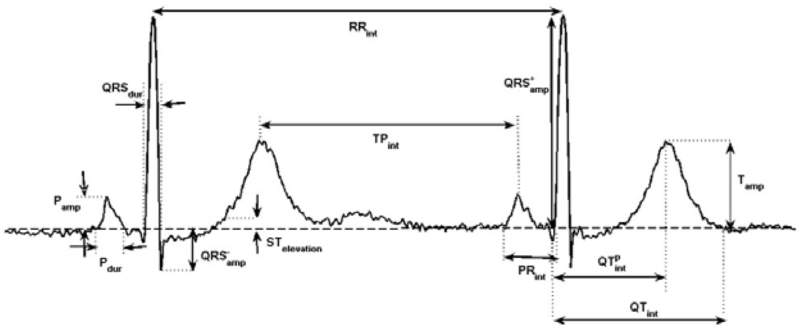
More recently an alternative scheme was proposed for ECG denoising, based on piece-wise smoothness priors. This approach was shown to be closely related to wavelet denoising, Wiener filter and Tikhonov regularization

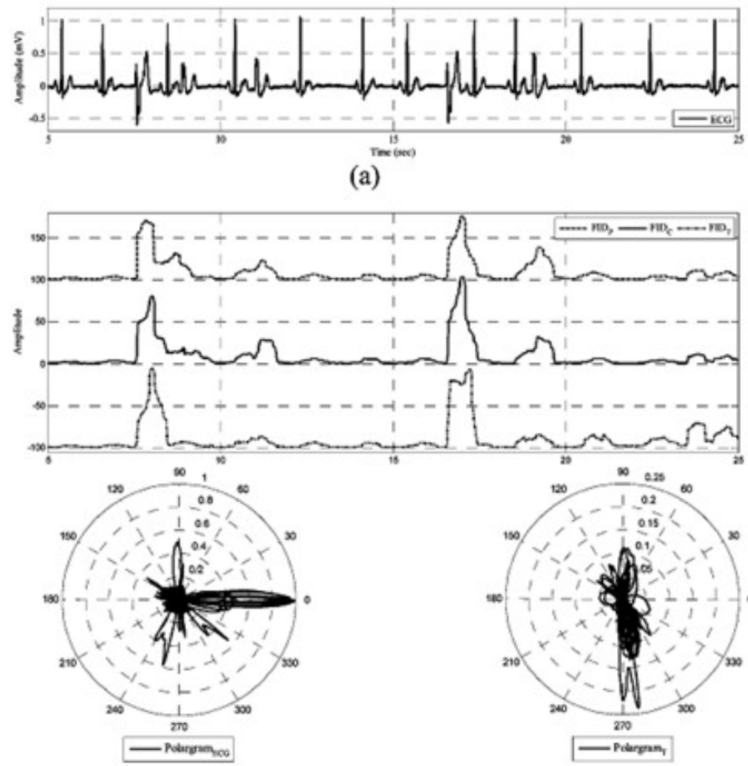


(Sameni 2016)

Model-Based ECG Signal Processing: Segmentation

Wave-based segmentation and analysis

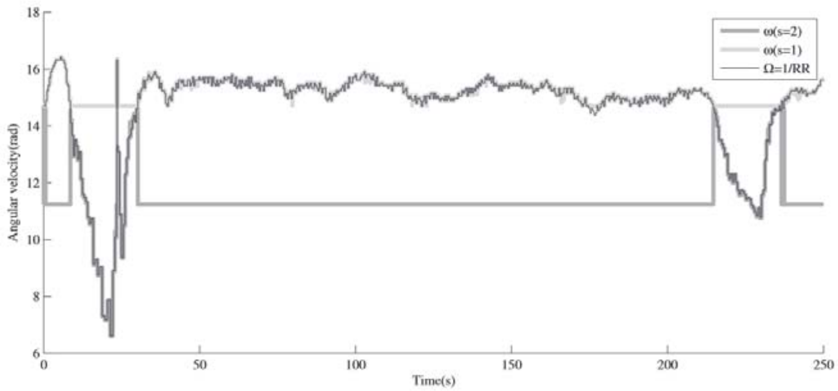




(Sayadi & Shamsollahi 2009)

