EMORY UNIVERSITY SCHOOL OF MEDICINE

Department of Biomedical Informatics

Advances in Noninvasive Fetal Electrocardiography

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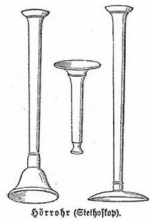
Disclosure

- I hold equity in MindChild Medical Inc
- Our US Patent (US8805485B2) in *extraction of cardiac signals* is licensed to MindChild Medical Inc and is used in their product

Prenatal Fetal Cardiac Monitoring Technologies

A review

Auscultation and Phonocardiography



1650 — Late 1600s — 1816 — 1818 — 1819 — 2016 — 2022

Late 1600s: Killian proposed the relationship between fetal heart-rate and well-being

1818: Mayer reported the presence of fetal heart sounds when he placed his ear on the maternal abdomen

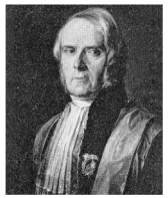
2016: The first PhysioNet Challenge on heart sound classification (including fetal heart sounds data)

1650: Marsac heard the fetal heart sound from the maternal abdomen (acknowledged in a French poem by LeGaust)

1816: Laennec invented mediate auscultation

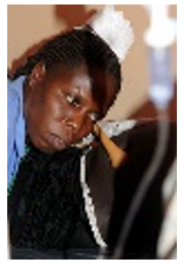
LAENNEC
(1781–1826)

1819: Kergaradec used Laennec's stethoscope for fetal cardiac auscultation



KERGARADEC
(1787–1877)

An electronic stethoscope



A U.S. Army Reserve nurse uses a Pinard horn in Uganda (2009)

2022: The PhysioNet Challenge on murmer detection in pediatric patients

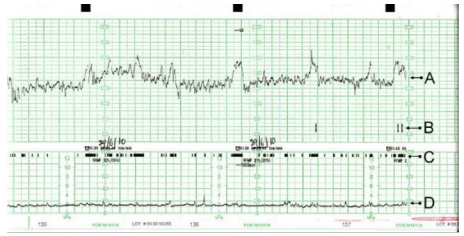
Doppler Ultrasound

1940s

Early Doppler technologies

Early 1960s

The use of electronic methods for acquiring and recording fetal heart rate (FHR) and uterine contraction (UC) by Hon, Caldeyro-Barcia, and Hammacher



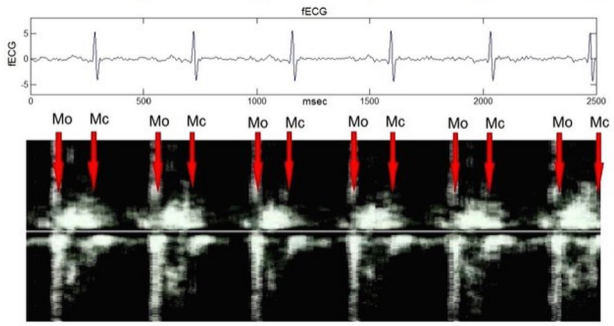
1968

The first commercial fetal monitor by Hammacher and Hewlett-Packard

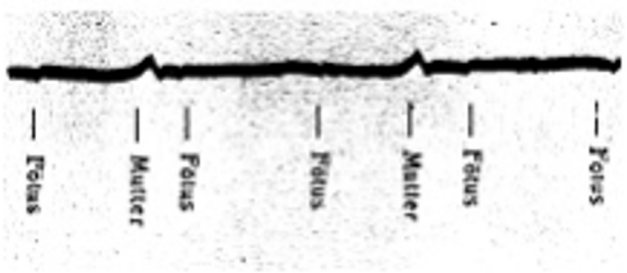
The first fetal CTG monitor by Hewlett-Packard 8020A

2010 onwards

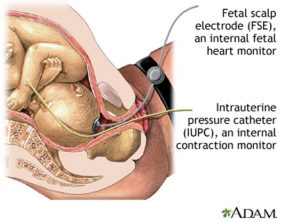
- Low-price 1D Doppler for home monitoring
- Multimodality (Simultaneous fECG and Doppler)



Fetal Electrocardiography



The first fetal ECG trace by Cremer



1901

Einthoven recorded the first ECG by string galvanometer

1906

Cremer recorded the first fetal ECG using abdomino-vaginal and abdomino-rectal leads

1940s

Improvements in measurement and amplification techniques

1960s

Invasive fetal scalp blood sampling during labor (Saling, 1964)

The beginning of the digital electronics and signal processing era

1970s

Noninvasive fetal ECG enhancement by signal processing

Development of the SQUID technology

Fetal Magnetocardiography

1990s

Development of multichannel blind source separation algorithms

2010 onwards

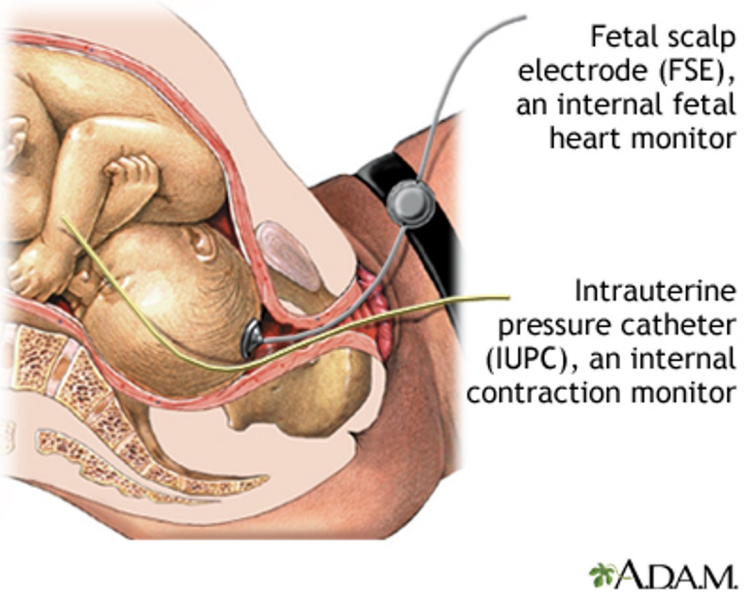
The first clinical noninvasive fetal ECG monitors

Fetal Electrocardiography

Technologies and Algorithms

Invasive fetal ECG

- Used in normal vaginal deliveries after amniotic sac rupture
- Used to identify fetuses at risk of hypoxia (oxygen deficiency) during labor



Drawbacks:

- Only applicable during labor
- May result in scalp lesions and infections
- May result in maternal infections

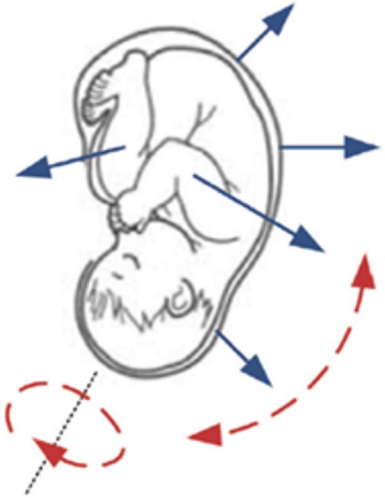
Noninvasive fetal ECG

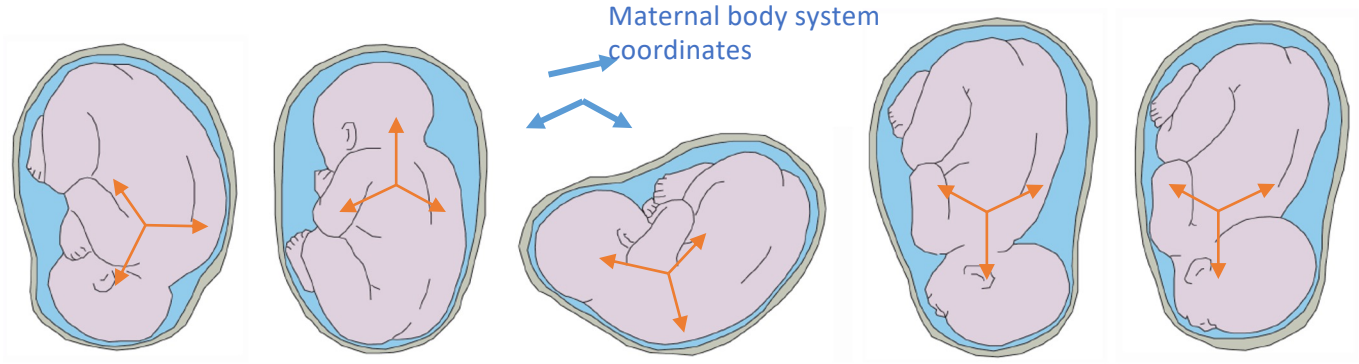
- Can be used throughout pregnancy (mainly the third trimester) without any risk

- Drawbacks: Challenges of noninvasive fetal ECG extraction from abdominal recordings

Complications of noninvasive fetal ECG extraction

- Weakness of fetal cardiac signals
- Strong maternal ECG interference
- Change of fetal body coordinates with respect to the surface leads during fetal motion
- Electrode positioning
- Multiple pregnancies (twin, triplet, ...)
- Electrically insulating layers such as the *vernix caseosa*



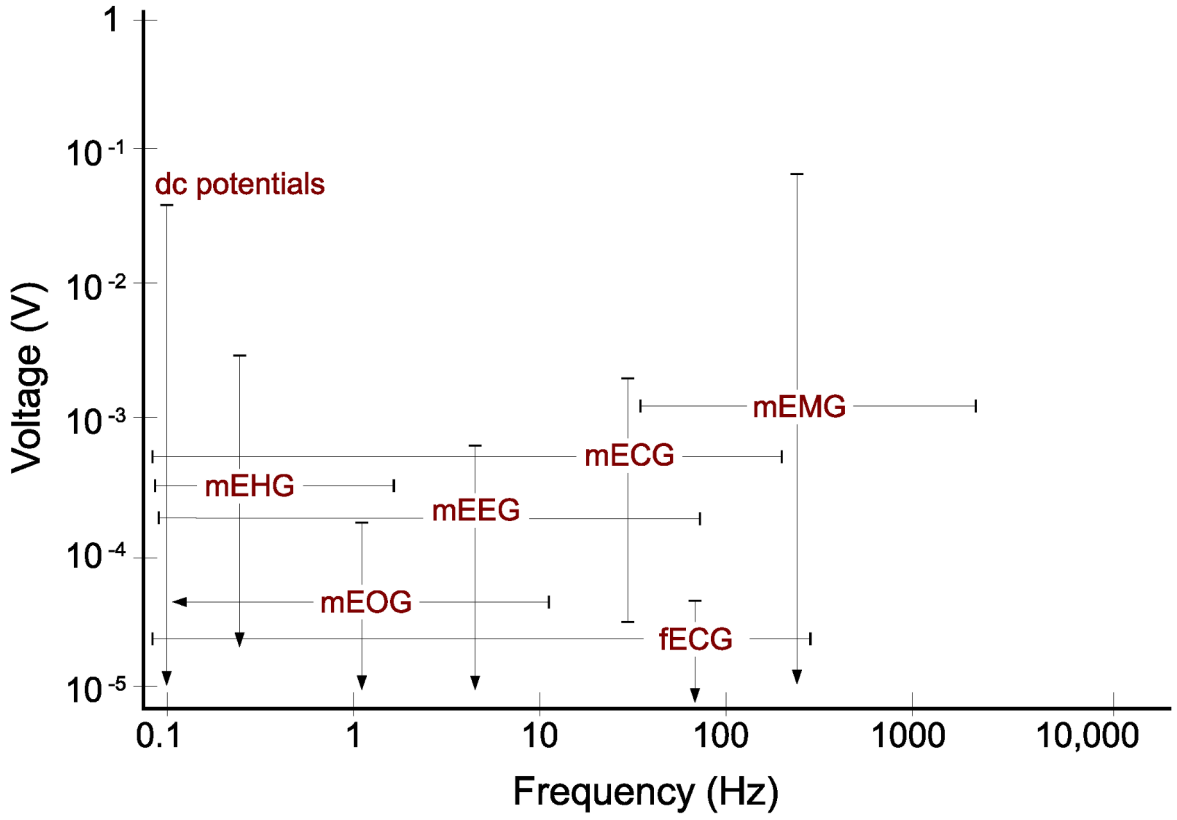


Major interferences

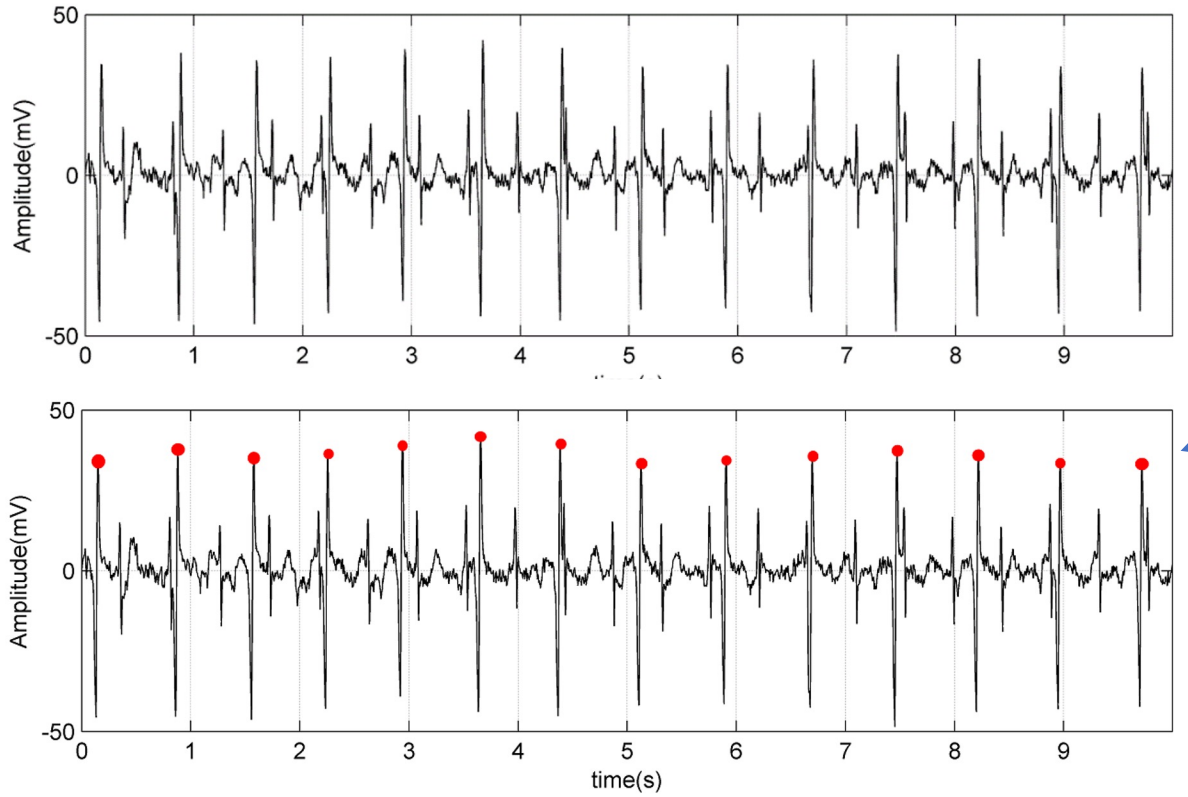
- Maternal interferences:
  - Mother's ECG (the major interference)
  - Uterus and muscle contractions
  - Baseline wander due to maternal respiration
- Device noises (inductive and conductive):
  - Power-line noise
  - Bedside monitors
  - Infusion pumps
  - Cellphones
  - USB devices
  - etc.
- Other fetal interferences: in multiple pregnancies

Major Fetal ECG Noises and Interferences

- The noises and interferences overlap with the fECG in all domains

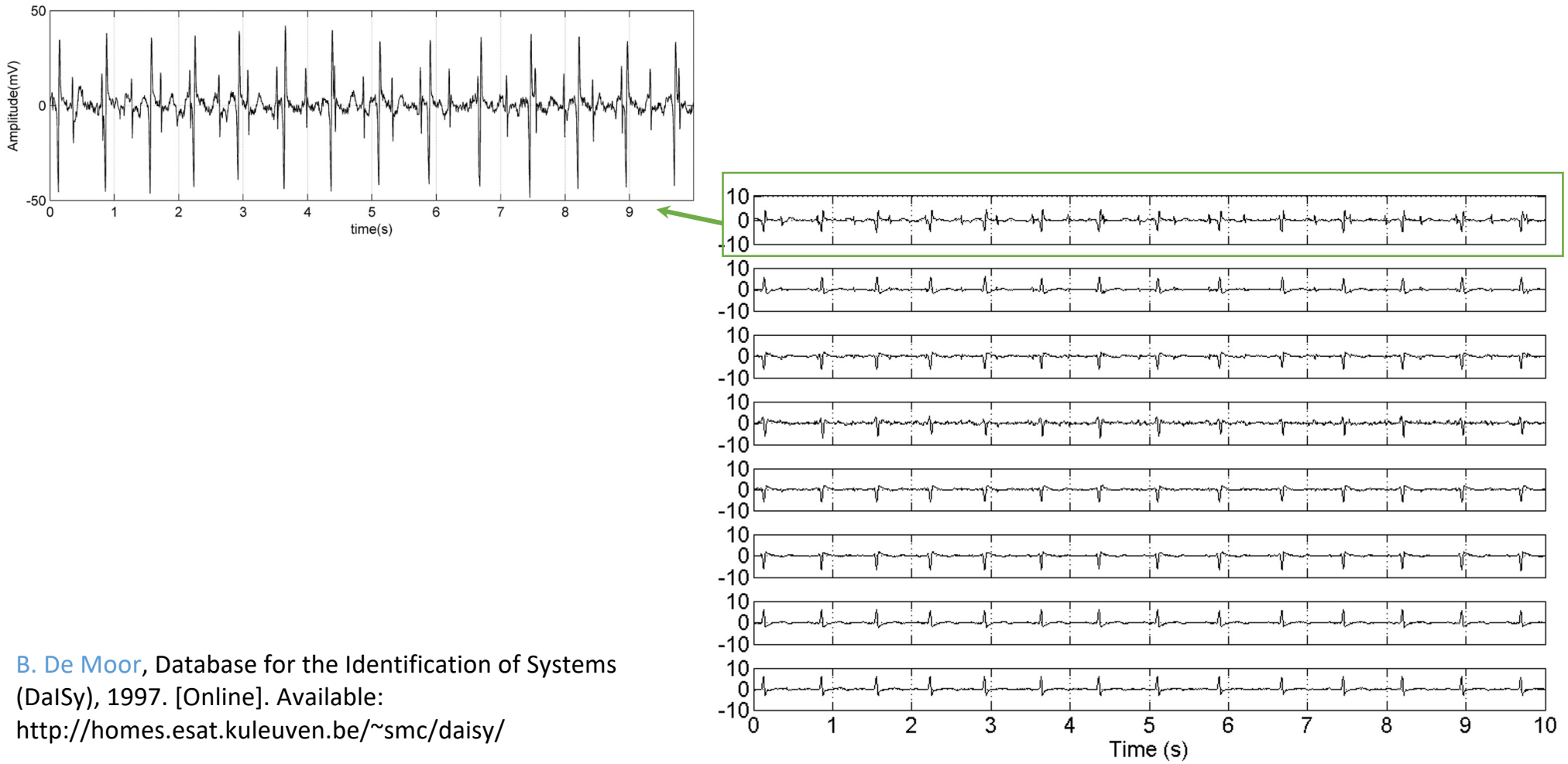


A typical fetal ECG observed on the maternal abdomen



maternal R-peaks

A typical fetal ECG observed on the maternal abdomen



B. De Moor, Database for the Identification of Systems (DaISy), 1997. [Online]. Available: http://homes.esat.kuleuven.be/~smc/daisy/

