Noninvasive Fetal ECG

The PhysioNet/CinC Challenge 2013

Computing in Cardiology 2013

Zaragoza, Spain

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Noninvasive Fetal ECG

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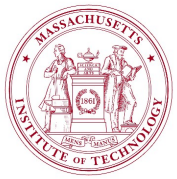
Ikaro Silva, Joachim Behar, Reza Sameni, Tingting Zhu, Julien Oster, Gari Clifford, George B. Moody

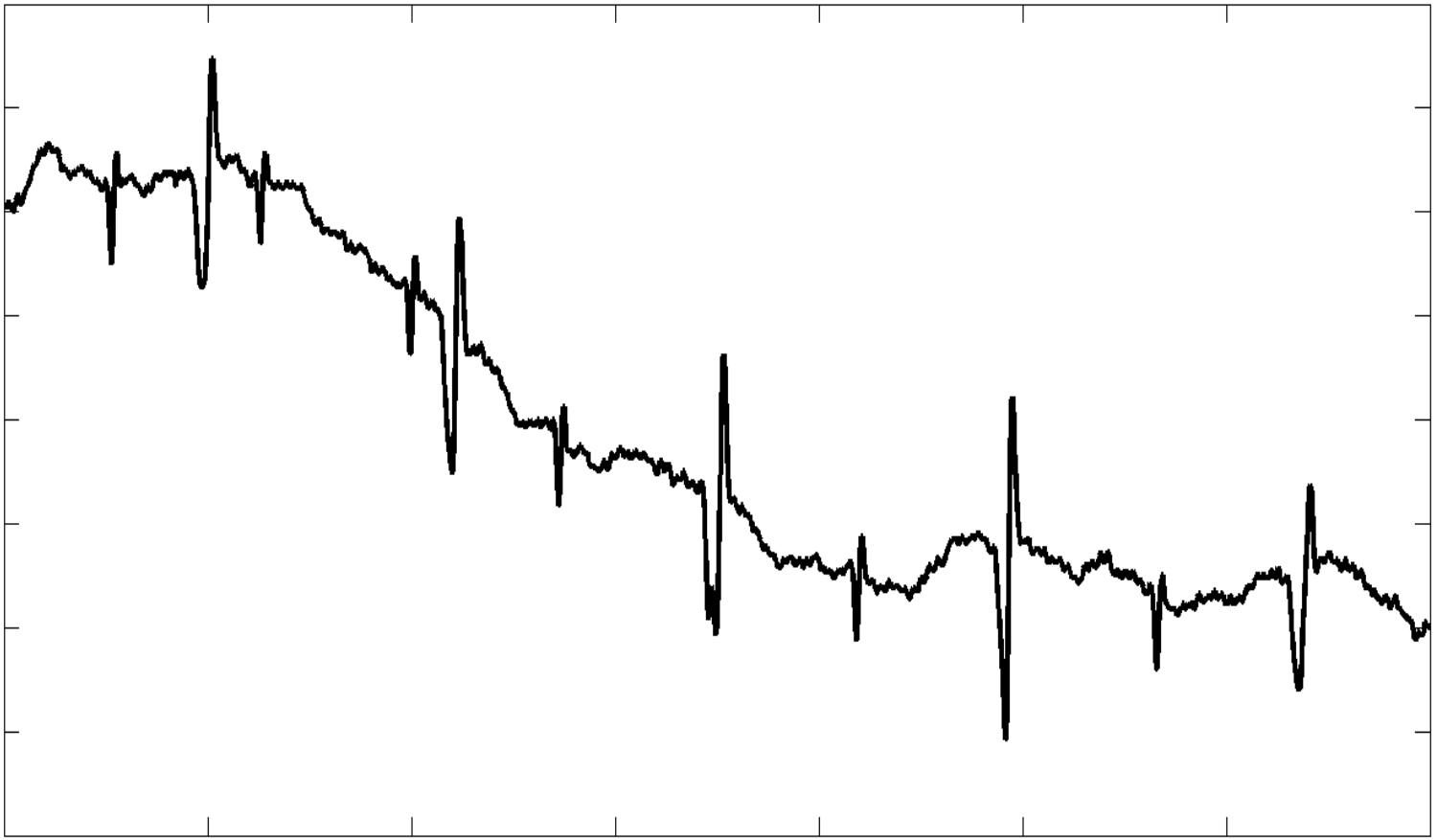
September 24, 2013



Motivation

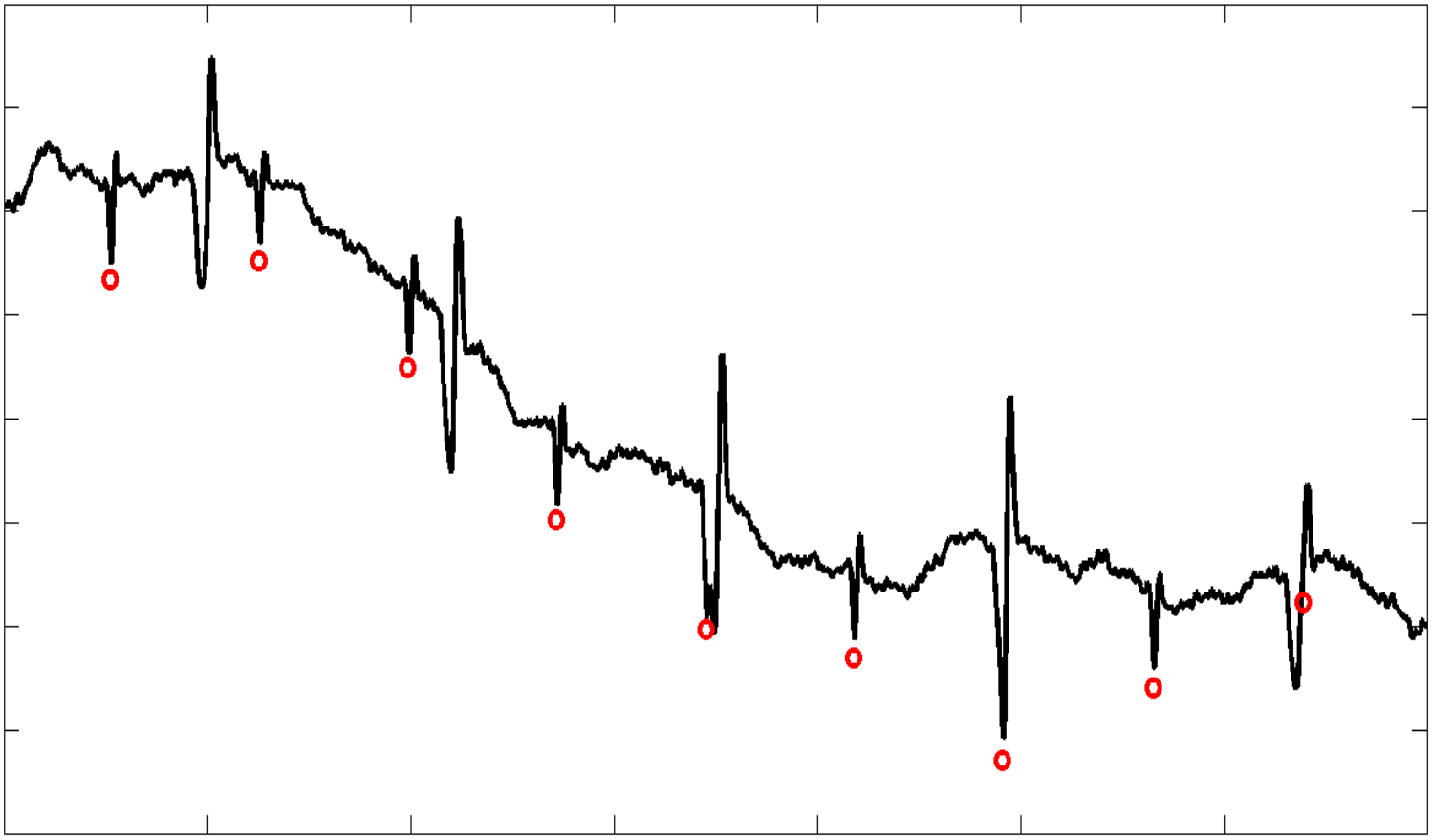
- Fetal heart rate (FHR) has been associated with fetal distress (for review see: Sameni and Clifford; 2010).
- Continuous FHR monitoring has improved over the years, but fetal scalp ECG still remains the most accurate measurement technique.
- Fetal scalp ECG, however, is possible only during labor and is not common in current clinical practice because of associated risks.
- With the current signal processing techniques, can we do better with non-invasive estimation of fetal ECG from maternal abdominal leads?

Estimating FECG from Abdominal Leads



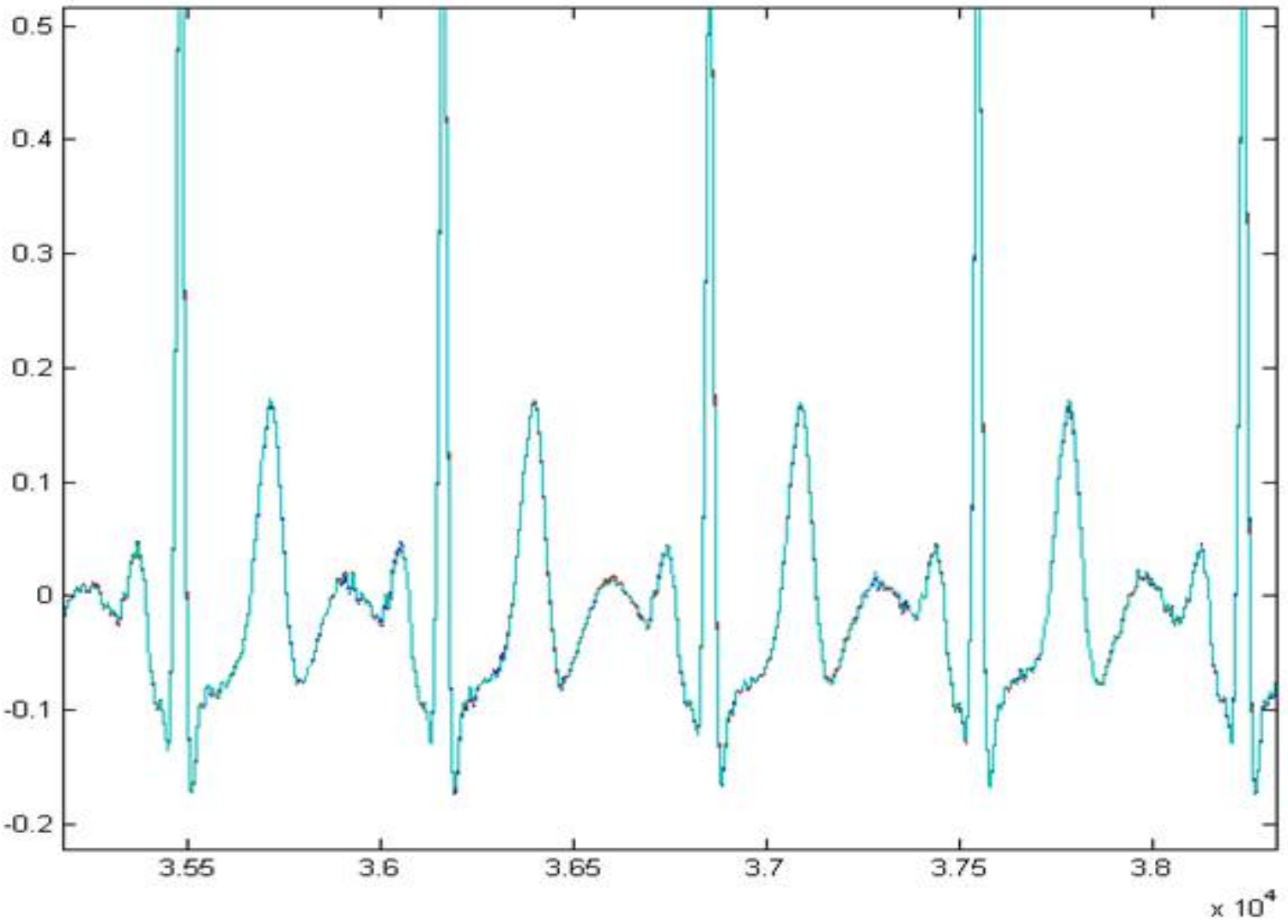
Duration: 4 seconds

Estimating FECG from Abdominal Leads

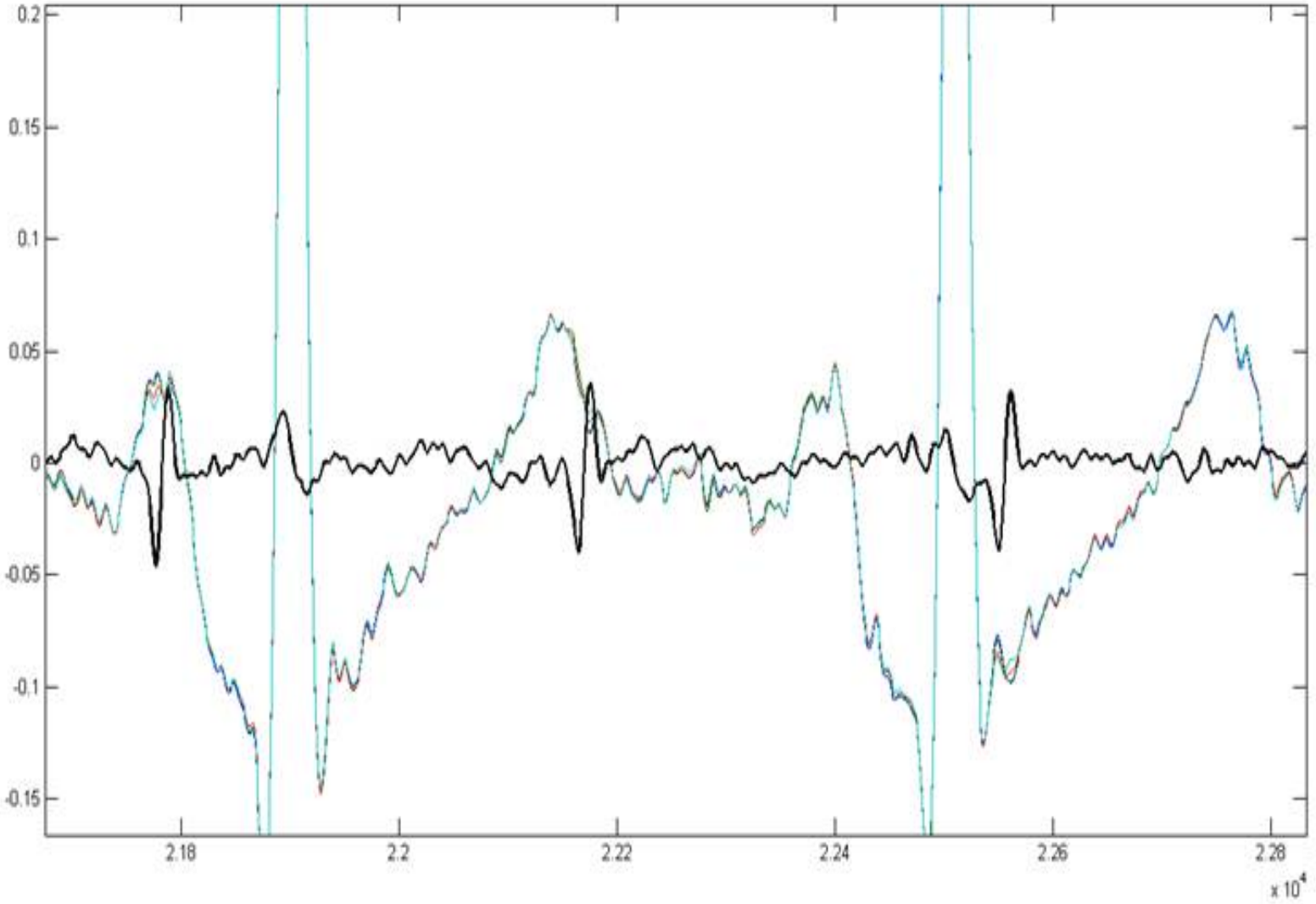


Duration: 4 seconds

Motivation: Extraction Example (Behar;2013)



Motivation: Extraction Example (Behar;2013)



Data Set

- Maternal abdominal recordings from different 5 collections
- 1 minute length, sampled at 1 kHz, 4 abdominal leads
- Data Sets:
  - Training Set A: 75 records *(not used for ranking since annotations were provided)*
  - Test Set B: 100 records *(open, for events 4 and 5)*
  - Test Set C: over 200 records *(hidden, for events 1, 2, & 3)*

Challenge Events

	Set B (Open Data)	Set C (Closed Data- Open Source)
Event 1 (91 entries from 28 teams)		Heart Rate Estimation
Event 2 (91 entries from28 teams)		RR Time Series Estimation
Event 3 (16 entries from 5 teams)		QT Duration Estimation
Event 4 (208 entries from 53 teams)	Heart Rate Estimation	
Event 5 (208 entries from 53 teams)	RR Time Series Estimation	

Challenge Scoring

The events focused on estimation of:

- **Fetal heart rate (FHR)**: using set C in event 1, and set B in event 4. Scores were calculated based on the mean squared error of FHR in (beats/minute)^2.
- **Fetal RR intervals (FRR)**: using set C in event 2, and set B in event 5. Scores were calculated based on RMS error of FRR in milliseconds.
- **Fetal QT interval (FQT)**: using set C in event 3. Scores were calculated based on RMS error of FQT in milliseconds.