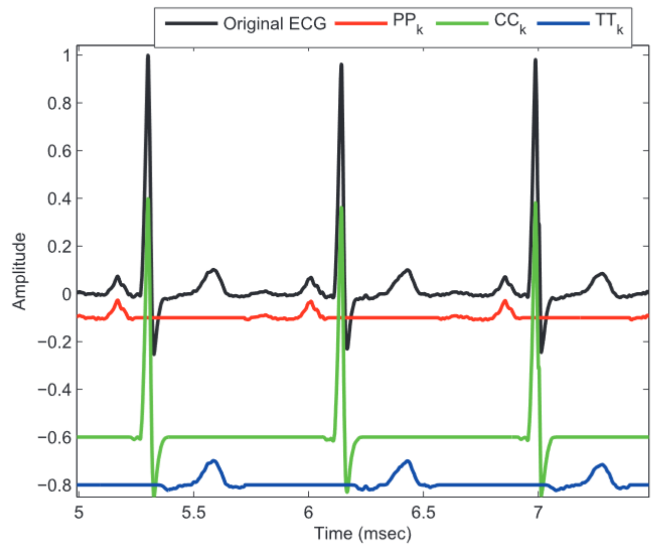
Model-Based ECG Signal Processing: Parameter Estimation and Anomaly Detection

ECG-based apnea bradycardia detection



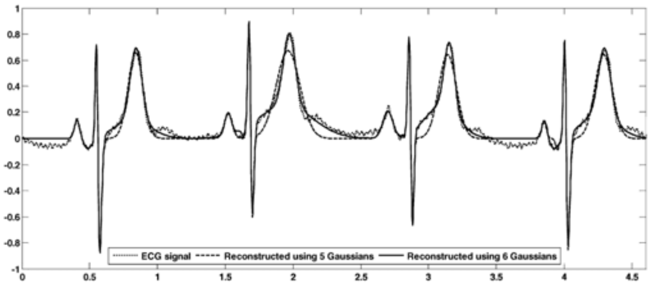
(Montazeriet al. 2016)

Dynamic segmentation & fiducial-point extraction

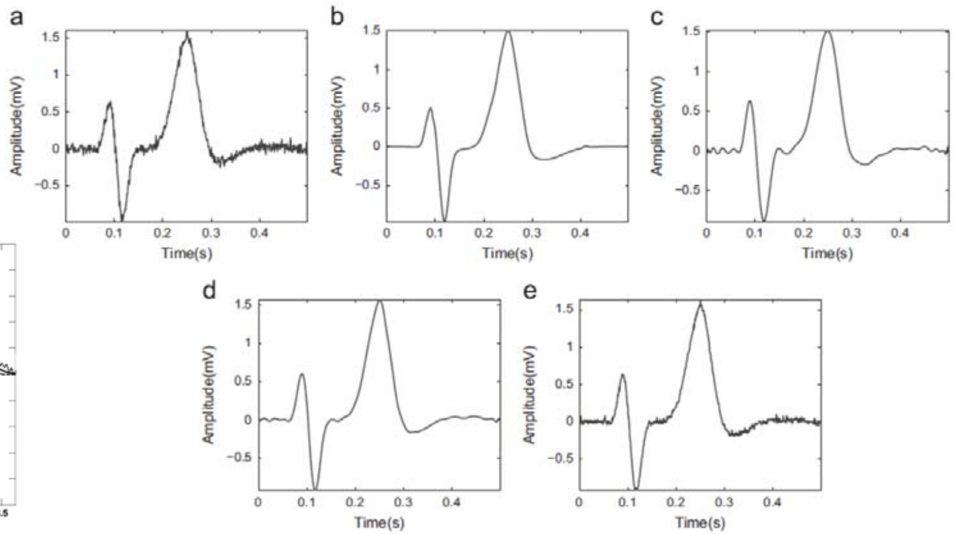


(Akhbari et al. 2016)