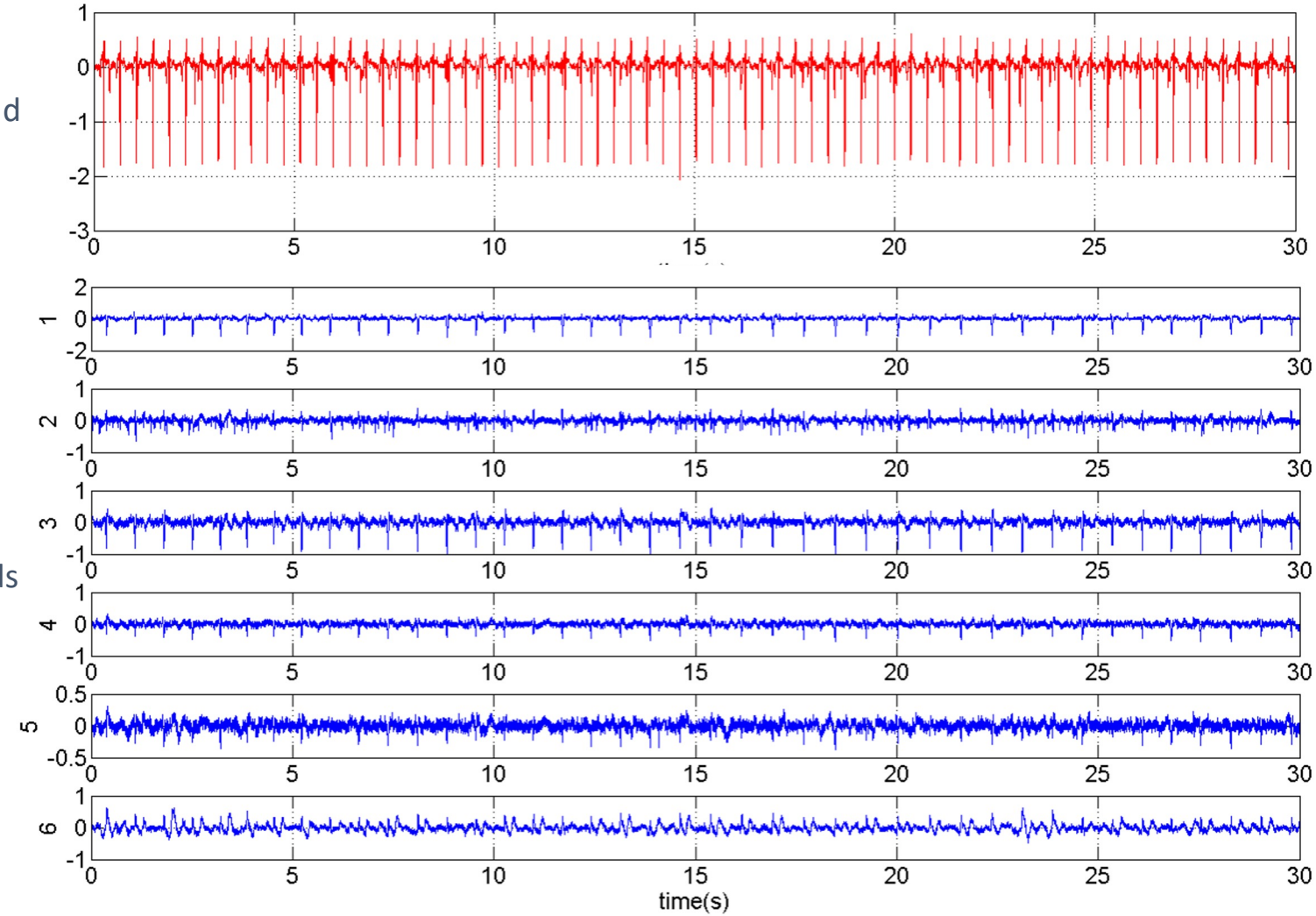
A typical fetal ECG observed on the maternal abdomen

Sample data recorded by Dr. Evelyn Huhn and provided by Dr. Raphael Schneider

Simultaneous invasive and noninvasive fetal ECG

Fetal scalp lead

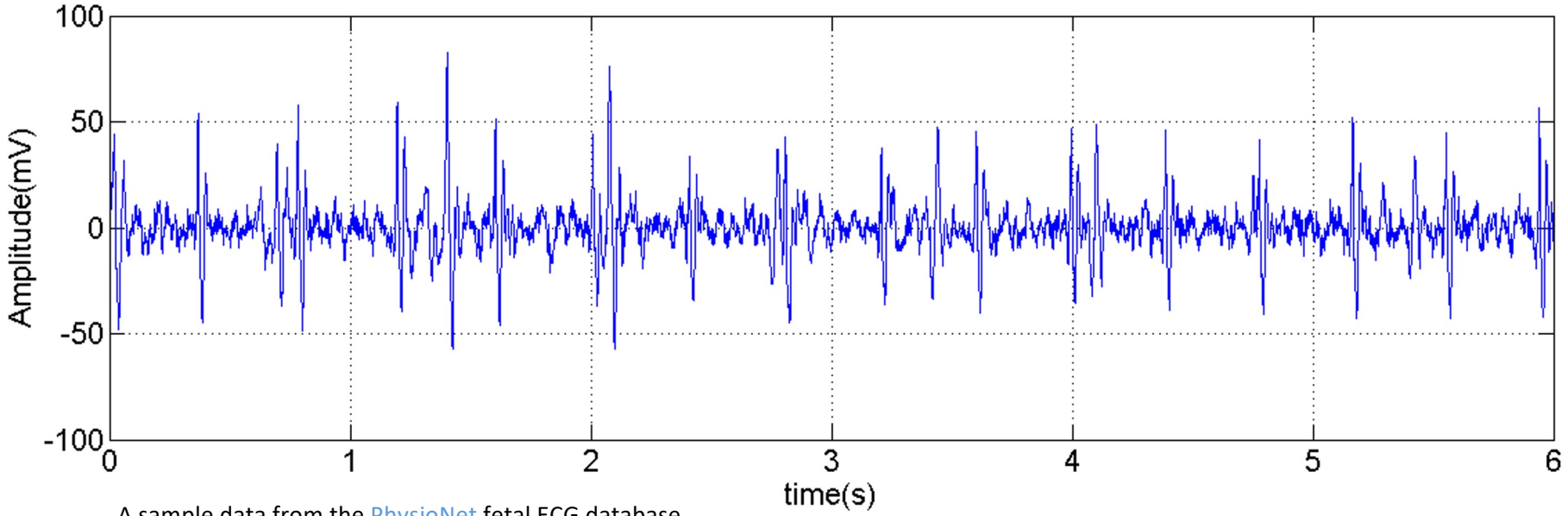
Maternal abdominal leads



Sample data provided by Dr. Adam Wolfberg, Tufts University

A typical fetal ECG observed on the maternal abdomen

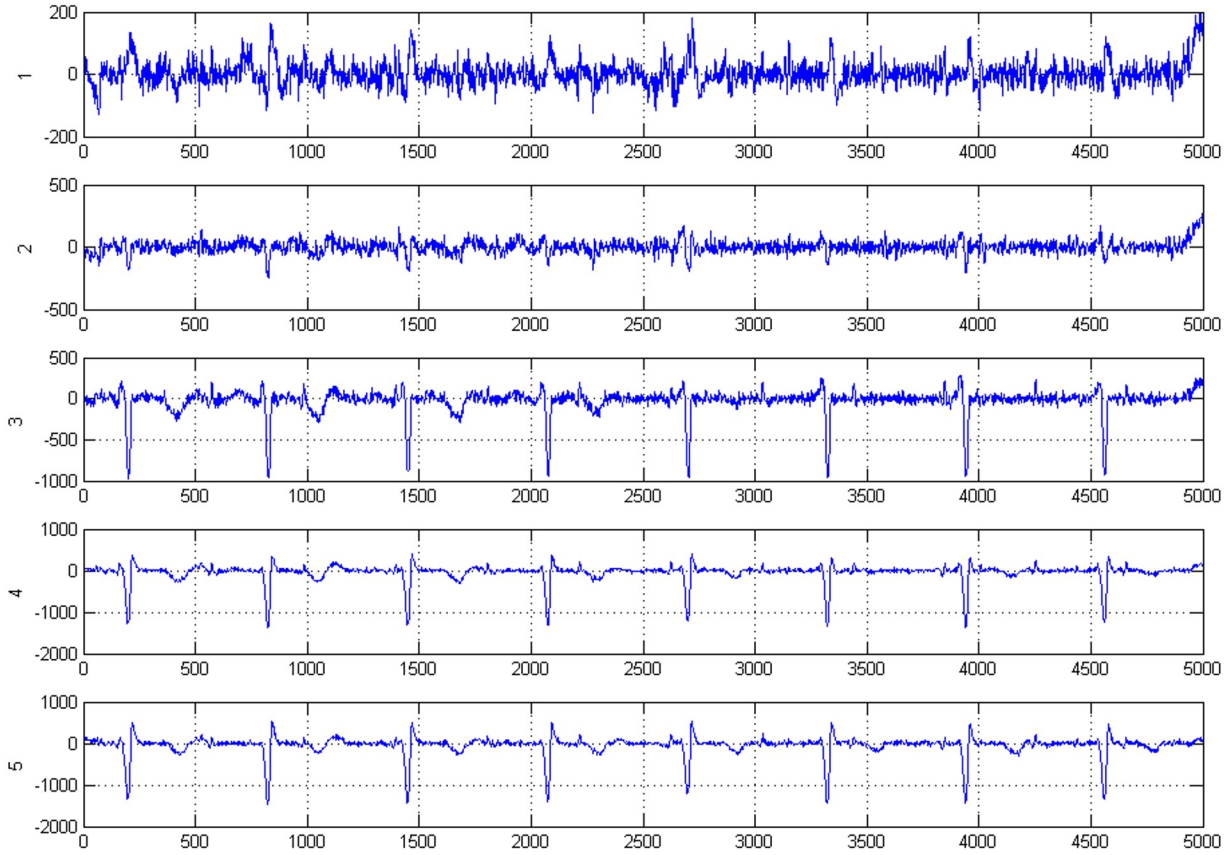
Notice the interferences from the maternal ECG



A sample data from the PhysioNet fetal ECG database

A typical fetal magnetocardiogram

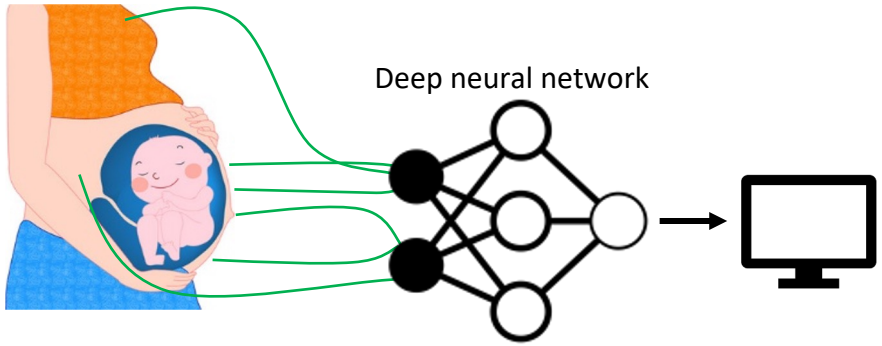
Morphologically resembles the ECG



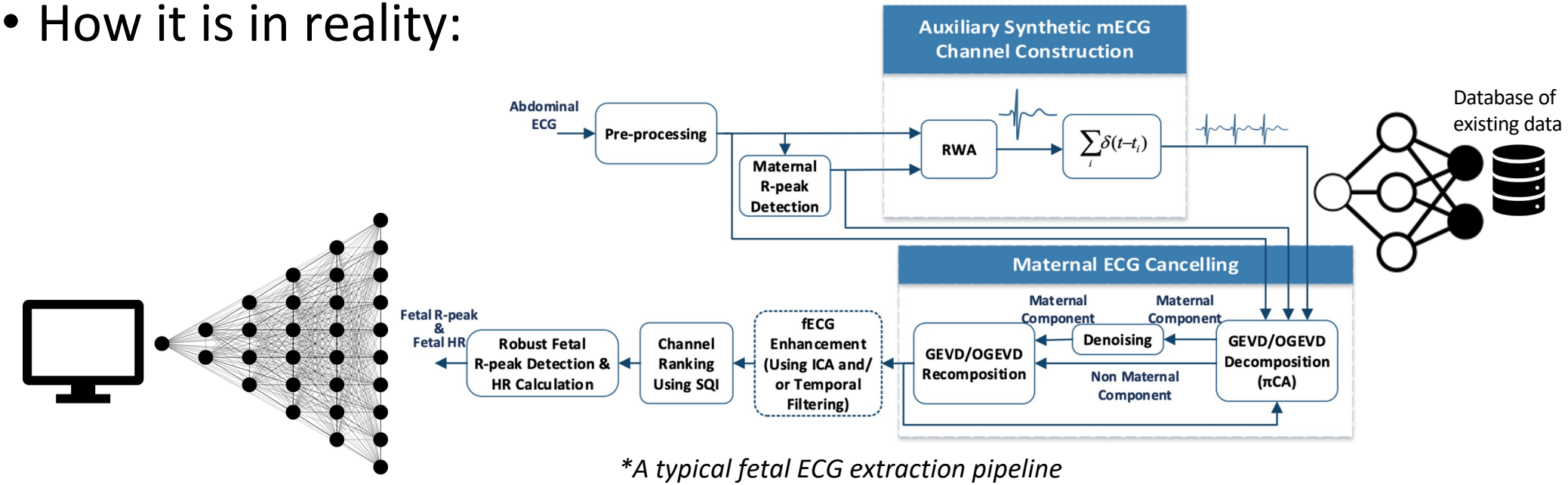
Sample data provided by Dr. Dirk Hoyer, Jena University

How to extract the fetal ECG

- What it may sound like:



- How it is in reality:



**A typical fetal ECG extraction pipeline*

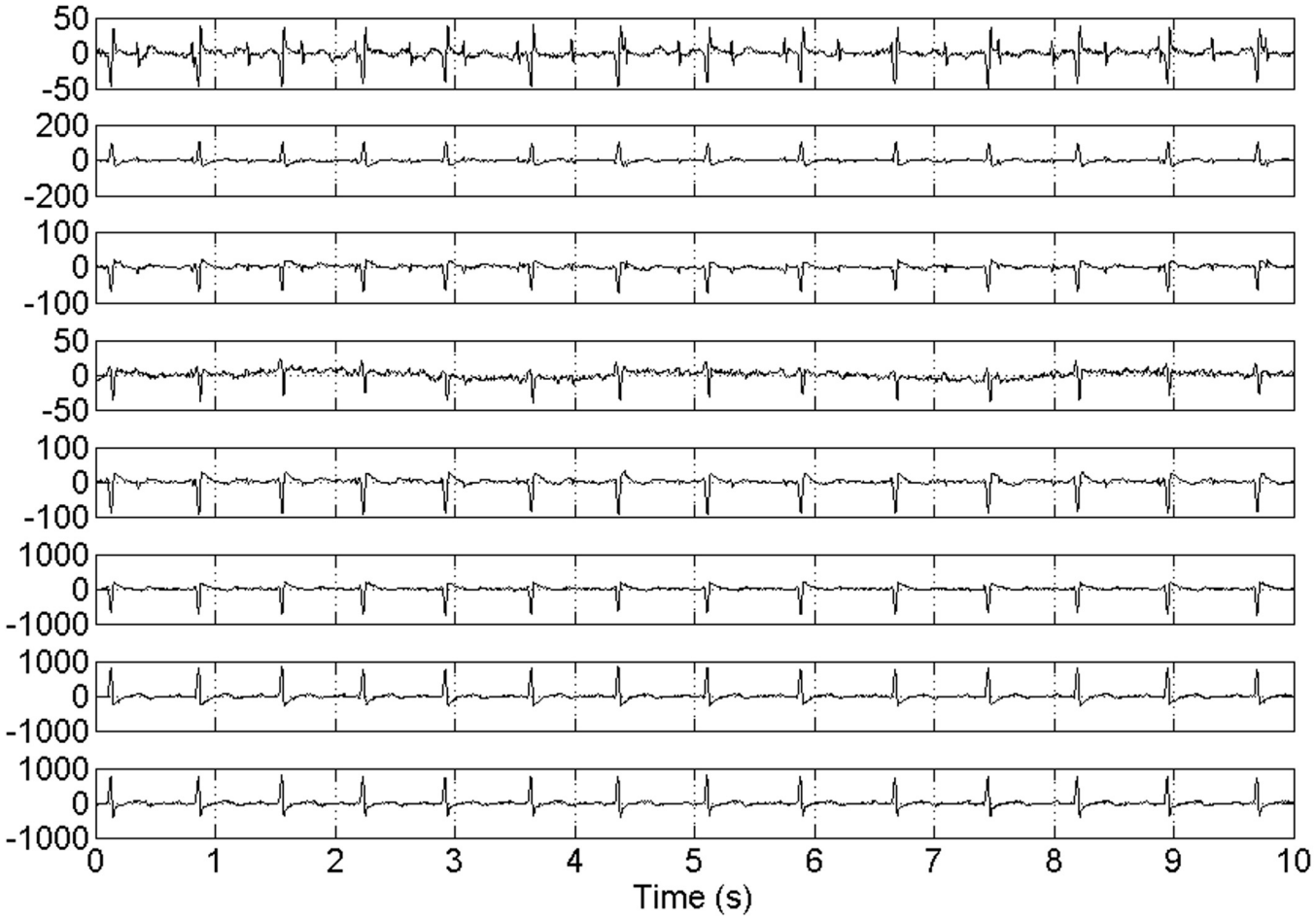
Why not just use generic deep neural networks?!