Reference FQTs were obtained from 7 humans and merged via a Bayesian crowd-sourcing approach, which will be described this afternoon by our coauthor Tingting Zhu in session S64.

Acknowledgments

Prof. Vyacheslav Shulgin and **Dr. Anton Tokarev**, from the Biomedical Signal Processing Laboratory of National Aerospace University, Kharkov, Ukraine

Qiao Li and **Marisol Martinez Alanis**, from University of Oxford

Thanks to all participants!

The speakers' slides are printed in the booklets in order of presentations in sessions S33 and S43. Extra copies of the booklet can be printed from http://physionet.org/challenge/2013/slides.pdf

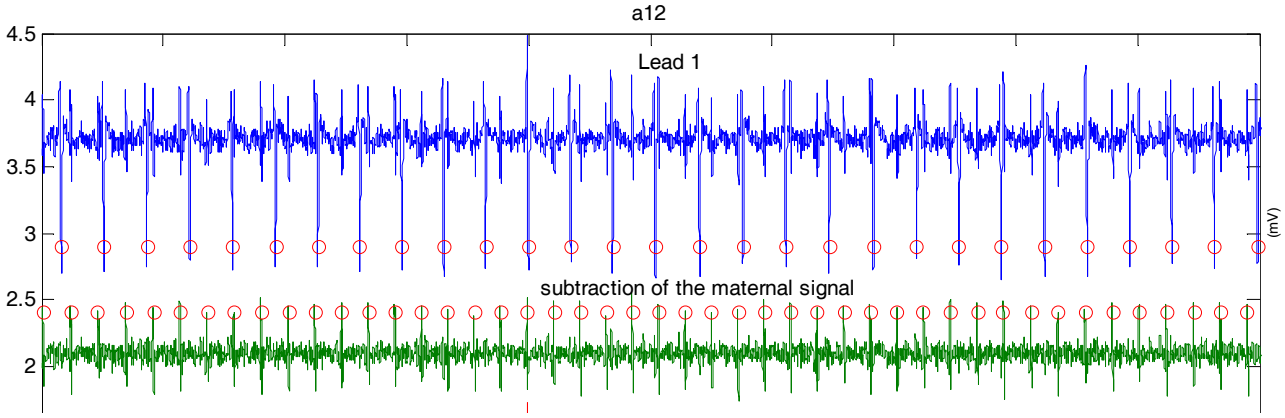
Thanks to *Physiological Measurement* for underwriting the cost of printing the booklets!

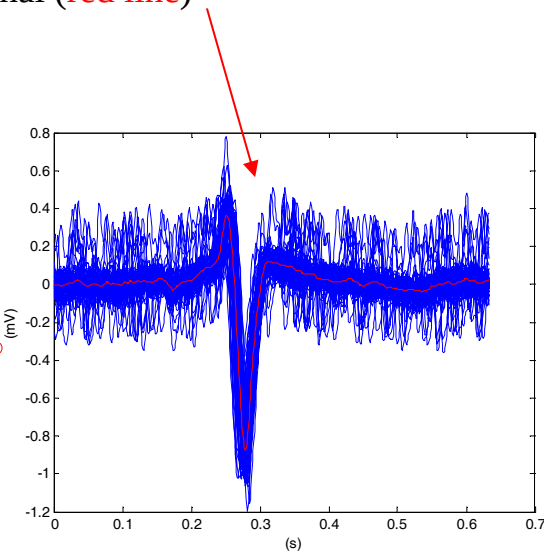
Cancellation of the Maternal and Extraction of the Fetal ECG in Noninvasive Recordings

Ivaylo Christov, Iana Simova, Roger Abächerli

Aproach:

- Detection of the maternal QRSs
- Superimposition of P-QRS-T intervals (blue lines) and calculation of the mean signal (red line)
- Subtraction of the mean signal
- Fetal QRSs detecton





Weaknesses:

In cases of narrow and high amplitude maternal QRSs small residues remain after the cancellation of the maternal ECG. If the residues are grater than the fetal QRSs they result in false positive detections

Results:

Events 1/4, Fetal heart rate measurement: 285.132;
Events 2/5, Fetal RR interval measurement:19.962

Extracting R-wave position from an FECG record using multichannel shapes

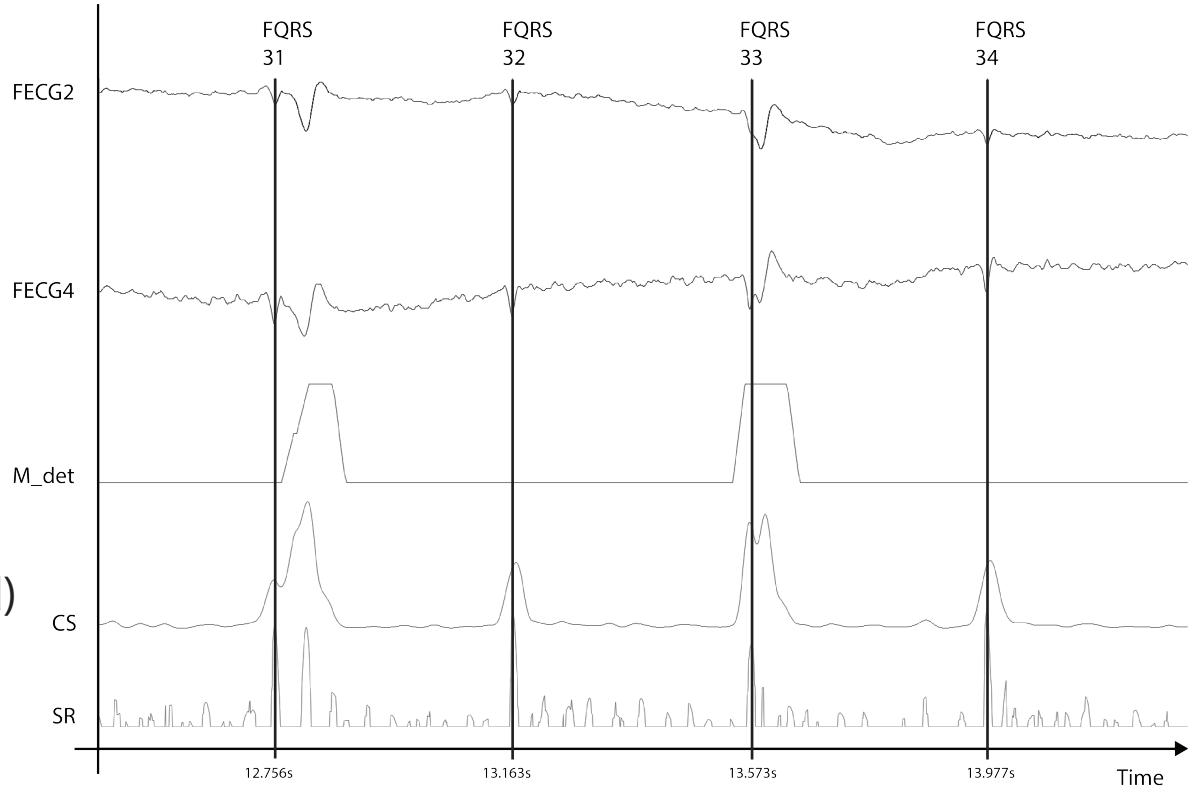
INSTITUTE OF SCIENTIFIC INSTRUMENTS
Academy of Sciences of the Czech Republic, v. v. i.

F. Plešinger
P. Jurák
J. Halámek

Approach:

1. Removing channels with low s/n ratio
2. Reducing effect of maternal ECG
3. Finding of a multichannel shape of FECG
4. Creating of preliminary annotations list
5. Finding of less-evident annotations

Programmed in C# language using .NET 4.5



Strengths:

Capable of finding of FQRS hidden in MQRS
Process speed (3 seconds for 1-minute record)
Tolerates loss of channels (max. 2 from 4)
Denominated credibility of the results

Weaknesses:

When child rotates during the recording, our method is unusable.

Results:

Event 4 (MSE of FHR): **395.06** (Score from April 2013) -> **688.489** (The same files after change of scoring)
Event 5 (MSE of FHR): **10.45** (Score from April 2013) -> **26.792** (The same files after change of scoring)

Feature work:

Parallelize the process. Prepare software for online FQRS detection with an experimental hardware unit.

Advanced maternal ECG removal and noise reduction for application of fetal QRS detection

Jukka A. Lipponen and Mika P. Tarvainen

Approach:

- Augmented PCR model to remove maternal ECG
- Envelope method to equalize noise levels
- Multilead template matching technique to detect fQRS

Strengths:

- PCR model remove mECG successfully
- After noise equalization, template matching reveals fQRS complexes with high accuracy

Weaknesses:

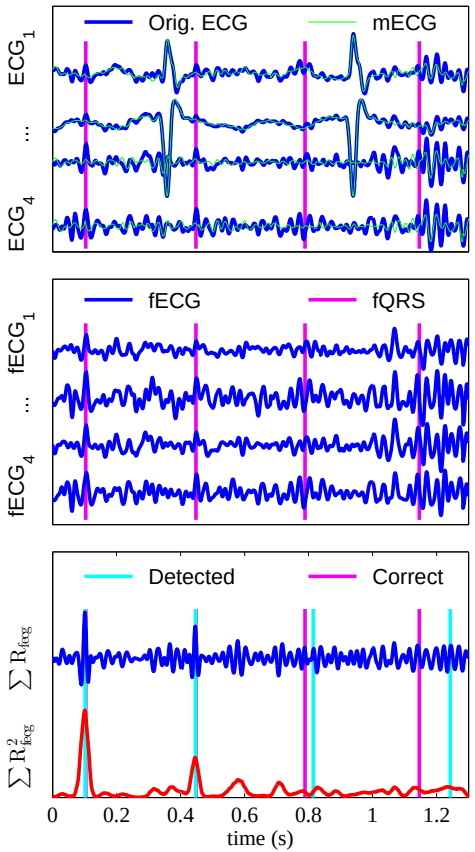
- Morphological changes of fECG are troubled
- 0% accuracy, if templates are not found correctly

Results:

- Maternal ECG removed with high accuracy
- Events 4: 28.89, Events 5: 4.844

Alternatives studied / future work:

- Improvement of noise removing algorithm
- Dynamical template estimation/update
- Analysis of longer measurements



Fetal QRS detection and RR interval measurement in noninvasively registered abdominal ECGs

C Maier, H Dickhaus
Heidelberg University

Approach

Maternal ECG attenuation

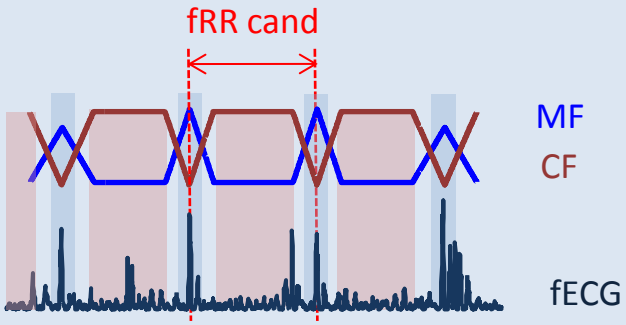
PQRST Template subtraction
PCA (separate for P, QRS, T)

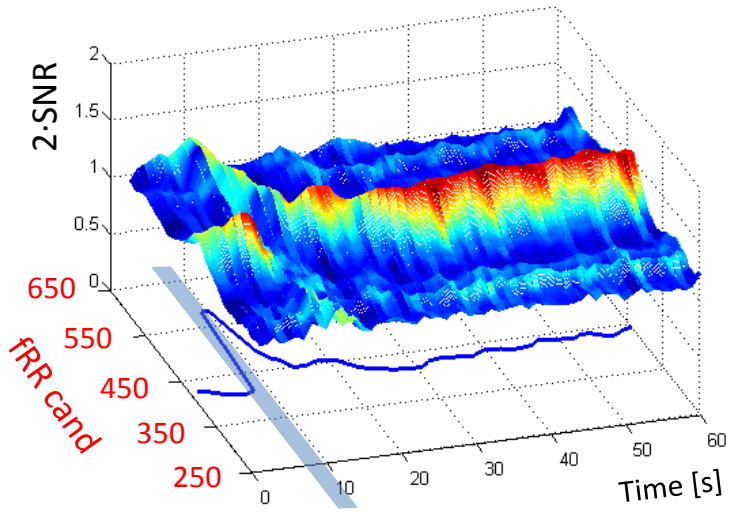
Fetal QRS-detection

Impulse-train „matched filter“ (energy of fRR)
„Complementary filter“ (capture noise energy)

Use *max(MF / (MF+CF))* in each 1s-epoch as estimate of SNR
Select fRR cand-path that corresponds with „ridge“ of SNR

Refinement of fQRS positions in final step



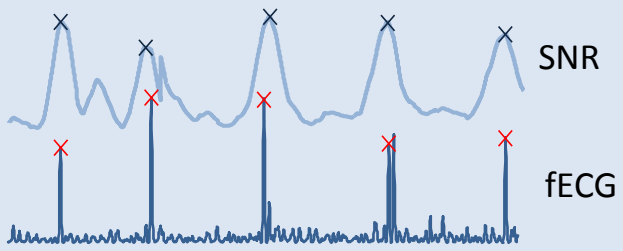


Results

Event 4 (MSE of fetal HR):	118.353 bpm^2
Event 5 (RMS of fetal RR):	9.353 ms

Properties

- \+ Provides estimate of SNR
- \+ Robust against dynamic loss of up to 3 out of 4 leads
- \+ Potential not yet fully exploited
- – Estimate of fRR cand-path („rigde-tracking“) is critical
- – Occasional deletion of fetal QRS by PCA
- – Algorithm „expects“ regular rhythm