Model-Based ECG Signal Processing: Compression



(Sayadi & Shamsollahi 2008)



(Kheirati & Sameni 2013)

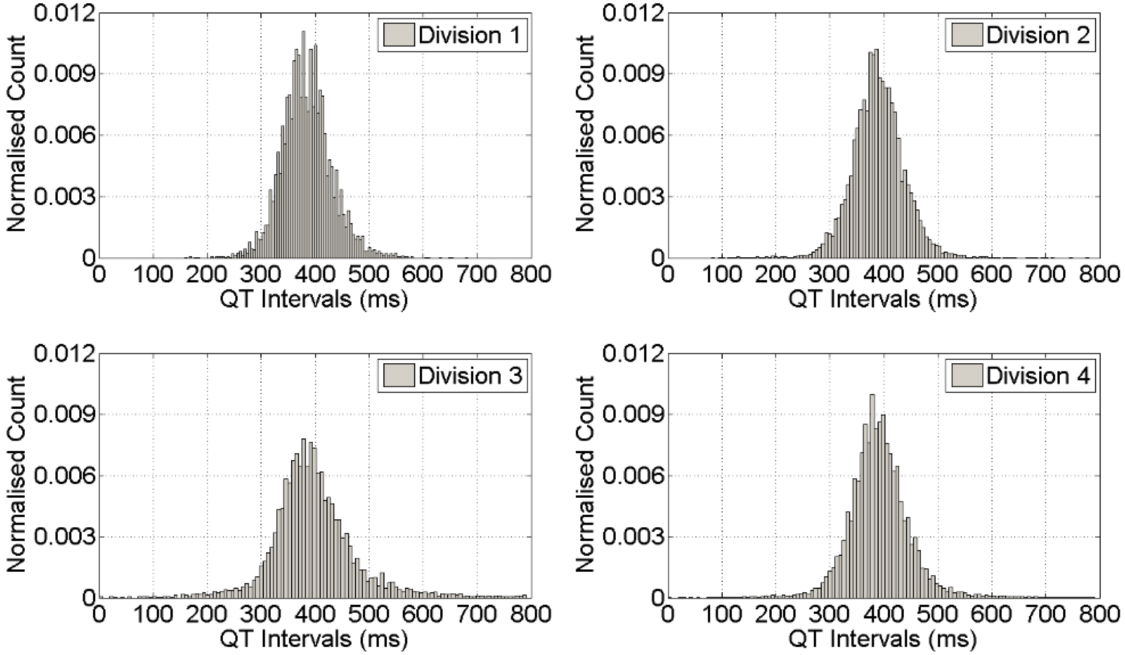
Statistical lower bounds for estimation errors

- By having a model, one can evaluate the performance of parameter estimation and even the annotation quality
- Facts:
  - ECG parameters have intrinsic beat-wise variability (modeling error)
  - Measurements and expert annotations are always noisy (observation noise)
- Result: A lower limit exists on the achievable parameter estimation quality

(similar to the CRLB in Estimation Theory)

Crowd-sourced Annotation of ECG

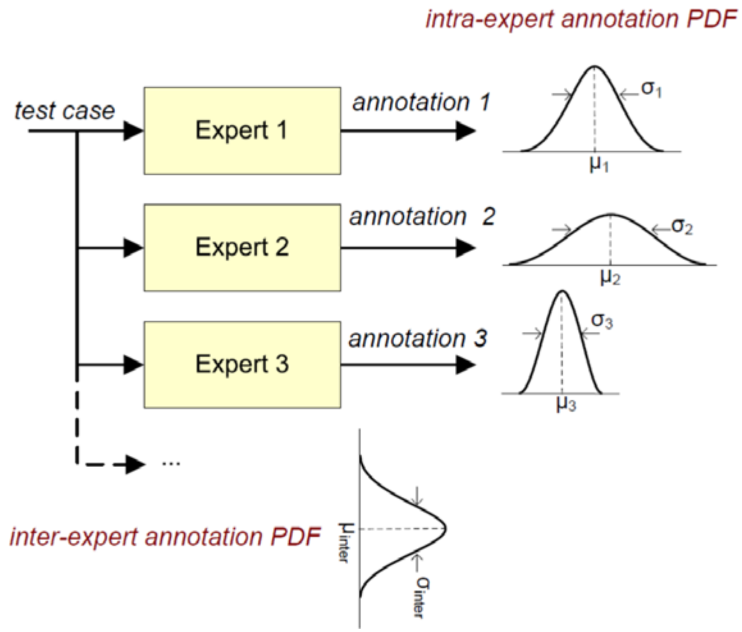
Objective: Using a Bayesian framework for averaging or obtaining consensus between a group (crowd) of expert or algorithmic annotations