- Deep neural networks are data greedy
- Lack of sufficient data from border cases; *the critical cases are underrepresented in clinical data*
- Lack of “explainability” and generalizability
- Blind learning, is not guaranteed to learn what it should! Examples:
  - Learning from measurement noise due to patient sweating
  - Learning from environmental artifacts and background noise

Result: *current fetal ECG extraction algorithms are a combination of well-designed signal processing and machine learning pipelines that use hand-crafted features*

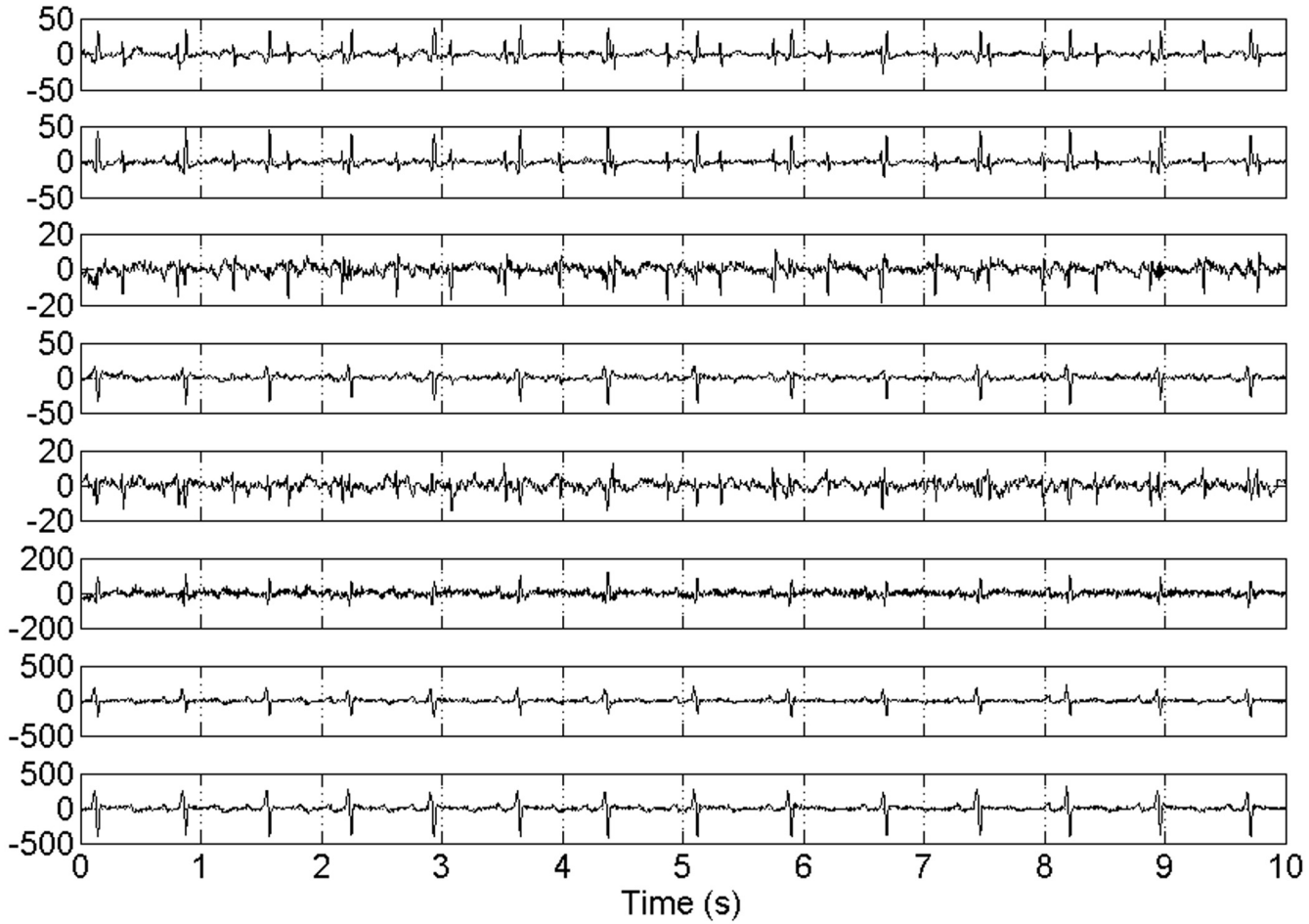
A deflation procedure for fetal ECG extraction

Example 1: Original signal



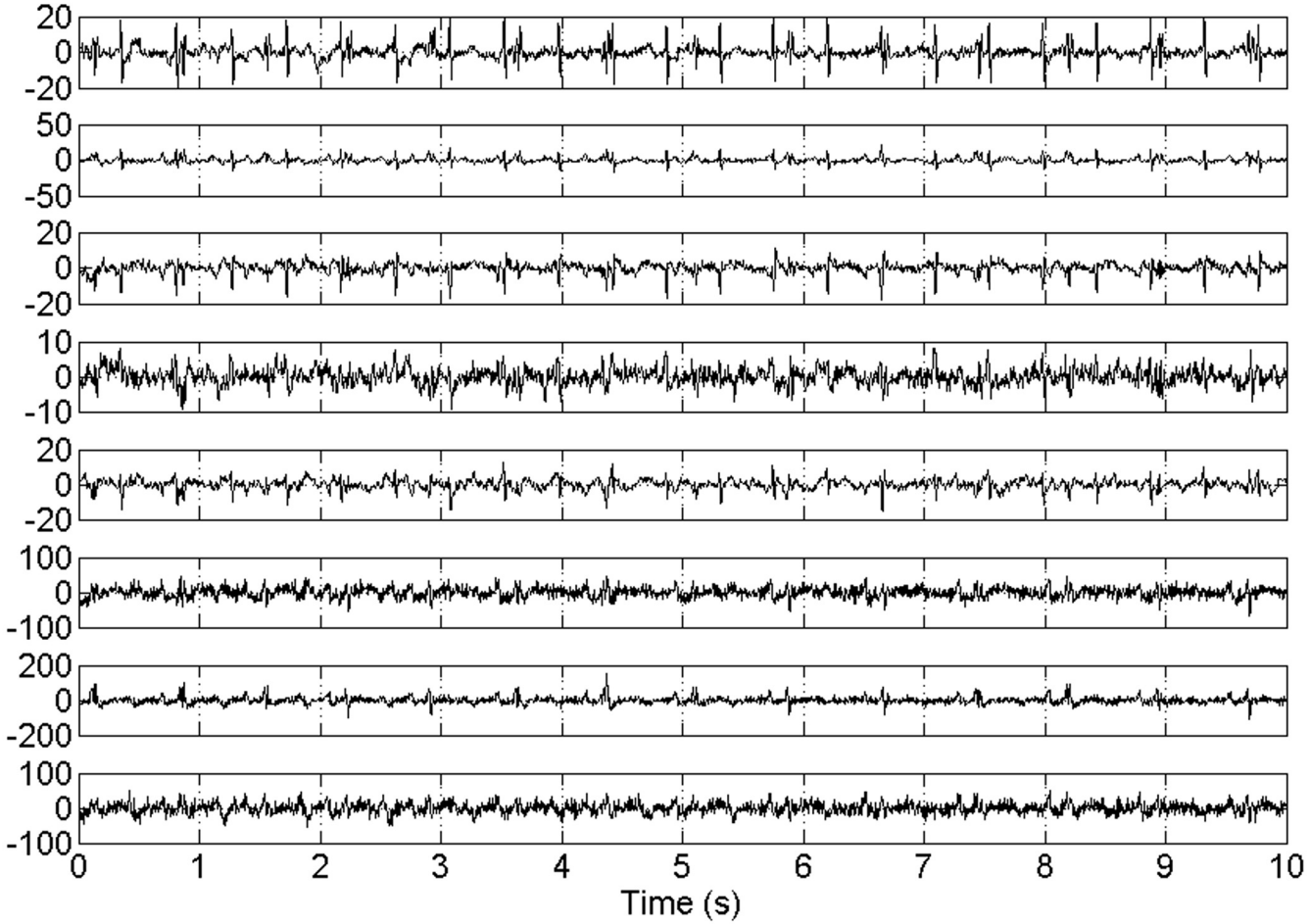
A deflation procedure for fetal ECG extraction

Example 1: After 1st iteration



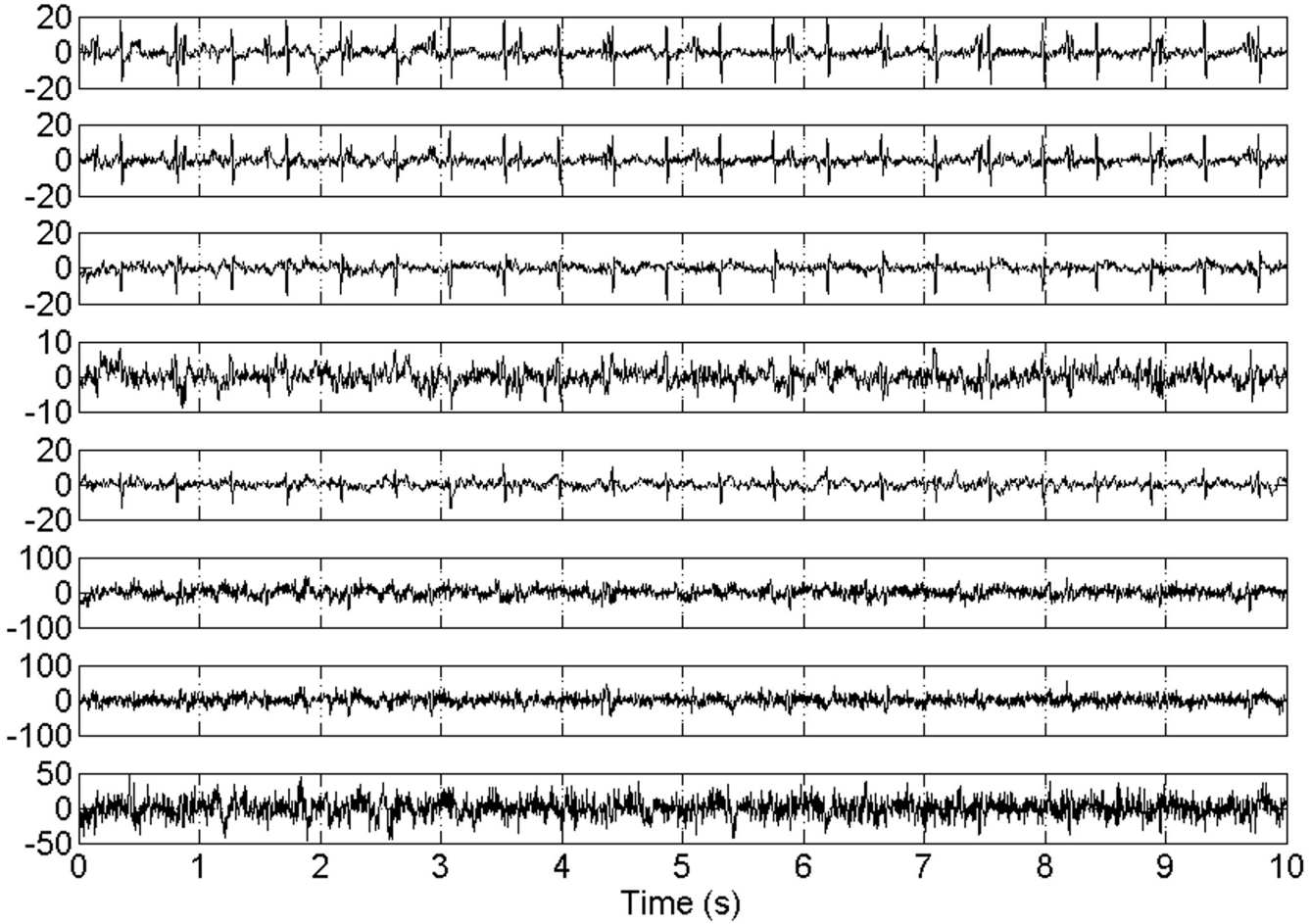
A deflation procedure for fetal ECG extraction

Example 1: After 2nd iteration



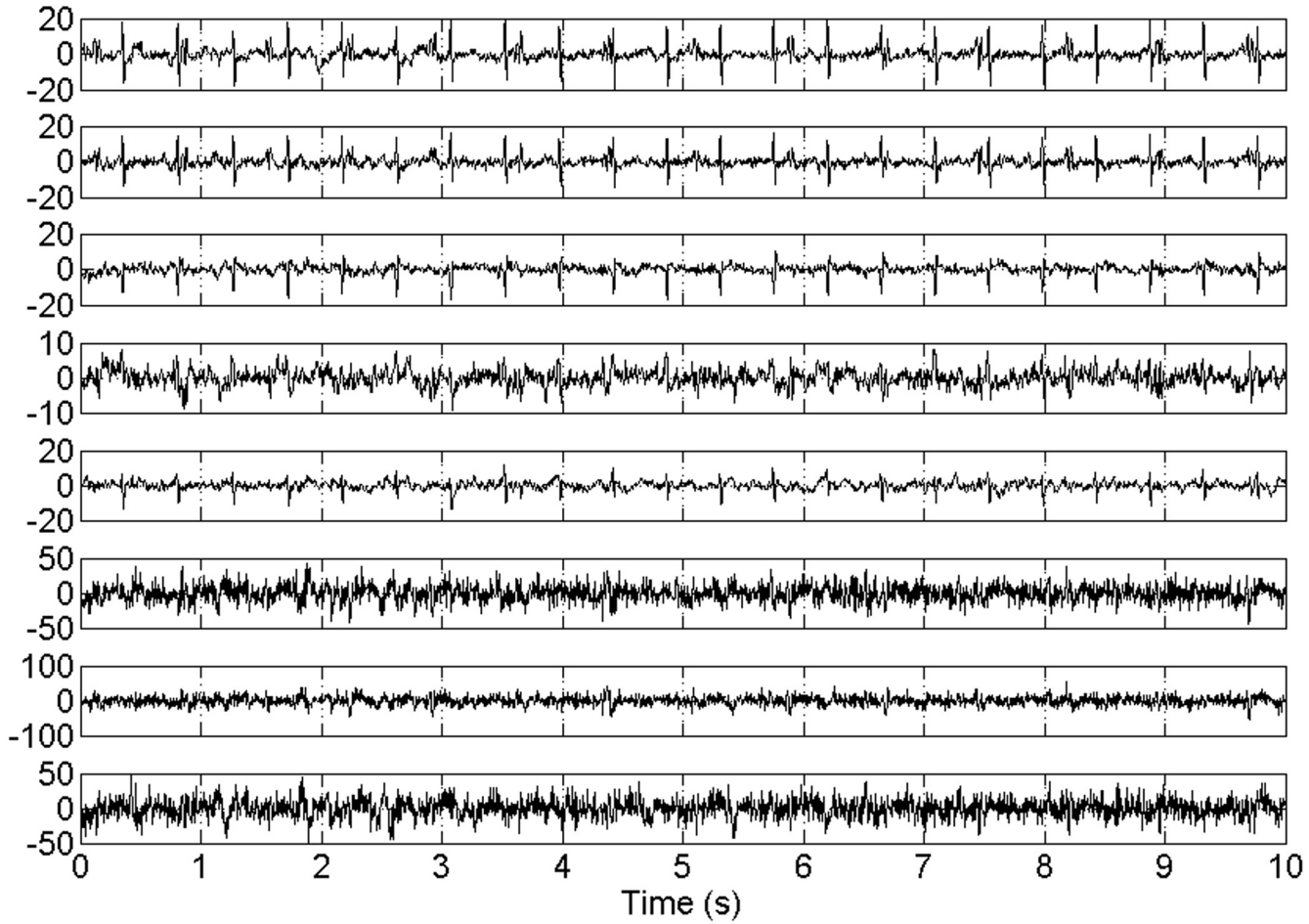
A deflation procedure for fetal ECG extraction

Example 1: After 3rd iteration



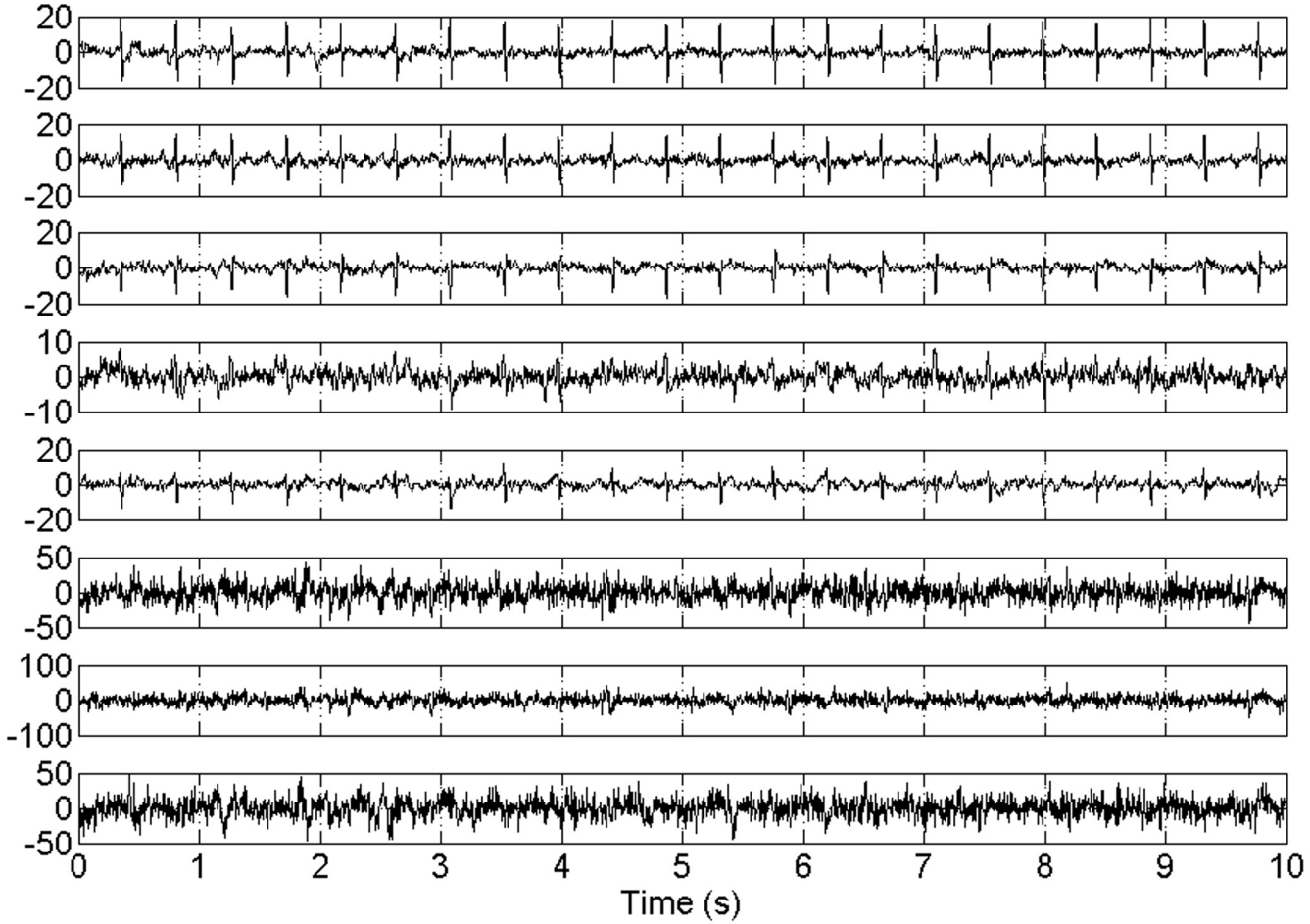
A deflation procedure for fetal ECG extraction