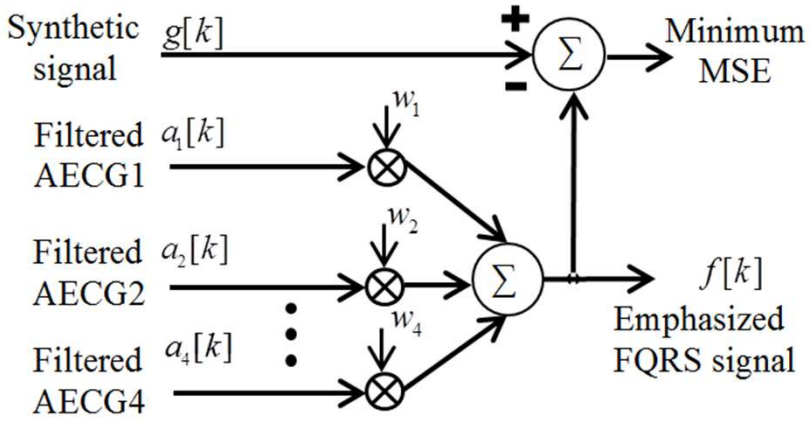


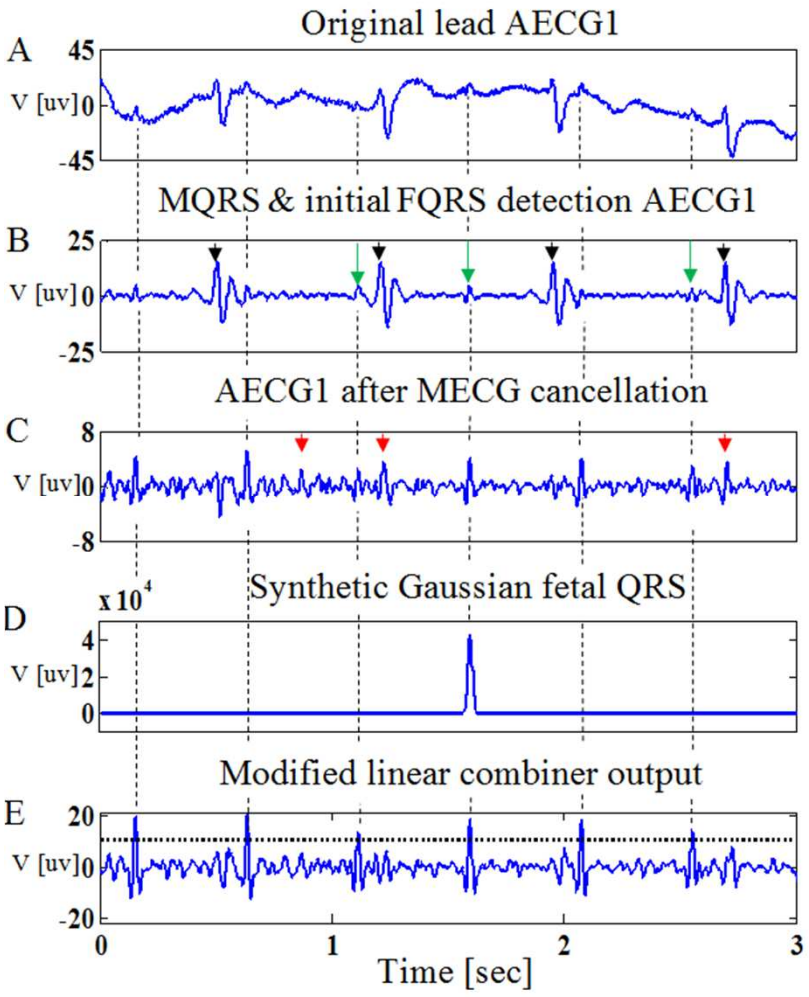
Noninvasive Fetal QRS Detection Using Linear Combination of Abdomen ECG Signals

Or Perlman, Amos Katz, Yaniv Zigel

Approach:

- Detecting a single FQRS and using it as an input to a modified linear combiner so that it will produce an output signal containing peaks in the respective locations of all FQRS complexes.





Results:

- Event 4 (MSE of fetal HR): 262.076
- Event 5 (RMS error of fetal RR): 27.848

fECG Extraction From Abdominal Recordings using Array Signal Processing

Masoumeh Haghpanahi, David A. Borkholder

Approach:

- Remove mECG using Kalman filtering
- Detect polarity using a greedy algorithm
- Use hybrid time & frequency criteria to locally select and merge fECG signals
- Detect fQRS using matched filter

Observation:

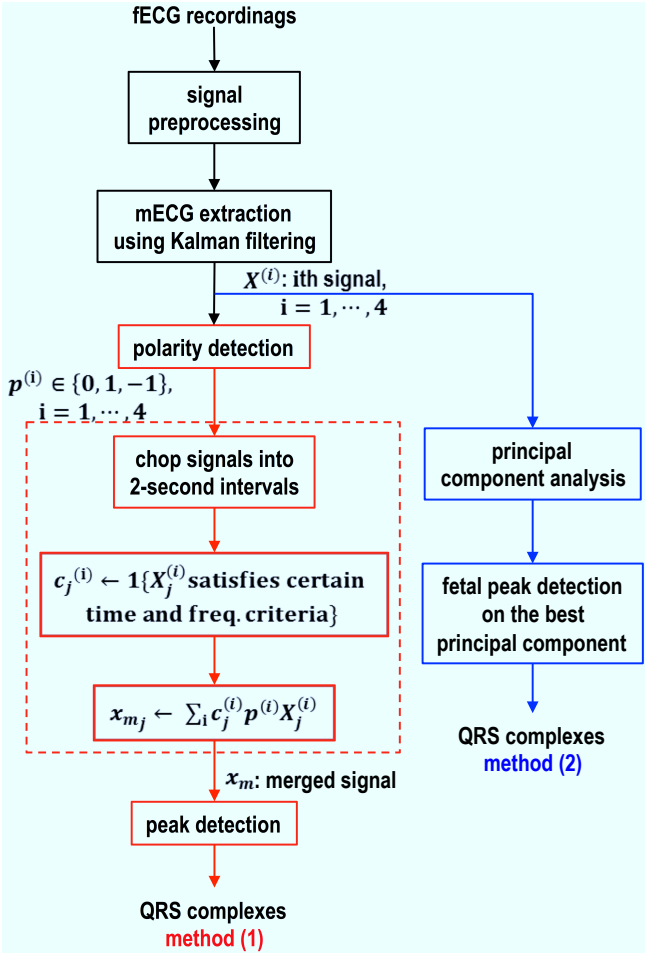
- Dominant principal component could reveal fQRS when filtered fECG signals are too noisy.

Results:

- Events 1/4 (MSE of fetal HR): 50.063
- Events 2/5 (RMS error of fetal RR): 9.062

Future work:

- Study when/how to incorporate information about fQRS from principal components
- Improve signal preprocessing and initialization of dynamic model parameters



Adv. sig. proc. techniques for fECG analysis Jakub Kuzilek, Lenka Lhotska

Approach:

- Set of filters to remove noises and enhance ECG
- Reuse of mECG cancellation
- Different fQRS detectors and selection of best fQRS estimate

Strengths:

- Accurate fetal RR measurement
- Uses all abdominal ECGs and selects best result

Weaknesses:

- Strongly affected by EMG
- mECG sometimes not removed properly
- QT estimation not implemented

Results:

- Events 1/4 (MSE of fetal HR): 249.8, 492.4
- Events 2/5 (RMS error of fetal RR): 22, 35.7
- Event 3 (RMS error of QT): N/A

Alternatives studied / future work:

- Correction of estimated fetal RR measurement (error detection and correction)
- Better suppression of EMG noise
- To do: QT estimation, better mECG cancellation

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Panel Discussion

FQRS Detection Using Semi-Blind Source Separation Framework

F.Razavipour,M.Haghpanahi,R.Sameni

Approach:

- ECG source extraction using semi-blind source separation
- Cardiac components extraction by πCA algorithm
- Wavelet de-noising to decrease the effect of maternal ECG
- Improving the SNR of fetal ECG by matched filter

Strengths:

- Accurate estimation of cardiac components
- Preserving the fetal ECG subspace

Weaknesses:

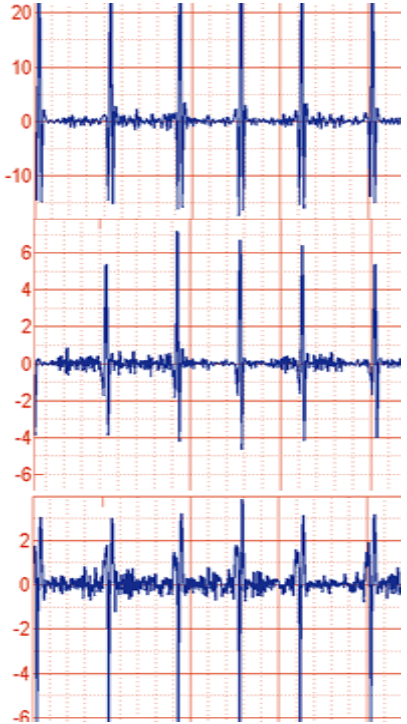
- Not strong for single or limit channel signals
- High dependency on matched filter template

Results:

- Events 1/4 (MSE of fetal HR): 210, 216
- Events 2/5 (RMS error of fetal RR): 21, 23
- Event 3 (RMS error of QT): ?

Future work:

- Finding appropriate condition clause for de-noising loop



Maternal ECG,matched filtered and fetal ECG signal

Fetal QRS Complex Detection Based on Three-Way Tensor Decomposition

Mohammad Niknazar, Bertrand Rivet, and Christian Jutten

Approach:

- Tensor decomposition to extract mECG components
- Reconstruction and subtraction of mECG from mixture
- Simple peak search to detect fetal QRS

Strengths:

- Estimate mECG amplitude for each beat
- Applicable when mECG and fECG waves fully overlap
- Applicable to as few as two channels

Weaknesses:

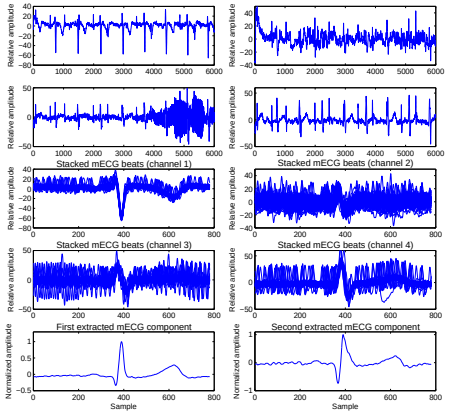
- Not applicable to pathological mECG, where mECG morphology varies significantly

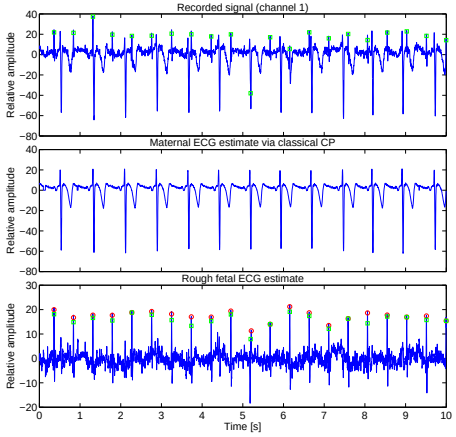
Results:

- Events 1/4 (MSE of fetal HR): 1514.59
- Events 2/5 (RMS error of fetal RR): 57.01

Alternatives studied / future work:

- Improvement of fetal QRS detection method after mECG cancellation





Fetal Electrocardiogram R-peak Detection using Robust Tensor Decomposition and Extended Kalman Filtering

Mahsa Akhbari, Mohammad Niknazar, Christian Jutten,
Mohammad B. Shamsollahi, Bertrand Rivet

Approach:

- Reconstruct mECG by tensor decomposition
- Rough estimate of fetal R-peak positions
- Tensor decomposition to reconstruct rough fECG
- Extended Kalman filter (EKF) with 25 states for fetal R-peak detection, in which ECG beat is modeled by 3 state equations (P, QRS and T)

Strengths:

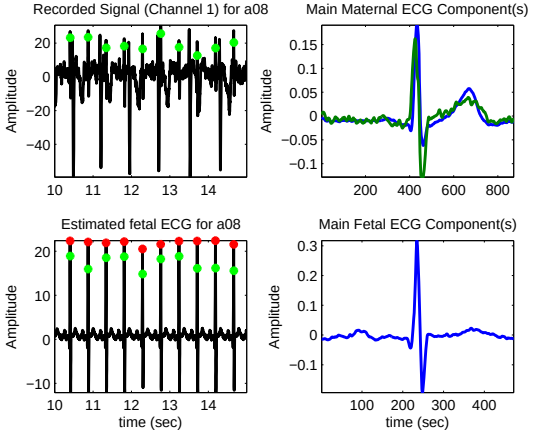
- Estimate rough denoised fECG
- Estimate fetal R-peaks accurately

Weaknesses:

- Demand accurate initial values of EKF Parameters

Results:

- Events 1/4 (MSE of fetal HR): 1326.21
- Events 2/5 (RMS error of fetal RR): 45.06



Alternatives studied / future work:

- Propose automatic method robust to initialization of values of EKF parameters

Maternal signal estimation by Kalman Filtering and Template Adaptation for fetal heart rate extraction

F. Andreotti, M. Riedl, T. Himmelsbach, D. Wedekind, S. Zaunseder, N. Wessel, H. Malberg

Approach:

- Maternal QRS detector (ICA + decision making + matched filter)
- Kalman Smoother (EKS) / Template Adaption (TA) to estimate mECG
- Simulated annealing based fetal QRS (fQRS) detector
- Statistical decision-making and corrections (fQRS postprocessing)

Strengths/Weaknesses:

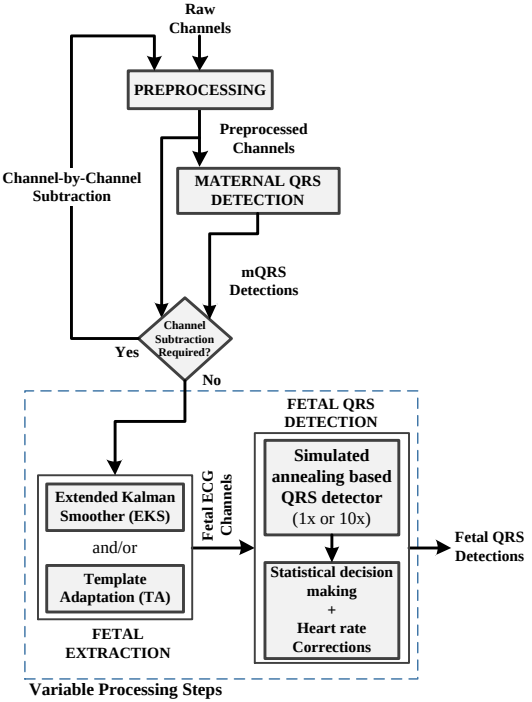
- Extreme reliable fetal detections
- Tolerates missing peaks (postprocessing)
- Expected HR information leads to errors if fHR strongly varies
- EKS crosses fetal peaks out

Results (Set-B):

- Events 1/4 (MSE of fetal HR): 20.43 (TA) 219.46 (EKS)
- Events 2/5 (RMS error of fetal RR): 4.57 (TA) and 7.69 (EKS)
- Best result: 18.08 / 4.38 (10x TA)

Future work:

- Validate maternal QRS detector
- Improve EKS for further combination with TA



Signal processing chain.