(Zhu et al. 2014)

Intra and Inter-Rater Variability

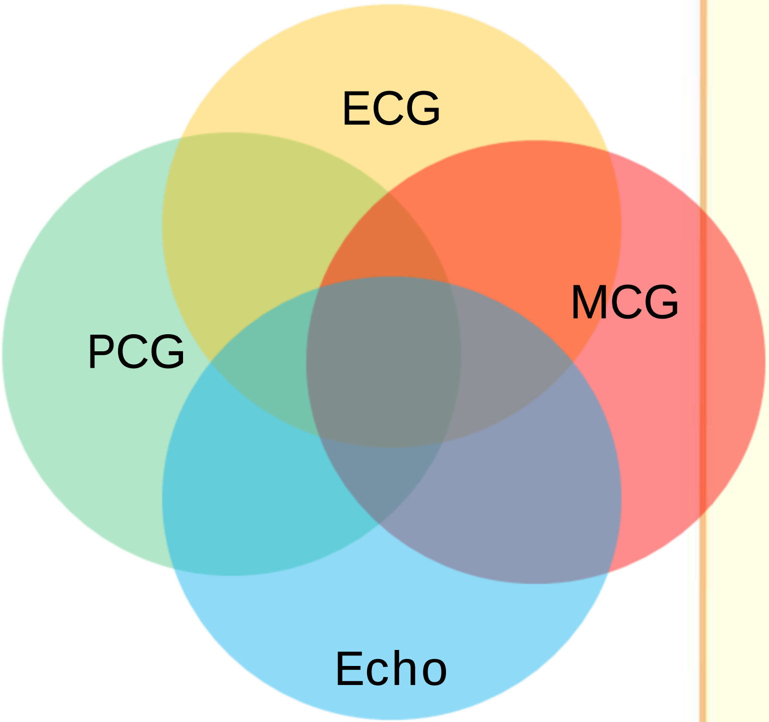
Objective: Developing a Bayesian framework for modeling expert intra and inter-rater annotation variability. Considering expert annotations as gold-standard (yet noisy) labels, this study can lead to CRLB-like lower bounds for automated ECG parameter extraction systems.



Current research at
Shiraz University
(Sameni© 2017)

