Current state of Automated Analysis of CTG signals at the CTU in Prague

Václav Chudáček, Jiří Spilka et al.

Skupina zpracování biologických dat
FEL ČVUT v Praze

v.0.98 MFF UK Praha
Latest revision: 18.12.2013

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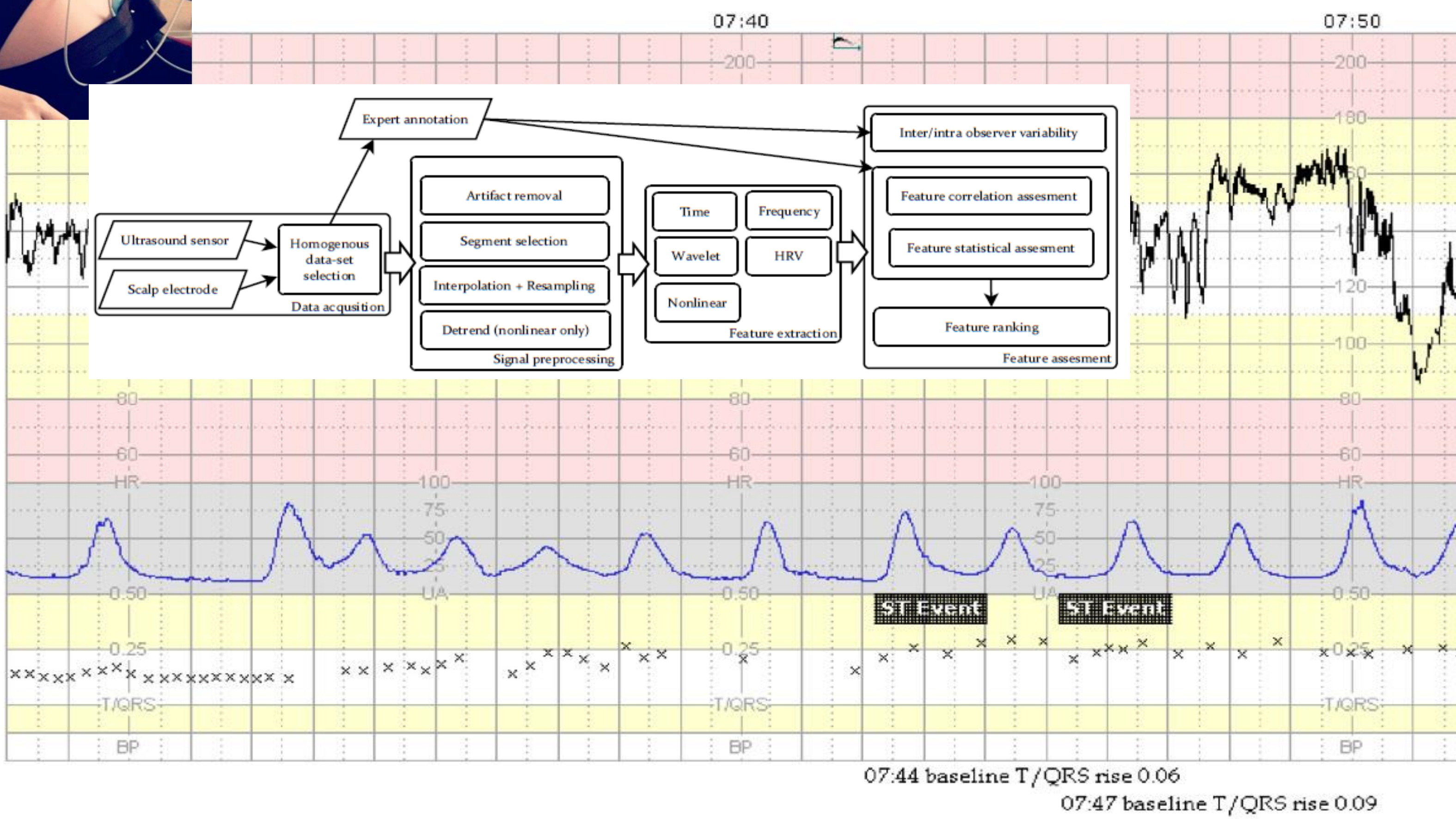
Overview

- Intro: What is CTG?
- Motivation: From wishfull thinking to possible outcomes
- General automated evaluation framework
  - Database
  - Signal pre-processing
  - Signal representation (features etc.)
  - Classification
  - Outcome evaluation
- Interesting sub-topics in more detail
  - Scattering transform
  - Results from other non-linear features
  - Results based on clinical agreement measures

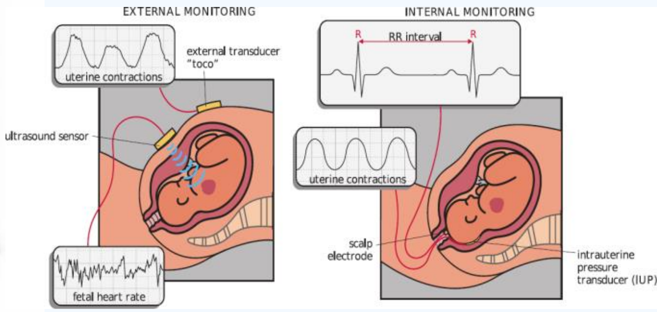
Intro

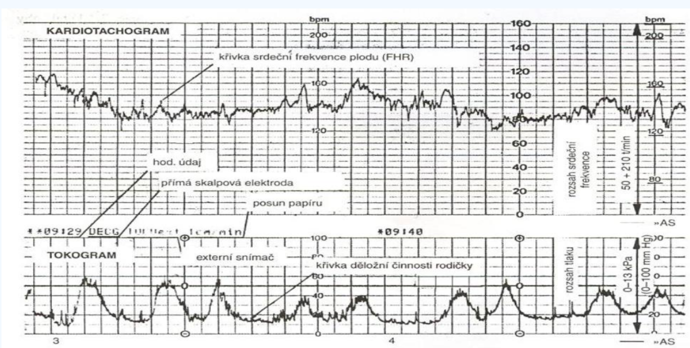
Intro: What is CTG?

- Fetal heart rate + uterine contractions
- Used for estimation of fetal well-being



Intro: Current state of evaluation





- FHR is measured by USG or fECG
- Signs of hypoxia are sought for
- Decision are made based on FHR and clinical data

- Outcomes:
  - Healthy babies
  - Caesarean sections (20-50% in CZ)
  - Missed “pathologies” (1-3%) –> severe cases may result in neurological damage such as cerebral palsy etc.

Motivation

Motivation: Known problems

- High variability in expert evaluation (features, outcomes)
- Weak relation of objective (pH, BDecf) outcome measures to the FHR
- Incomplete understanding of fetal physiology

- High stakes (medical and legal) in missing the pathology
- Medical and financial burden of increased number of Caesarean Sections on the health system
- Future inclusion of midwifes into the decision making

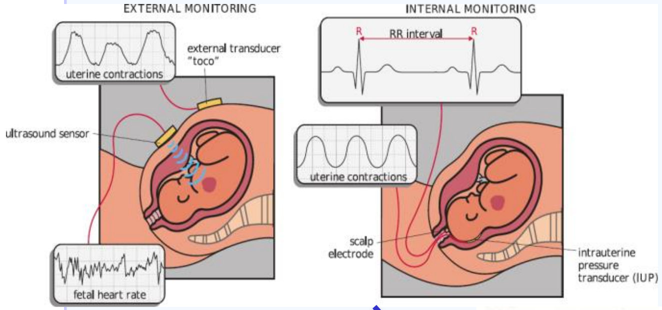
Motivation: Possible goals

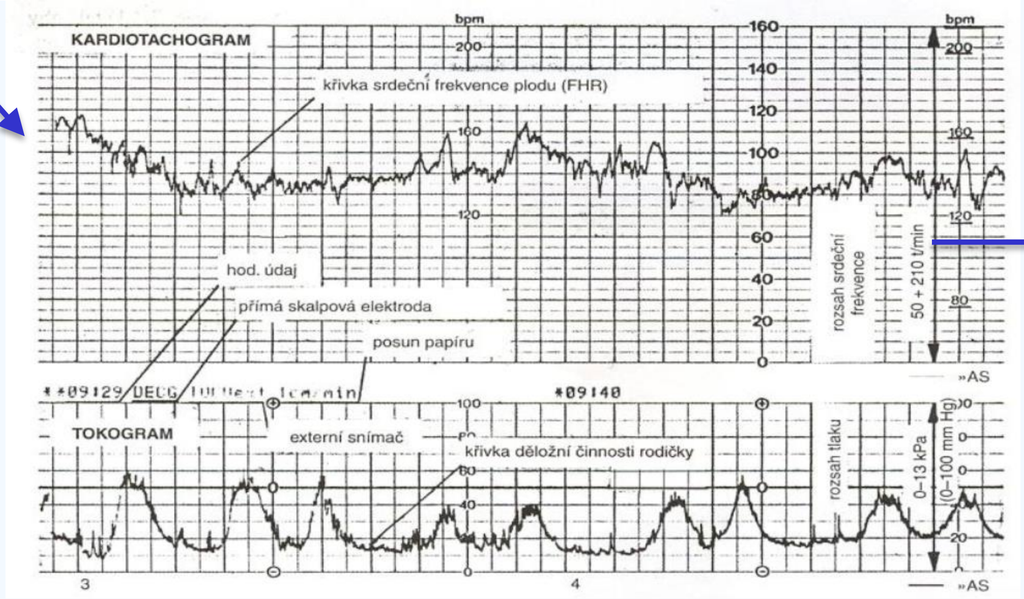
- Saving all the babies
- Reducing number of deliveries with low pH
- Automated prediction of delivery outcome
- Objectivization of clinical decission making
- Automated evaluation of FHR

- Computation of features from FHR and publishing results on them in journal papers