Spatial filtering and adaptive rule based fetal HR extraction from abdominal fetal ECG

Minnan Xu-Wilson, Eric Carlson, Limei Cheng and Srinivasan Vairavan

Philips Research North America (PRNA), Briarcliff Manor, NY, USA

Approach:

- Spatial filtering (PCA and Orthogonal Projection) to attenuate maternal ECG (MECG)
- PCA clustering and adaptive rule based fQRS detection
- Merge fQRS from different approaches for an accurate fQRS detection

Strengths:

- Accurate fetal RR measurement
- Capable of handling low signal-to-noise ratio fQRS

Weaknesses:

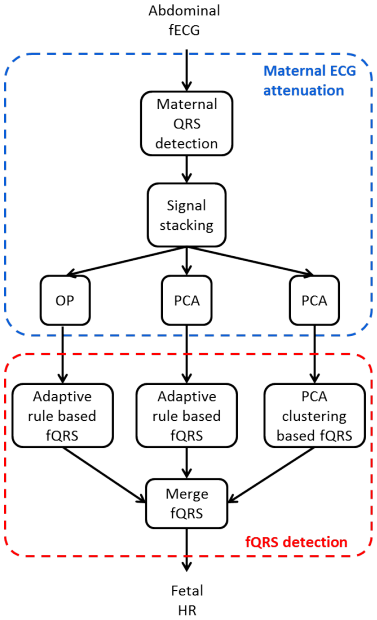
- Cardiac residues after MECG attenuation
- Adaptive fQRS beat insertion may not be at true QRS location

Results:

- Events 4 (MSE of fetal HR): 52.496
- Events 5 (RMS error of fetal RR): 10.618

Alternatives studied / future work:

- Better MECG attenuation techniques
- Better fQRS beat insertion techniques



A Robust Framework for Noninvasive fECG Extraction

Marzieh Fatemi, Mohammad Niknazar, Reza Sameni

Approach: MINC

- DEFL $\Longrightarrow$ mECG removal
- Iterative PCA denoising $\Longrightarrow$ fEEG removal
- Kalman Filter $\Longrightarrow$ fECG Enhancement

Strengths:

- Single and multichannel, temporal and statistical properties of the ECG
- No additional assumption:

  Full rank noise, correlated and/or distributed sources
- Preserving dimensionality:

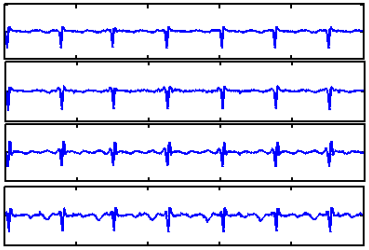
  Multichannel fECG, more interpretive for physicians than ICA)

Results on data test:

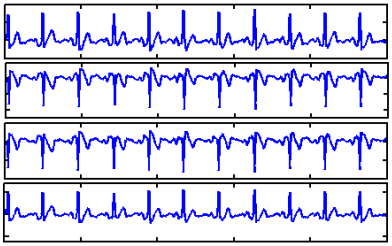
- Events 1/4 (MSE of fetal HR): 291.458, 274.268
- Events 2/5 (RMS error of fetal RR): 33.016, 32.085

future work:

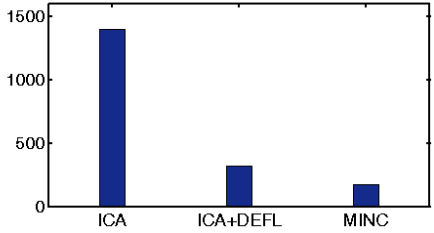
- Automatic estimation of effective Dimension and number of Iterations using quality assessment criteria



Preprocessed Signal



Extracted fECG after denoising



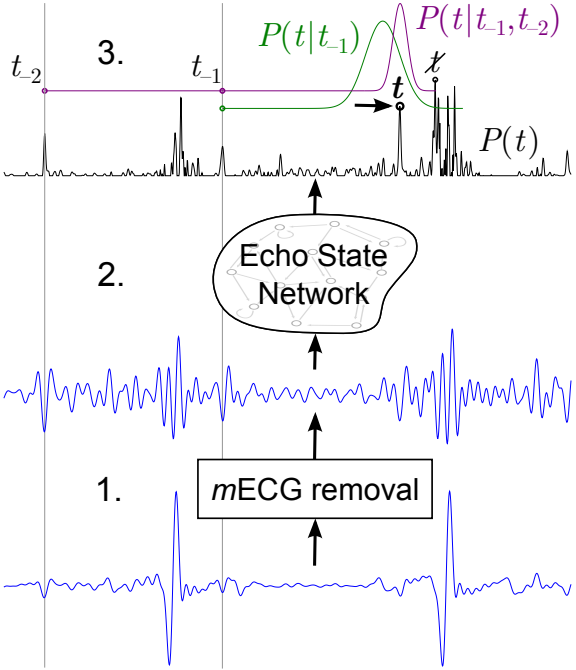
The error Score comparison on data train

Noninvasive Fetal QRS Detection Using Echo State Network

Mantas Lukoševičius*, Vaidotas Marozas / Kaunas University of Technology, Lithuania

Approach:

1. Mean *m*ECG cycle removed
2. Trained Echo State Network indicates $P(t)$ of *f*R
3. Dynamic Programming includes *f*QRS statistics $P(t|t_{-1})$, $P(t|t_{-1},t_{-2})$ to find the next *f*R event t



Strengths:

- Good accuracy, robust, fast (2x real time)
- Generic and adaptable: works even without (1.)

Weaknesses:

- Quality training data is vital
- No *f*QT measurements (yet?)

Results:

- Event 4 (*f*HR): **66.327**, 147.236
- Event 5 (*f*RR): 11.027, **8.239**

Alternatives studied / future work:

- Using $P(t|t_{-1})$ and $P(t|t_{-1},t_{-2})$ gives different benefits. A better combination of P's in (3.)?
- A more rigorous comparison of different (3.) algorithms.
- Performance can be improved sacrificing speed: bigger networks (2.); also with better (1.)

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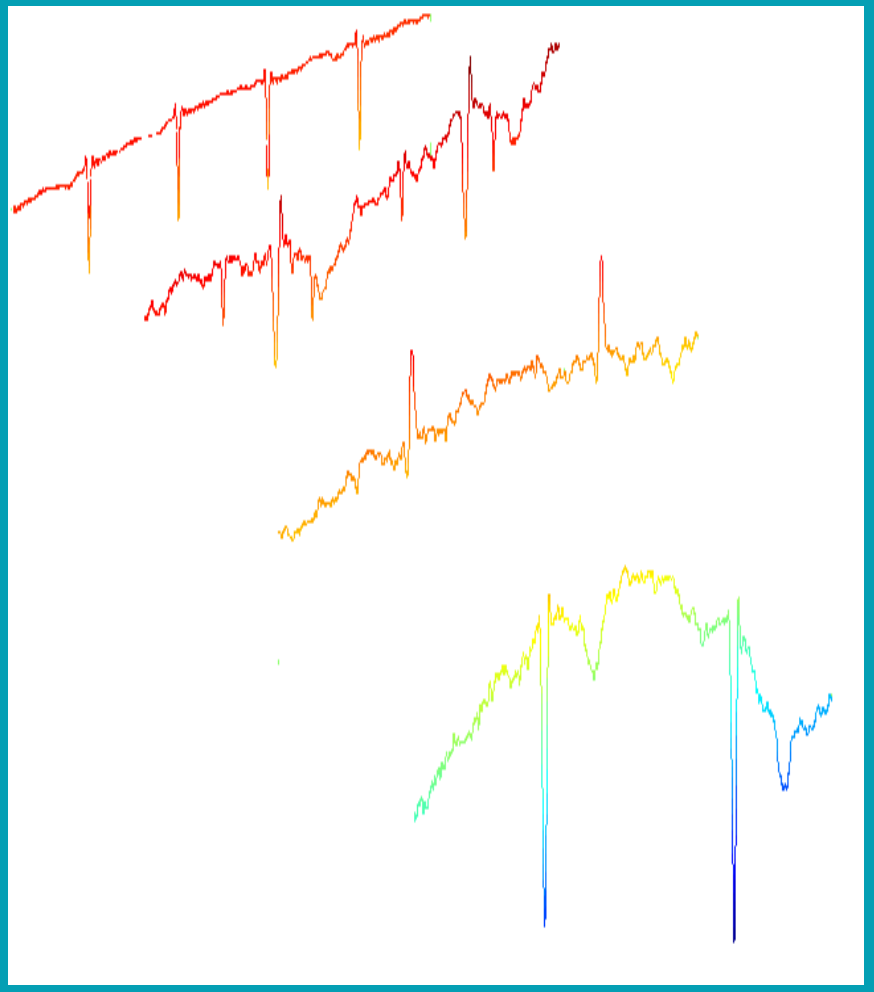
Panel Discussion

Computing in Cardiology Focus Issue on

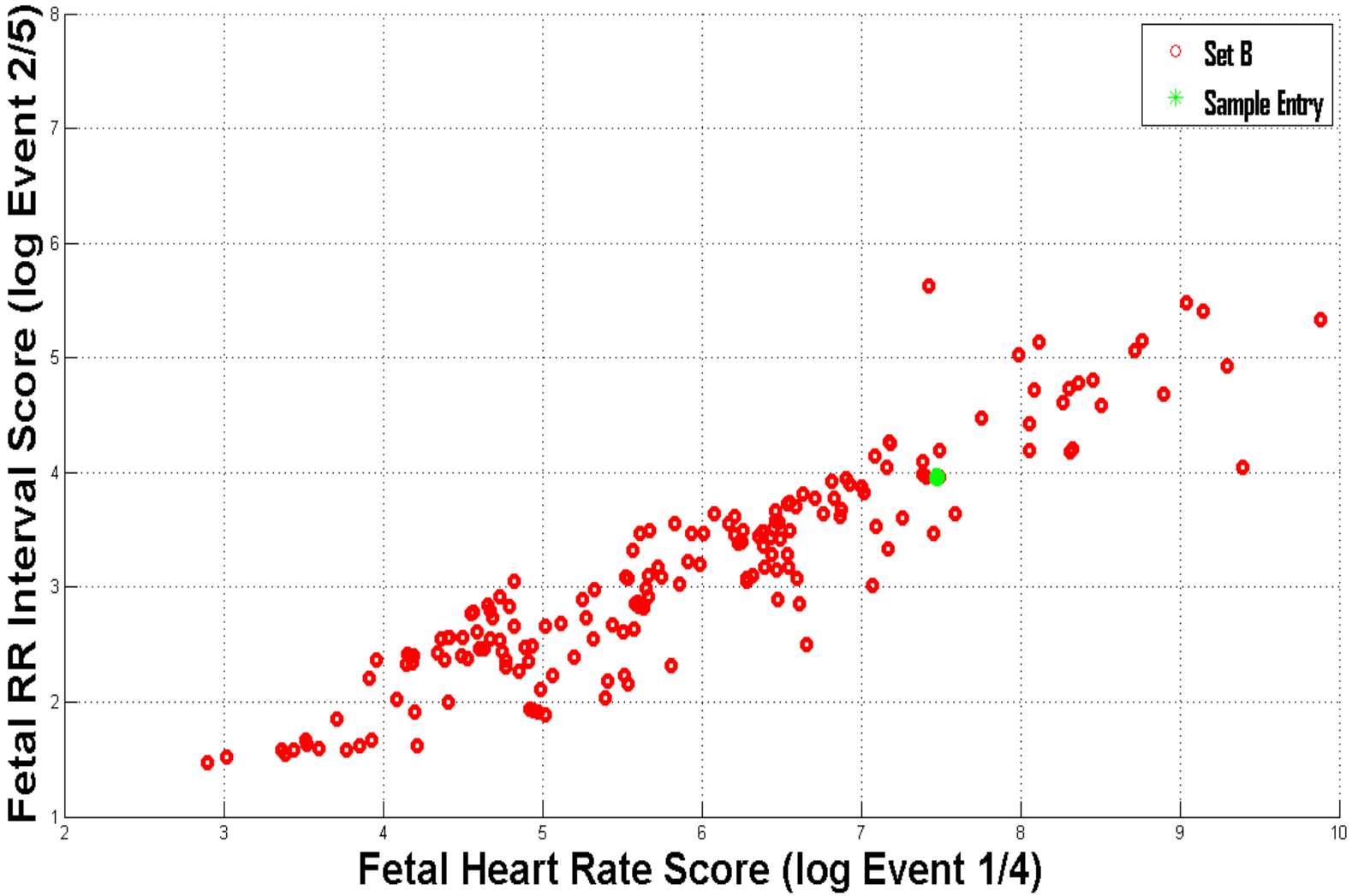
Physiological Measurement

Noninvasive Fetal ECG: The PhysioNet/Computing in Cardiology Challenge 2013

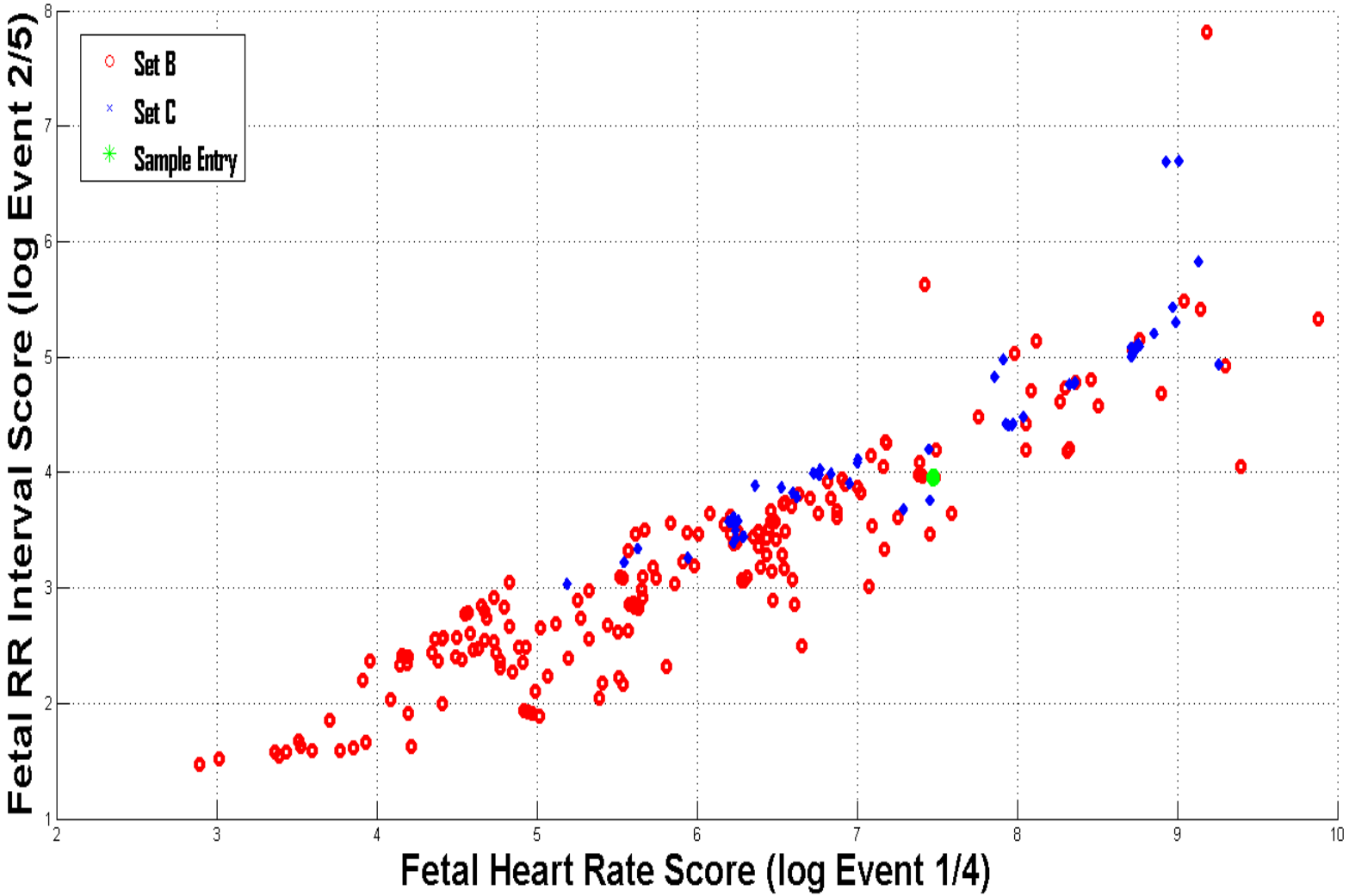
- Guest editors – Gari Clifford, George Moody, Ikaro Silva, and Joachim Behar
- Deadline for submission – February 28, 2014
- Date of publication – Sept 2014
- More details will be posted at: **http://iopscience.org/pmea**



Results:


Set B
Sample Entry
Fetal RR Interval Score (log Event 2/5)
Fetal Heart Rate Score (log Event 1/4)
1
2
3
4
5
6
7
8
2
3
4
5
6
7
8
9
10

Results:


Set B
Set C
Sample Entry
Fetal RR Interval Score (log Event 2/5)
Fetal Heart Rate Score (log Event 1/4)
1
2
3
4
5
6
7
8
2
3
4
5
6
7
8
9
10

Results: Winners

Varanini, Tartarisco, Billeci, Macerata, Pioggia, and Balocchi	Event 1: 187.091 (bpm)^2 Event 2: 20.975 ms
Podziemski and Gierałtowski	Event 3: 152.71 ms
Andreotti, Riedl, Himmelsbach, Wedekind, Zaunseder, Wessel, and Malberg	Event 4: 18.083 (bpm)^2 Event 5: 4.337 ms

Behar, Oster, and Clifford achieved unofficial scores of 179.439 (bpm)^2 and 20.793 ms in Events 1 and 2 respectively.