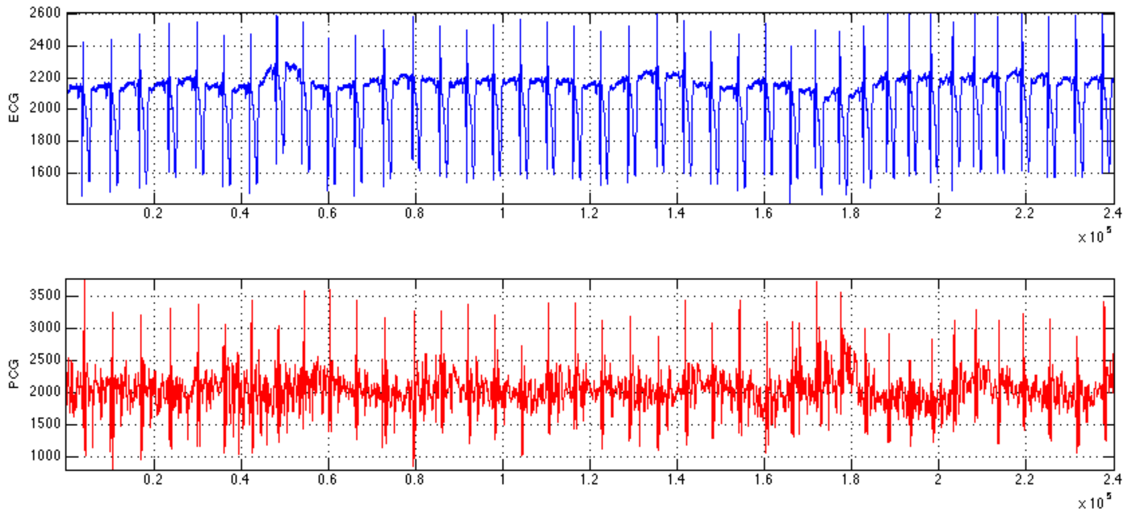
Multimodal analysis

- Multimodal analysis
  - PCG/ECG
    - (Noorzadeh et al. 2015)
    - (Samienasab et al. 2014)
  - ECG/MCG
    - (Razavipour and Sameni 2011)
  - Echo/ECG
    - (Nikoo et al. 2016)



Multimodal ECG/PCG

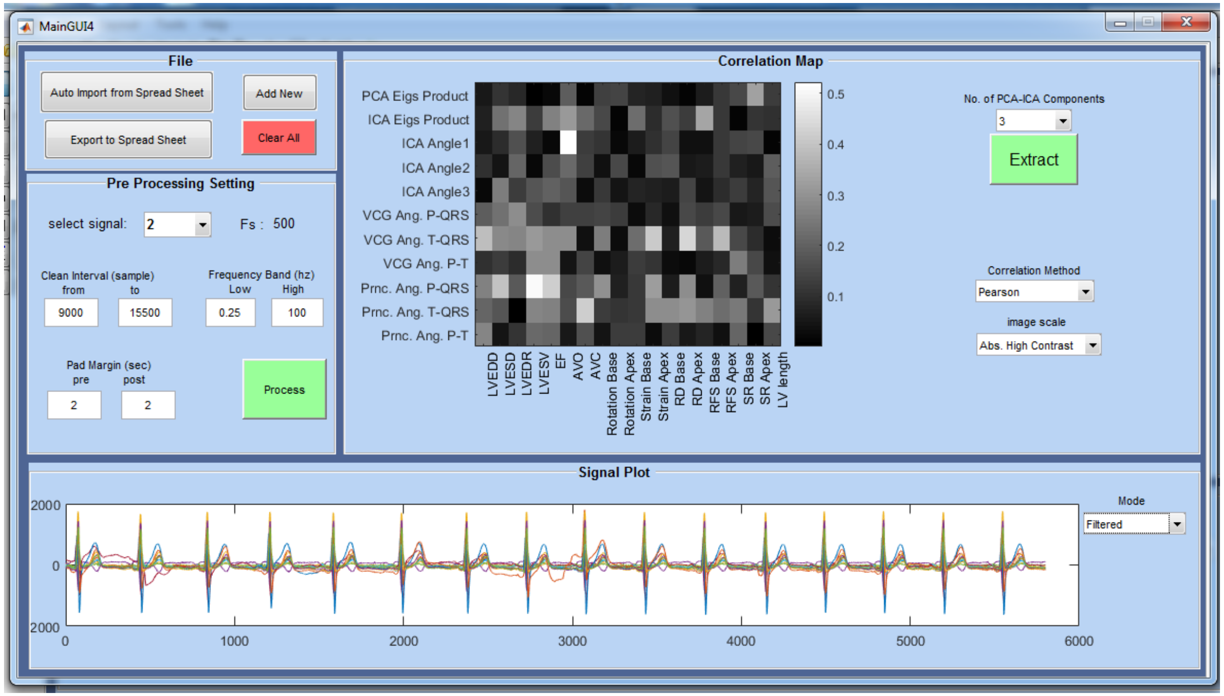
- Objective: To study the electro-mechanical coupling of the heart via phonocardiogram (PCG) and ECG



Current research at Shiraz University (Sameni © 2017)