General framework for automated evaluation

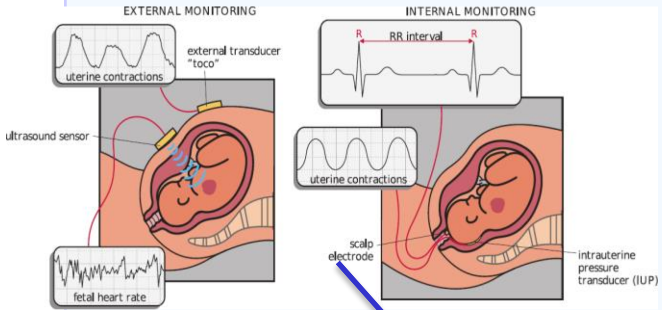
Automated analysis

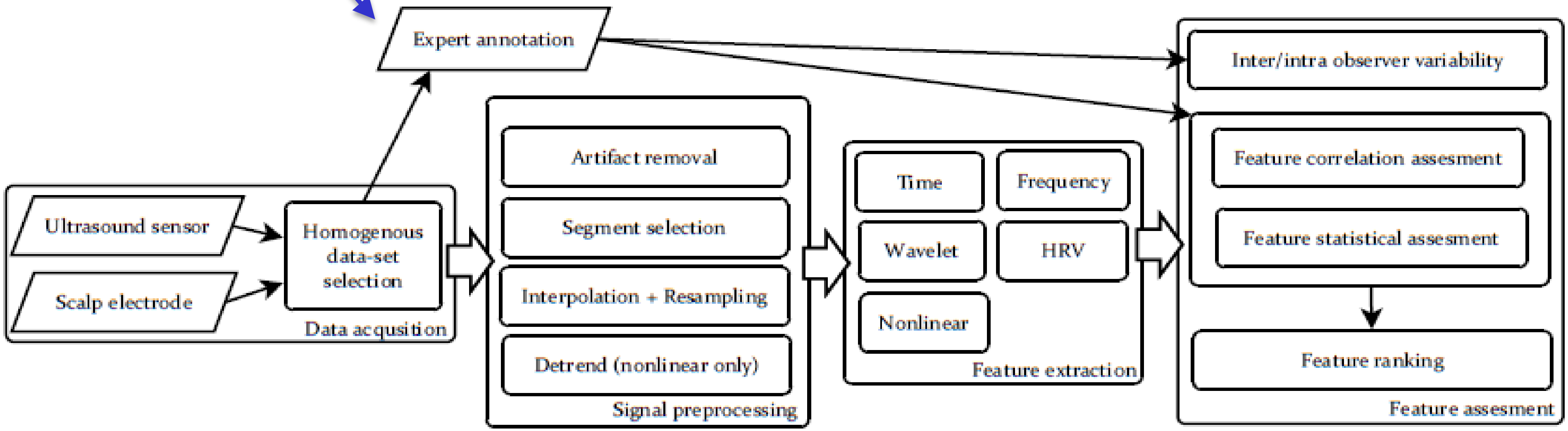




- Instead of evaluation by eye

Automated analysis





- Automated description of FHR is used

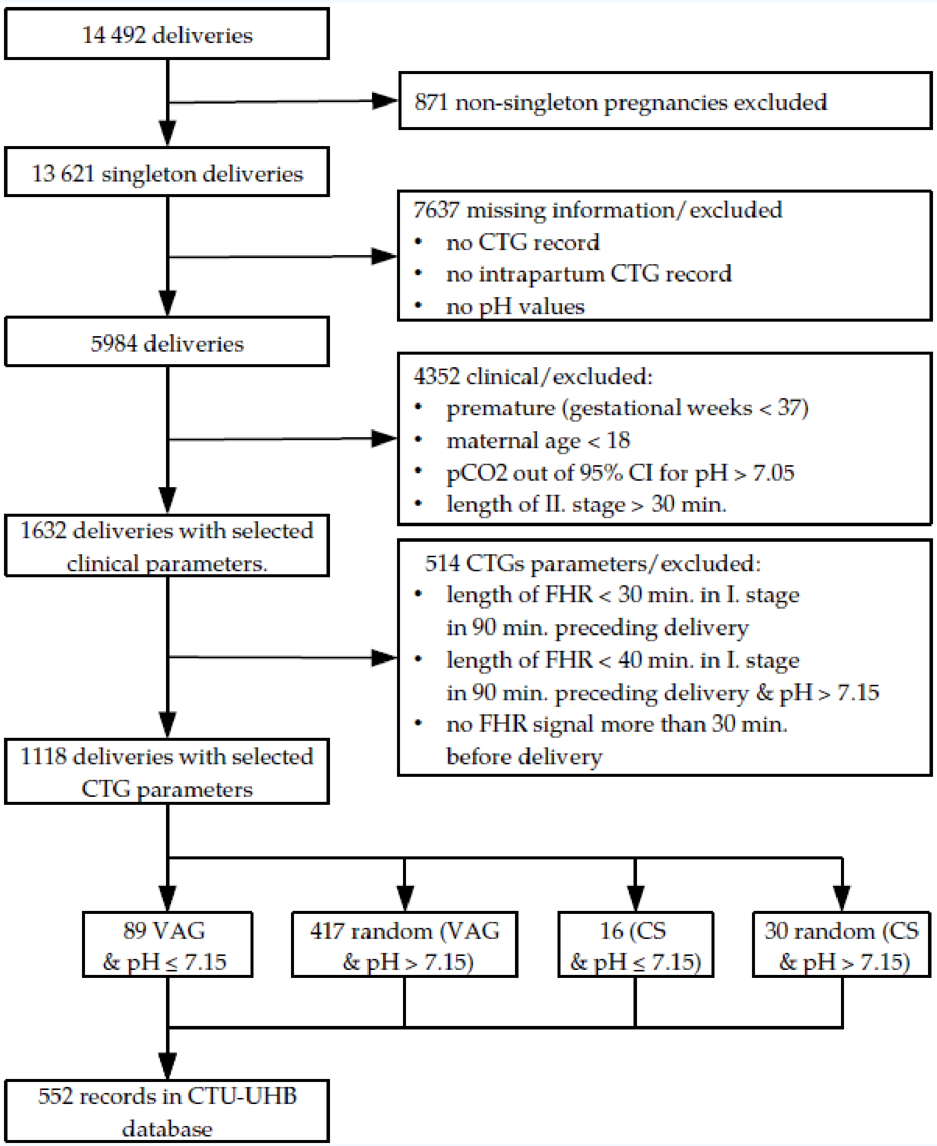
Automated analysis - overview

- Proper database
- Signal pre-processing
- Feature extraction
  - FIGO features (macroscopic, but clinically well-known)
  - Other features (time, frequency, time-frequency, nonlinear, etc.)
- Feature selection
- Classification with regards to:
  - Objective evaluation
  - Subjective evaluation (experts)
  - Sophisticated combination (Latent Class Model)

Database

CTU-UHB cardiotocograpic database

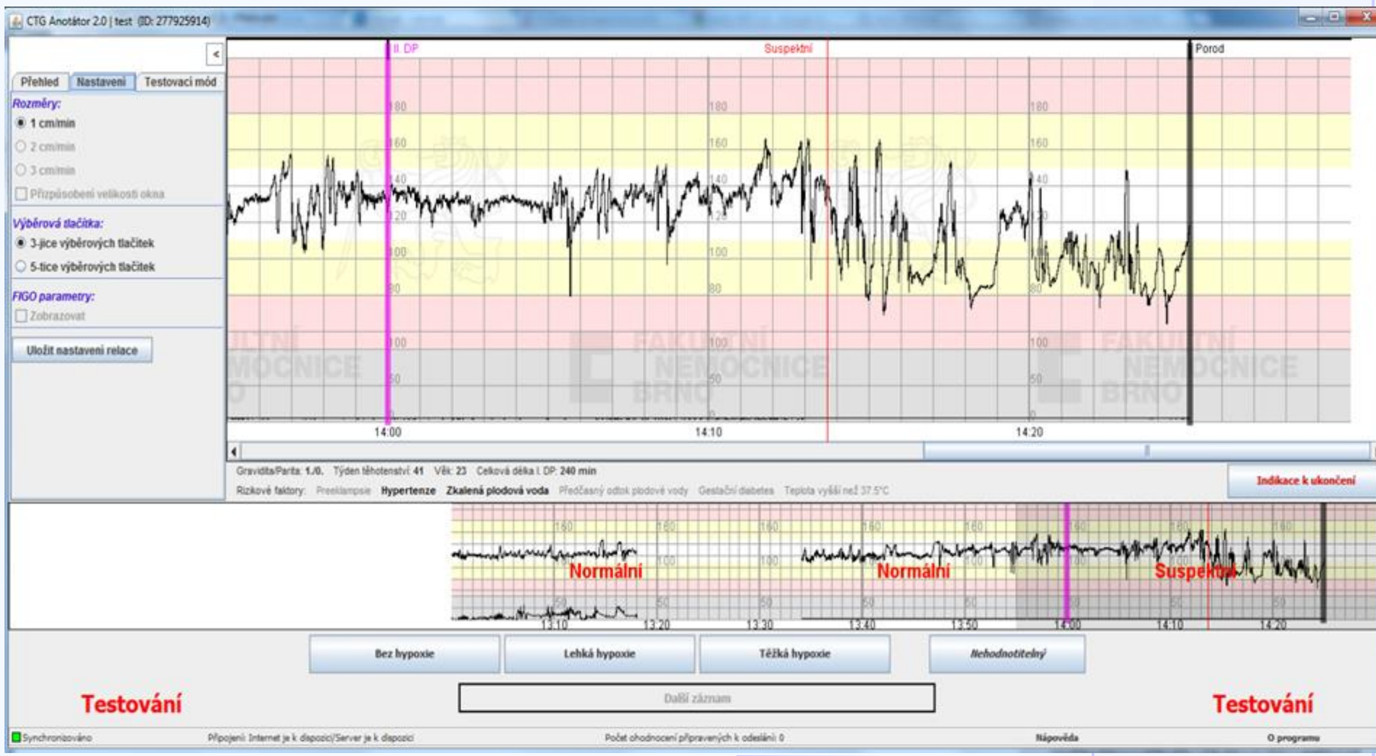
CTU-UHB database



- Data from Ob&Gyn clinic of FN Brno
- USG and STAN data
- Only mature fetuses
- First open-access CTG database
- Common ground for algorithm comparison

Available outcome measures

- Subjective – expert evaluation
  - Annotations acquired via CTG Annotator (L. Zach et al.).
  - Majority voting, Latent class model based on 9 experts
  - Apgar score
- Objective
  - pH
  - BDecf, BE
  - pCO_2
- Mixture
  - Majority
  - LCMs

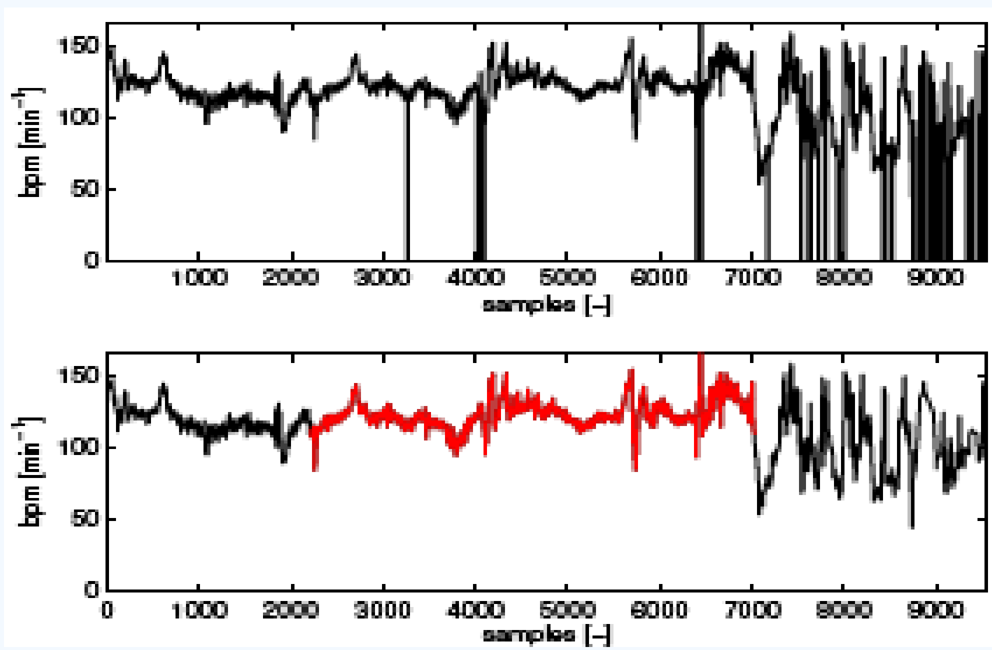


FHR pre-processing and FIGO features

Signal pre-processing

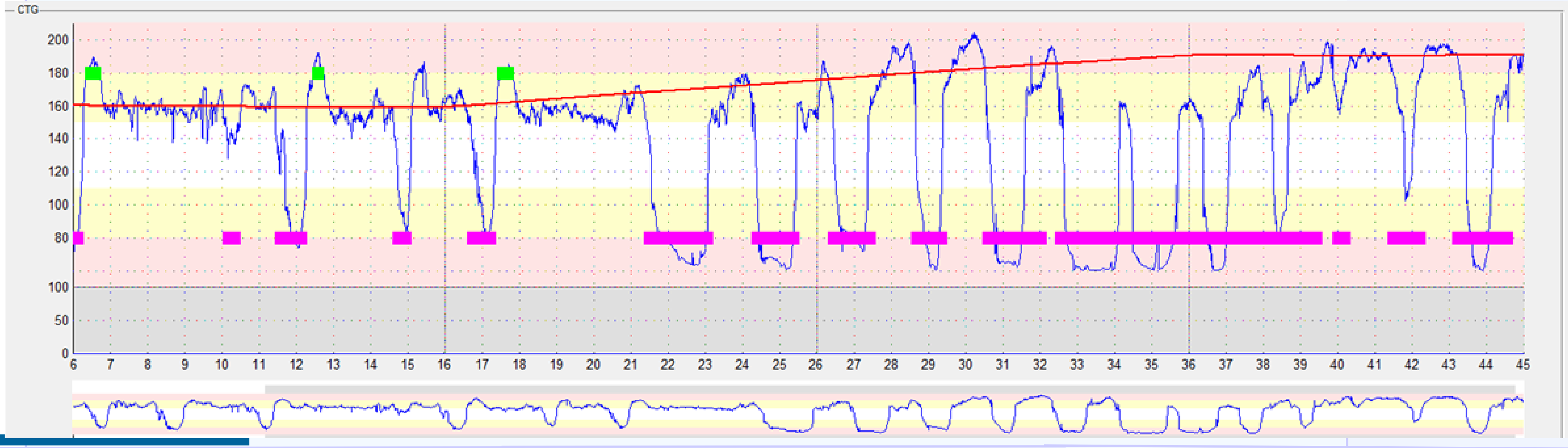
❖Gap & Artefact detection

- ❖ Gap removal (< 15s)
- ❖ Artefact rejection
- ❖ Bernardes inspired thresholds
- ❖ Adapted to 4Hz from beat to beat

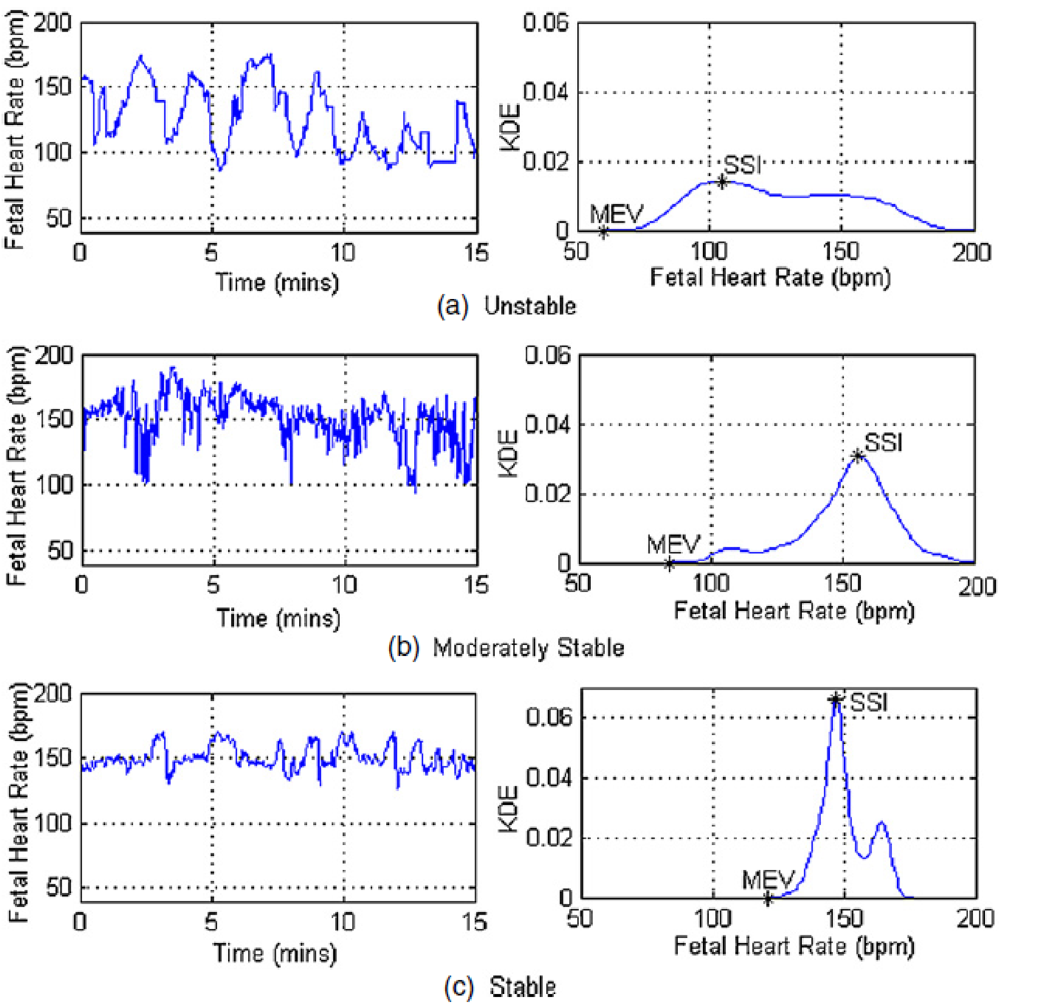


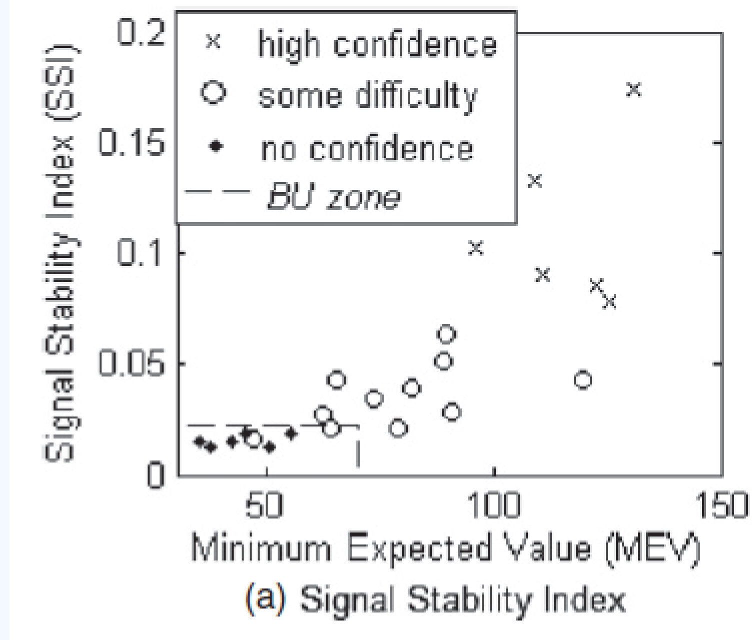
FIGO features

- Official obstetrics guidelines for CTG evaluation
- Circular definition of Acceleration/Deceleration
- Baseline detection based on histogram assessment