Challenge Contributions

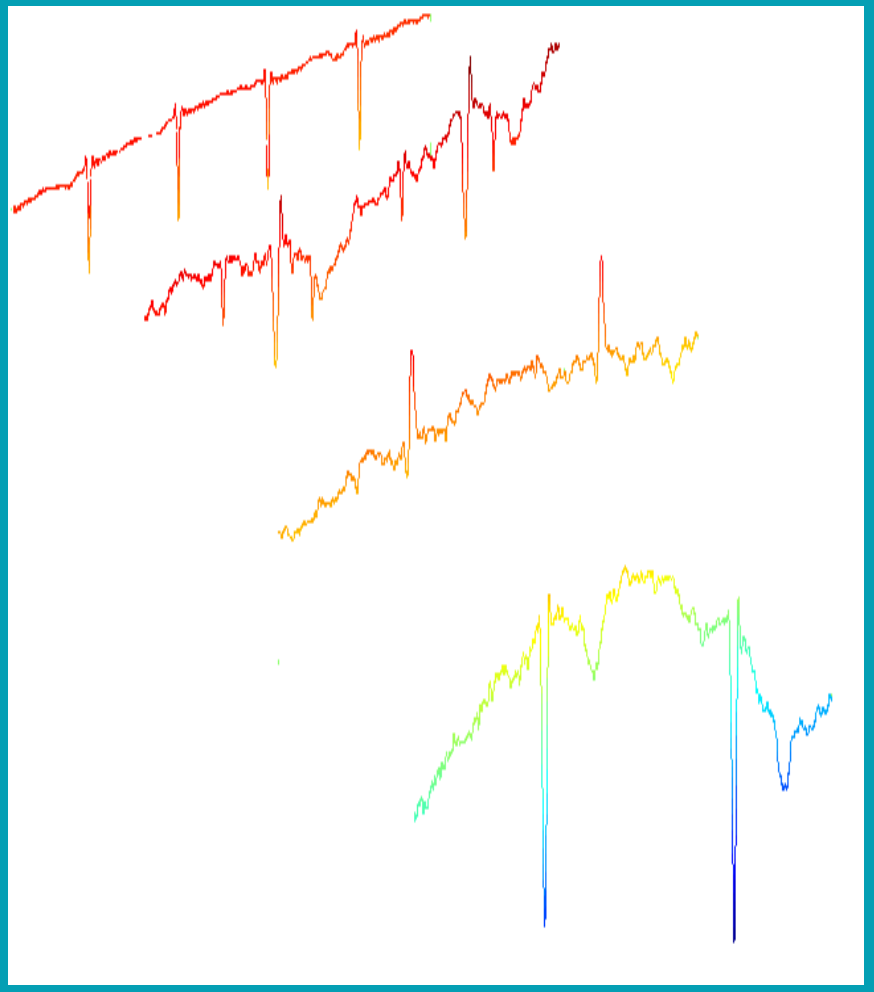
- Large open set of maternal abdominal ECG records from several different databases
- QRS annotations corrected via Bayesian crowd-sourcing (Zhu;2013)
- 91 open-source fetal QRS detection algorithms

Computing in Cardiology Focus Issue on

Physiological Measurement

Noninvasive Fetal ECG: The PhysioNet/Computing in Cardiology Challenge 2013

- Guest editors – Gari Clifford, George Moody, Ikaro Silva, and Joachim Behar
- Deadline for submission – February 28, 2014
- Date of publication – Sept 2014
- More details will be posted at: **http://iopscience.org/pmea**



Noninvasive Fetal ECG

The PhysioNet/CinC Challenge 2013

Computing in Cardiology 2013

Zaragoza, Spain

24 September 2013

A multi-step approach for non-invasive fetal ECG analysis

Approach:

1. Pre-processing to remove baseline and power line
2. ICA to enhance maternal ECG
3. Interpolation 4 KHz and maternal QRS detection
4. SVD to remove maternal ECG using QRST approximation
5. ICA to enhance fetal ECG
6. Fetal QRS detection improved with AR model of RR series

Strength:

- The combination of ICA and SVD improves the cancellation of maternal ECG
- The second ICA enhances fetal ECG

Weaknesses:

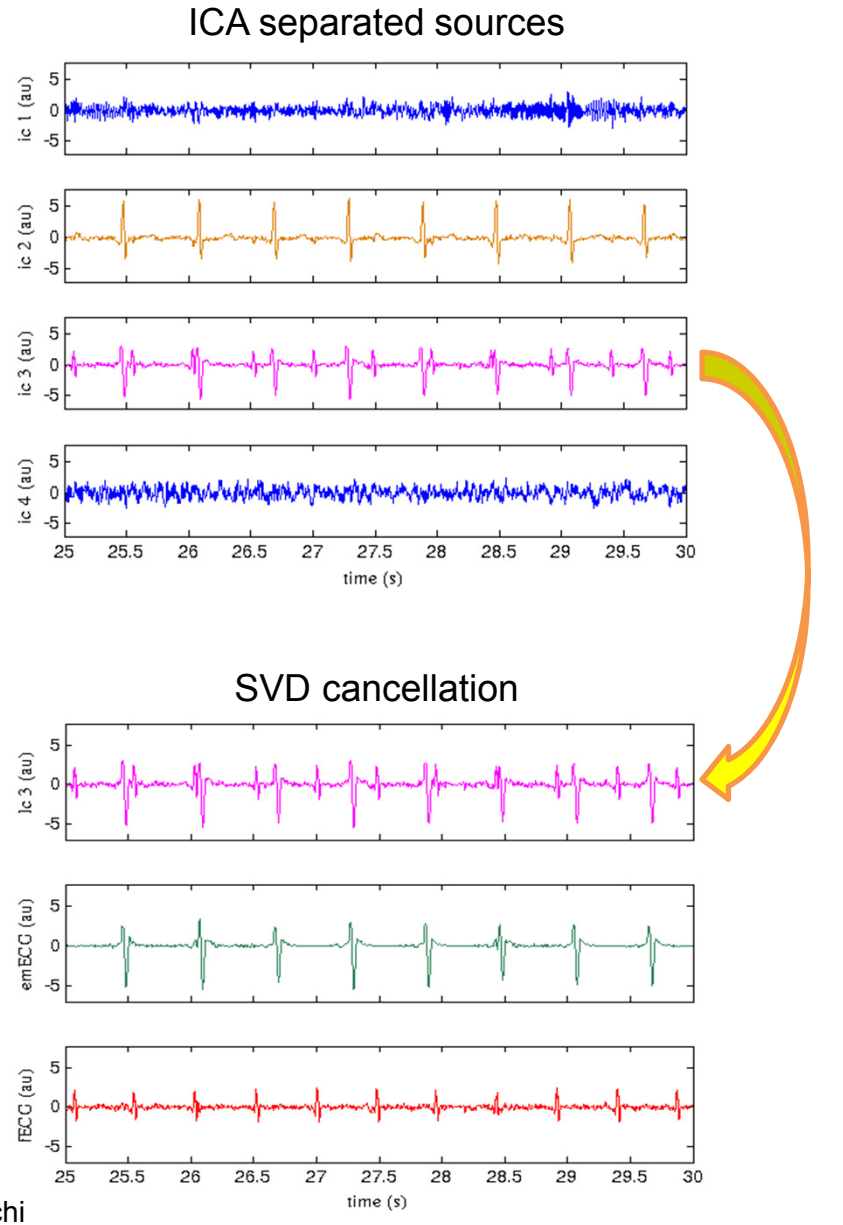
- Measurement/EMG noise impairs the effects of ICA
- Trade-off Maternal ECG cancellation/fECG preservation

Results:

- Events 1/4 (MSE of fetal HR): 187.091, 33.952
- Events 2/5 (RMSE of fetal RR): 20.975, 5.098

Conclusions/future work:

- Improving fQRS detector to manage inaccurate maternal ECG cancellation
- Avoid SVD canceling when ICA separates the fECG source



Authors: M. Varanini, G. Tartarisco, L. Billeci, A. Macerata, G. Pioggia, R. Balocchi

Fetal ECG Estimation Based on Linear Transformations

Llamedo et al.

Approach:

- Average heartbeat to remove maternal ECG
- PCA, ICA, πCA decomposition to enhance FECG
- Wavelet based delineator to detect/delineate fQRS
- SNR measure based in coherent averaging
  - Statistical model to accept measurements

Strengths:

- Exploits well spatial separation
- Specific

Weaknesses:

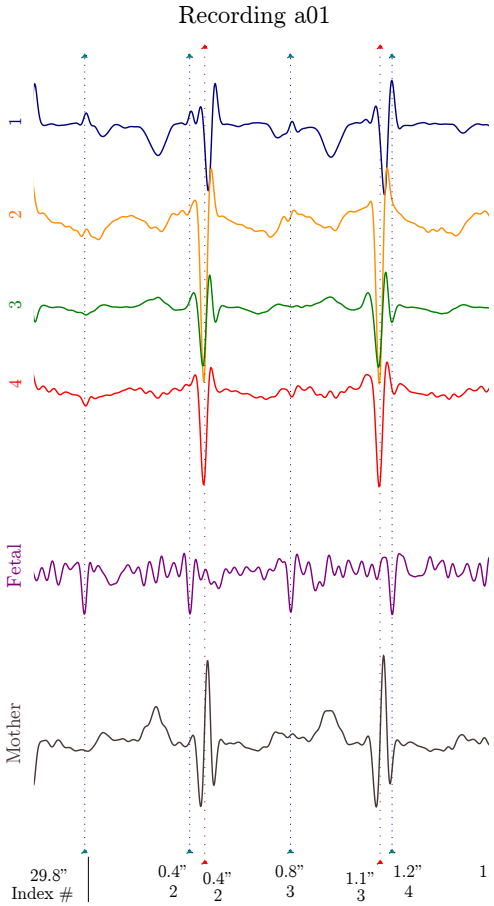
- Spatial overlapp
- Sensitivity

Results:

- Events 4 (MSE of fetal HR): 4714.6
- Events 5 (RMS error of fetal RR): 121.6

Alternatives studied / future work:

- Ensure spatial sepparation
- Improve statistical model of fQRS



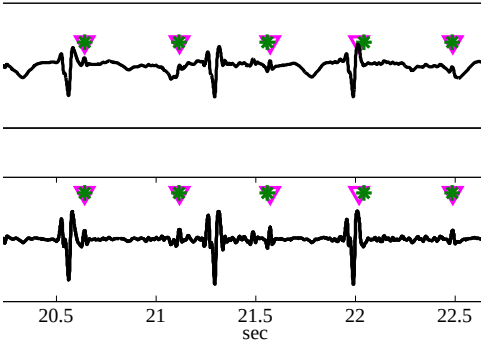
A WT Meth. for Assessing Fetal Cardiac Rhythms from Abdominal ECGs

Rute Almeida, Hernâni Gonçalves, Ana Paula Rocha, João Bernardes

Goal: WT based ECG delineator → fetal QRS detector using similar strategy → score 5

Approach: similar to maternal QRS detection

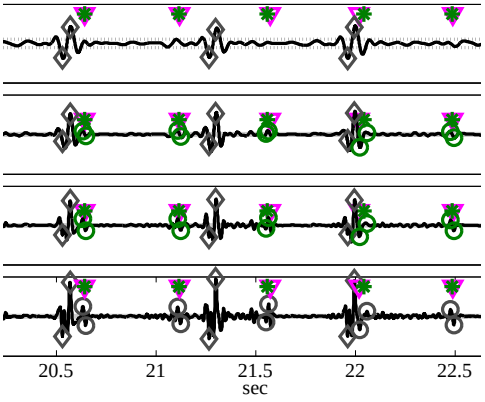
- search Maximum Modulus Lines across scales
- QRS: zero crossings between MML
  - refractory period and searchback
- combine SL marks: one annotation
- **Adapting for fetal physiology:**
  - adapt scales, thresholds and time neighborhood
  - maternal QRS MML lines → excluded



Results:

- set A: score 27 / Sensitivity 78% / +Predictivity 82%
- set B: score 33
- detect overlaped fetal/maternal QRS **(strength)**
- arbitrary number of leads (1, 2, ...) **(strength)**

but affected by artifacts in more than 1 lead **(weakness)**



Future improvements:

- to reduce FP by minimum signal quality restrictions

Intelligent Recognition of the Fetal QRS Complex

Ali Ghaffari[1], Seyyed Abbas Atyabi[1], Mohammad Javad Mollakazemi[1*], Maryam Niknami[2] , Ali Soleimani[1]

[1]CardioVascular Research Group (CVRG), Department of Mechanical Engineering at K.N.Toosi University of Technology, Tehran, Iran
[2]Cardiovascular Division of Imam Hossein Hospital, Isfahan University of Medical Sciences, Golpayegan, Iran

Approach:

1.Regenerating the missing data based on the statistical distribution of the data.

2.Preprocessing and denoising the FECG signal using wavelet transform based on estimation of noises of wavelet coefficients .

3.Decomposing the deniosed signal using discrete wavelet transform in level 10 with 'db6' wavelet function

4.Reconstructing signal of details 1 , namely as D1 signal

5.Finding Maternal QRS complex from original signal

6.Eliminateing Maternal QRS complex from D1 signal

7.Find other high frequency points (using D1 signal)

8.Keep high frequency points that have an special order and memorize the order

9.Approximate the other points using the order

10.Do these steps for all 4 leads

11.Score the leads with 2 parameters:

a=less noise distribution

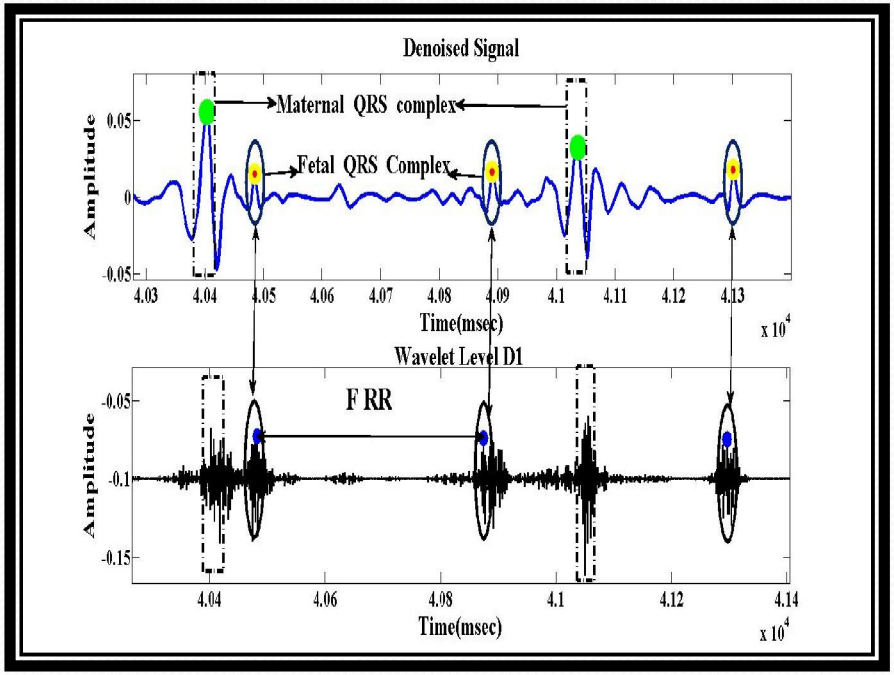
b=having more proper members in step 10

12.Select the more reliable members of step 10 vectors

13.Combine the reliable members of the leads with a priority (the priority is the score of leads)

14.Predict the eliminated FQRS

15.Combine step 13 and 14 outputs



Results (Best Scores):

Events 4 and 5 from phase 1 : ***108.766*** *and* ***15.480***

Events 4 and 5 from phase2: ***63.750*** *and* ***11.198***

Non Invasive FECG Extraction From a Set of Abdominal Sensors

Behar Joachim, Oster Julien, Clifford Gari D.