Example 1: After 4th iteration



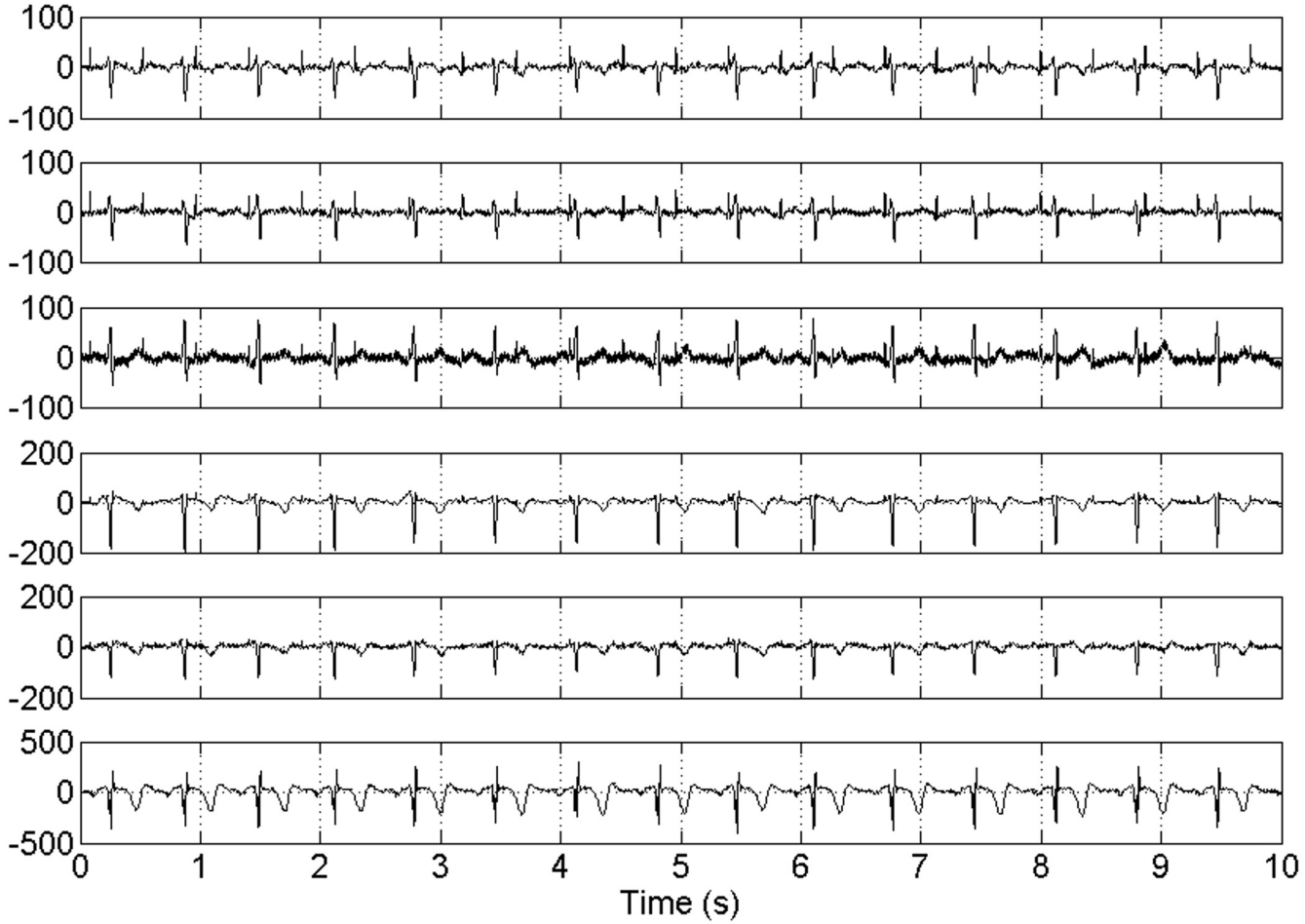
A deflation procedure for fetal ECG extraction

Example 1: After 5th iteration (maternal ECG fully removed)



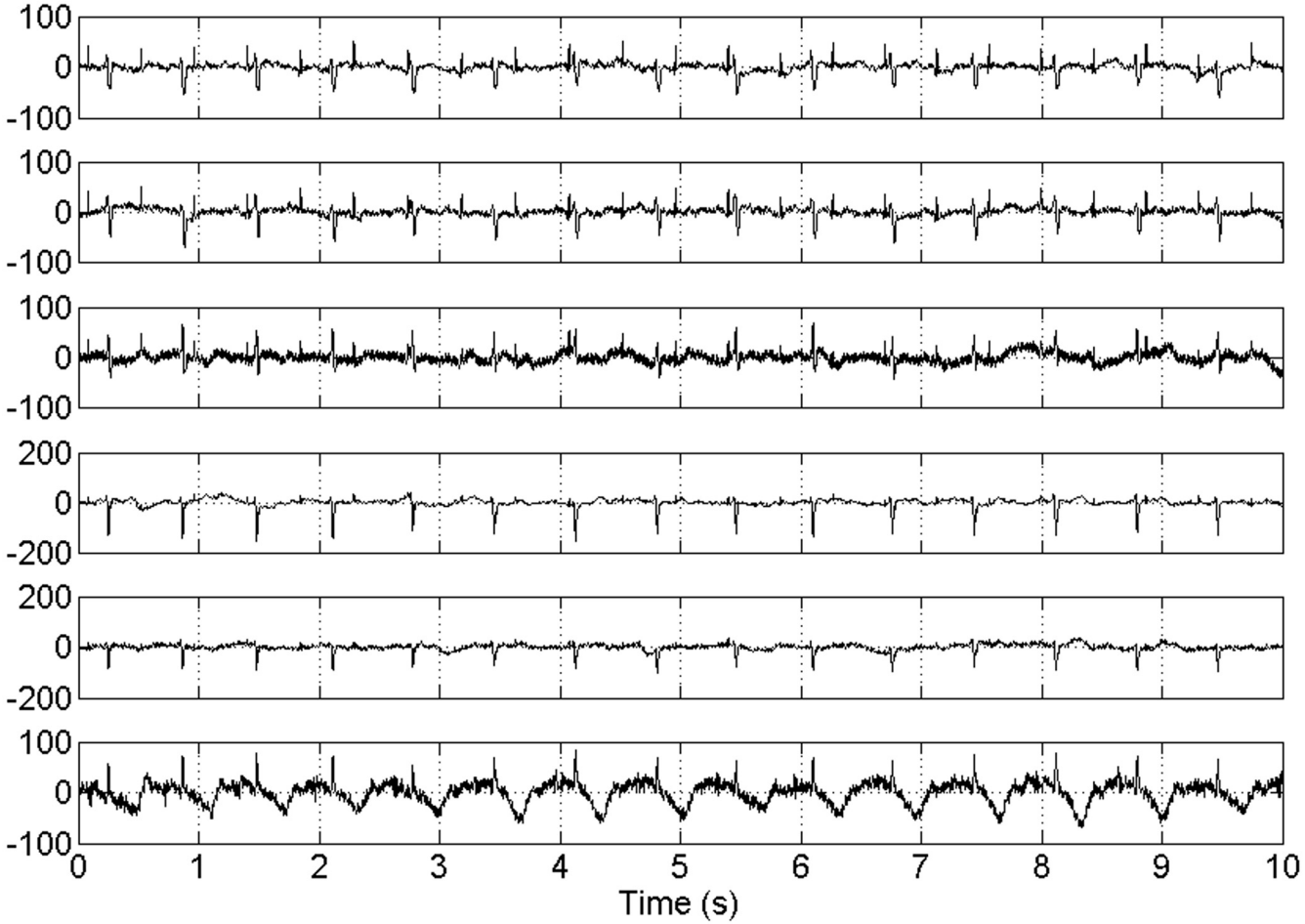
A deflation procedure for fetal ECG extraction

Example 2: Original ECG



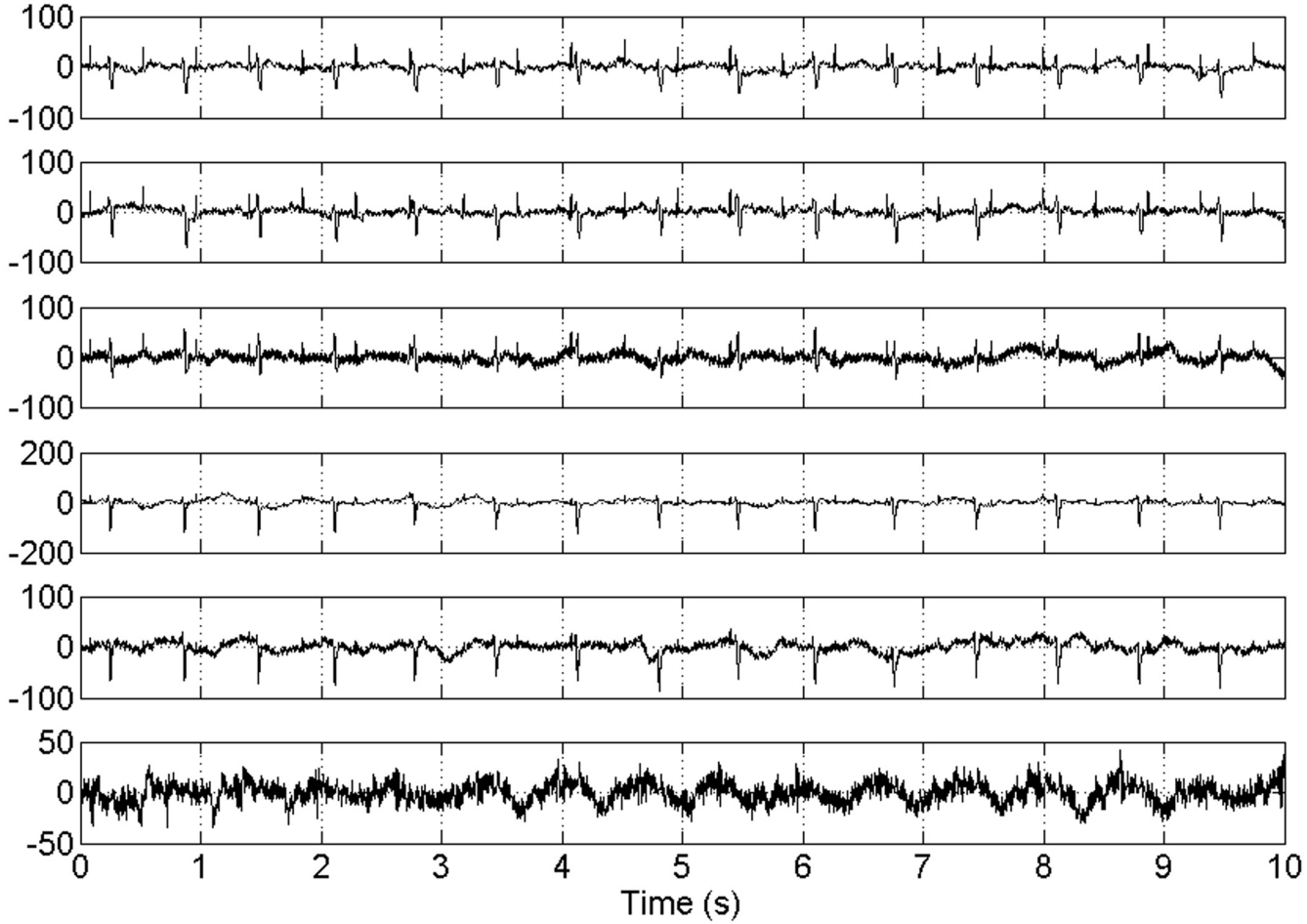
A deflation procedure for fetal ECG extraction

Example 2: After 1st iteration



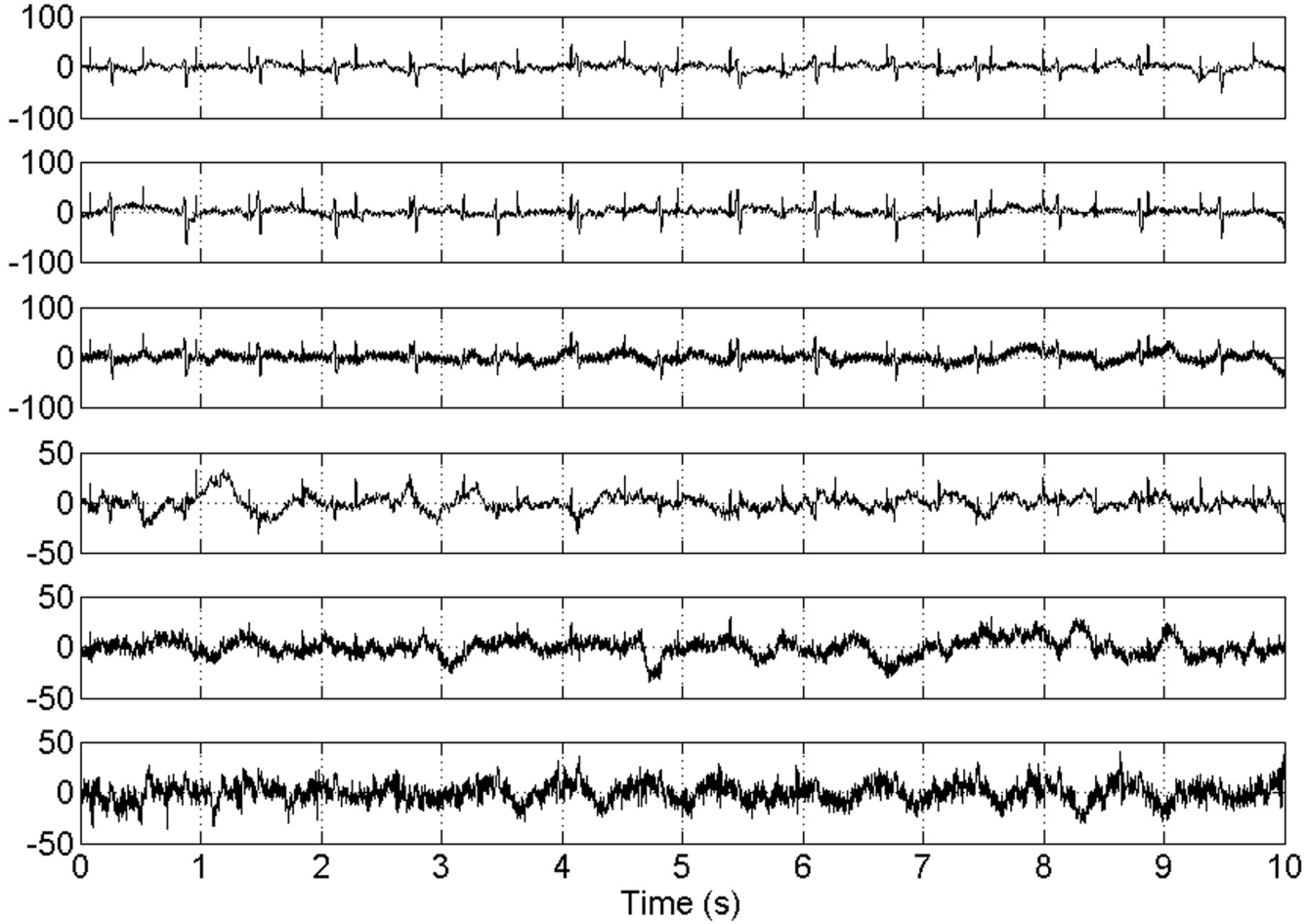
A deflation procedure for fetal ECG extraction

Example 2: After 2nd iteration



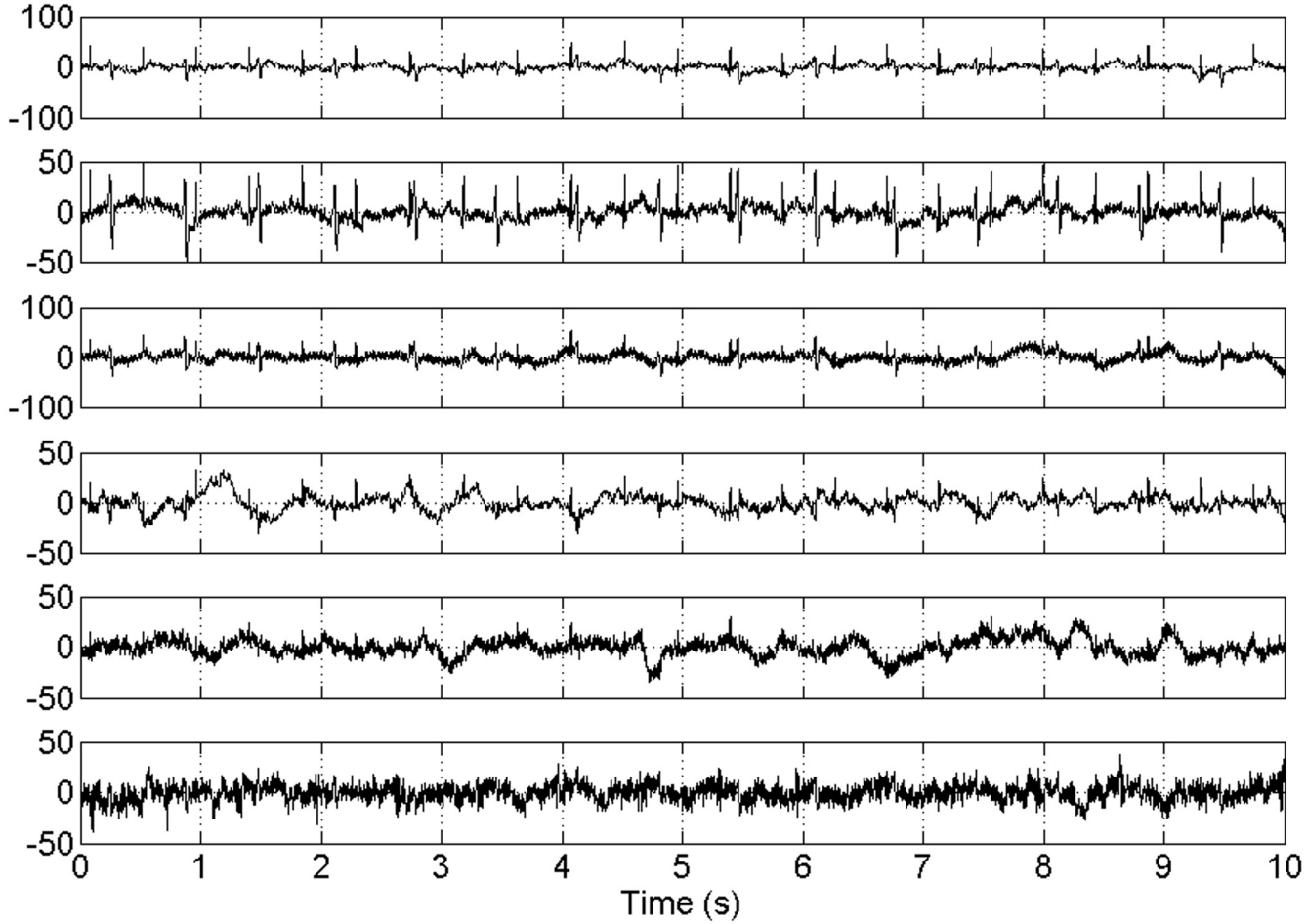
A deflation procedure for fetal ECG extraction