Baseline estimation

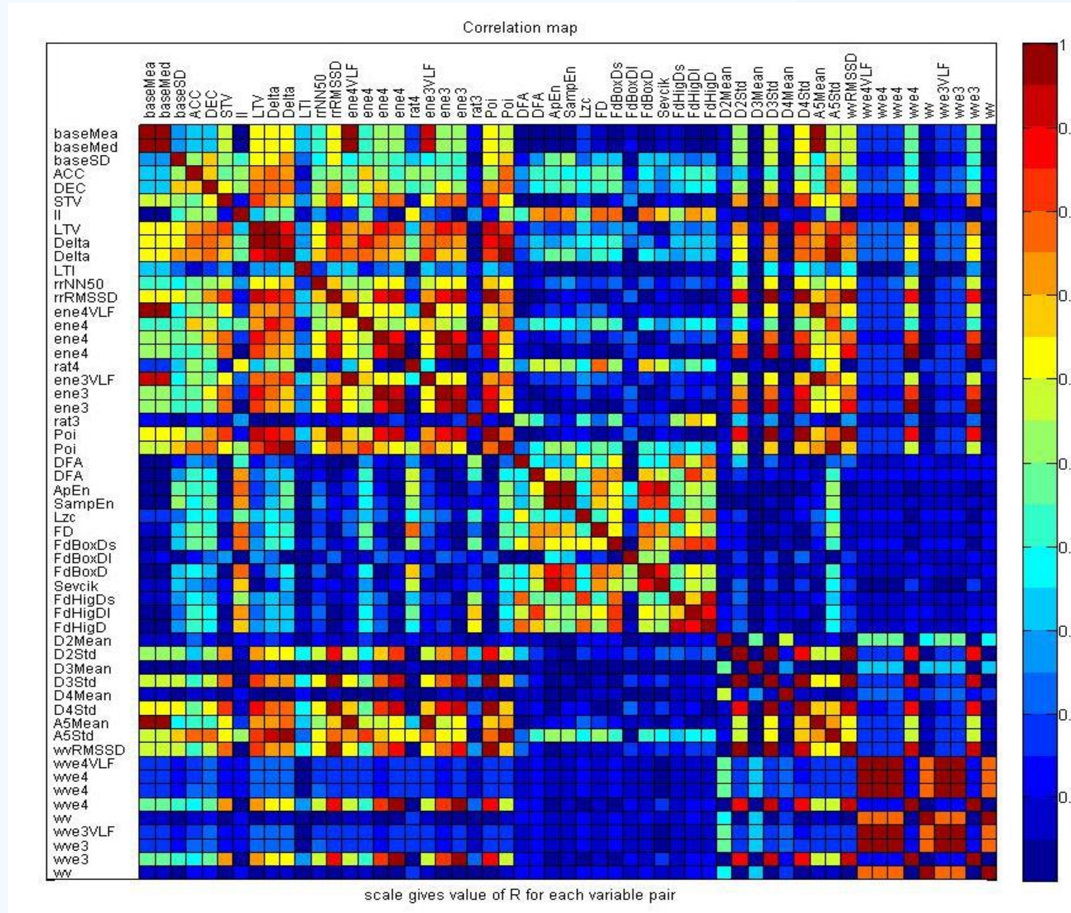




Other features

Features

- Morphological features (FIGO) (5)
- Time-domain (6)
- Freq.-domain (13)
- HRV (4)
- Wavelet (15)
- Nonlinear (12)



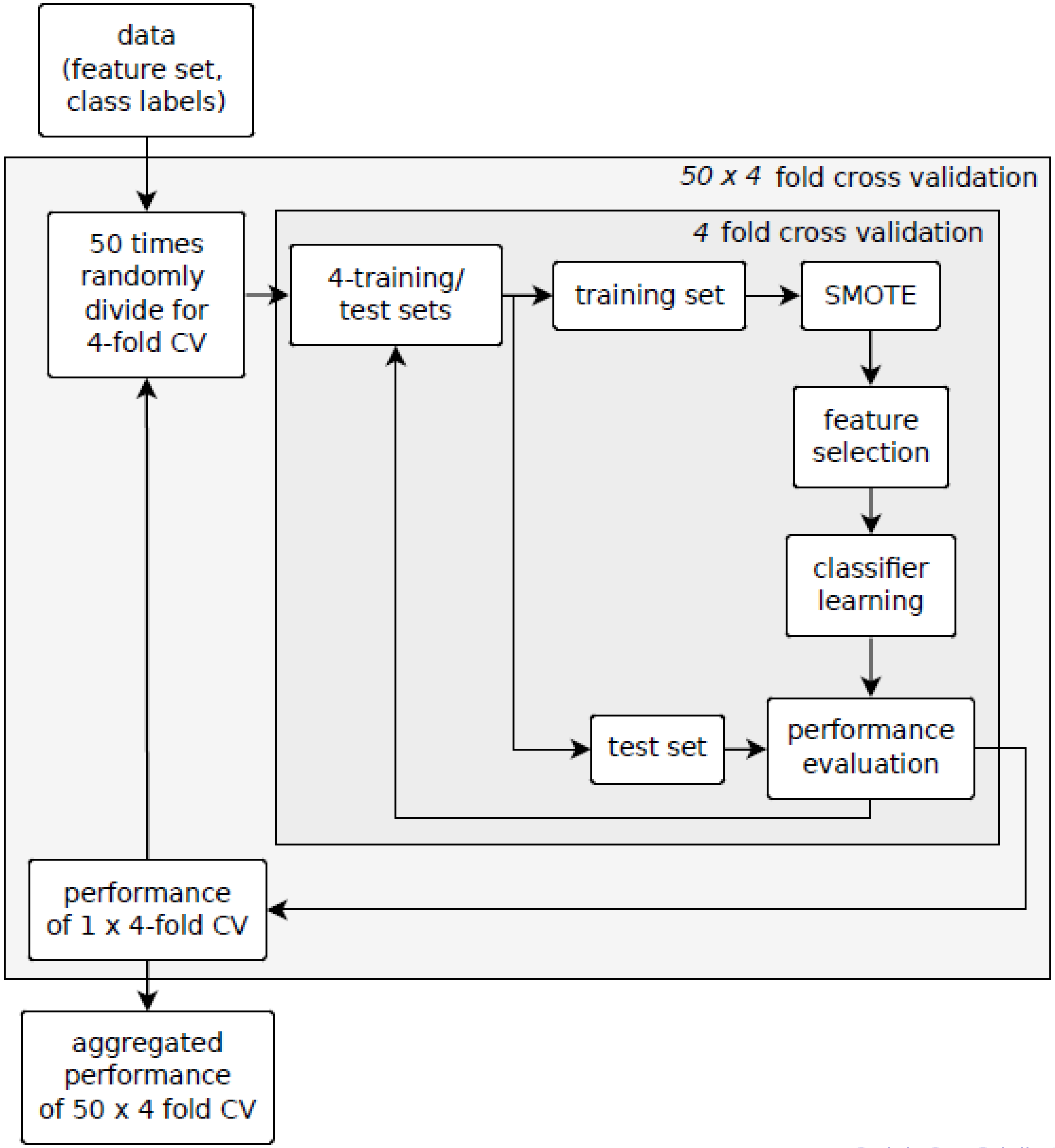
- In total 55 features

Classification

Classification

- Exact means of classification not crucial
- We have used:
  - Naïve Bayes
  - SVM
  - Decision trees
  - One-class classifiers
- What is important:
  - Correct methodology (well described)
  - Proper data with as low bias as possible (documented)
  - Proper and reliable outcome measures
  - Interpretability towards clinicians

Classification (2)



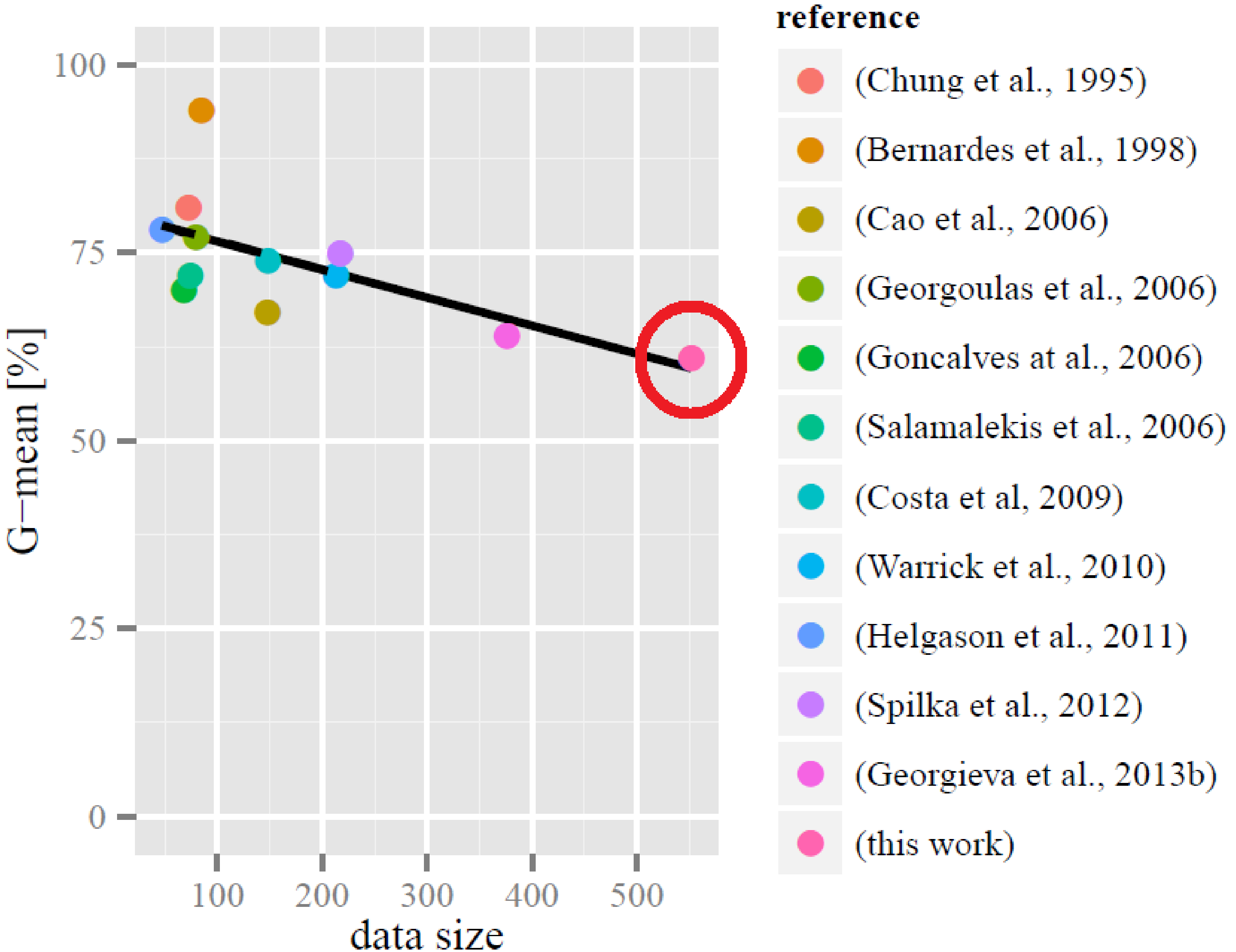
Classification (3)

- Selected features
  - Low spectral bands
  - Decelerations
  - Poincare plot SD2

	Naive Bayes		SVM	
sensitivity		60 (53–67)		53 (47–60)
specificity		75 (72–77)		78 (75–80)
precision		23 (20–25)		23 (20–26)
F-measure		33 (29–36)		33 (28–37)