❖ Approach

FUSE

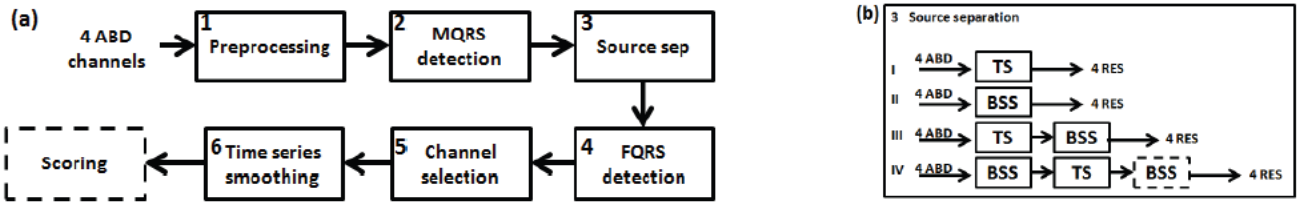


Figure 1. (a) FECG extraction block diagram. (1) The four ABD ECG channels are preprocessed, (2) MQRS detection, (3) source separation to extract the FECG from the ABD mixture, (4) FQRS detection, (5) one of the FQRS time series is selected, and (6) the resulting time series is smoothed. (b) Detail of the source separation block. ABD: abdominal, BSS: blind source separation, RES: residual, dashed line: optional step.

❖ Strengths

Robust extraction and selection of ABD channel

❖ Weaknesses

QT measurement requires different extraction condition

❖ Results

E4=29.6, E5=4.67

❖ Future work

- Better way of fusing information from the different residuals
- Evaluation on larger database
- Evaluation on pathological examples

CL	Method	HRE	RRE	F_1-10Hz	F_1-2Hz
		NU	NU	%	%
I	TS	656	27.9	81.6	81.1
I	TS_{PCA}	594	21.6	86.0	83.7
I	TS_{EKF}	841	26.2	82.0	79.9
II	ICA	2852	39.3	63.8	61.7
II	PCA	3891	45.3	51.6	52.6
III	TS-ICA	272	17.1	92.0	91.4
III	TS_{PCA}-ICA	156	16.9	93.0	92.4
III	TS_{EKF}-ICA	565	27.3	81.1	80.7
IV	ICA-TS	430	19.2	90.6	89.3
IV	ICA-TS-ICA	369	18.7	91.7	91.1
	CONST-HR (143 bpm)	172	8.9	22	–
	FUSE	136	12.5	95.0	94.6
	FUSE-SMOOTH	16	6.3	96	–
	FUSE-CHALL	4.8	2.3	74.5	–

Table 2. Performance of the different algorithms on set-a. TS: template subtraction, HRE: score for the heart rate challenge event, RRE: score for the RR challenge event, CL: class of the method, NU: no unit. F_1-10Hz and F_1-3Hz represent the F_1 measure with f_{bas}=10Hz and f_{bas}=2Hz respectively. HRE and RRE are given for f_{bas}=10Hz.

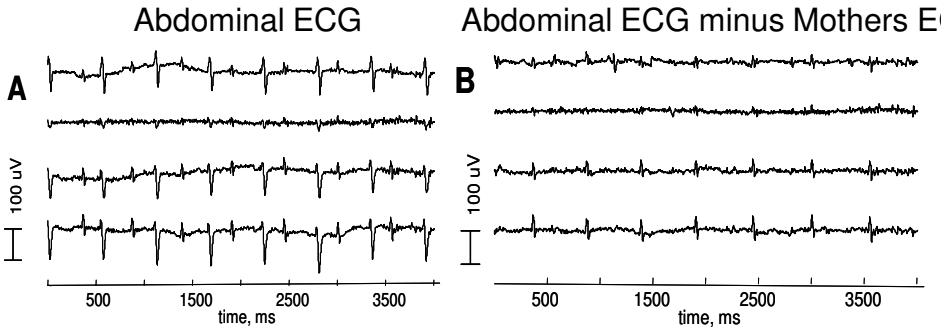
Multi Stage Principal Component Analysis Based Method for Detection of Fetal Heart Beats in Abdominal ECG

LIETUVOS SVEIKATOS MOKSLŲ UNIVERSITETAS
[1] Lithuanian University of Health Sciences, Kaunas, Lithuania
[2] Kaunas University of Technology, Kaunas, Lithuania

Robertas Petrolis[1], Algimantas Krisciukaitis[1,2]

Approach:

- R wave detection by two stage method using amplitude thresholding and maximization of correlation with sliding QRS template.
- Mother's ECG elimination by means of cardio cycle-vise Principal Component Analysis and truncated representation using only 3 first eigenvectors.
- Fetal ECG concentration into one lead by means of Principal Component Analysis of all signal leads after Mother's ECG cancellation.
- R wave detection in fetal ECG by means of two stage method using amplitude thresholding and maximization of correlation with sliding QRS template.



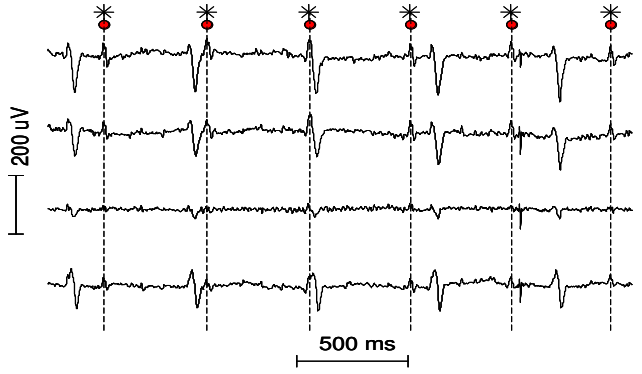
Strengths:

- Based on biophysical interpretation of the signal origin;
- As side product, provides morphological estimates of cardio cycles.
- No training set is required.

Weaknesses:

- Many parameters of the method are defined and adjusted "ad hoc": number of principal components, threshold levels etc.
- Possibility to analyze only intervals of certain minimal length.

Stars – our method, circles - reference time points



Results:

Events 4 (MSE of fetal HR): 341.503

Events 5 (RMS error of fetal RR): 32.810

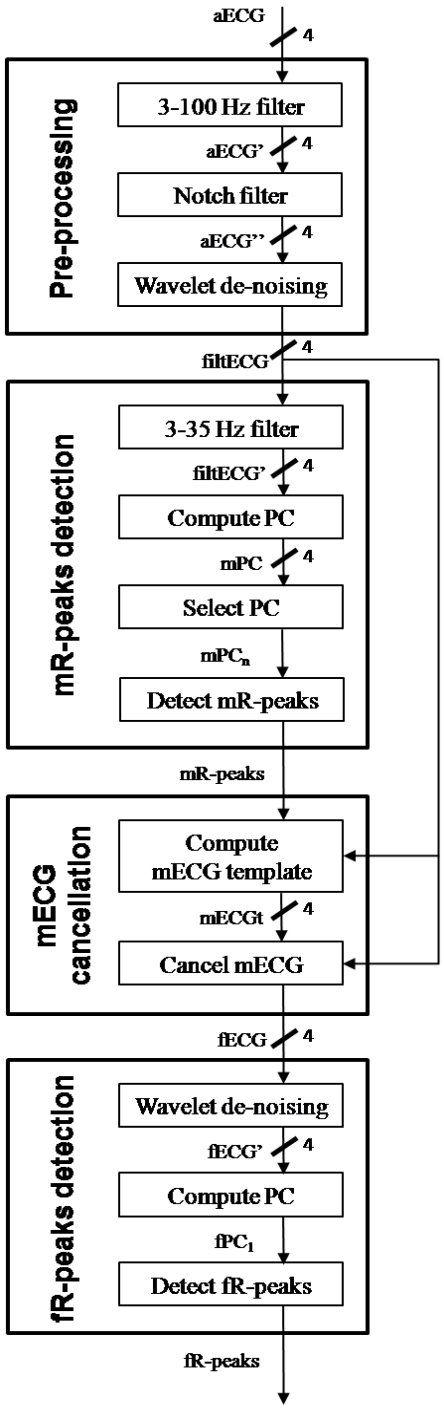
Alternatives studied / future work:

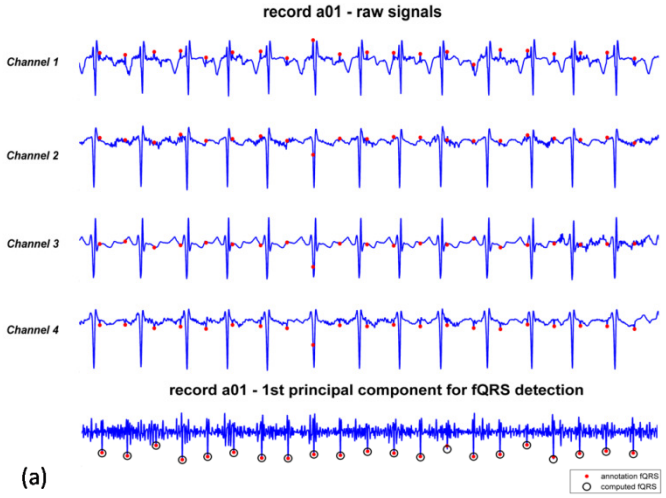
- We tried "classical" ICA, but it failed due to significant part of the signal energy occupied by independent noise components.
- Cardio cycle-vise reconstruction of fetal ECG by means of PCA for morphological analysis of the signal.

An Algorithm for the Analysis of Foetal ECG from 4-channel Non-invasive Abdominal Recordings

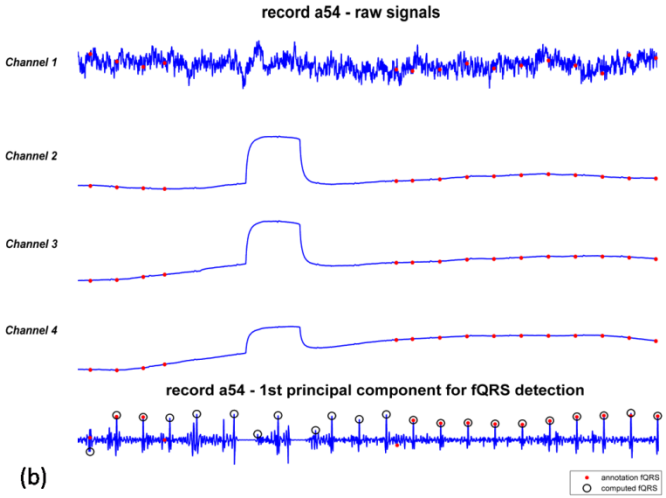
Di Maria C, Duan W, Bojarnejad M, Pan F, King S,
Zheng D, Murray A, Langley P

The Newcastle upon Tyne Hospitals NHS
NHS Foundation Trust
Newcastle University

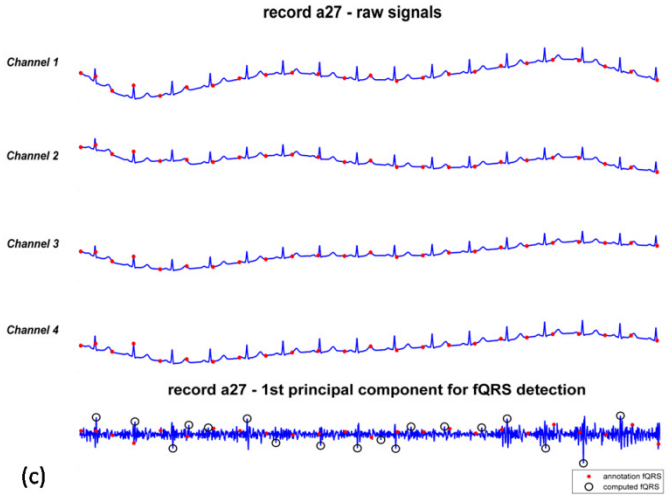




(a)



(b)



(c)

		Sample algorithm	This algorithm
fHR	***Set-A***	2910.90	512.82
	Set-B	3258.56	223.23
fRR	***Set-A***	106.65	27.63
	Set-B	102.75	19.34

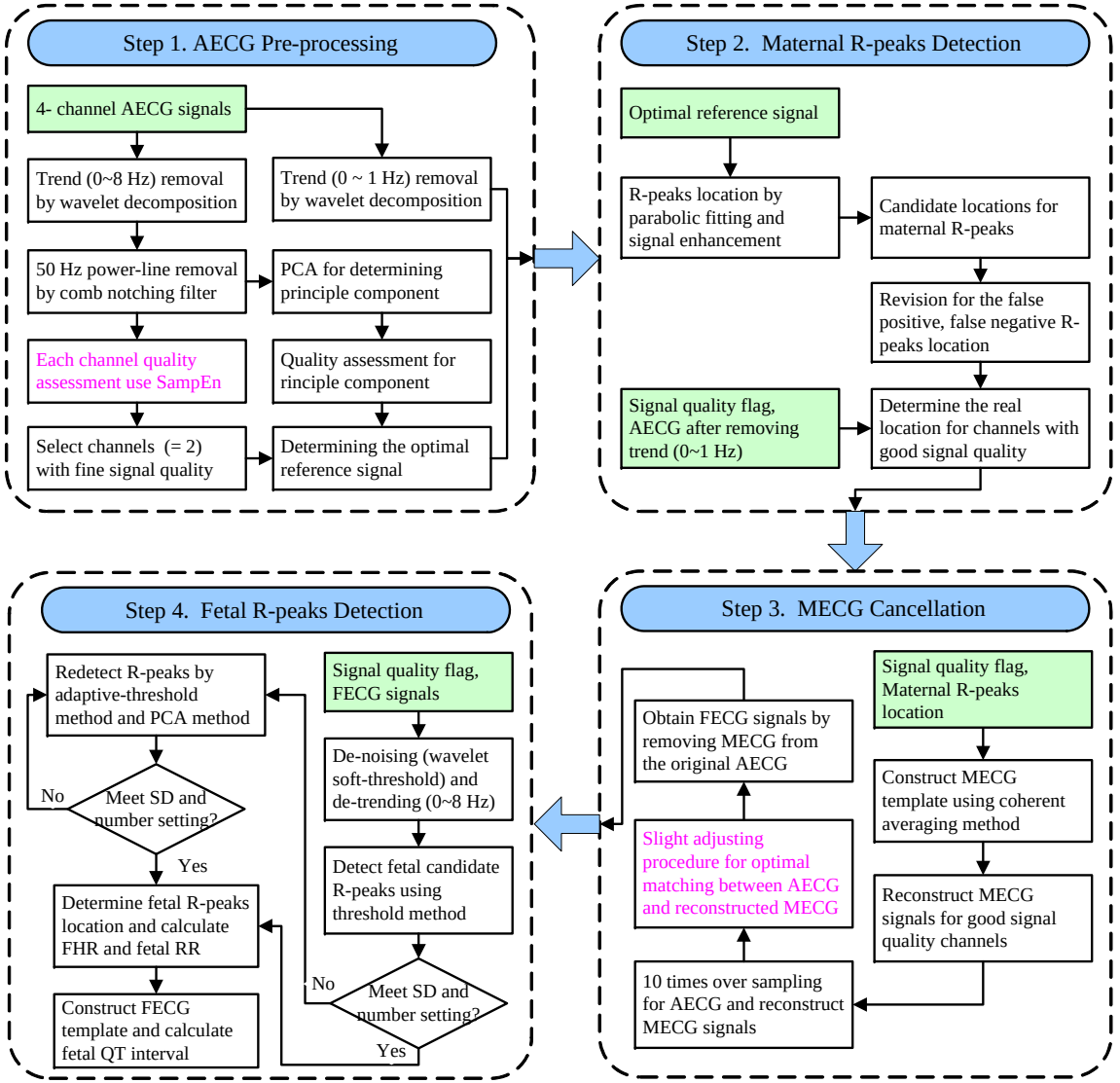
Noninvasive Fetal ECG PhysioNet/CinC 2013 Challenge

Panel Discussion

Systematic Methods for Fetal Electrocardiographic Analysis: Determining the Fetal Heart Rate, RR Interval and QT Interval