Example 2: After 3rd iteration



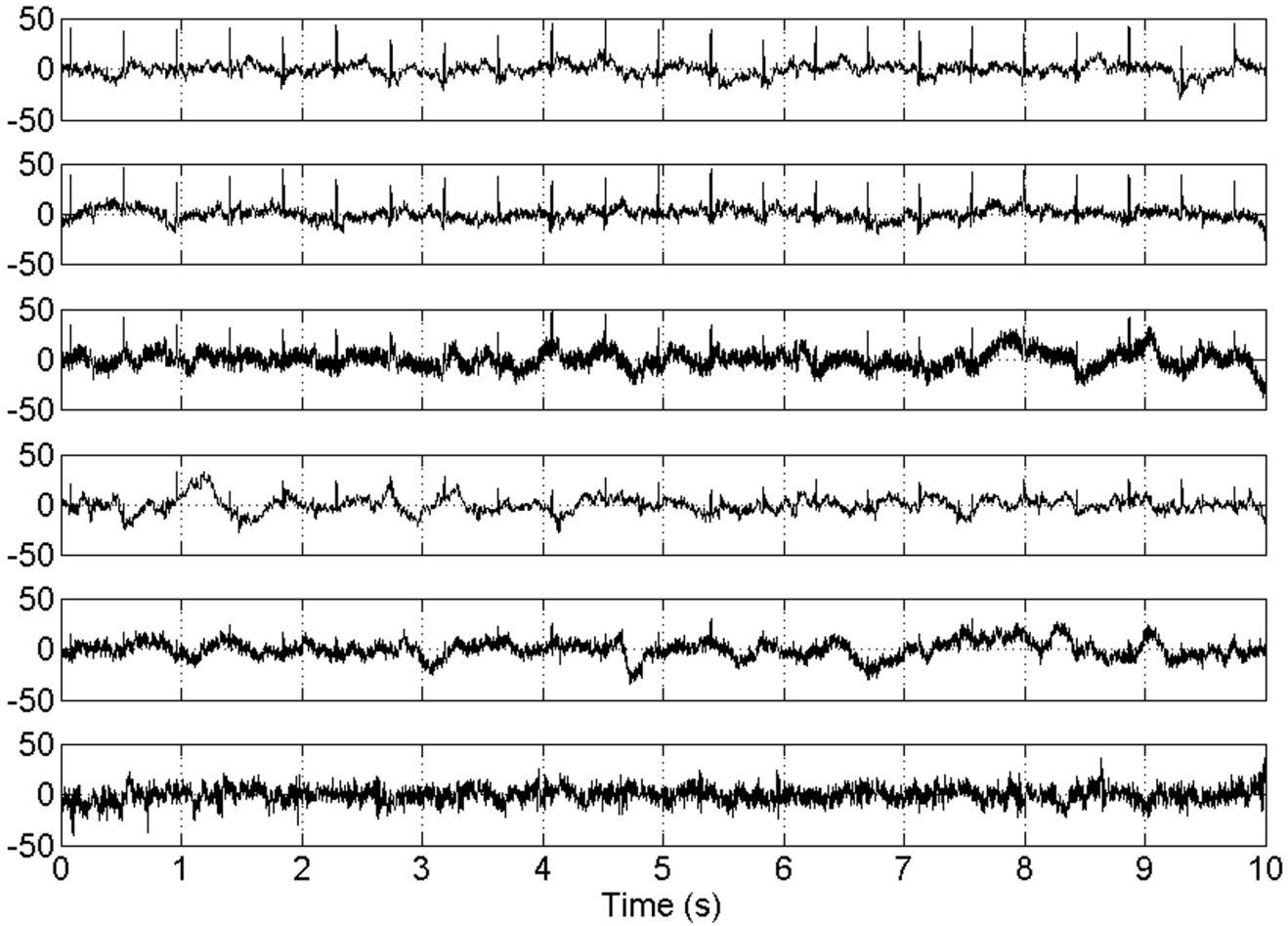
A deflation procedure for fetal ECG extraction

Example 2: After 4th iteration

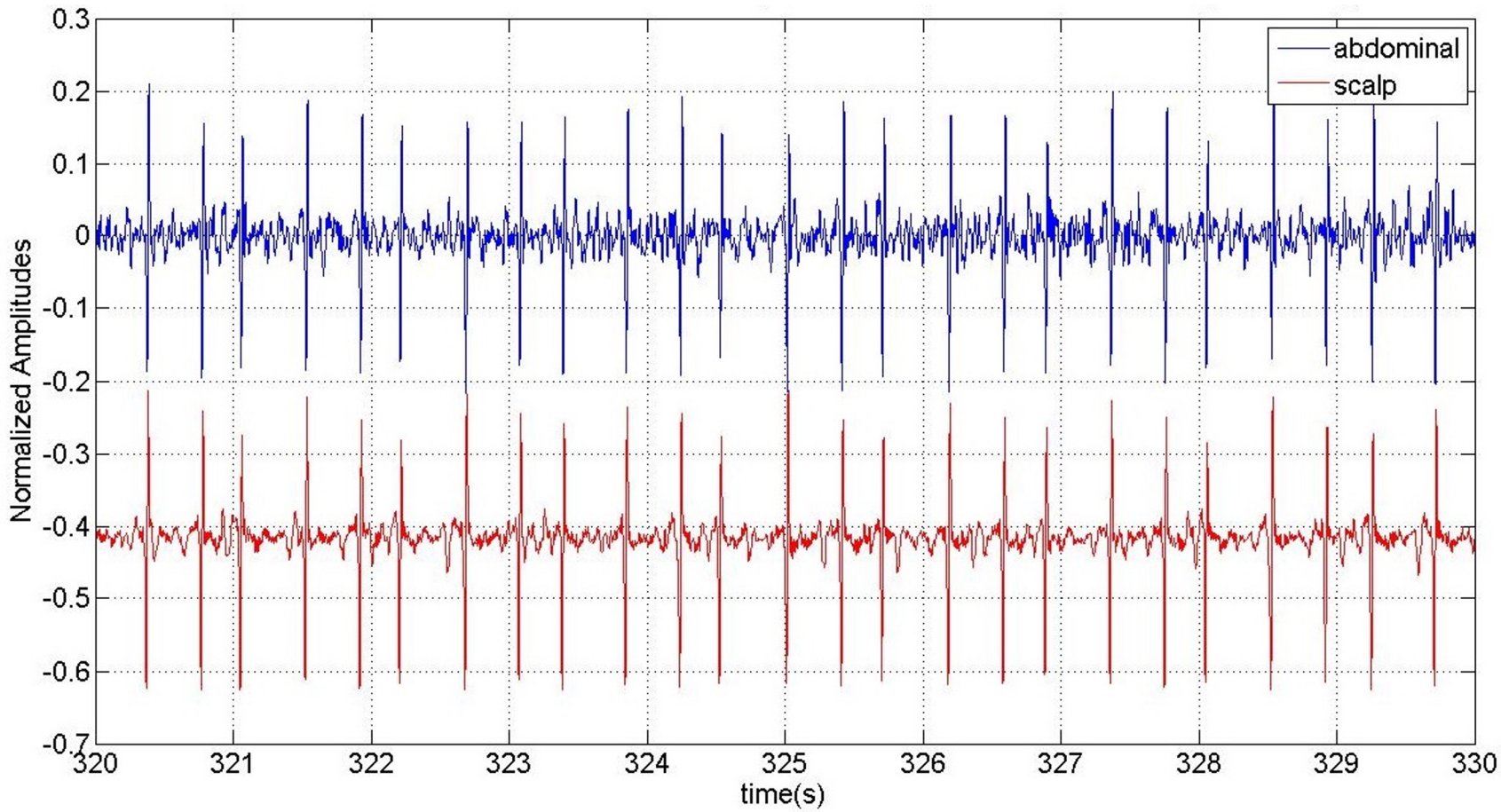


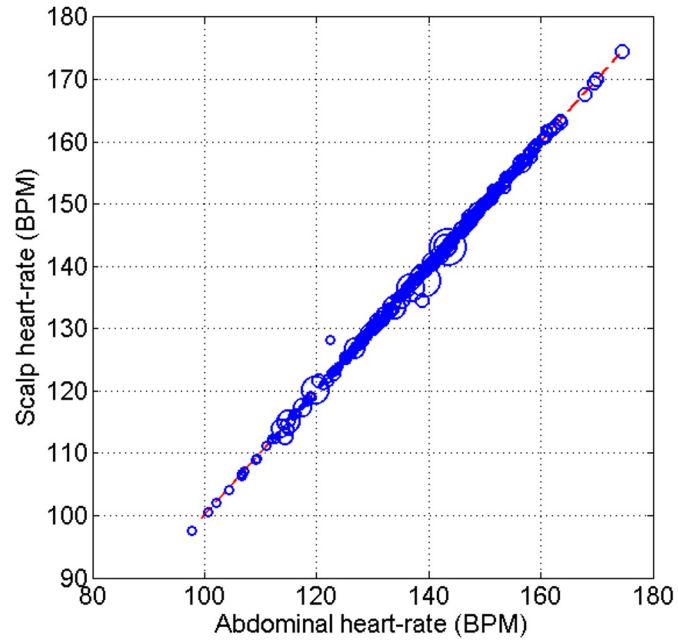
A deflation procedure for fetal ECG extraction

Example 2: After 5th iteration (maternal ECG fully removed)



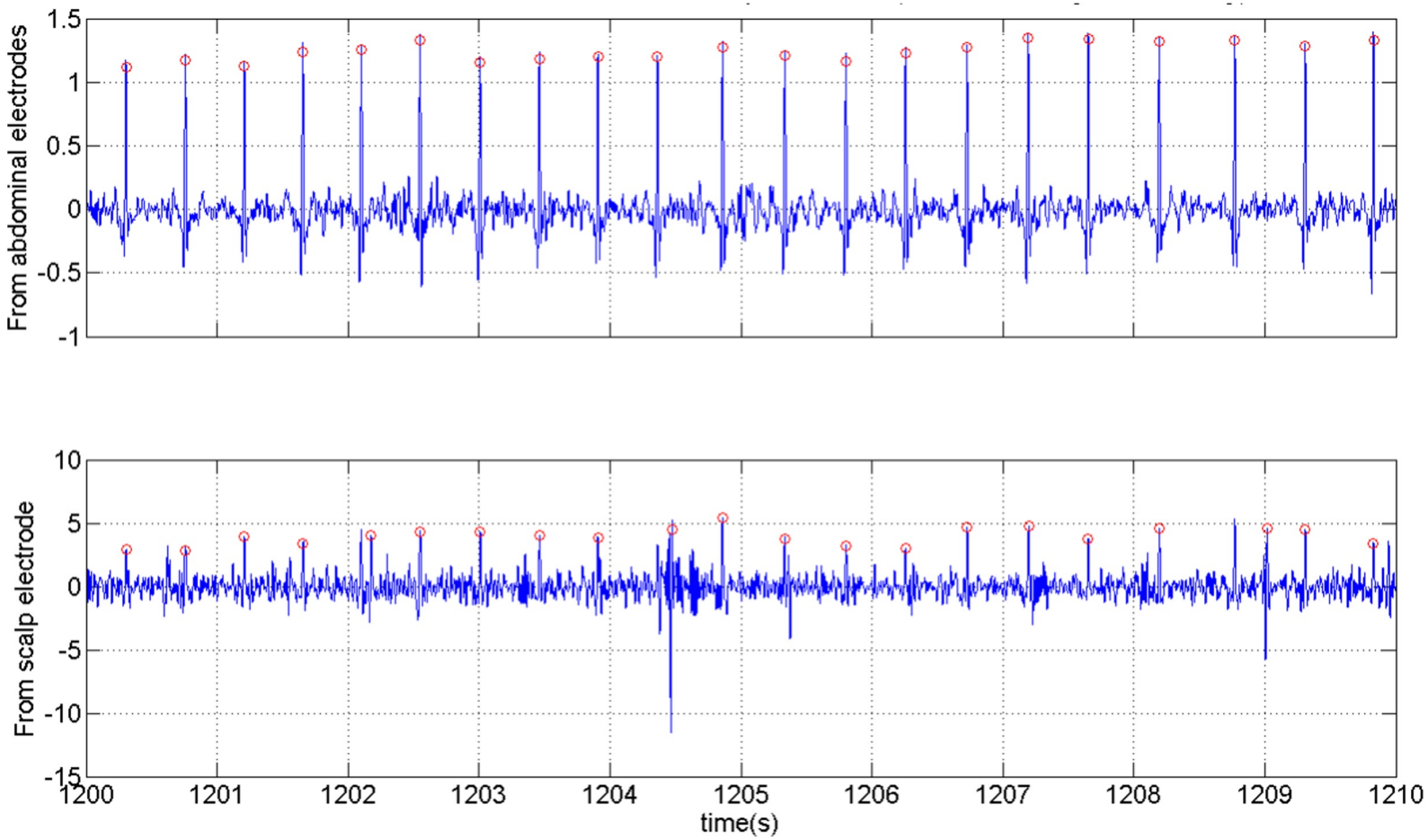
Maternal abdominal vs. fetal scalp lead ECG





Maternal abdominal vs. fetal scalp lead ECG

Example 2: The abdominal results may even be better than the scalp lead results in some cases

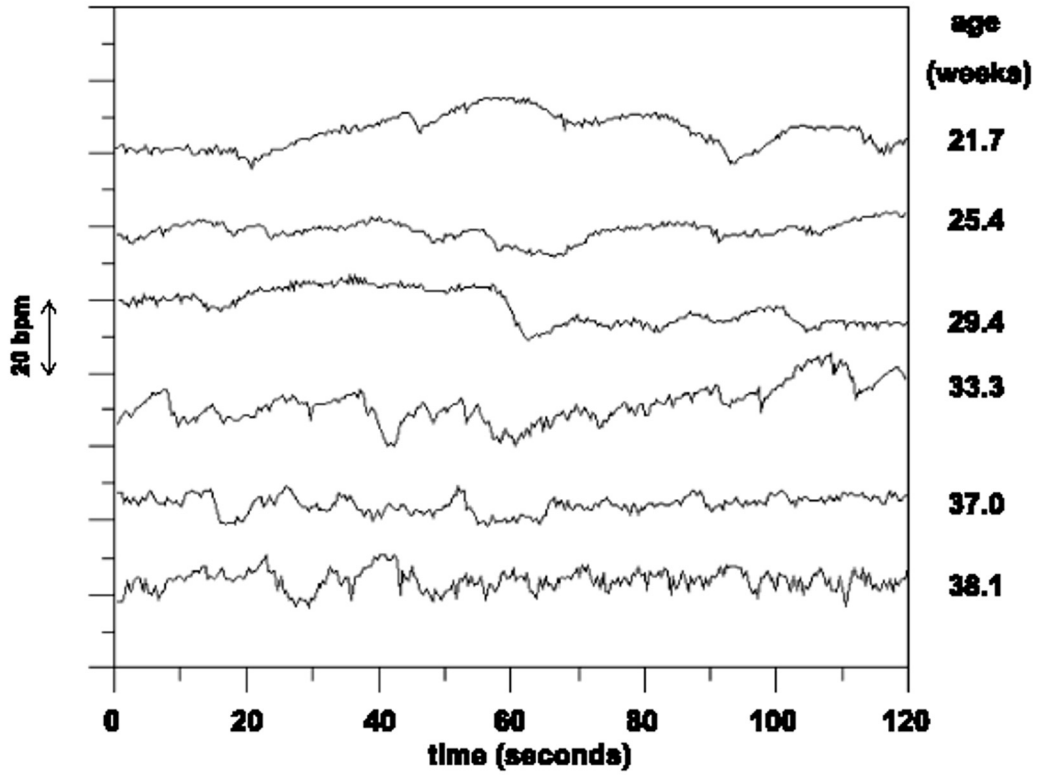


Clinical parameter extraction from the fetal ECG

- Fetal heart rate time-series
- Fetal ECG for twins
- Morphological parameters: QRS width, QT-interval, ST-segment, etc.
- Fetal position
- Fetal activity
- Uterine contractions

Evolution of fetal cardiac rhythms throughout pregnancy

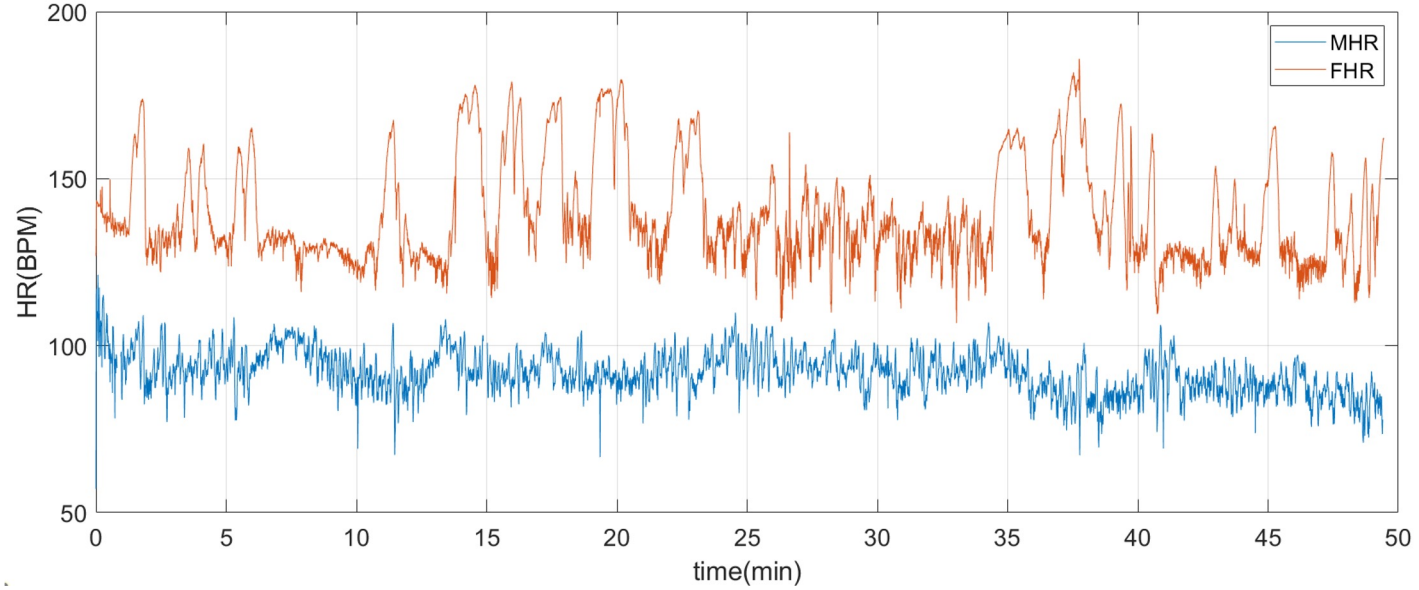
- The heart rate rhythm becomes more complex with fetal gestation age → can be used as an indicator of fetal brain and neural development

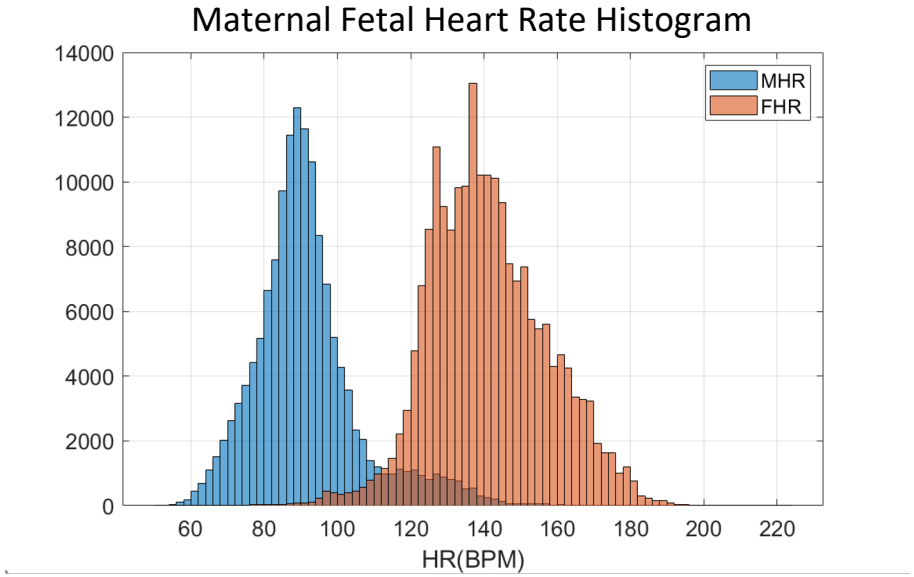


Ref: R. T. Wakai, Assessment of fetal neurodevelopment via fetal magnetocardiography. Exp Neurol, vol. 190 Suppl 1, pp. S65-S71, Nov 2004.