Results

Comparison of results



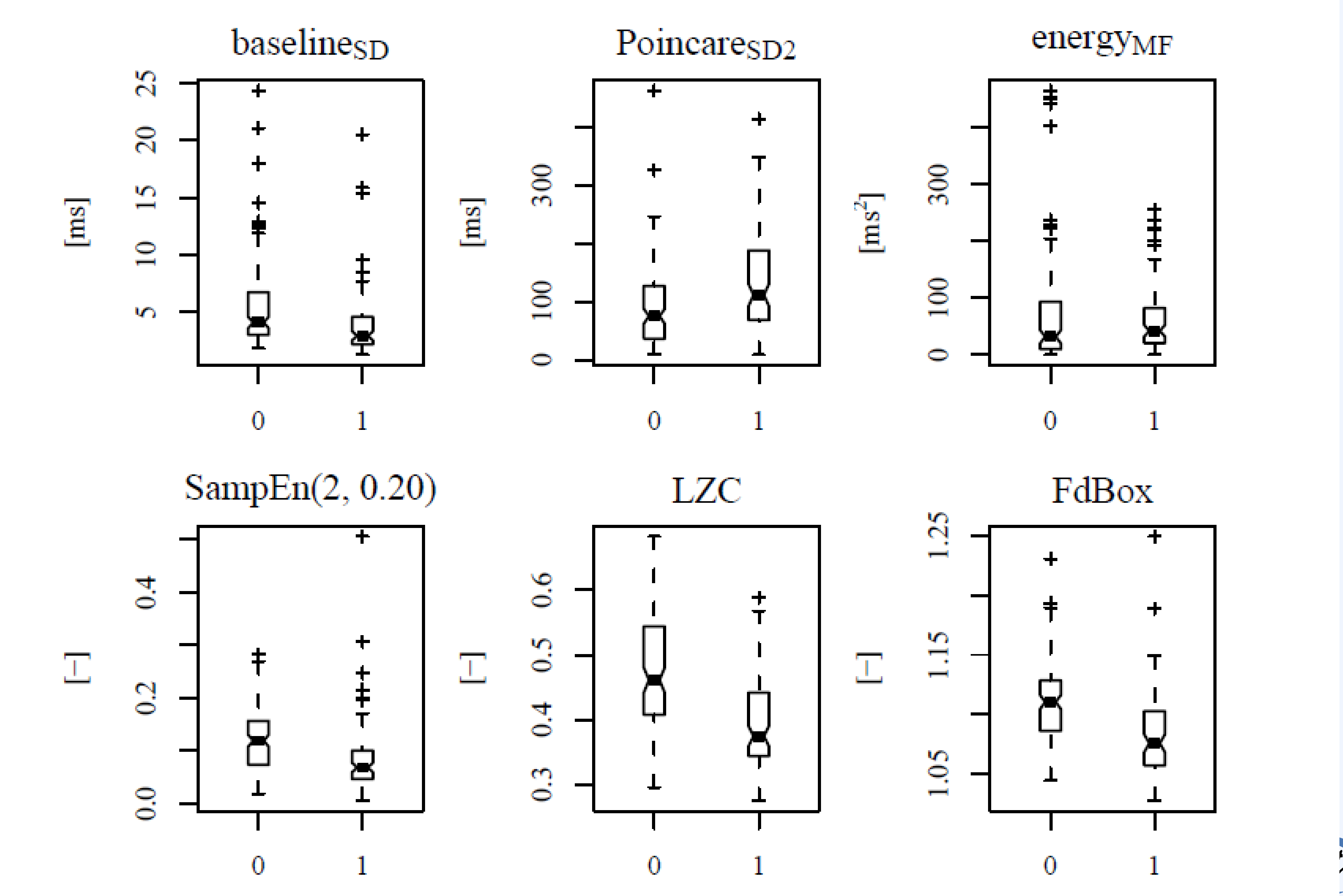
Results – obj. evaluation

Feature set	All in [%]	NaiveBayes	SVM	C4.5 Tree
FIGO-like	Sensitivity	66.0	50.0	55.3
	Specificity	68.3	79.7	65.9
	Precision	61.4	65.3	55.3
	F-measure	63.6	56.6	55.3
	AUC	0.70	0.65	0.60
HRV-based	Sensitivity	44.7	30.0	59.6
	Specificity	82.1	93.5	69.9
	Precision	65.6	77.8	60.2
	F-measure	53.2	43.1	59.9
	AUC	0.71	0.60	0.60
Nonlinear	Sensitivity	68.1	66.0	77.7
	Specificity	78.0	79.7	64.2
	Precision	70.3	71.3	62.4
	F-measure	69.2	68.5	69.2
	AUC	0.77	0.73	0.67
FS-Complete	Sensitivity	**71.3**	69.1	73.4
	Specificity	**78.0**	76.4	66.7
	Precision	**71.4**	69.1	62.7
	F-measure	71.3	69.1	67.6
	AUC	**0.76**	0.73	0.68

- Small data set
- 98 pathological
- 10-fold crossval.
- FS complete – 6 selected features

- Conclusion: Additional features (to classical ones) improve results

Results – obj. annotation (2)



Results – expert evaluation I.

All in [%]	Expert #1	Expert #2	Expert #3
Sensitivity pH	34.38	48.96	40.63
Specificity pH	14.07	16.30	8.55
Sensitivity GS	71.80	72.45	85.90
Specificity GS	92.72	92.72	67.55
Intra-observer variability	70.83	56.20	76.67
Inter-observer variability		80.61	
Kappa statistics		0.36	

Results – expert evaluation II.

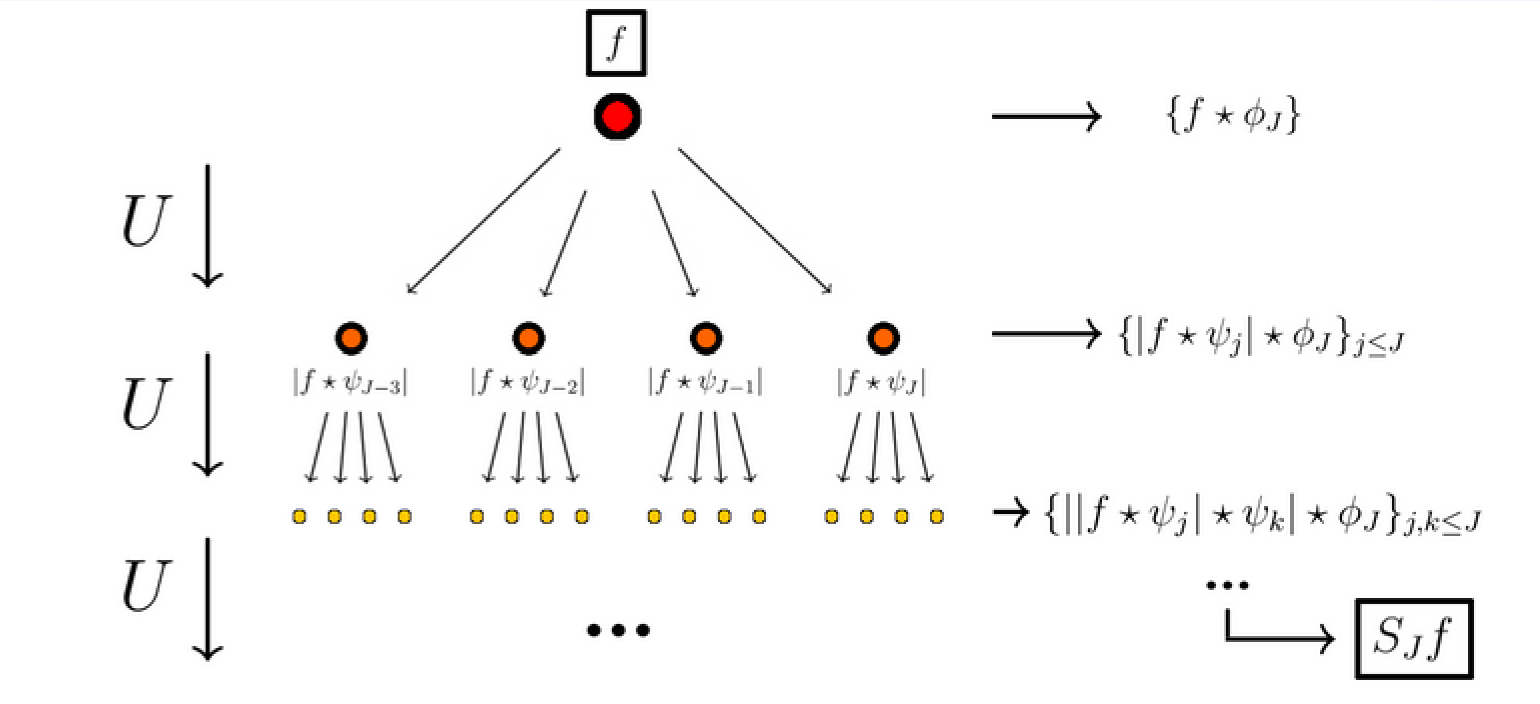
Domain	Features	Statistical significance of features					
		Exp #1	Exp #2	Exp #3	GS	Rank (indiv.)	Rank (class.)
Time	baselineSD	–	✓	–	–	10	9
	# Accel.	✓	✓	✓	✓	1	1
	# Decel.	–	–	✓	✓	4	2-3
	II	–	✓	–	✓	8	5
Frequency	VLF	✓	–	–	–	6	7-8
Wavelet	D2mean	–	✓	✓	✓	11	6
Nonlinear	ApEn	–	✓	–	✓	9	11
	LZc	–	–	✓	✓	3	2-3
	FD_BoxDl	✓	✓	✓	✓	7	10
	FD_HigD	✓	✓	–	✓	5	4
	FD_Var	✓	✓	✓	✓	12	12
	Poincaré SD2	✓	✓	✓	✓	2	7-8

Case studies – different experiments / projects in the field of CTG processing

“Case study ” 1: Scattering transformation

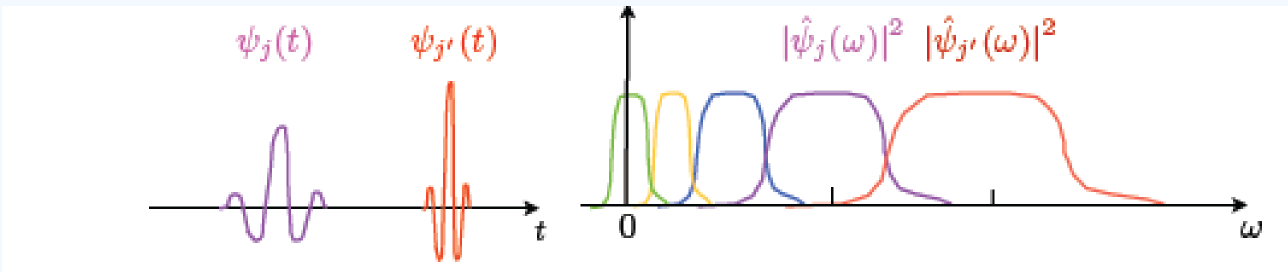
Scattering transform

- Introduced by S. Mallat (http://www.di.ens.fr/data/scattering/)



Scattering transform (2)

- Wavelet transform

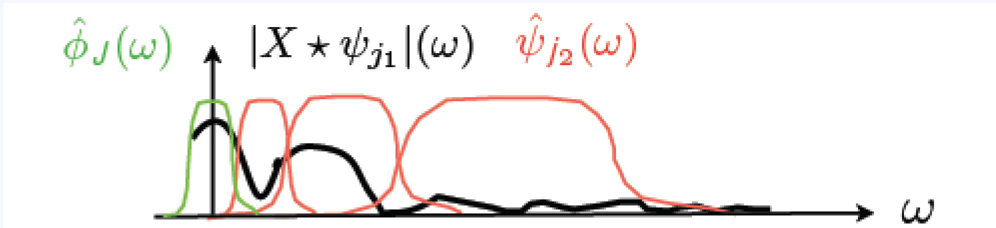


- Complex mother wavelet $\psi(t)$
- Dilated and translated wavelets $\psi_{j,k}(t) = 2^{-j}\psi(2^{-j}(t-k))$
- Wavelet coefficients $X \star \psi_{j,k}$
- First-order coefs: Local time averages of abs. value of wavelet coefs.

$$SX(j,k) = \mathbb{E}\{|X \star \psi_j|\} \approx N^{-1}\sum_{l=k}^{k+N} |X \star \psi_{j,l}|$$

Scattering Transform (3)

- Second order -> beyond Wavelets



- Wavelet transform of absolute values of wavelet coefs.

$$SX(j_1, j_2) = \mathbb{E}\{||X \star \psi_{j_1}| \star \psi_{j_2}|\} \approx N^{-1} \sum_{t=1}^{N} ||X \star \psi_{j_1}| \star \psi_{j_2}(t)|$$

- 2nd order renormalized by the first

$$\widetilde{S}X(j_1, j_2) = \frac{SX(j_1, j_2)}{SX(j_1)} \approx \frac{\sum_{t=1}^{2^J} ||X \star \psi_{j_1}| \star \psi_{j_2}(t)|}{\sum_{t=1}^{2^J} |X \star \psi_{j_1}(t)|}$$

- Nonlinear transform:
  - Goes beyond wavelet
  - Explores dependencies beyond correlation (or spectrum)