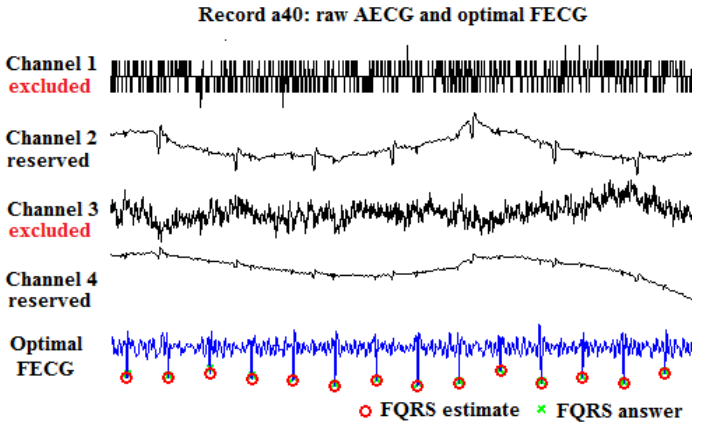
Chengyu Liu and Peng Li

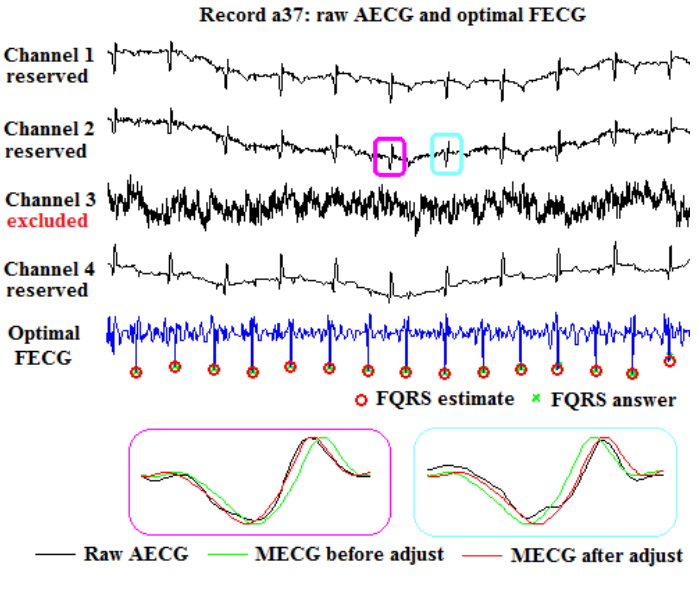
Method: algorithm flow chart



Results on Set B

Event 4: 264.87; Event 5: 9.04





* Please contact *bestlcy@sdu.edu.cn* for further information.

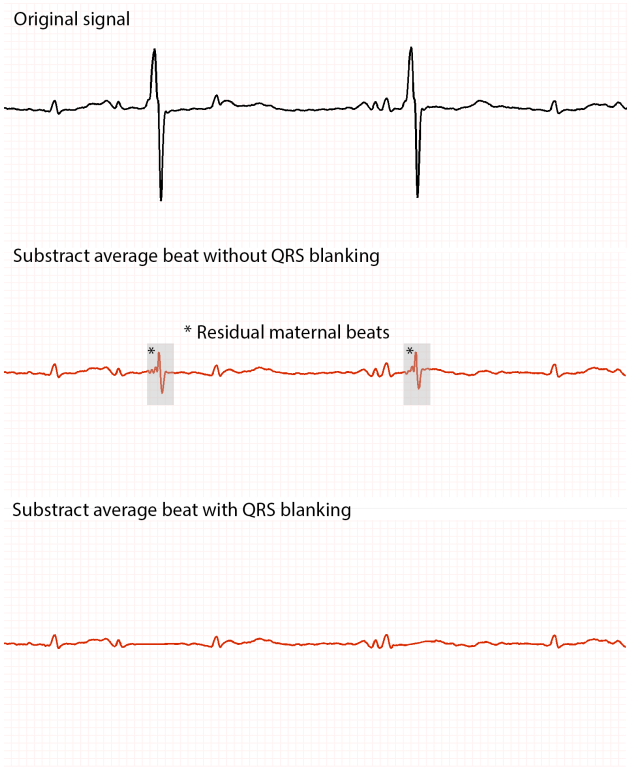
Ludwig Boltzmann Institute
Translational Heart Failure Research

AUSTRIAN INSTITUTE OF TECHNOLOGY

A robust algorithm for fetal heart rate and RR interval calculation using non-invasive maternal abdomen ECG

M. Kropf, R. Modre-Osprian, G. Schreier, D. Hayn

- Approach:
  - Detect maternal QRS [1], substract averaged QRS [2]
  - Detect fQRS
  - Calculate measure for fQRS detection quality
  - Select parameter set leading to best quality measure
  - Optimize fQRS sequence using statistical methods
- Strengths:
  - Unsupervised selection of best channel and quality
- Weaknesses / future work
  - fQRS detection should be improved to detect regular event sequences instead single events
- Results:
  - Events 1/4 (MSE of fetal HR): 82.438
  - Events 2/5 (RMS of fetal RR): 7.354



Different approaches to remove maternal ECG

[1] CinC challenge 2004, 1st place, Biomed Tech 2007; 52:5-10
[2] CinC challenge 2011, 1st place, Physiol. Meas. 33 (2012) 1449-1461

Noninvasive multilead FQRS Detection

Vito Starc

Approach:

- Preprocessing: 4 lead signals -> **8 signals**: with two bandpass filters (5 - 40 Hz & 1 - 80 Hz)
- Maternal PQRST **cancellation**
- **FQRS detector** with adjustable threshold
- **FQRS filter** for Outlier rejection
  by minimizing error = $\sum (RR_i - \text{median } RR)^2$
- Final selection: FQRS series with the minimal error
- Automated analysis, Delphi-Pascal

Strengths:

- Multilead RR assessment better than single lead
- Tolerates loss of 1 to 3 (of 4) ECG signals

Weaknesses:

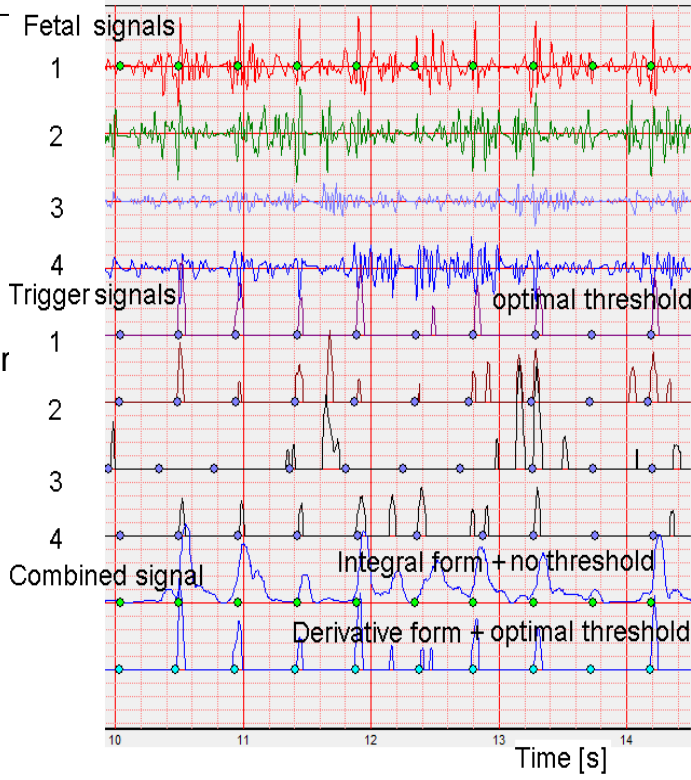
- Static filtering does not adapt to instant. noise
- QT estimation is unreliable due to filtering

Results:

- Events 1/4 (MSE of Fetal HR): 963, 195, 181
- Events 2/5 (RMS error of FRR): 37.1, 15.4, 10.9

Alternatives studied / future work:

- $\sum (dU/dt_i)^2$ signal better for FQRS detection than SVD
- Future - Matching of instantaneous FQRS to the template



Fetal signals, Trigger signals and beat fiducial points

Identification of Fetal QRS Complexes in Low Density Non-Invasive Biopotential Recordings

Alessia Dessì, Danilo Pani, Luigi Raffo*

Approach:

- Joint filter-based and template matching strategy to identify QRS complexes and maternal QRS template
- Periodicity analysis and correction of the time series
- Clustering to identify maternal annotation
- Maternal QRS template subtraction
- Similar approach to identify fetal QRSs complexes

Strengths:

- MECG cancellation preserves fetal QRS complexes

Weaknesses:

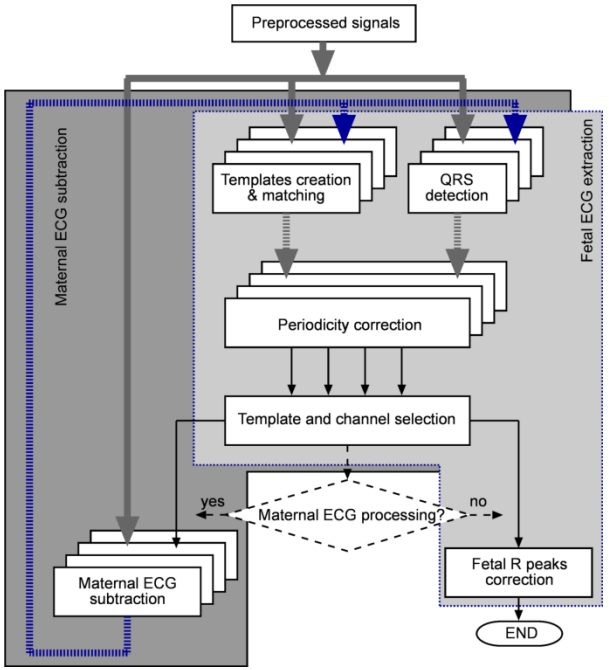
- Too much sensitive to high frequency P/T waves
- Rules for the identification of maternal complexes

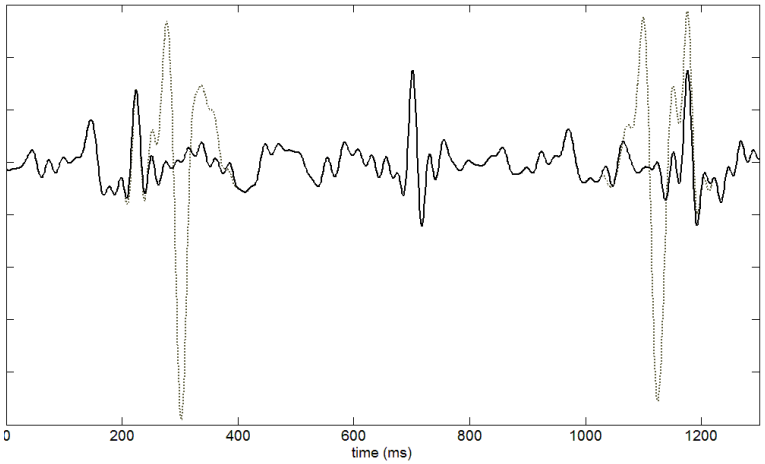
Results:

- Events 1/4 (MSE of fetal HR): 648.158 639.465
- Events 2/5 (RMS error of fetal RR): 47.990 23.821

Alternative studies/future work:

- Improve clustering rules
- Improve fetal QRS detection in low SNR signals
- Include the P and T waves in the subtraction of averaged maternal complexes



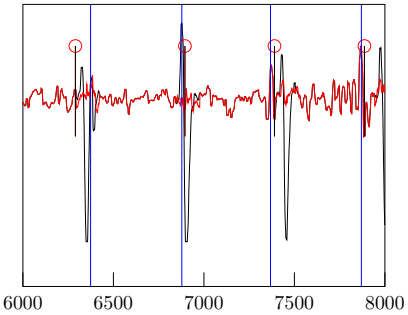


Fetal ECG detection in abdominal recordings: a method for QRS location

Rui Rodrigues

Approach:

- Median filter, Notch and low pass linear filters
- Detect MQRS using *all 4 channels*
- Remove MECG in the *neighbourhood* of each MQRS using adaptive filter
- Peak detector to locate FQRS on each channel
- Choose one of the 4 sets of FQRS detections: Max {number of detections -0.5*std(RR interval)}



record a03: channel 1

Weaknesses:

- Criteria to choose channel from where FQRS detections are taken

Results:

-Event 1: 278.755 -Event 2: 28.201

-Event 4 : 124.803 -Event 5 : 14.351

future work:

- Eliminate steep mother P and T waves (example: a43)
- Reconstruction of MQRS using other methods(neural networks??)
- Criteria to choose channel from where FQRS detections are taken

Foetal Heartbeat Detection by Expectation-weighted Estimation of Fiducial Points

LY Di Marco, A Marzo, A Frangi
CISTIB - University of Sheffield, UK

Approach:

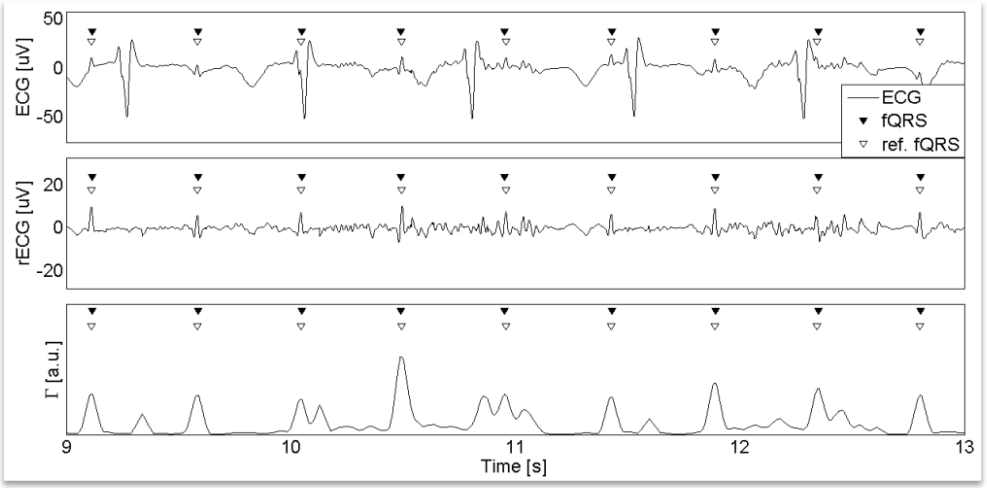
- Template-based cancellation of mQRS to obtain rECG
- Band-pass filter to enhance fQRS
- Gaussian distribution to weight expectation (EWE) of next fQRS

Strengths:

- Accurate foetal RR measurement
- Tolerates loss of N-1 signals

Weaknesses:

- Choice of 'best' channel for fQRS
- Assumption of 'fairly stable' fHR



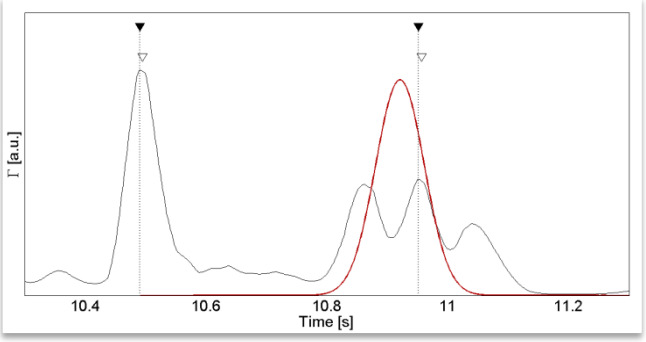
Abdominal ECG (top), residual ECG (central) and filtered signal (bottom)

Results:

Event	Phase 1 Score	Final Score
4	135.18	205.01
5	7.11	12.87

Future work:

- Apply EWE to a combination of rECG signals instead of N individual signals
- Improve expectation criterion to account for sudden acceleration/deceleration of fHR



Expectation-weighted estimation of next fQRS

Fetal Heart Rate Discovery: algorithm for detection of fetal heart rate from noisy, non-invasive fetal ECG recordings

Piotr Podziemski
Jan Gierałtowski

Faculty of Physics, Warsaw University of Technology, Poland

Approach:

- moving median to remove trends
- adaptive RS slope detection to find fQRS
- covariance of fQRS with abdominal ECG to enhance fECG

Strengths:

- multichannel but works also for single channel
- works extremely well for partially noisy signals
- can detect fetal QRS in fused fQRS and mQRS
- universal approach to signals with different properties

Weaknesses:

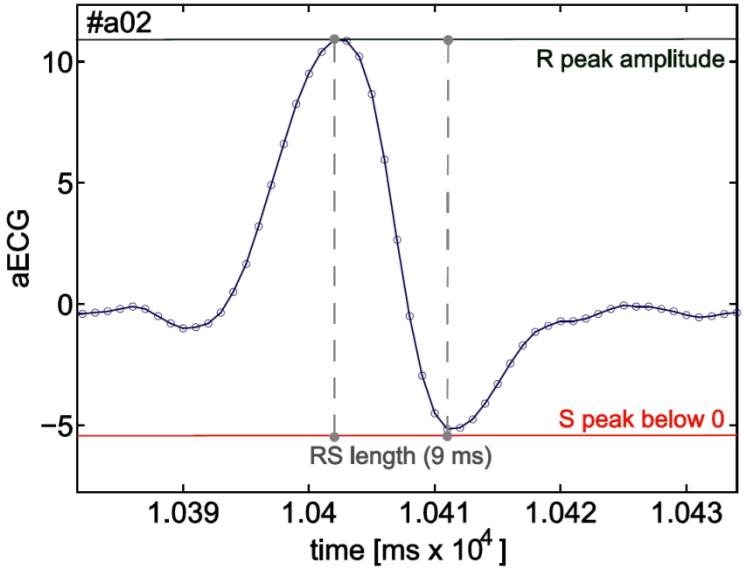
- QT estimation unreliable
- sloppy noise filtration

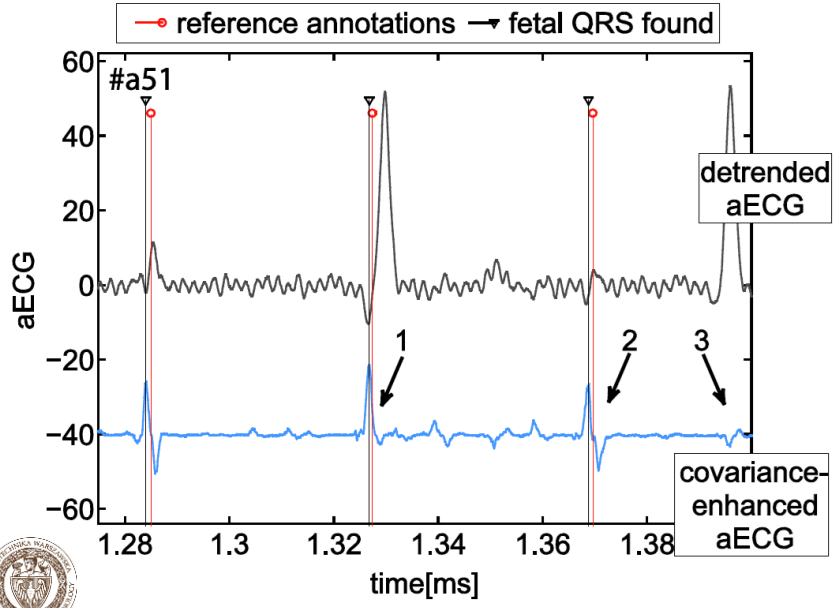
Results:

- 118.221 (event 4) and 10.663 (event 5).

Future work:

- cross-covariance of different channels
- better noise filtering





Noninvasive Fetal ECG PhysioNet/CinC 2013 Challenge

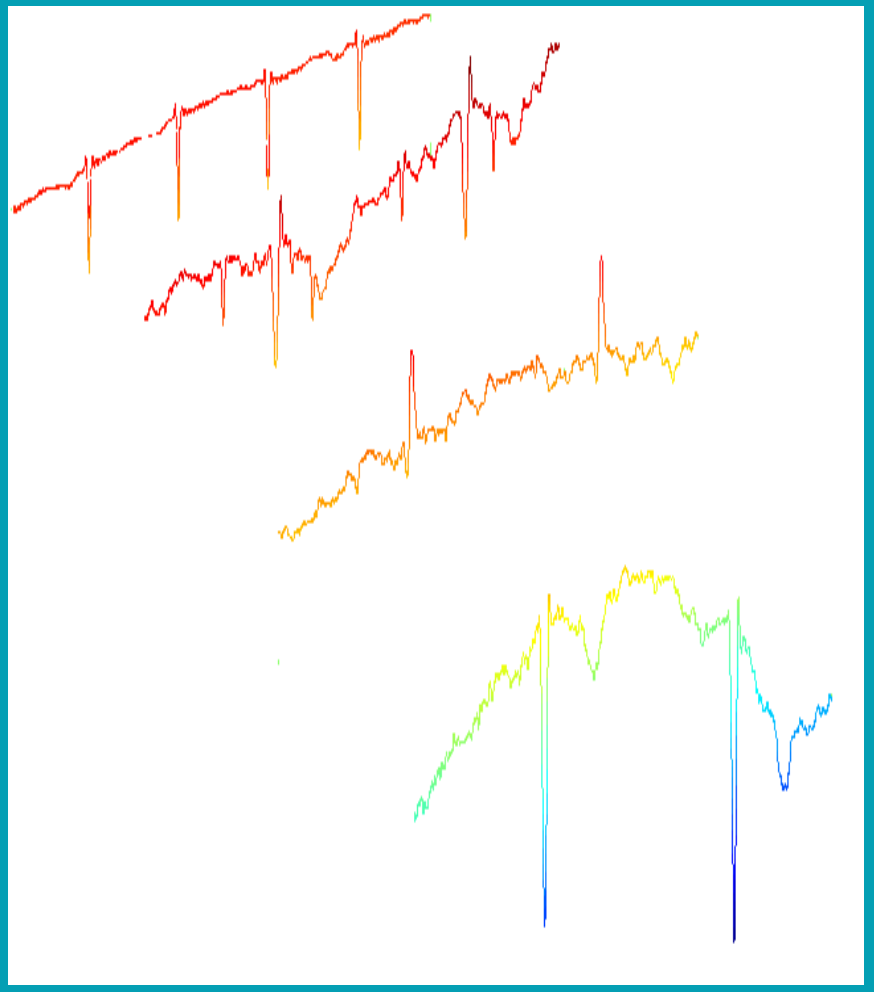
Panel Discussion

Computing in Cardiology Focus Issue on

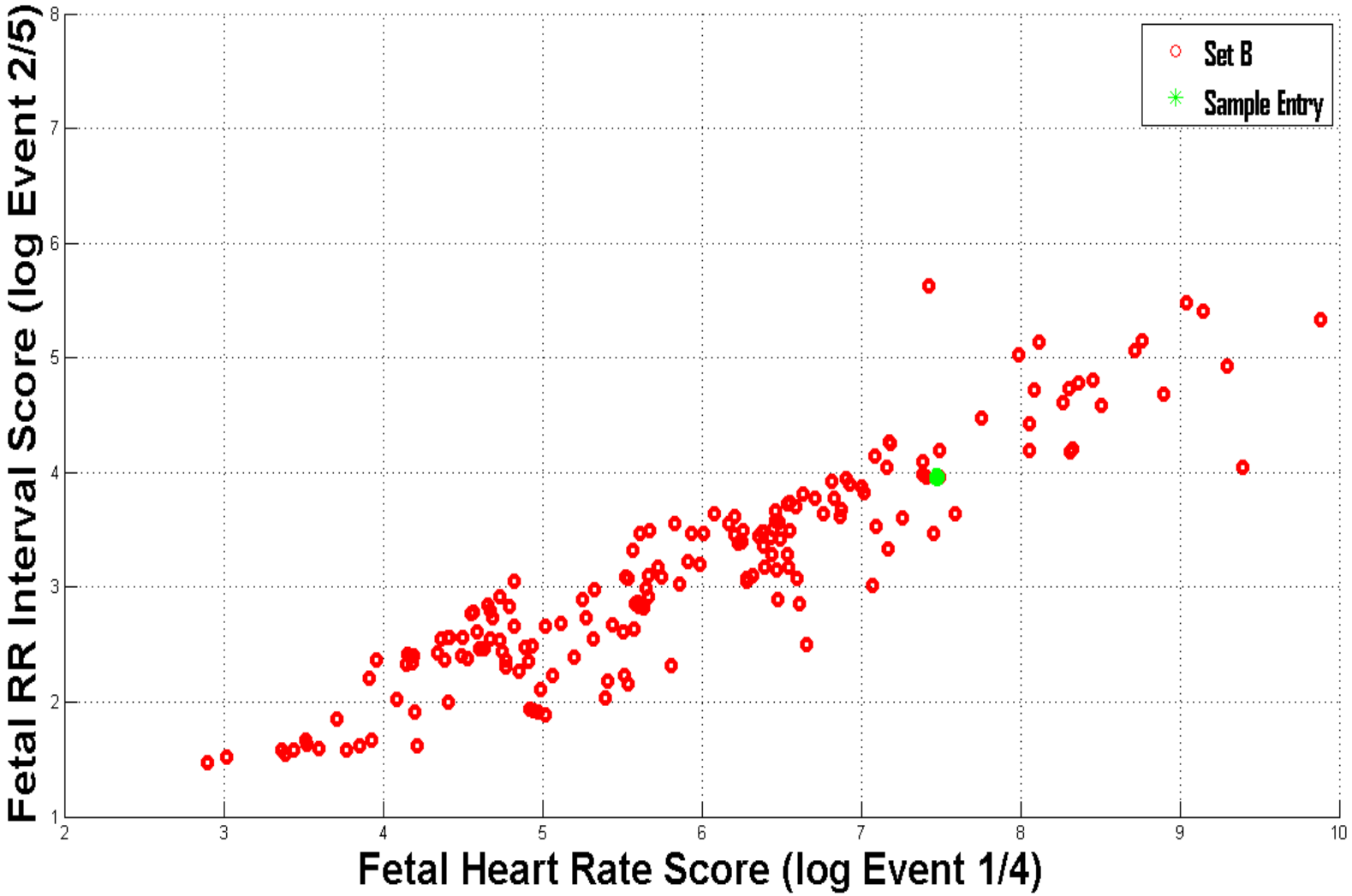
Physiological Measurement

Noninvasive Fetal ECG: The PhysioNet/Computing in Cardiology Challenge 2013

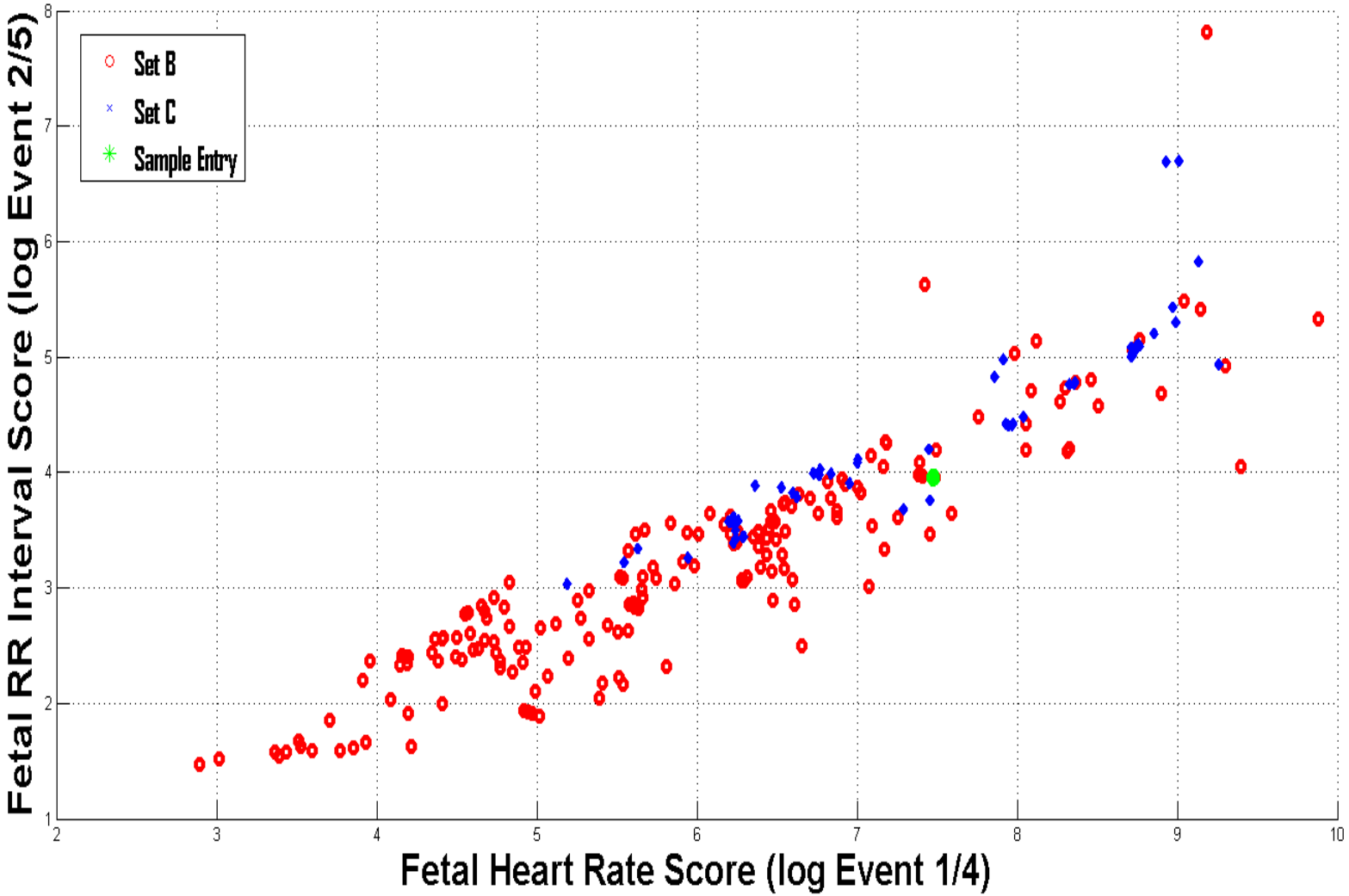
- Guest editors – Gari Clifford, George Moody, Ikaro Silva, and Joachim Behar
- Deadline for submission – February 28, 2014
- Date of publication – Sept 2014
- More details will be posted at: **http://iopscience.org/pmea**



Results:


Set B
Sample Entry
Fetal RR Interval Score (log Event 2/5)
Fetal Heart Rate Score (log Event 1/4)
1
2
3
4
5
6
7
8
2
3
4
5
6
7
8
9
10

Results:


Set B
Set C
Sample Entry
Fetal RR Interval Score (log Event 2/5)
Fetal Heart Rate Score (log Event 1/4)
1
2
3
4
5
6
7
8
2
3
4
5
6
7
8
9
10

Results: Winners

Varanini, Tartarisco, Billeci, Macerata, Pioggia, and Balocchi	Event 1: 187.091 (bpm)^2 Event 2: 20.975 ms
Podziemski and Gierałtowski	Event 3: 152.71 ms
Andreotti, Riedl, Himmelsbach, Wedekind, Zaunseder, Wessel, and Malberg	Event 4: 18.083 (bpm)^2 Event 5: 4.337 ms

Behar, Oster, and Clifford achieved unofficial scores of 179.439 (bpm)^2 and 20.793 ms in Events 1 and 2 respectively.

Challenge Contributions

- Large open set of maternal abdominal ECG records from several different databases
- QRS annotations corrected via Bayesian crowd-sourcing (Zhu;2013)
- 91 open-source fetal QRS detection algorithms

Computing in Cardiology Focus Issue on

Physiological Measurement

Noninvasive Fetal ECG: The PhysioNet/Computing in Cardiology Challenge 2013

- Guest editors – Gari Clifford, George Moody, Ikaro Silva, and Joachim Behar
- Deadline for submission – February 28, 2014
- Date of publication – Sept 2014
- More details will be posted at: **http://iopscience.org/pmea**