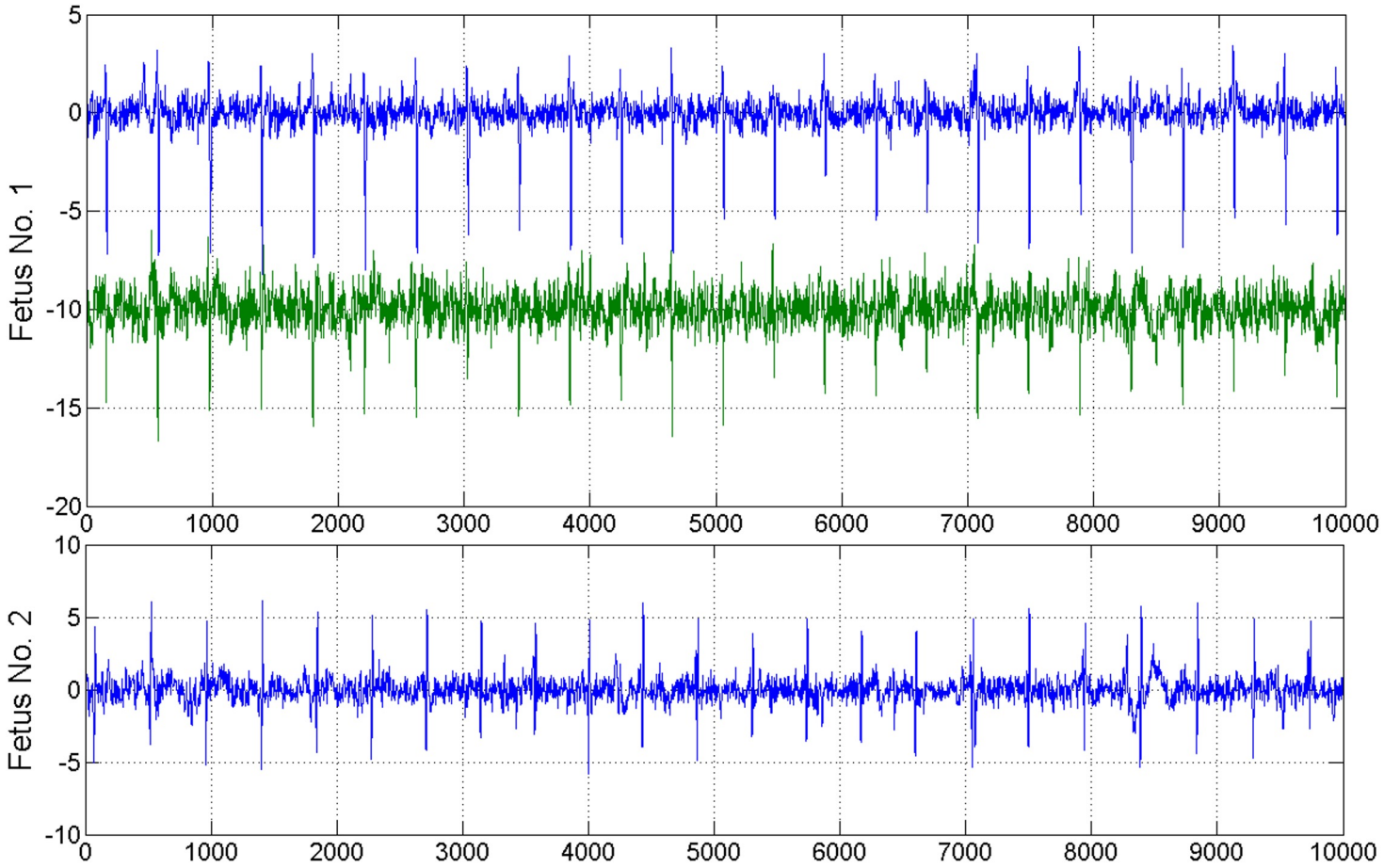
Maternal and fetal heart rate tracking

- Fetal heart-rate acceleration/deceleration





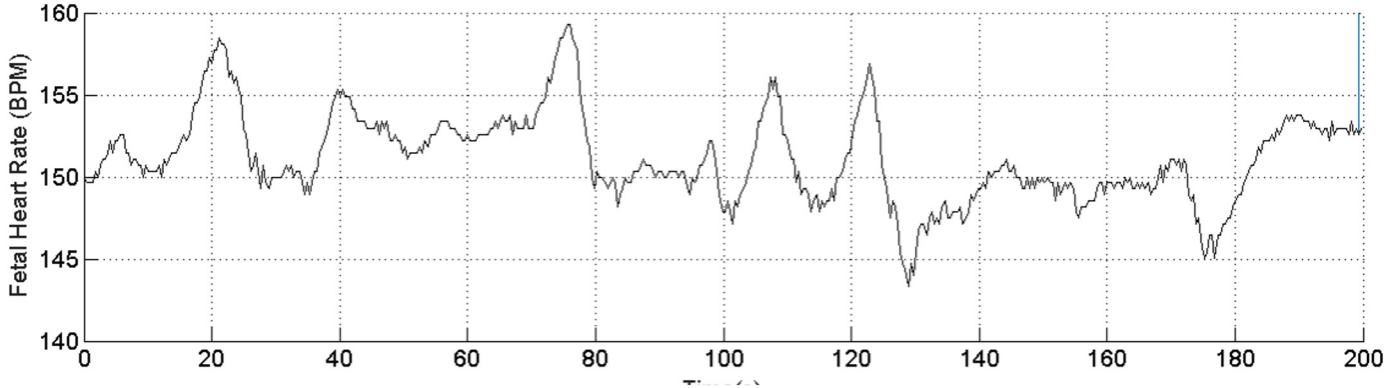
Fetal ECG/MCG monitoring for twins



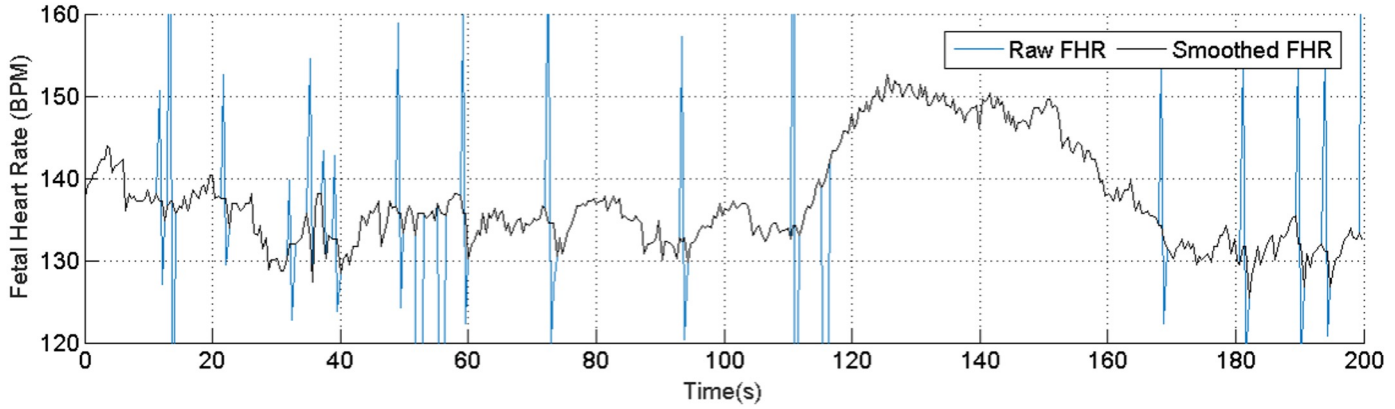
Ref: Sameni, R. (2008). *Extraction of fetal cardiac signals from an array of maternal abdominal recordings* Doctoral dissertation, Institut National Polytechnique de Grenoble-INPG; Sharif University of Technology.

Heart rate traces of twins

Fetus 1



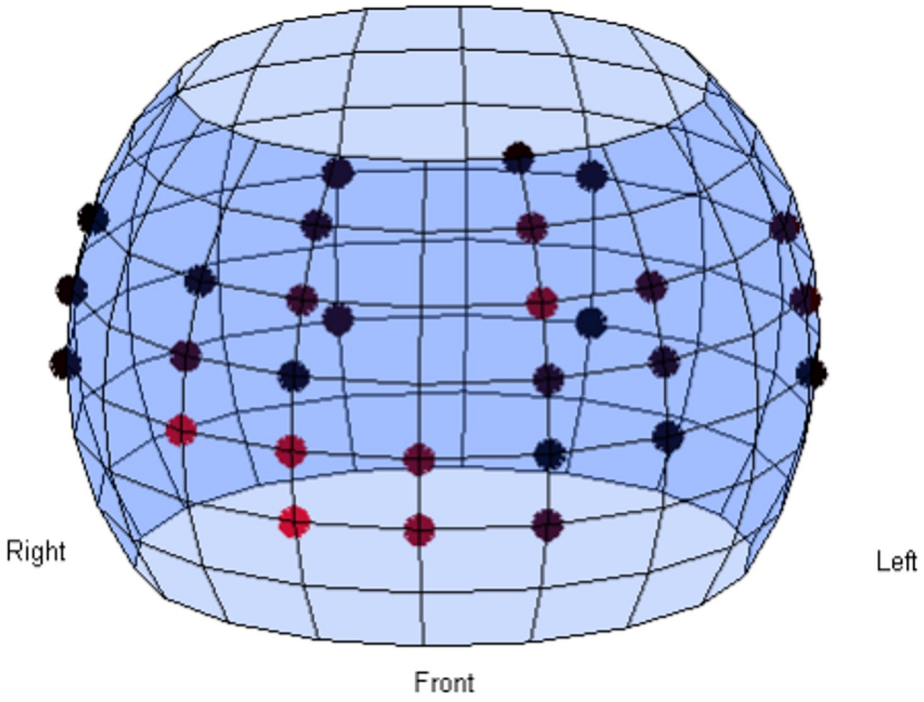
Fetus 2

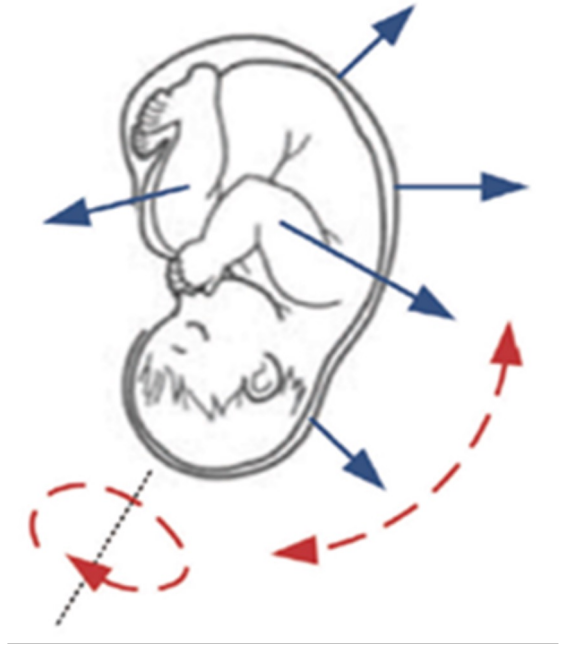


Ref: H. Biglari and R. Sameni, "Fetal motion estimation from noninvasive cardiac signal recordings," *Physiological Measurement*, vol. 37, no. 11, pp. 2003-2023, November 2016.

Fetal position and motion tracking

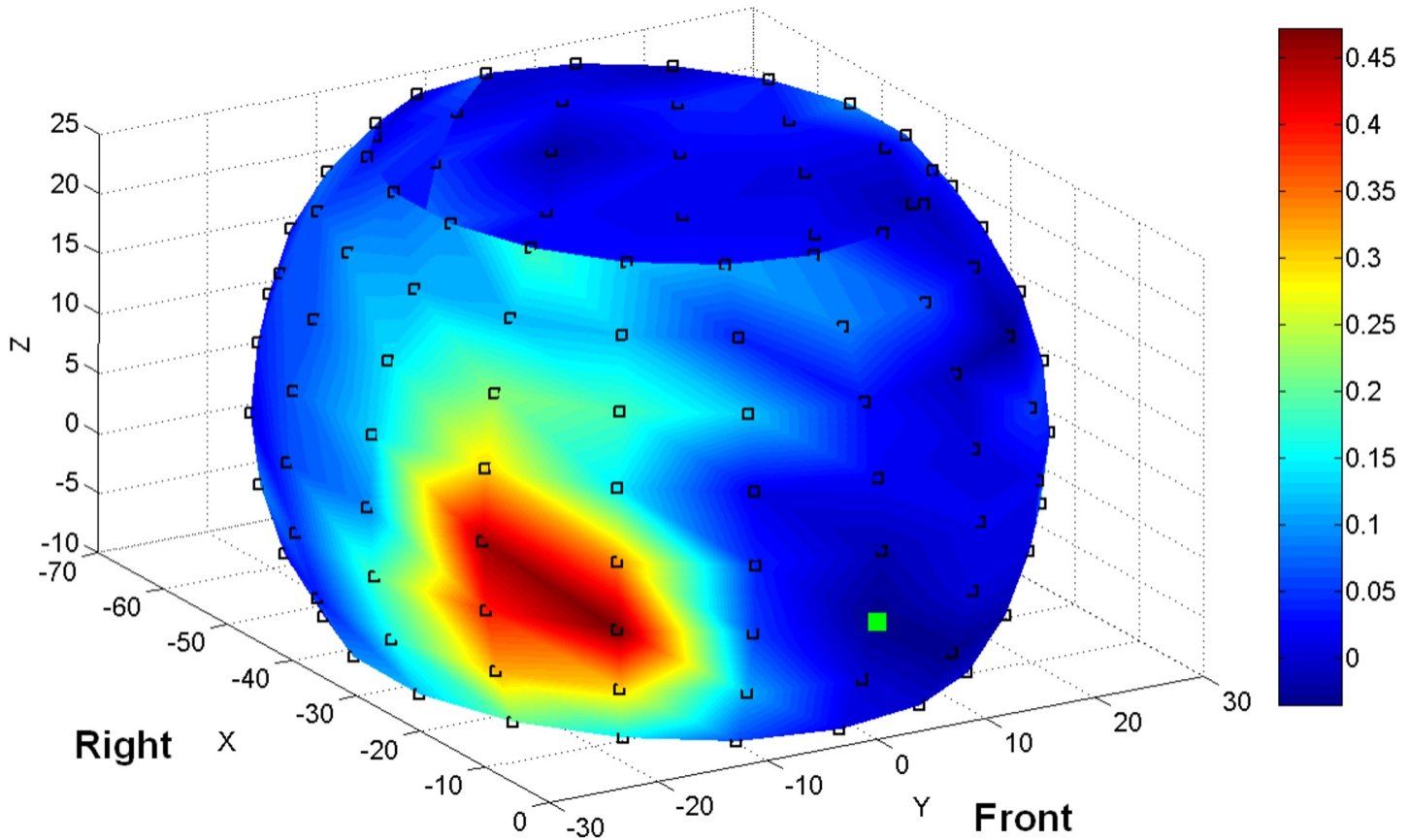
How? By mapping the fetal ECG back to the abdominal lead space, the energy distribution of the fetal ECG indicates the fetal position