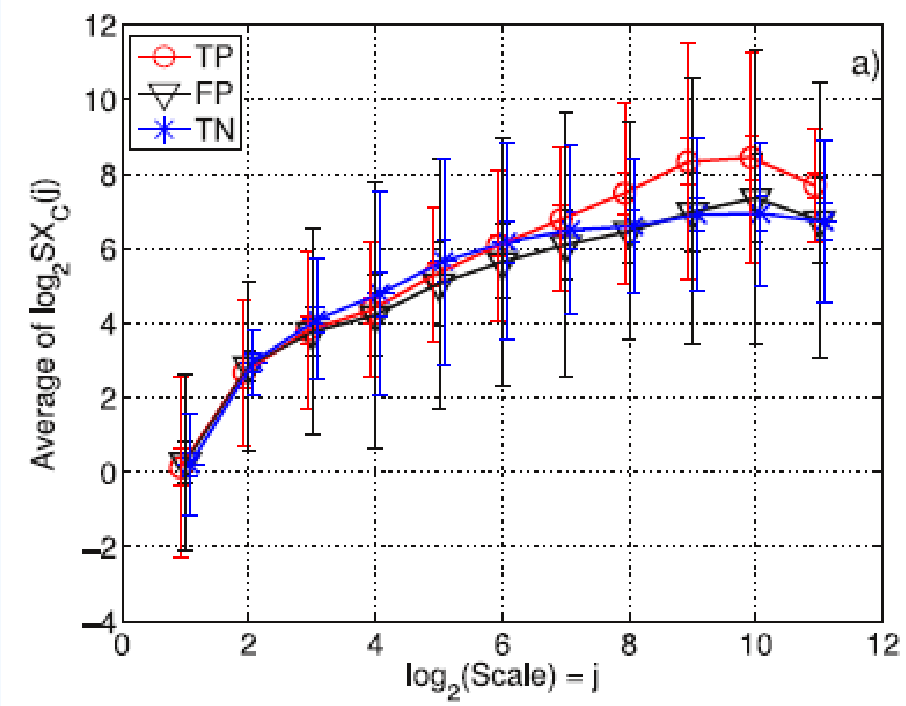
Relation scattering - scaling

- Relation between scattering and scaling $SX(j,k) \sim 2^{jH}$
- H – Hurst exponent
- $z(j_1)$ – scaling exponents that may depart from H

$$\tilde{S}X(j_1, j_2) \sim 2^{(j_1 - j_2) z(j_1)}$$

Fractal Dynamics of FHR

❖First order

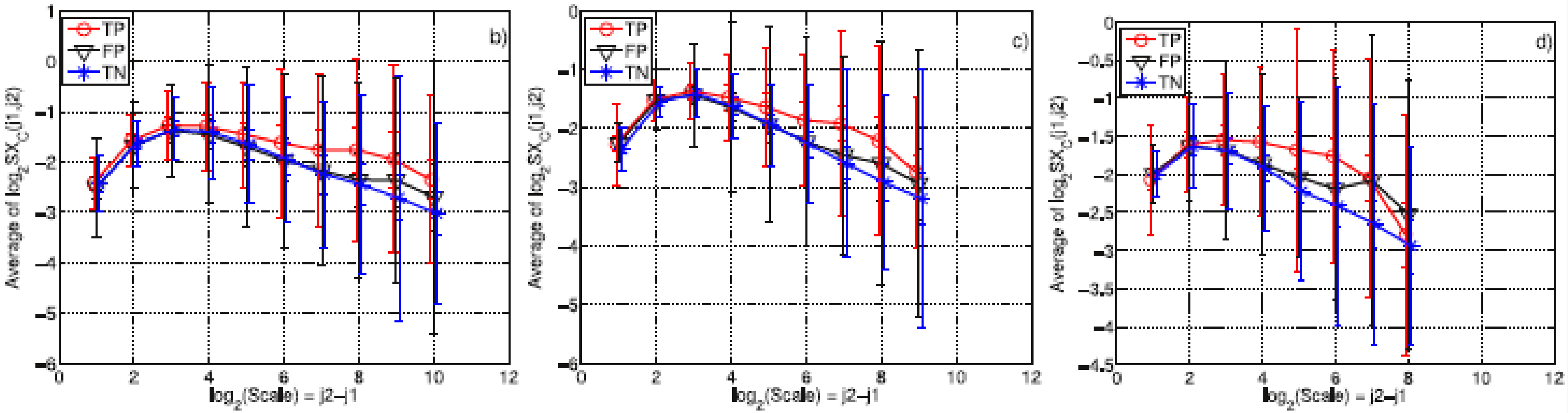


❖Fractal behaviour:

- ❖ Time scales ranging from 4s < a = 2^j < 60s

Fractal Dynamics of FHR (2)

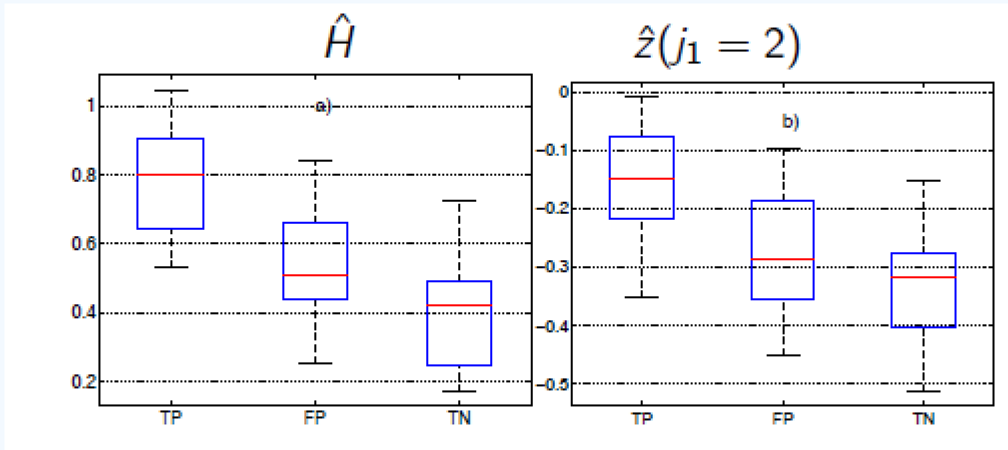
- Second order for $j_1 = 1, 2, 3$.



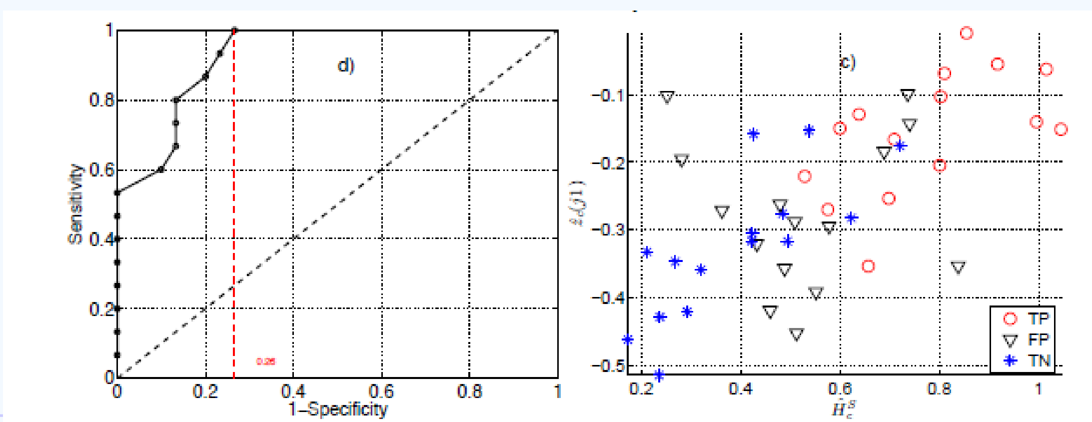
- Fractal behaviour:
  - Time scales ranging from 4s < a = 2^j < 60s

Results

❖ Discrimination power on SDB (HFME Lyon)



❖ Performance outcome

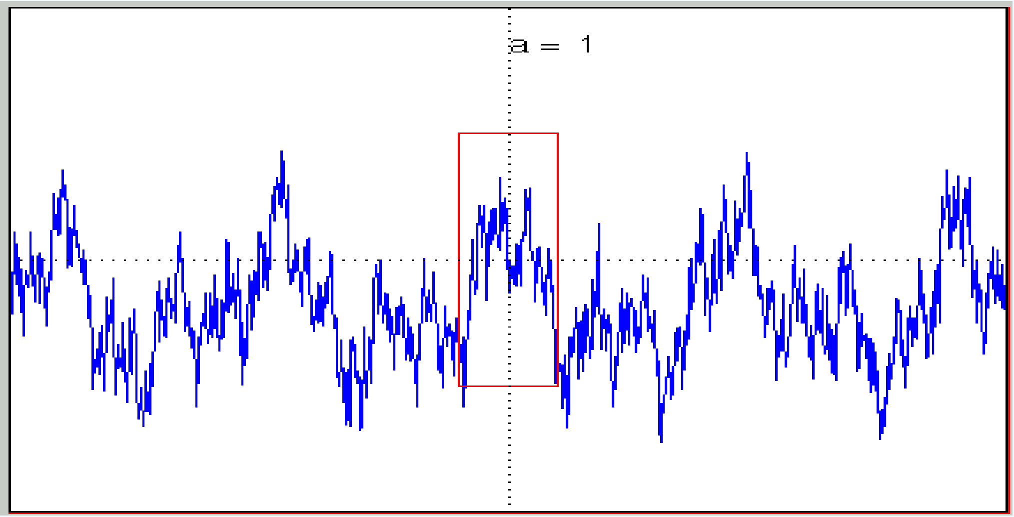


“Case study ” 2:
Scaling properties of FHR

Temporal dynamics

- Classical measures
  - STV – scale of a = 3.75s (antepartum)
  - LTV – scale of a = 60s (intrapartum)
- Why to limit ourselves to these arbitrary intervals?

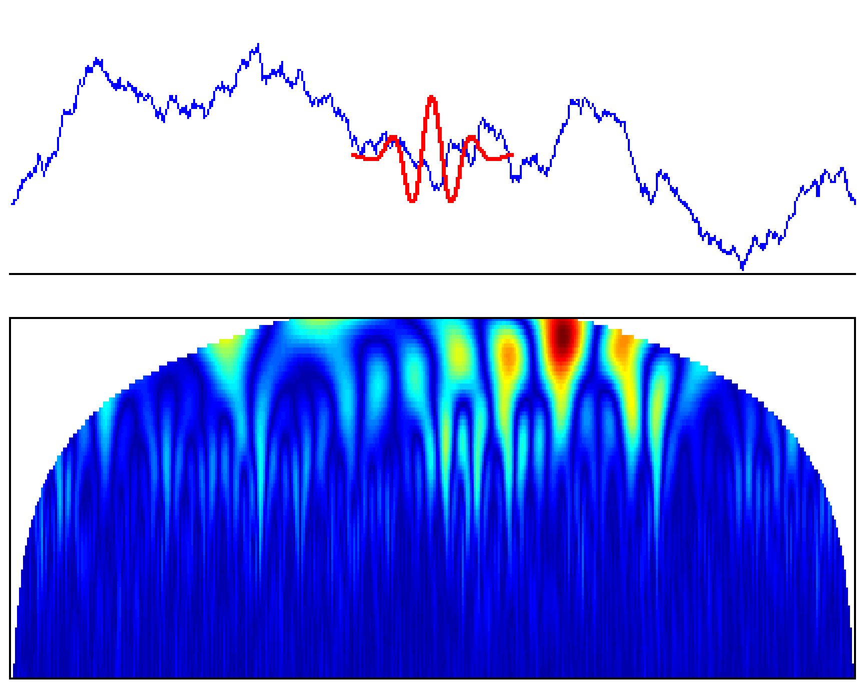
Properties of FHR



$$\text{"Spectrum"} : \Gamma_X(f) \sim C|f|^{-(2H-1)}, \ |f| \to 0$$

Continuous Wavelet Transform

$$X(t) \rightarrow T_X(a,t) = \langle \frac{1}{a}\psi\left(\frac{u-t}{a}\right) | X \rangle$$



- Joint time and frequency energy content

Fractal exponents

- Oscilations -> wavelet coefs.
- Variability is not characterized by actual value
- Scale invariance is measured instead -> H
- The H computed via wavelet spectrum provides
  - Variability at all scales jointly (not just STV/LTV scale)
  - Gives information of temporal dynamic of HF/LF ratio
- In practice:

$\Rightarrow$ Hurst exponent:

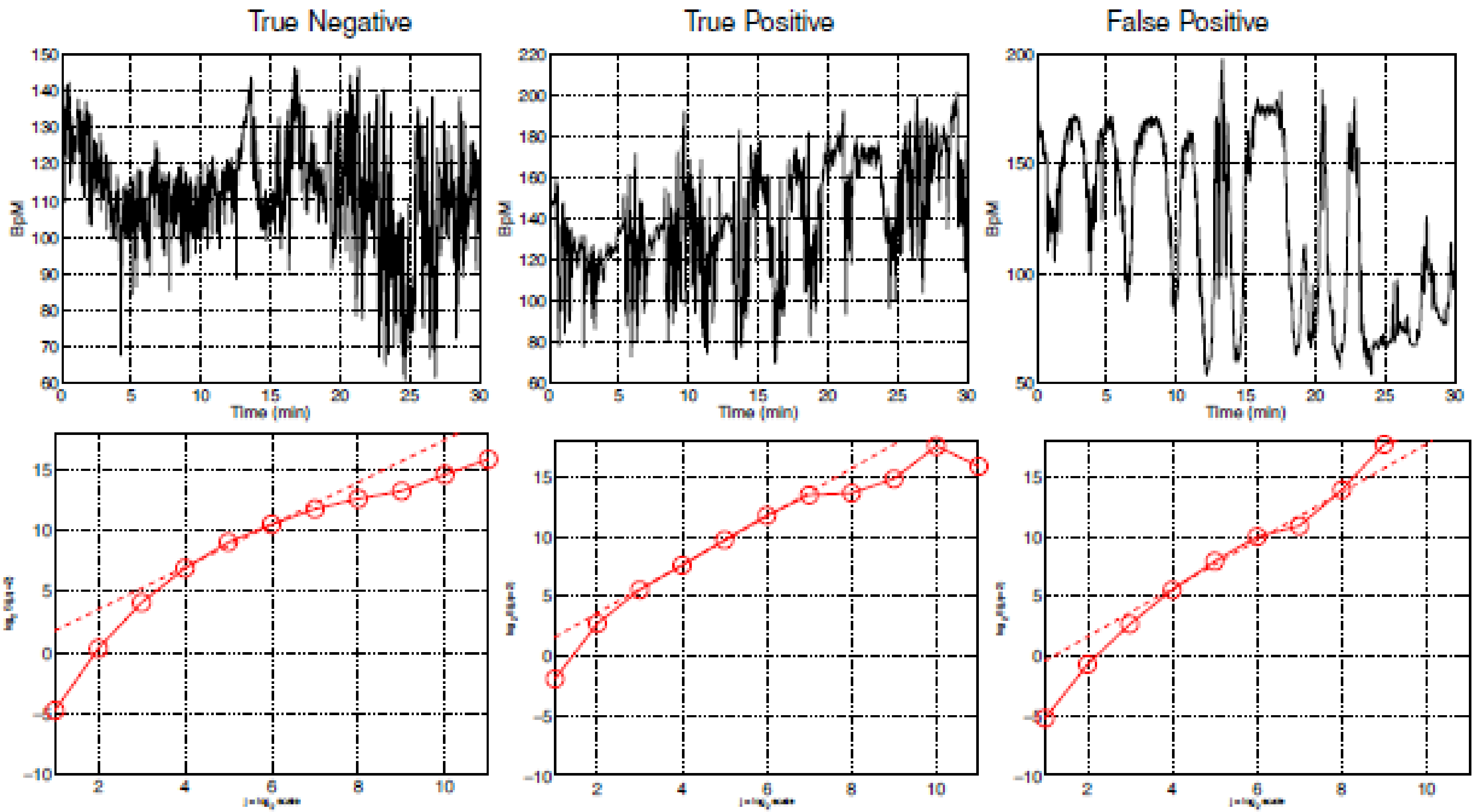
Time averages: $S(a) = 1/n_a \sum_k T_X(a,k)^2$