Multimodal ECG/Echo

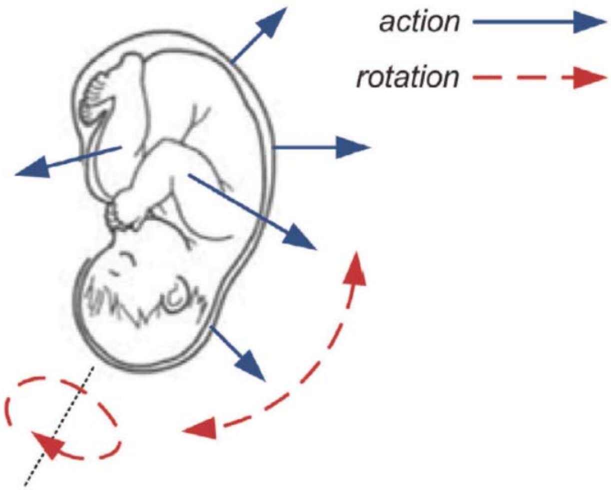
- Objective: To study the electro-mechanical coupling of the heart via echocardiogram and ECG

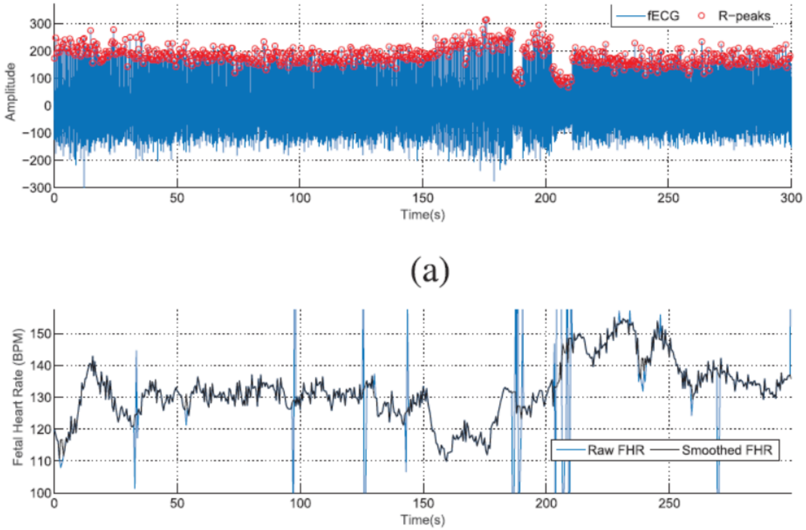


Current research at Shiraz University and Shiraz Medical University (Fattahi, Sameni, Roomi, Nikoo © 2017)

Fetal Cardiac Activity & Movements from ECG/MCG

Objective: To extract morphological, heart-rate and heart-rate driven information (e.g. fetal motion) from noinvasive fetal electro/magneto-cardiogram





(Biglari and Sameni 2016)

Thank you for your attention!

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References

1. A. M. Scher, A. C. Young, and W. M. Meredith, "Factor analysis of the electrocardiogram; test of electrocardiographic theory: Normal hearts," Circ. Res., vol. 8, pp. 519-526, 1960.
2. Sornmo, Leif, et al. “A method for evaluation of QRS shape features using a mathematical model for the ECG” IEEE Transactions on Biomedical Engineering 10 (1981)
→ Used Bessel Functions
1. Laguna, P., et al. “Adaptive estimation of QRS complex by the Hermite model for classification and ectopic beat detection” Med. Biol. Eng. Comput 34.1 (1996)
→ Used Hermite polynomials
1. McSharry, Patrick E., et al. “A dynamical model for generating synthetic electrocardiogram signals” IEEE Transactions on Biomedical Engineering 50.3 (2003): 289-294.
→ Used Gaussian kernels in a dynamical form

Statistical lower bounds for estimation errors

- By having a model, one can evaluate the performance of parameter estimation
  - Clifford (scoring consensus)
  - Finding CRLB for annotations (inter and intra-rater variabilities)
  - Finding CRLB for ECG parameter estimation (fiducial points)

Chaotic Behaviour in the RR-Intervals