Fetal position and motion tracking

Example

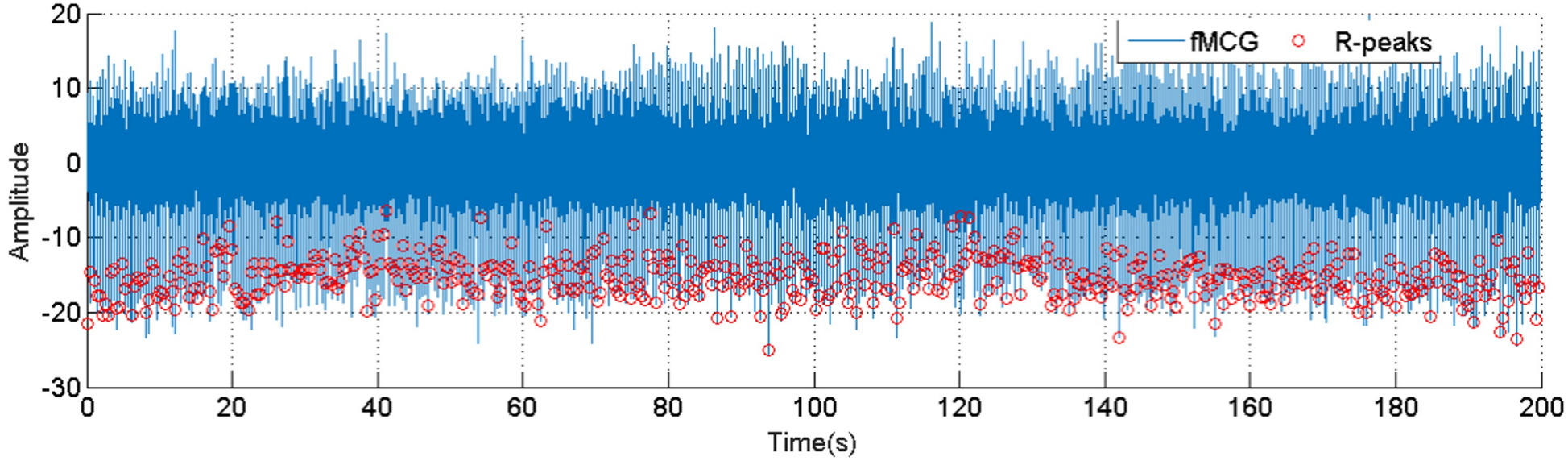


Motion detection and cardiotocography from fetal ECG

How? Tracking short-term variations in the fetal ECG amplitude

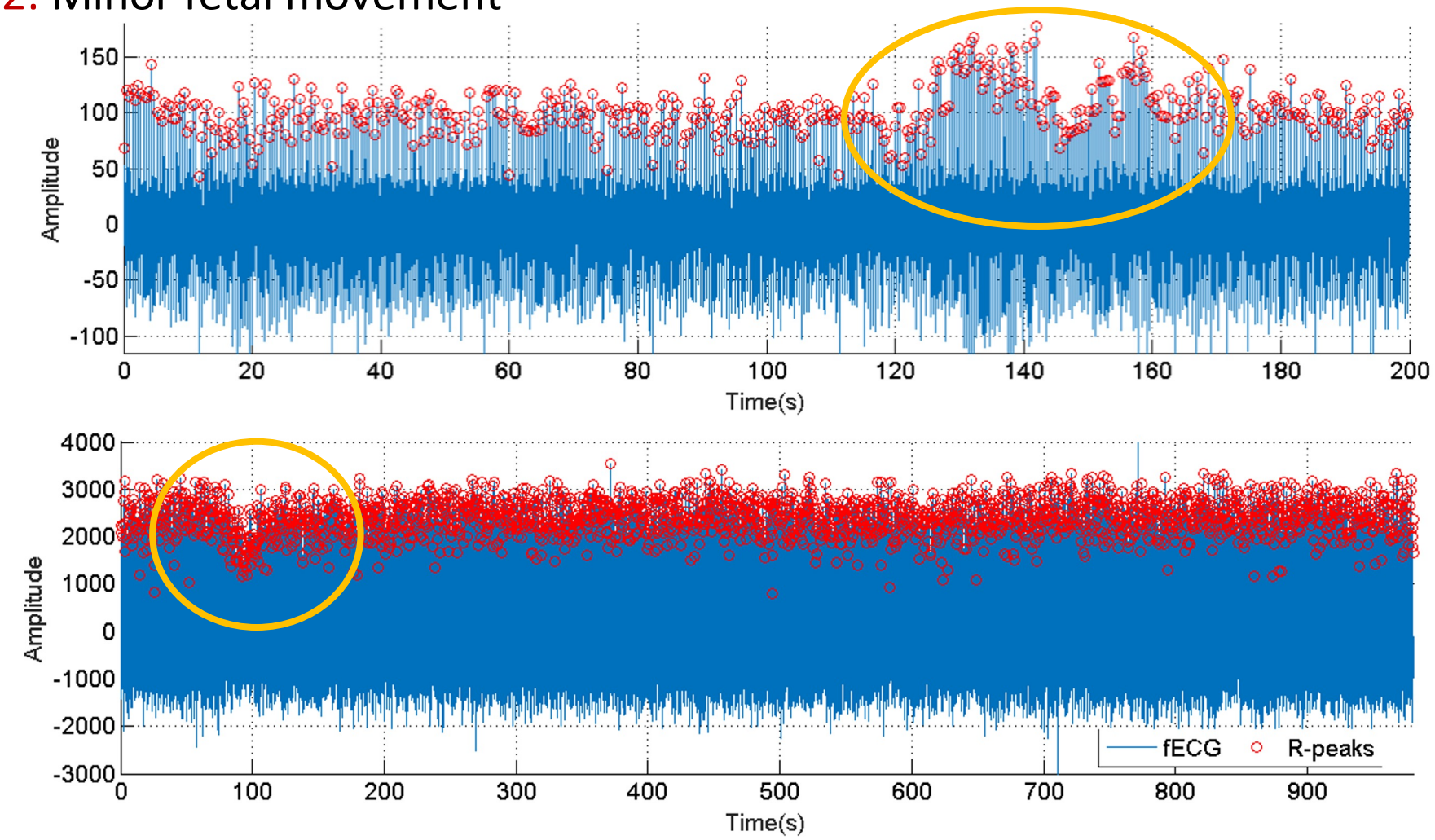
Motion detection and cardiotocography from fetal ECG

Example 1: No significant fetal motion observed



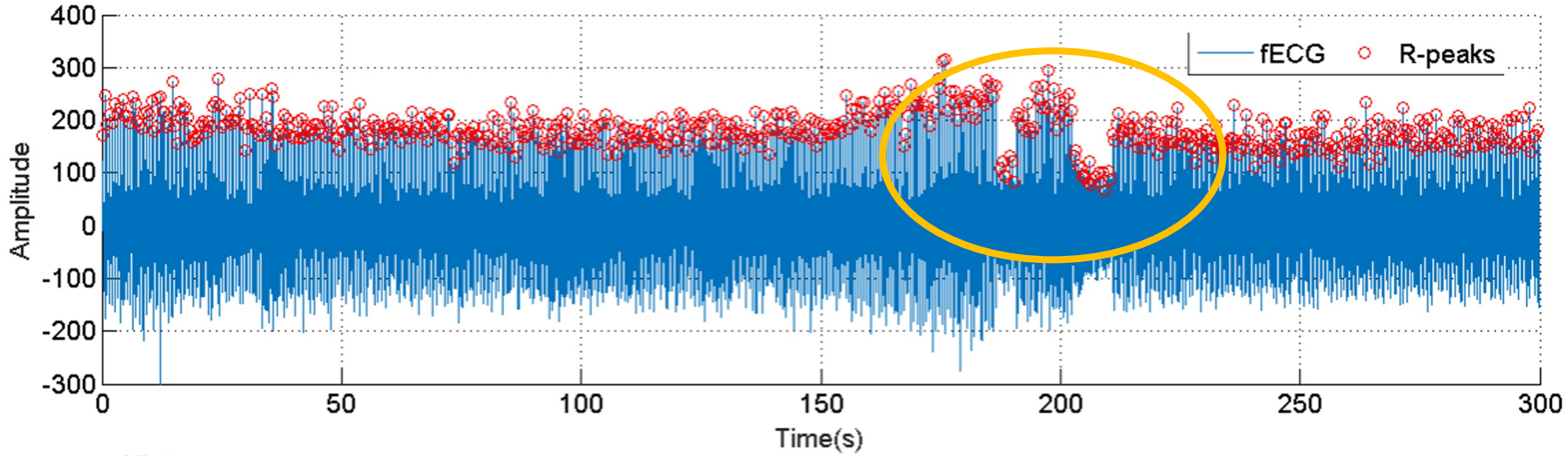
Motion detection and cardiotocography from fetal ECG

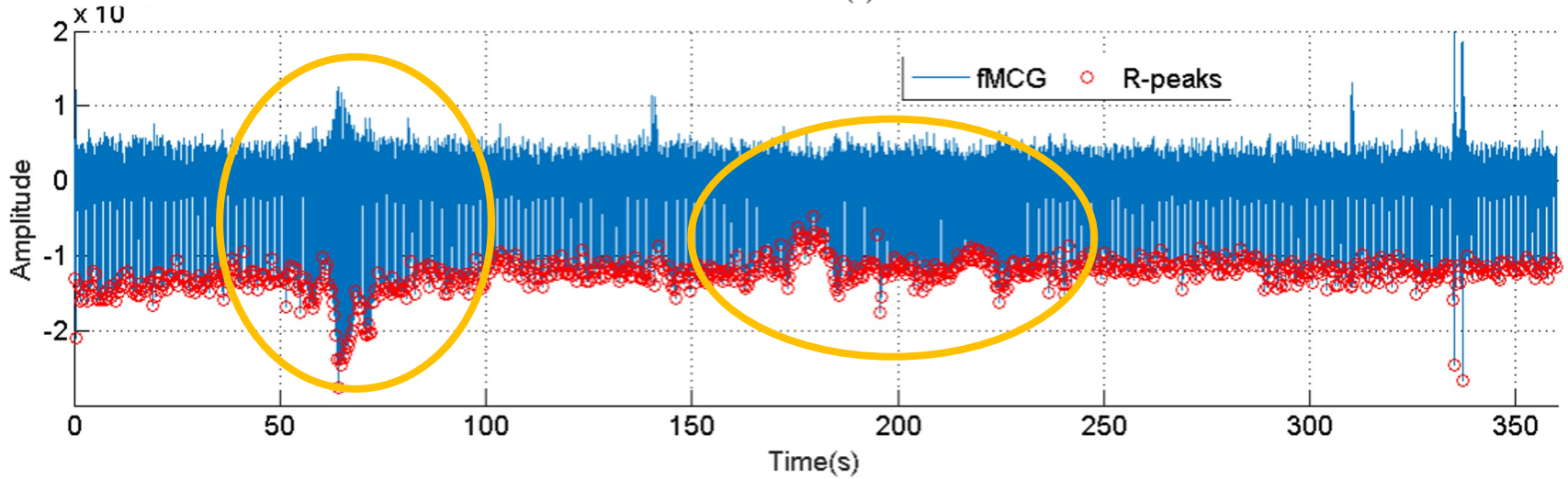
Example 2: Minor fetal movement



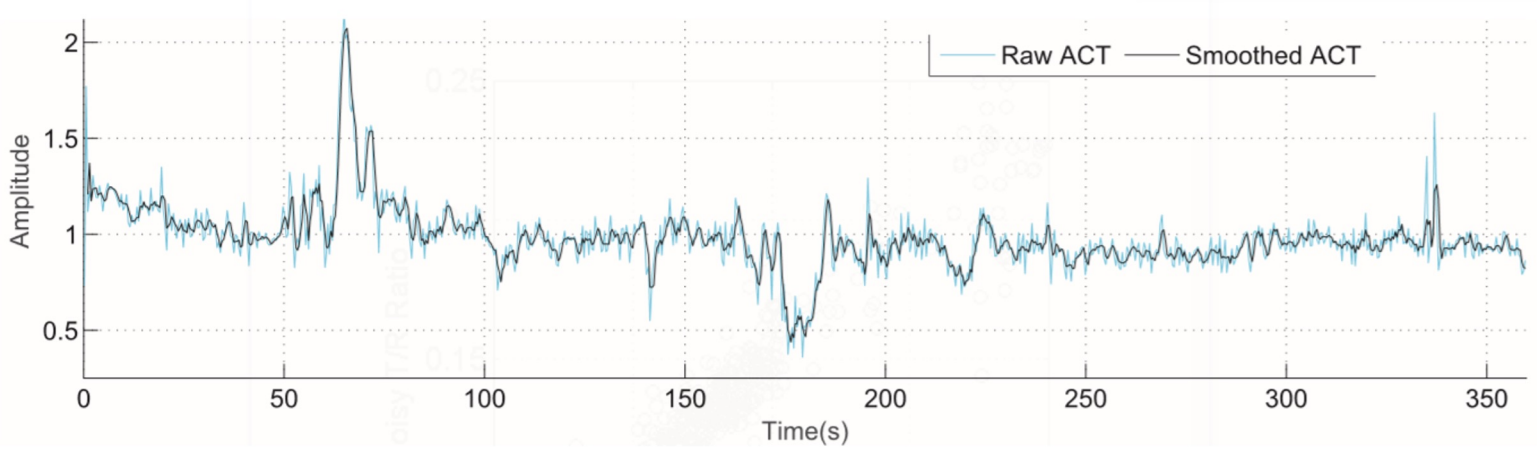
Motion detection and cardiotocography from fetal ECG

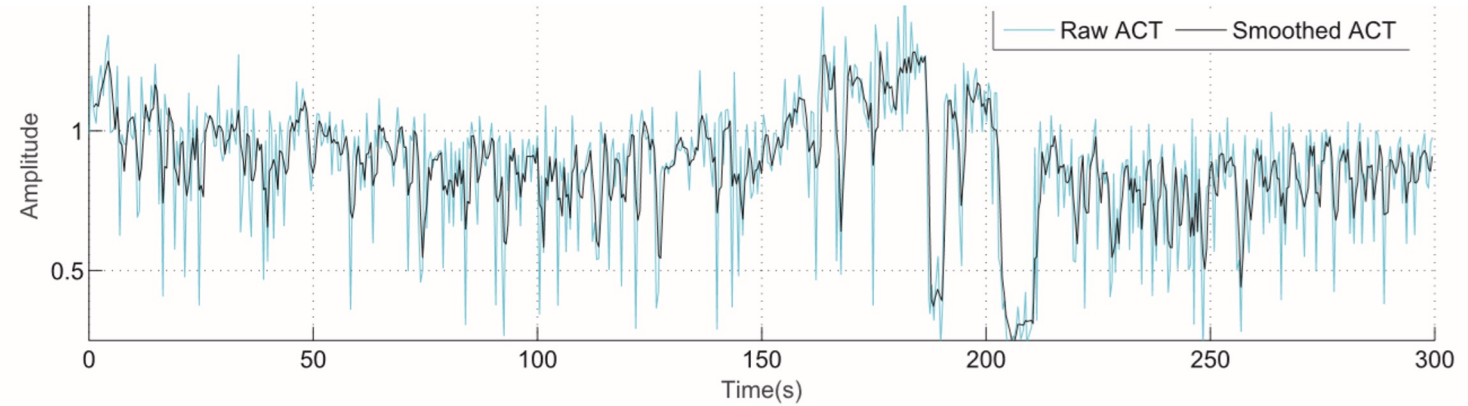
Example 3: Significant fetal movement





Fetal rotation tracking from fetal ECG



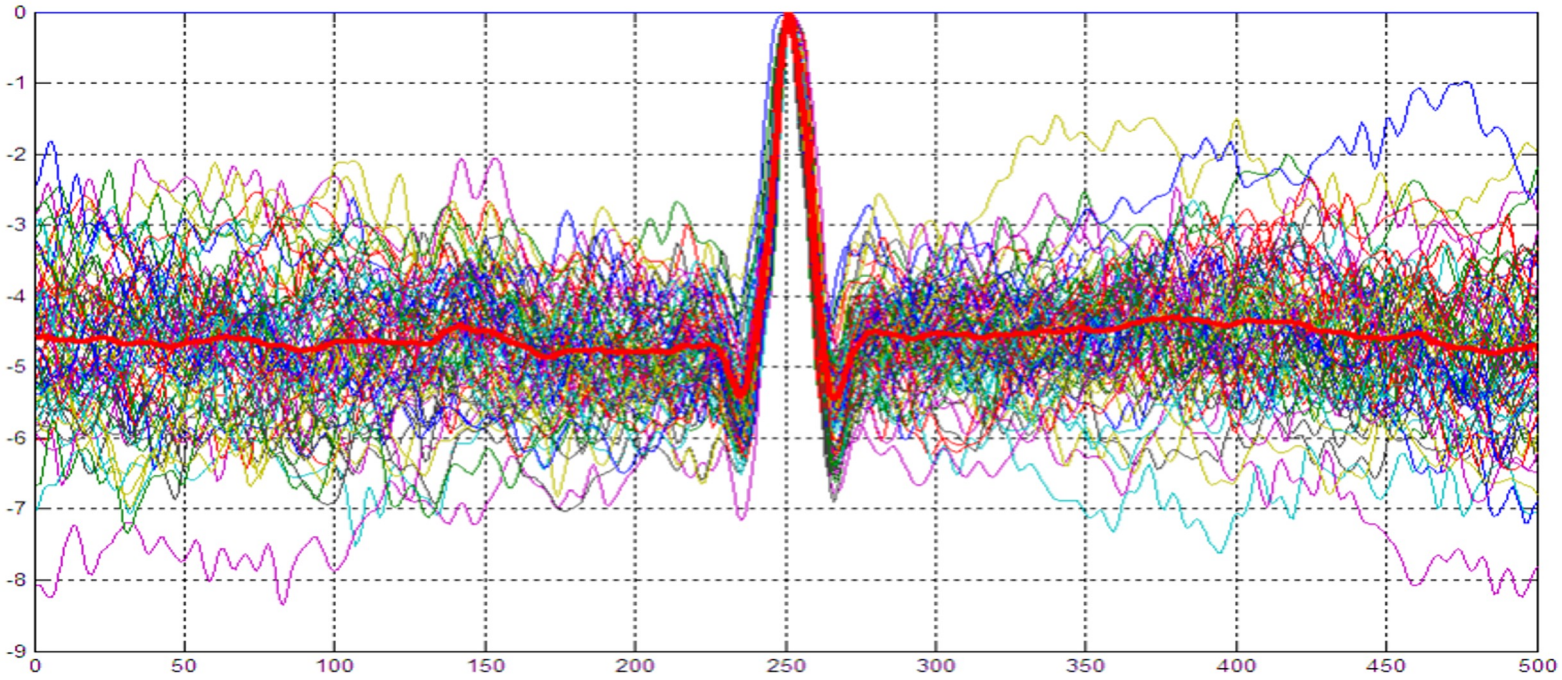


How? *Variations in the fetal ECG morphology across a session indicate fetal movement and rotation*

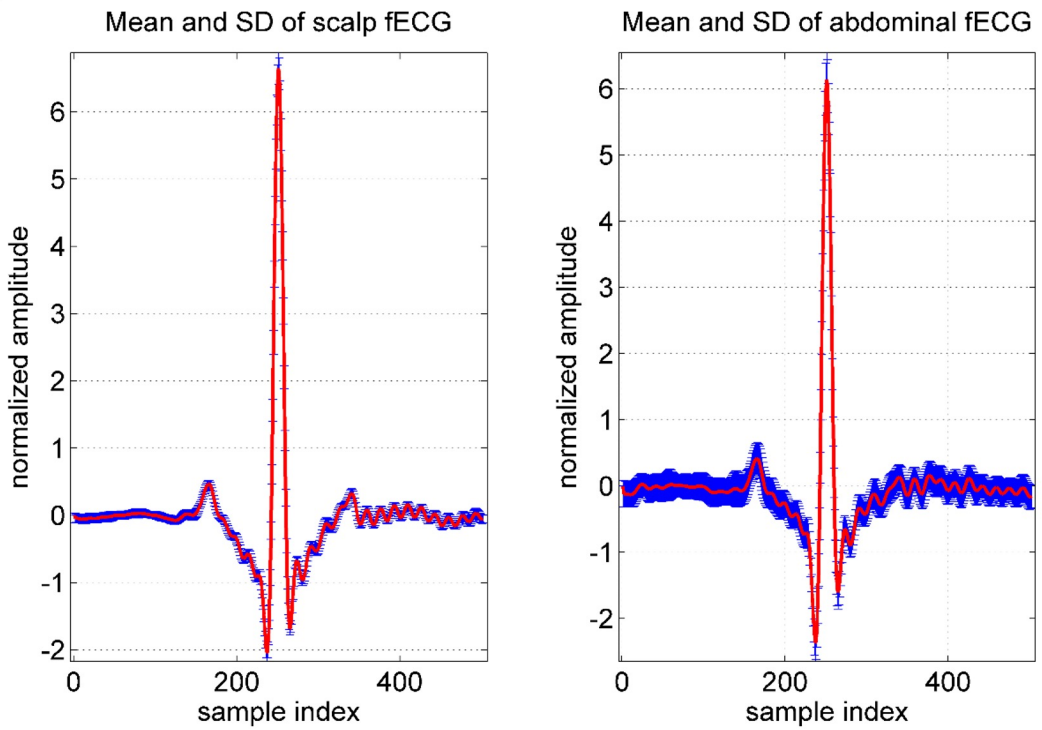
Ref: H. Biglari and R. Sameni, "Fetal motion estimation from noninvasive cardiac signal recordings," *Physiological Measurement*, vol. 37, no. 11, pp. 2003-2023, November 2016.