$\Rightarrow$ Global regularity exponent:

Scale invariance: $|T_X(a,t)| \simeq c(t) a^{h(t)}$

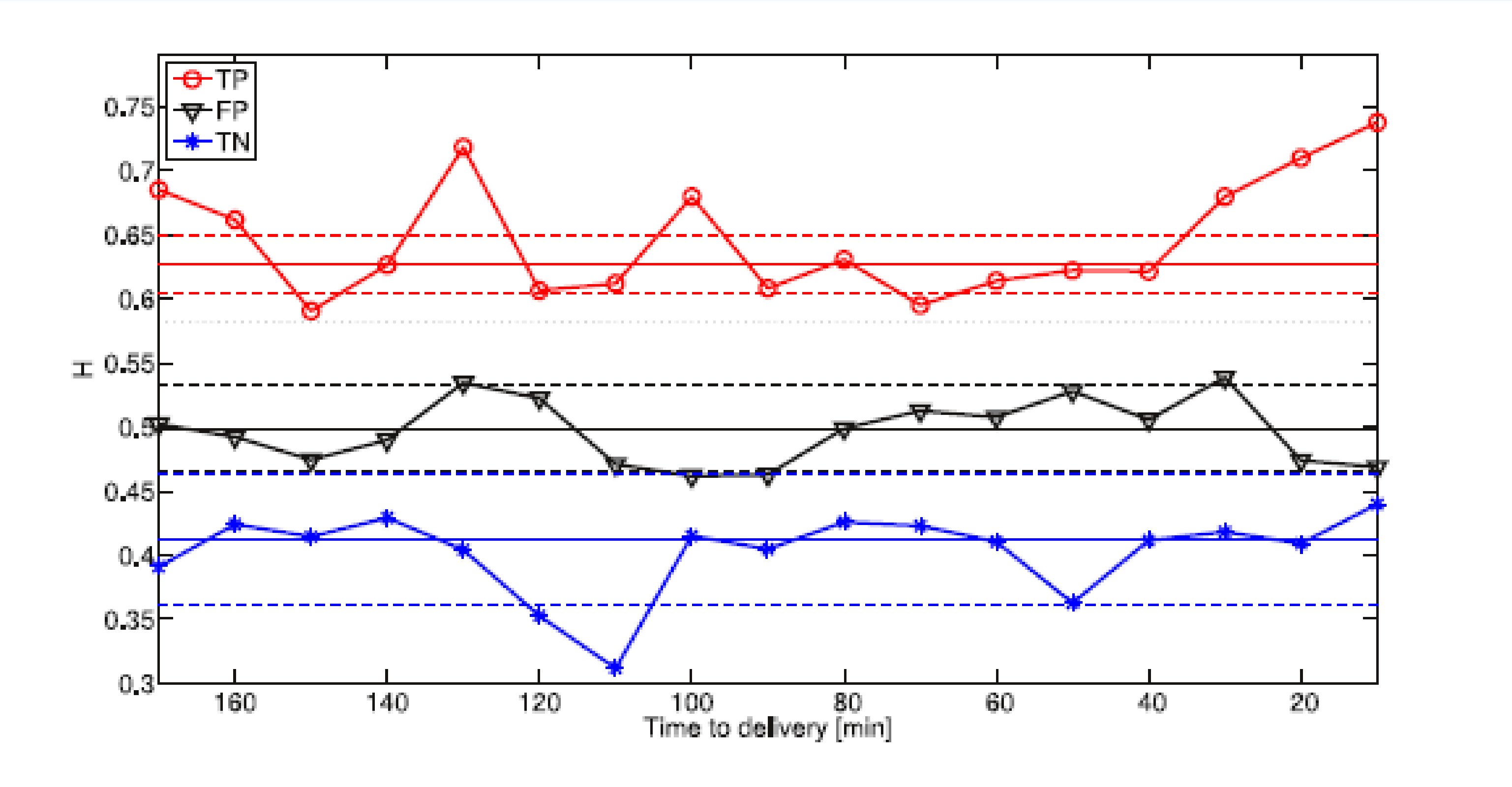
Global regularity: $h_{min} = min_t(h(t))$

Scale invariance in FHR

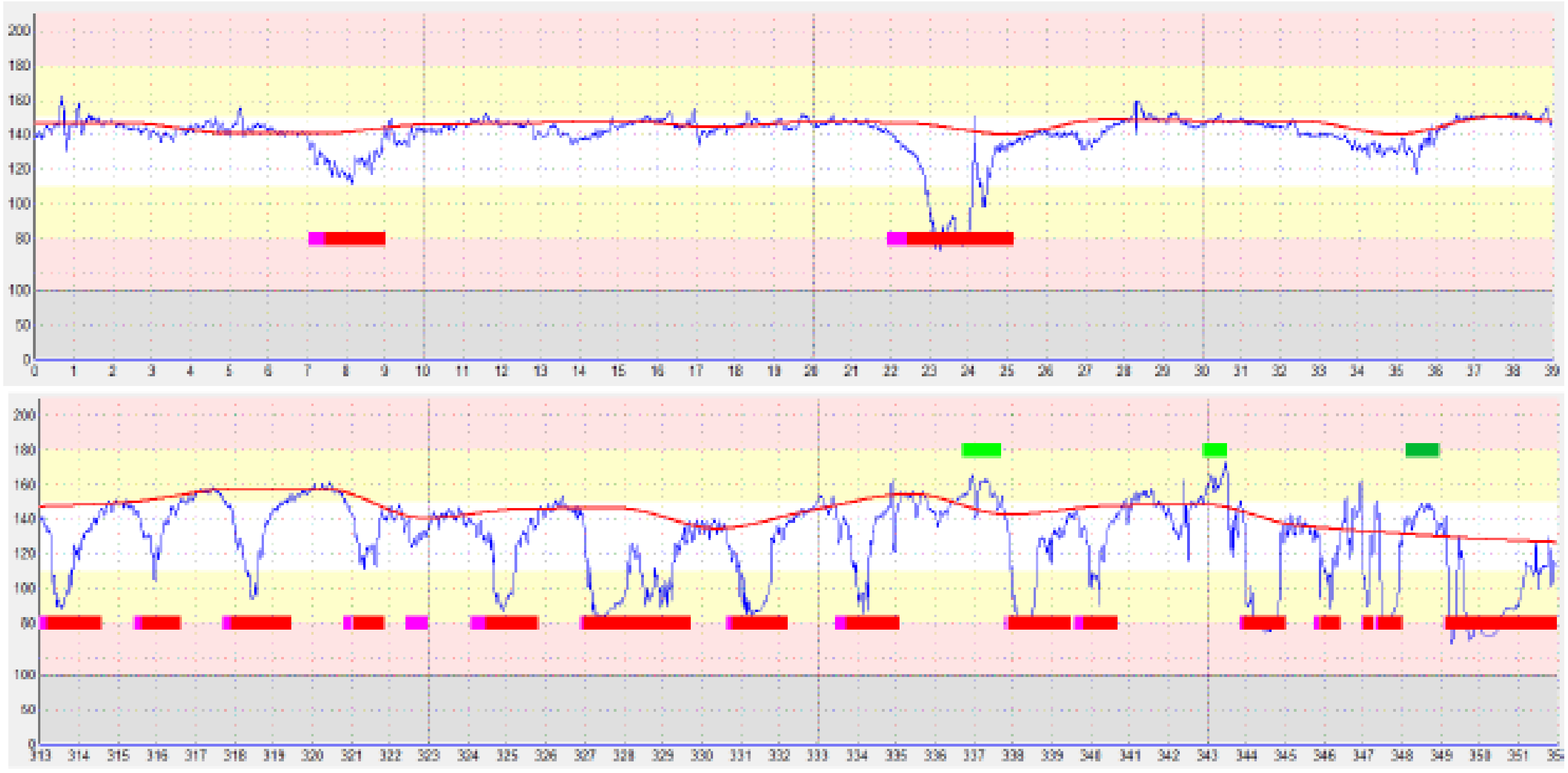


Power Law Behavior: $a_m = 2^3 \leq a \leq a_M = 2^7$

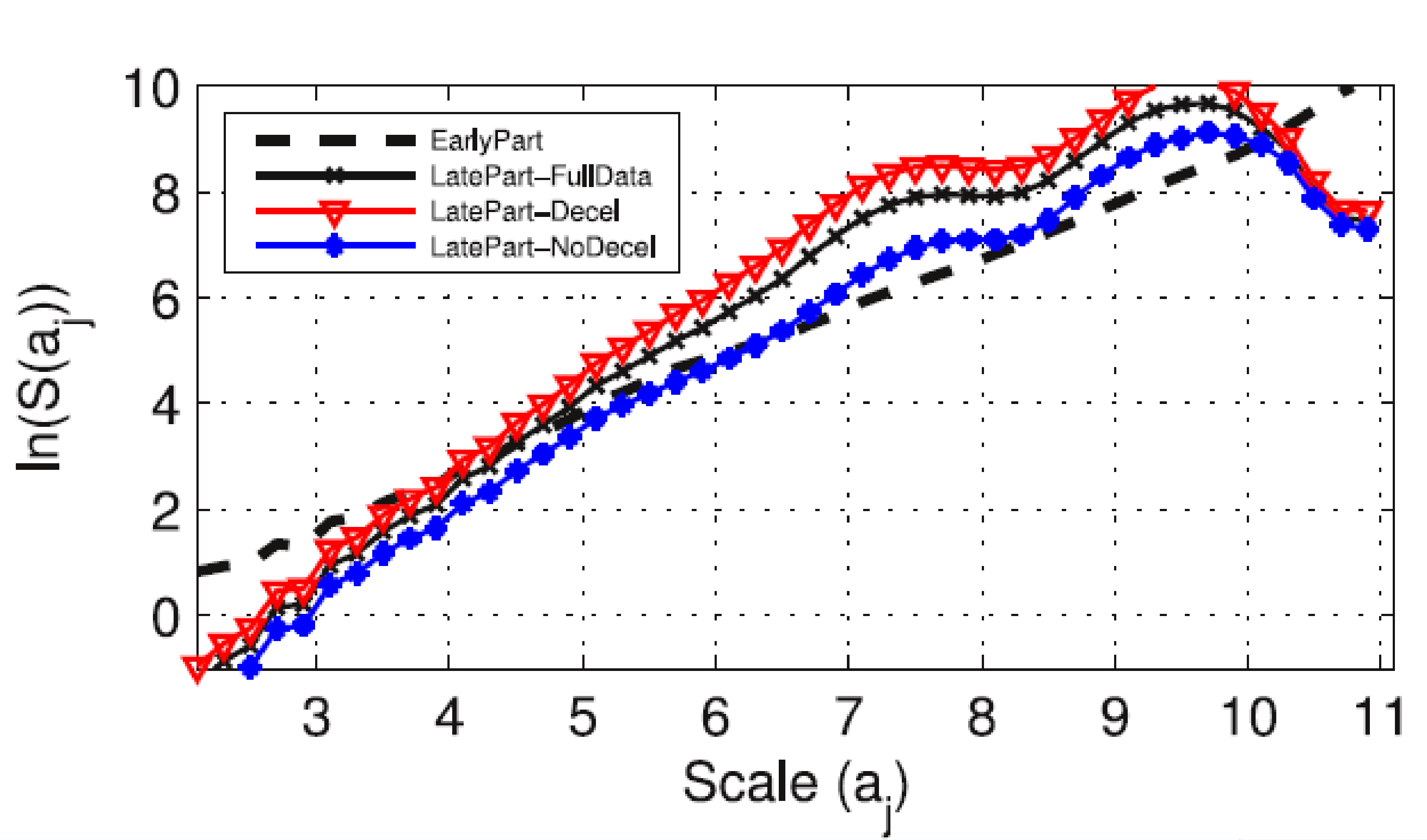
Values of H per class



Influence of decelerations



Influence of decels. on H



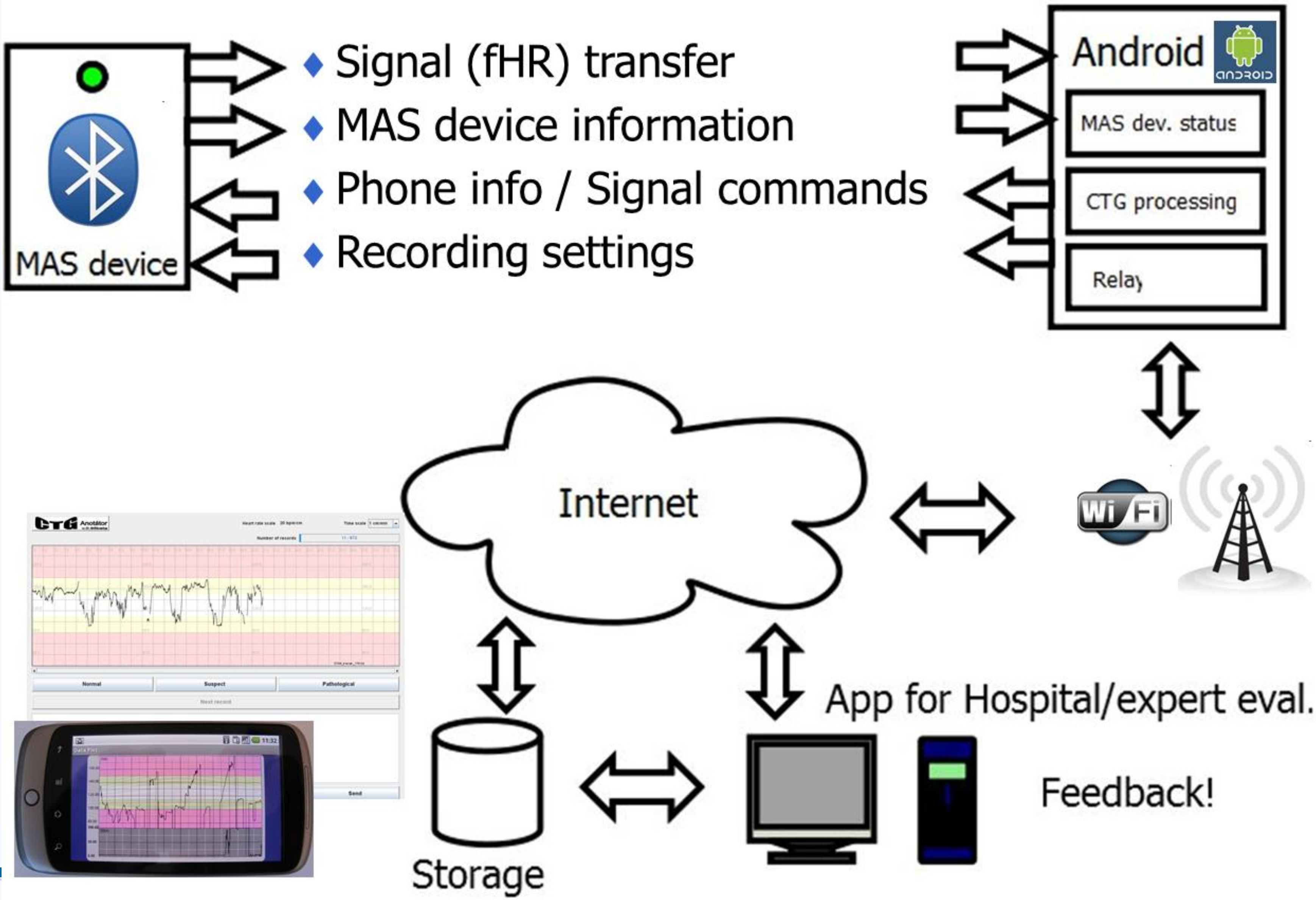
Conclusion

- Hurst exponent
  - Allows representation of time-scale properties of FHR by a single value
  - Measures embraces the Temporal Dynamics as Fractal Variability
  - Gathers time and spectral variabilities of the FHR in one feature
  - Describes temporal dynamics across range of scales rather than for specific scales
  - Simplifies the FHR analysis (in contrast to e.g. FIGO)