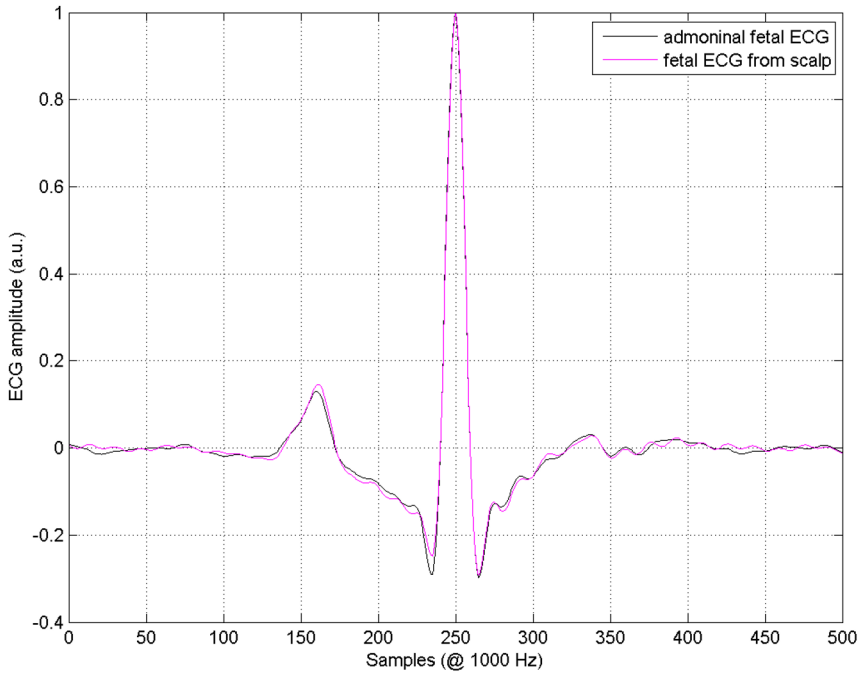
Fetal Morphologic Parameters

- Average beat morphologies are obtained by beat alignment and (weighted) averaging.
- The beat averaging can either be simple or by normalizing the RR-intervals, using the ECG phase signal $\theta(t)$ introduced before



Fetal ECG morphology

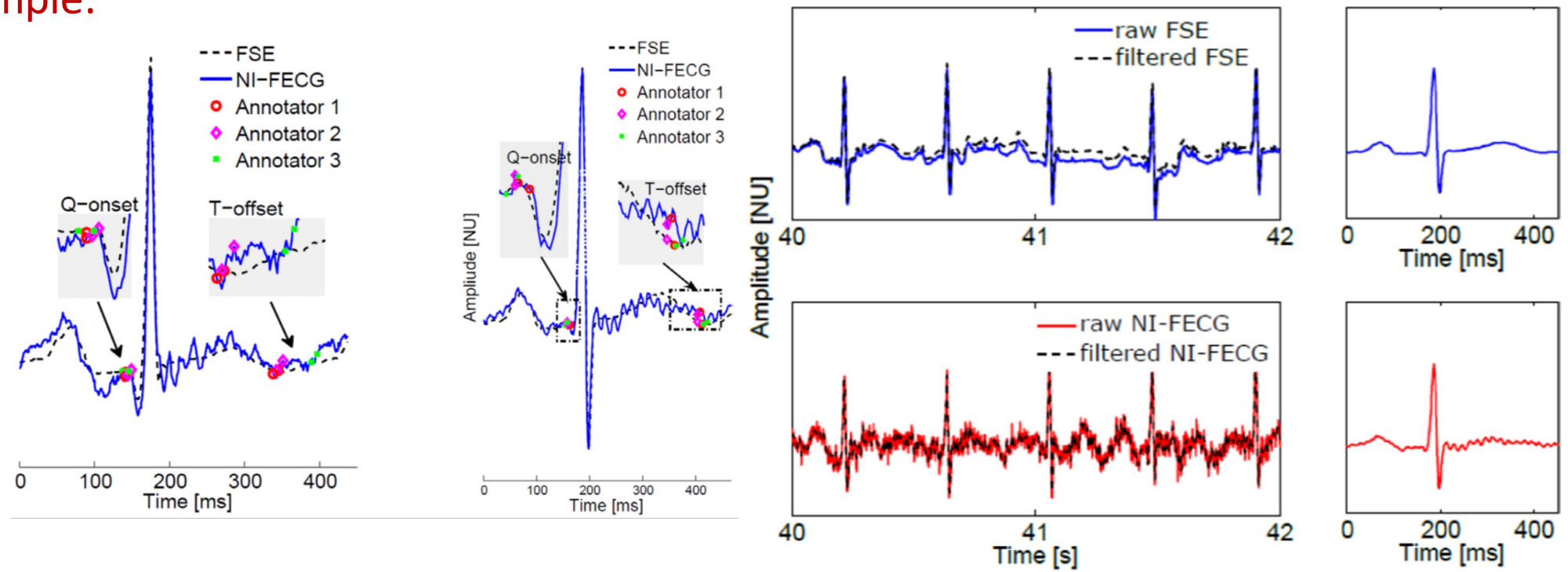




Note: *the fetal ECG morphology is not necessarily identical to the fetal scalp lead ECG, due to a different representation of the fetus*

Fetal QT Interval

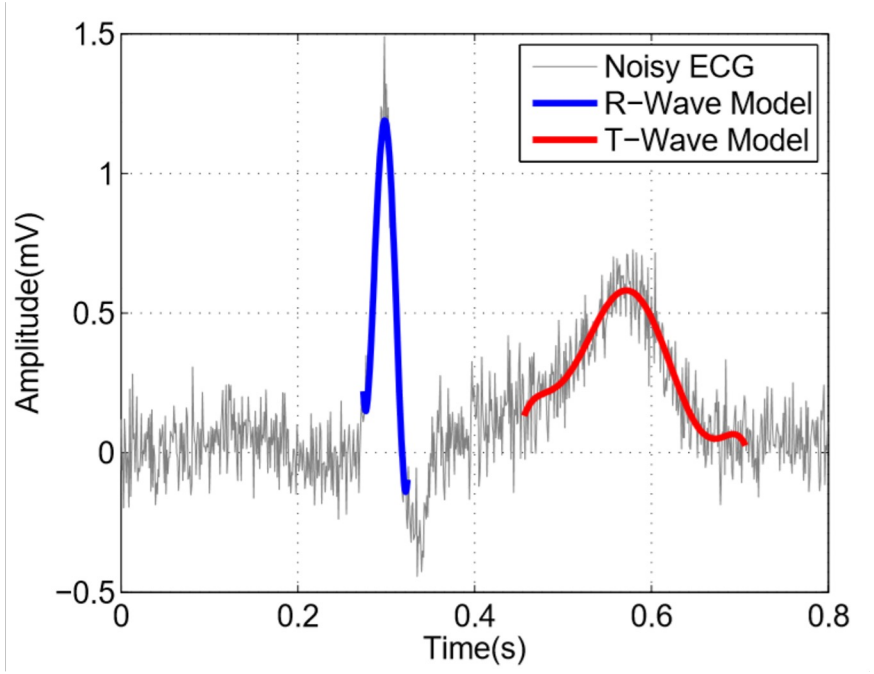
Example:

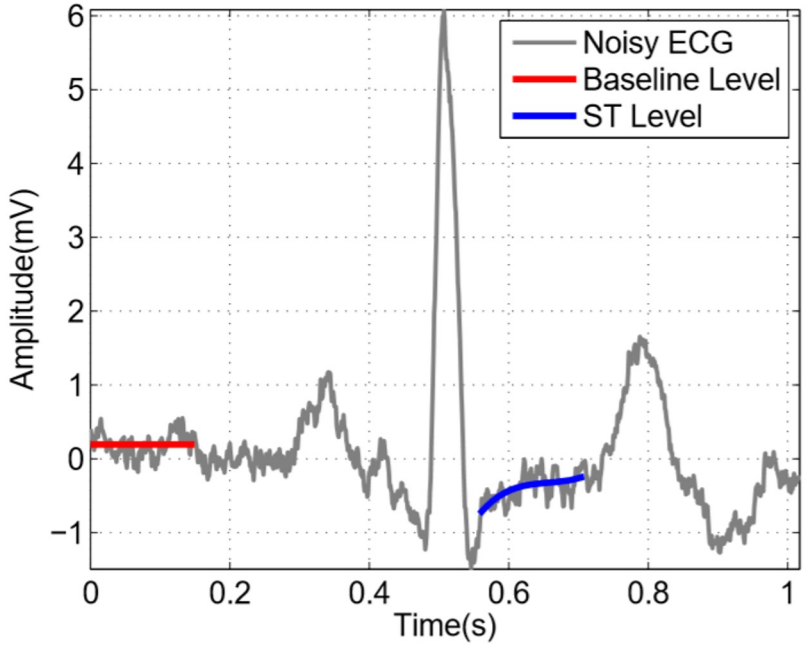


Ref: J. Behar, T. Zhu, J. Oster, A. Niksch, D. Y. Mah, T. Chun, J. Greenberg, C. Tanner, J. Harrop, R. Sameni, J. Ward, A. J. Wolfberg, and G. D. Clifford, "Evaluation of the fetal QT interval using non-invasive fetal ECG technology," *Physiological Measurement*, vol. 37, no. 9, pp. 1392-1403, September 2016.

Fetal ST-segment analysis

How? By fitting polynomial (or other) models over the ST and other fetal ECG segments



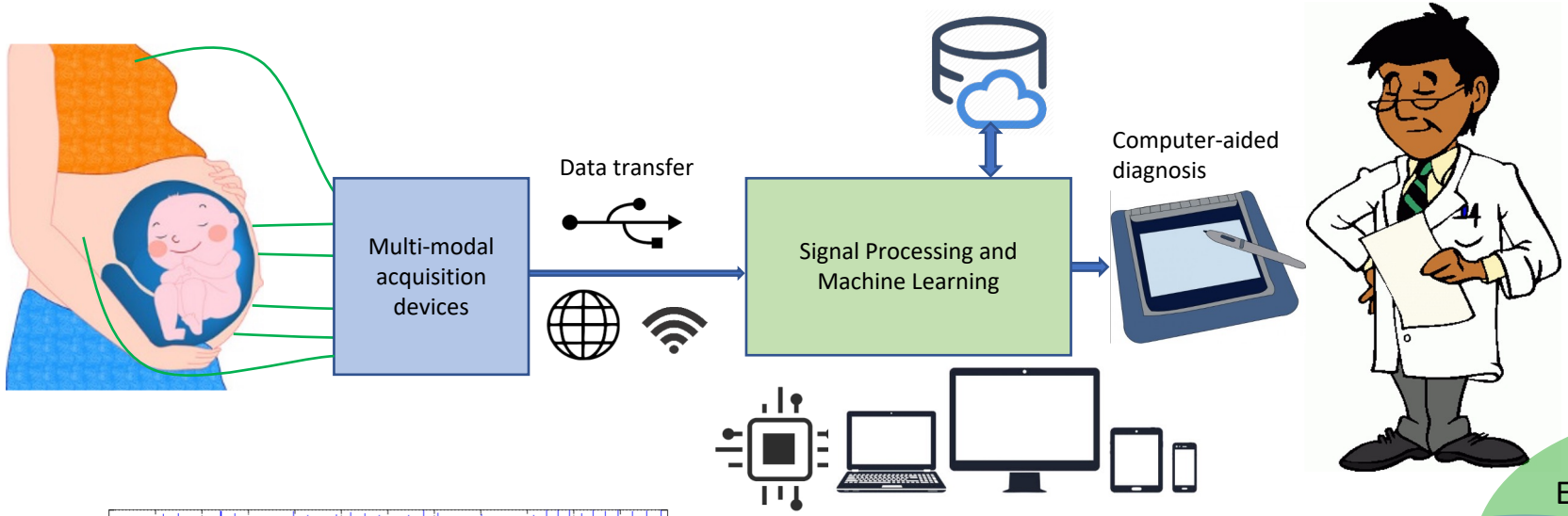


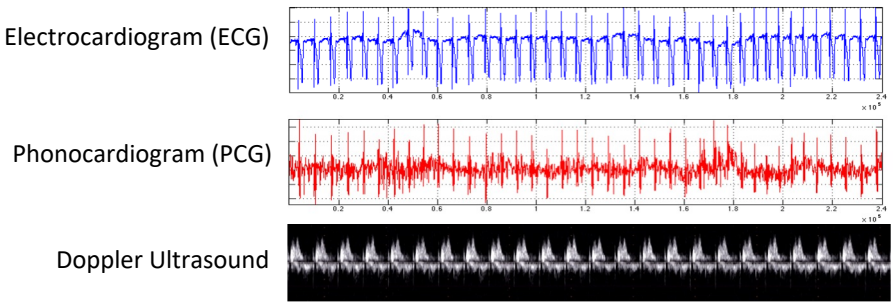
Ref: D. Fattahi, R. Sameni, Cramér-Rao Lower Bounds of Model-Based Electrocardiogram Parameter Estimation, IEEE Transactions on Signal Processing, vol 70, 3181 - 3192, 2022, DOI: https://doi.org/10.1109/TSP.2022.3182113

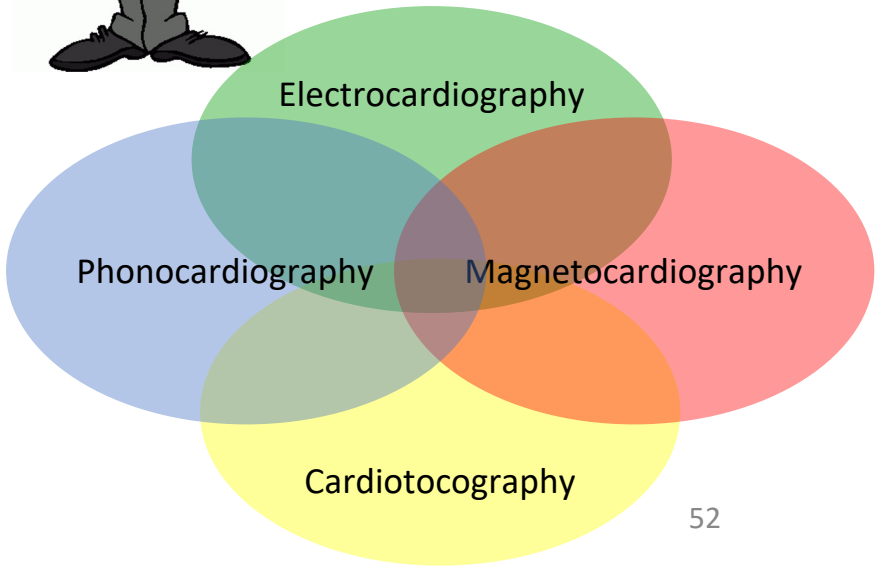
Future perspectives

Emerging technology: hyper-modal fetal monitors

Fusion of multiple modalities for fetal monitoring

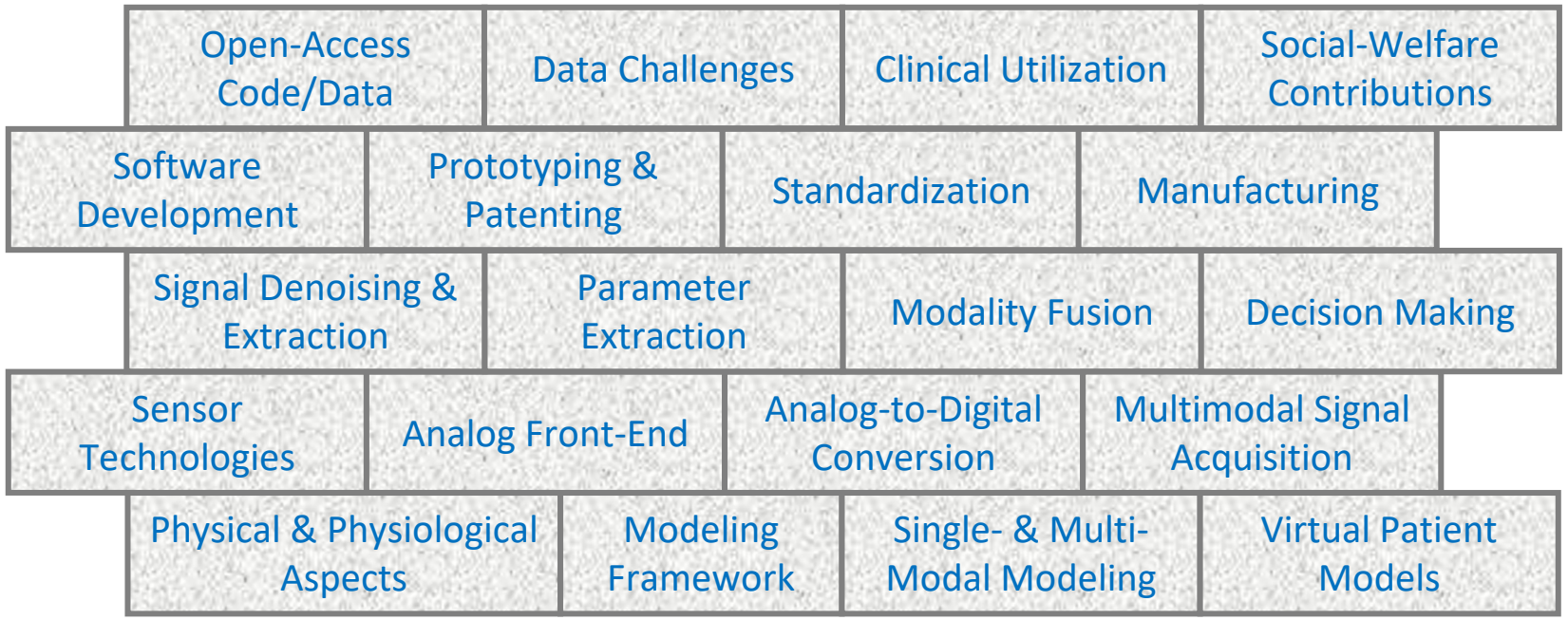






Future perspective

As with any other technologies, the technical aspects are only a small part of the problem



Thank you for your attention!

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