- Behaves consistently irrespective to decelerations

"Case study " 3: Mobile CTG

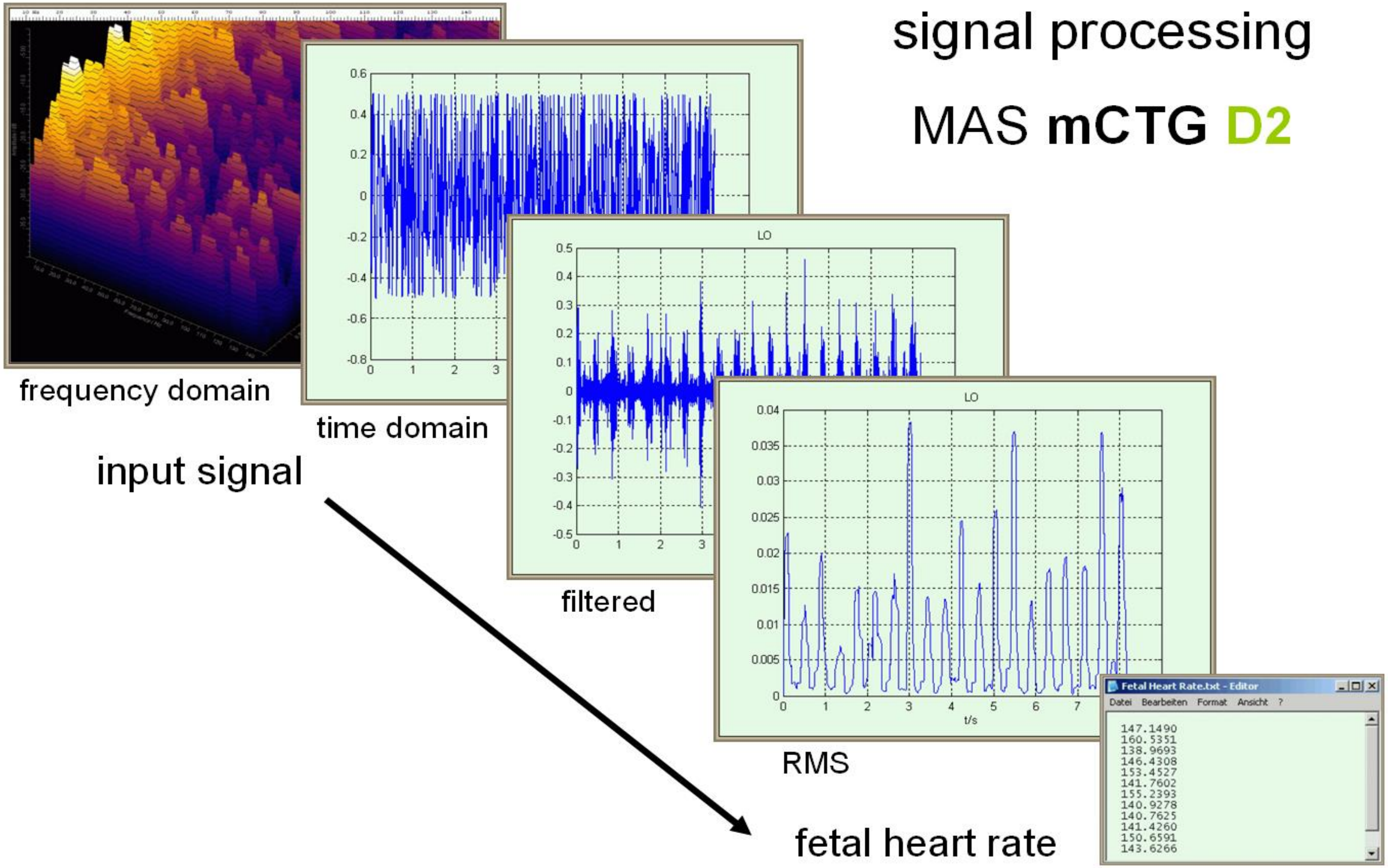
General schema of mCTG

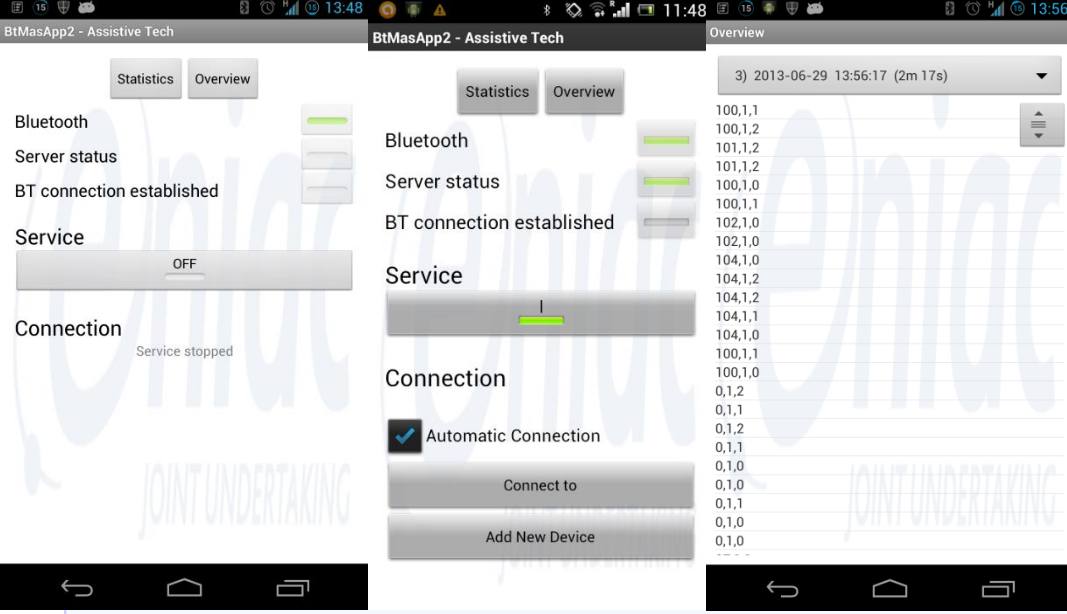


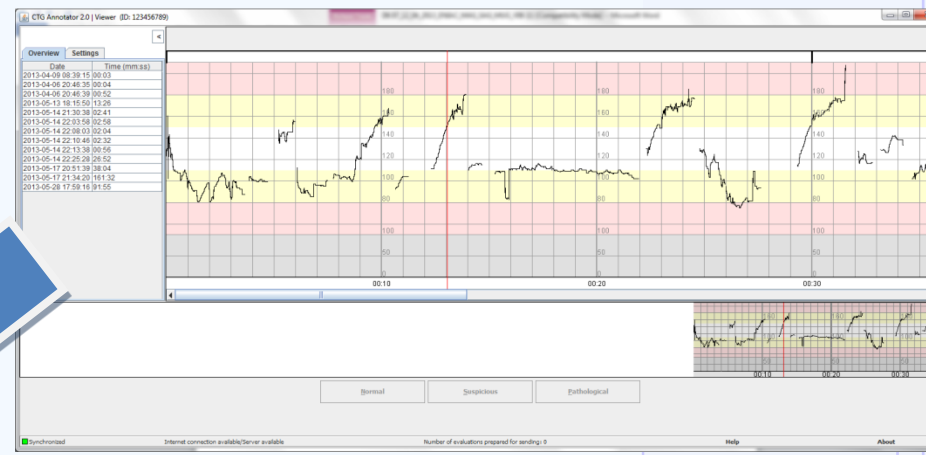
Phonography signal processing

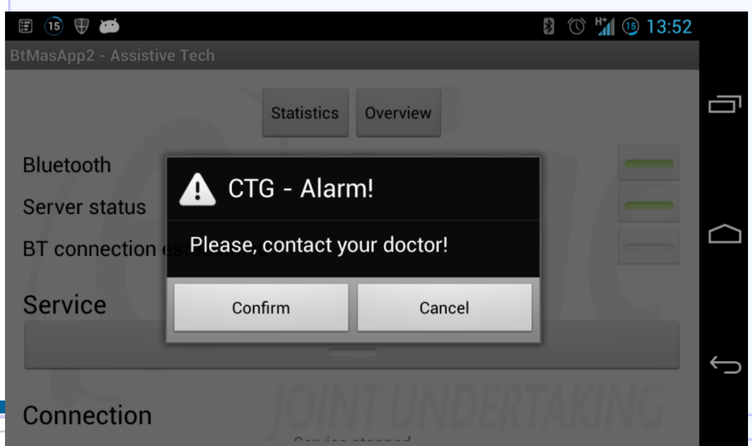
signal processing

MAS **mCTG** **D2**





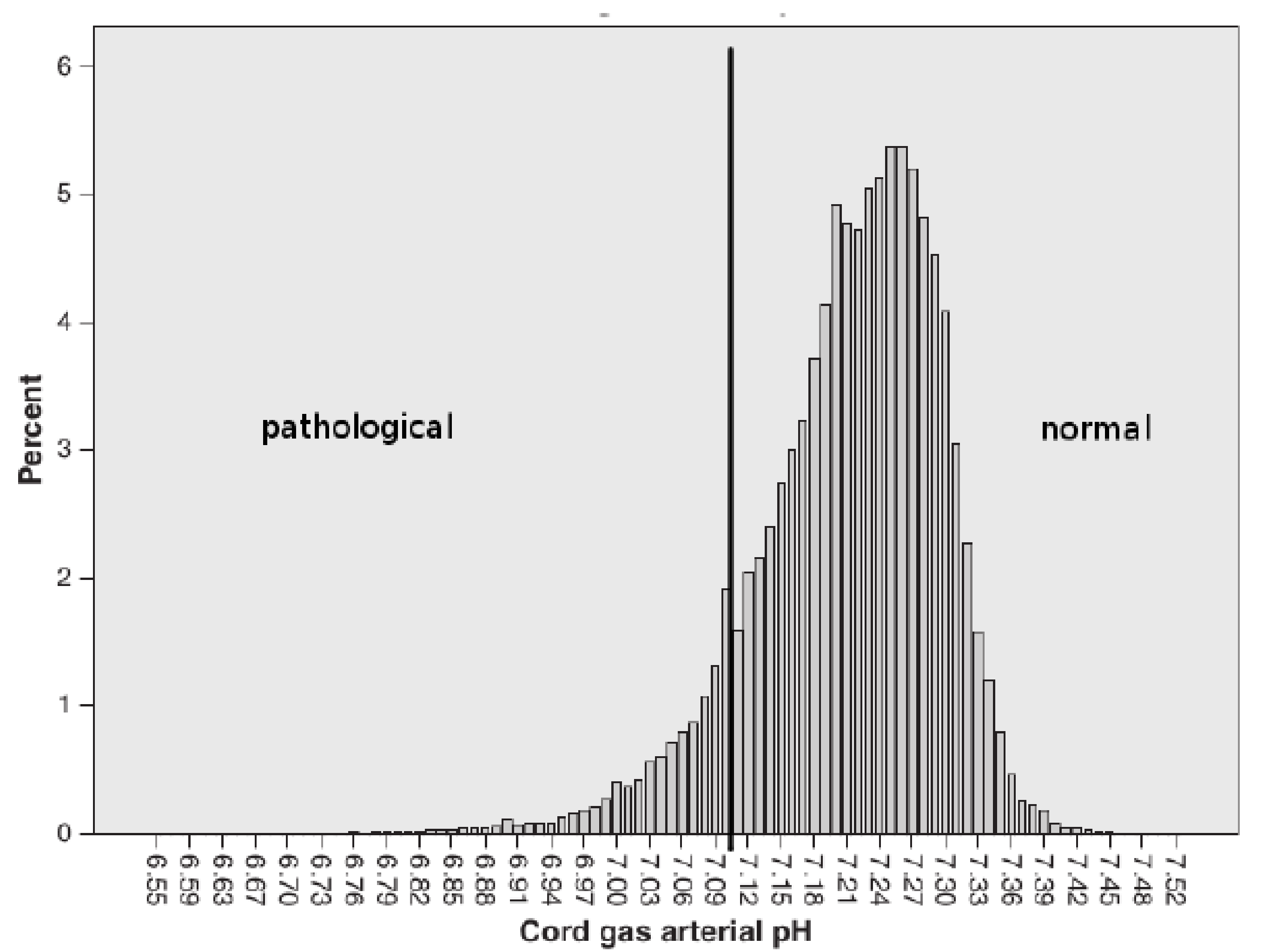




Biomedical Data Processing Group

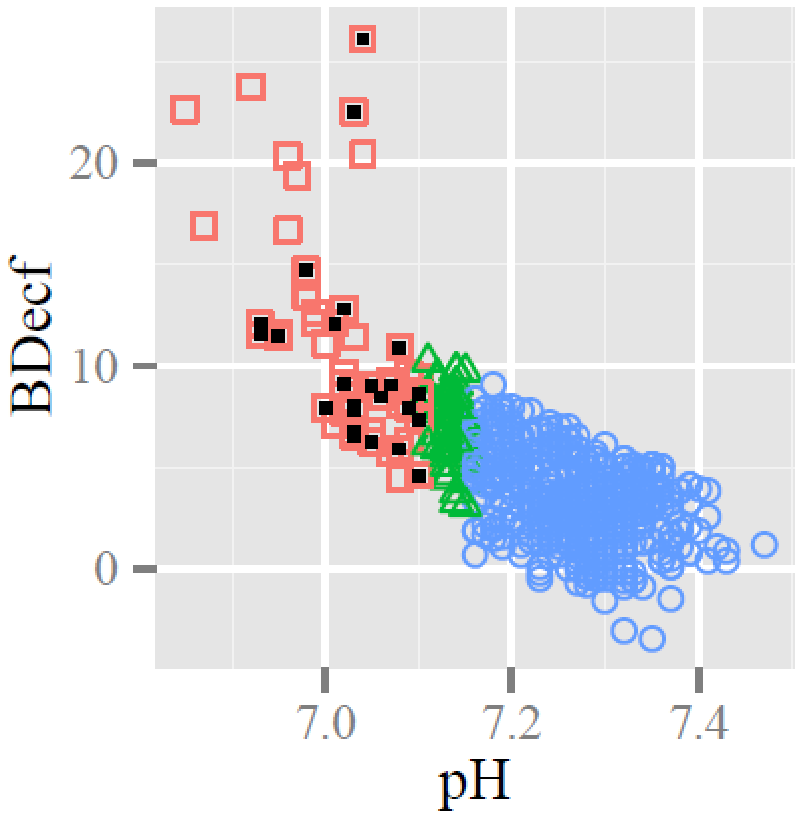
“Case study ” 4: Latent class model

Motivation



Percent
6
5
4
3
2
1
0
pathological
normal
6.55
6.59
6.63
6.67
6.70
6.73
6.76
6.79
6.82
6.85
6.88
6.91
6.94
6.97
7.00
7.03
7.06
7.09
7.12
7.15
7.18
7.21
7.24
7.27
7.30
7.33
7.36
7.39
7.42
7.45
7.48
7.52
Cord gas arterial pH

Results on pH

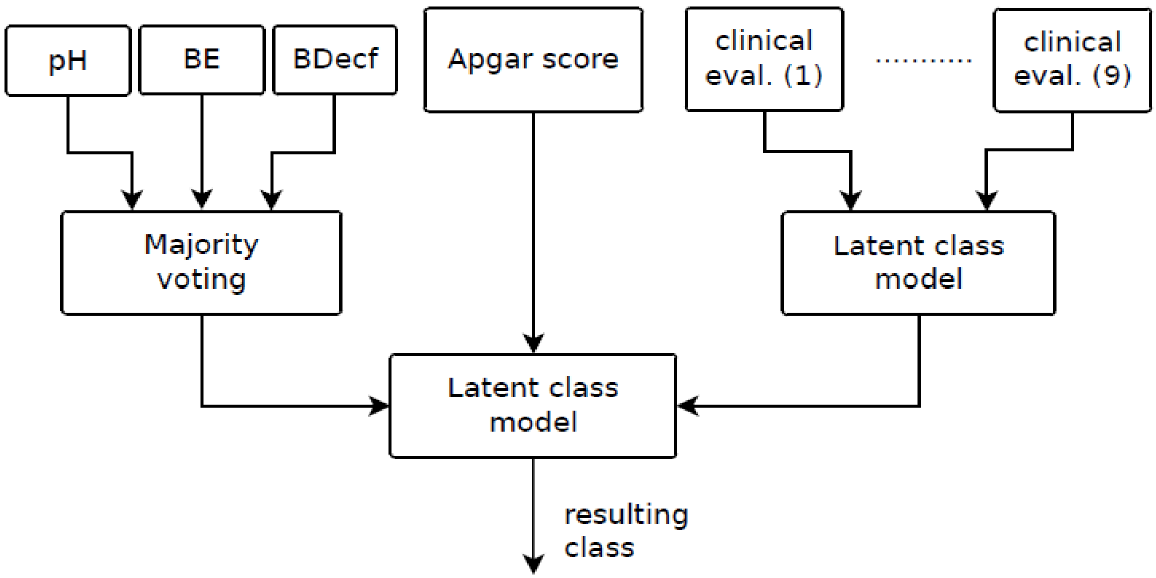


- used 3 class scenario
- black squares – false negatives
- pathological pH ≤ 7.10
- suspicious pH $(7.10, 7.15]$
- normal: pH > 7.15
- misclassification near boundary

- #16 recs. not pathological BDecf
- #11 recs. high Apgar score ≥ 9 (max. value 10)
- #11 recs. for each record ≥ 5 clinicians said FHR is normal

Latent class model

Latent class model (LCM)

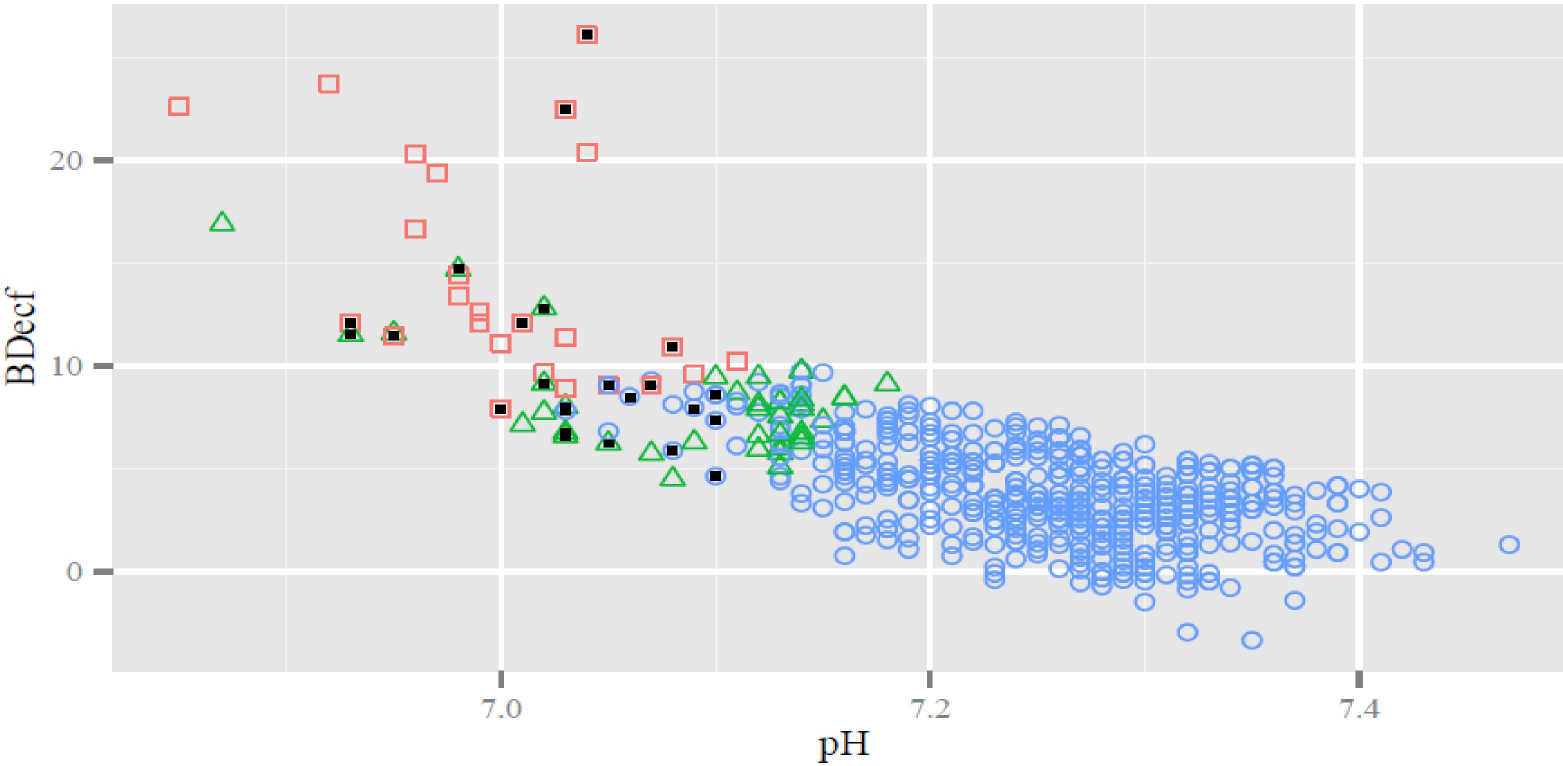


- **Input data**: noisy and imprecise
  - $y_i^j, \quad j = 1, \ldots, J \quad , i = 1, \ldots, N$
- **Goal**: estimate ground (unobserved) truth

$$\Pr[y_i^1, \ldots, y_i^J | \theta] = \prod_{i=1}^{N} \left[\sum_{c=1}^{C} \pi_c \Pr[y_i^1, \ldots, y_i^J | \theta_c] \right]$$

Results on pH with LCM

LCM – false negatives from supervised learning



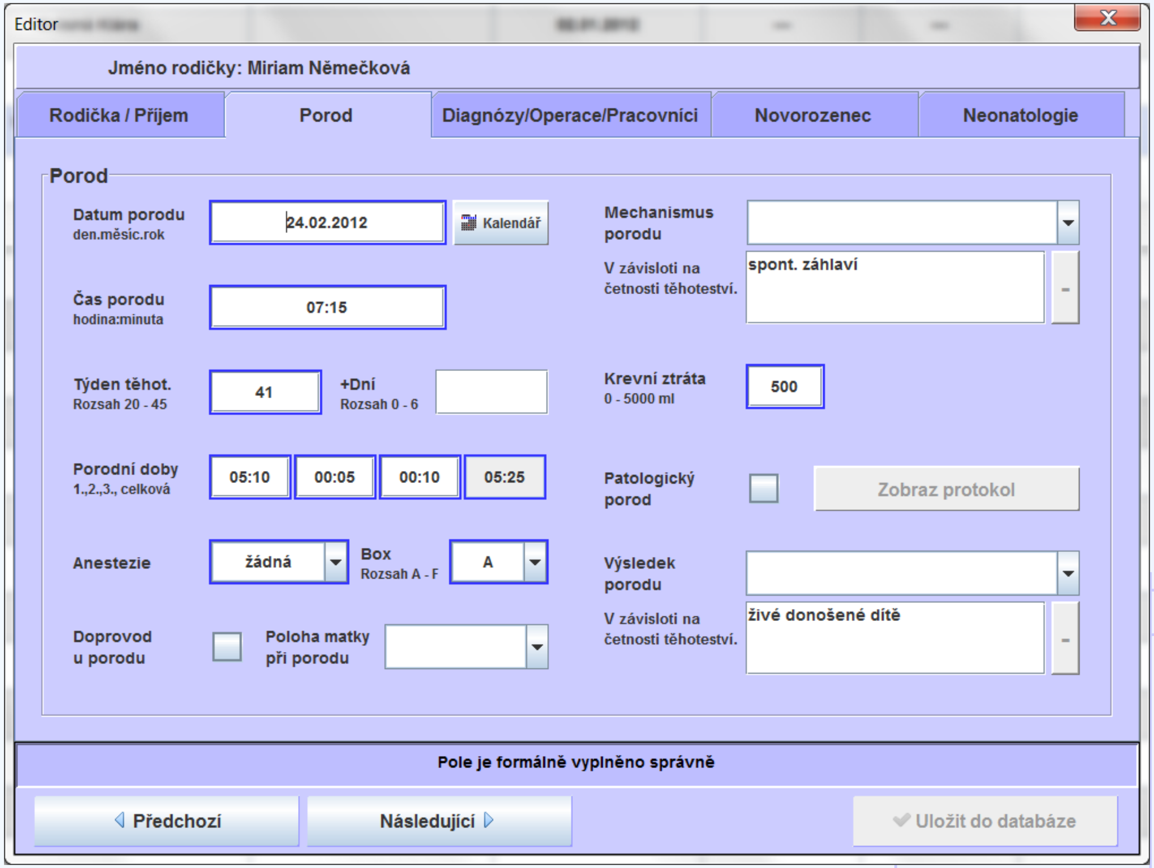
- no strict boundary: normal ○, suspicious △, pathological □
- false negatives (▪) – some explained by BDecf, Apgar score, clinical evaluation

“Case study ” 5:
OB information system – The Delivery Book

Biomedical Data Processing G r o u p

Data collected

- Mother's medical information
- Labor
  - E.g. diagnosis related to delivery or indication for surgery
- Newborn
  - E.g. umbilical cord blood pH and BDecf
- Neonatology
  - E.g. number of days at NICU, seizures,



Acknowledgments

- **prof. Lenka Lhotská**
  - My boss and main fundraiser
- Jiří Spilka
  - PhD student, coinvestigator
- Lukáš Zach
  - BSc./MSc. student, programmer
- Miroslav Burša, Michal Huptych
  - Database guys/PhD students
- Michal Koucký
  - Obstetrician, 1st Medical Faculty Charles University in Prague.
  - First contact with the topic (2008)
- Petr Janků
  - Chief obstetrician in FH Brno
  - IGA grant with Faculty Hospital in Brno
- Lukáš Hruban, Martin Huser
  - Part of the IGA team in FH Brno

Thank you for your attention!