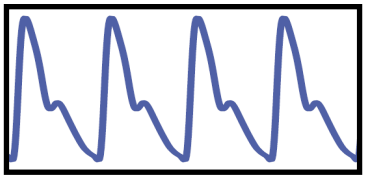
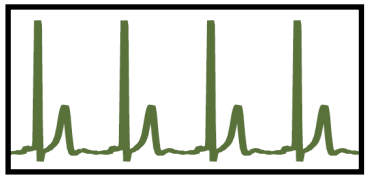
An assessment of algorithms to estimate respiratory rate from the electrocardiogram and photoplethysmogram

P. H. Charlton and T. Bonnici, L. Tarassenko, D. A. Clifton, R. Beale and P. J. Watkinson





DOI: 10.1088/0967-3334/37/4/610

Respiratory Rate

- The most sensitive marker of clinical deterioration
- Notoriously poorly recorded
  - Missing
  - Inaccurate
- Difficult to measure manually
- Thoracic bands uncomfortable

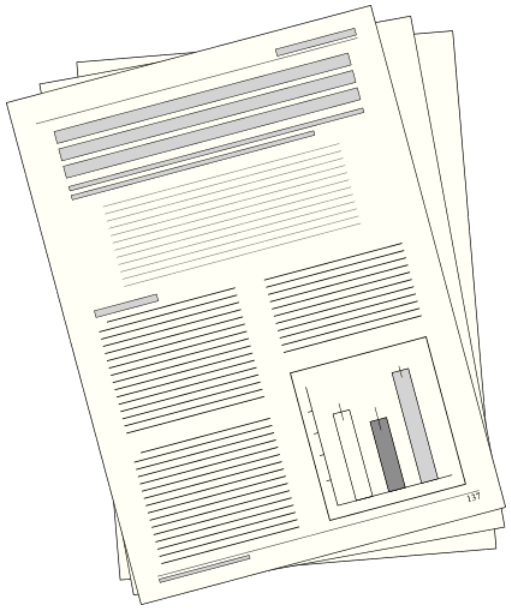
Literature

- Over 100 RR algorithms
- Not possible to compare algorithms using the published results
- Limitations:
  - No standard algorithm implementations for benchmarking
  - Atypical populations - ventilated subjects, children
  - Different statistical measures
  - No compensation for repeated measures

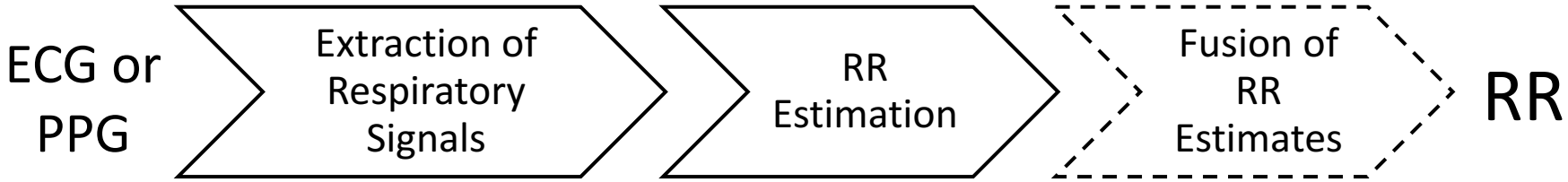
Aims

1. Identify which algorithm performs the best using appropriate statistical measures
2. Contextualise algorithm performance by comparing with the current non-invasive standard, impedance pneumography
3. Compare performance when using ECG or PPG
4. Provide a benchmark toolbox of algorithms and data for the benefit of other researchers

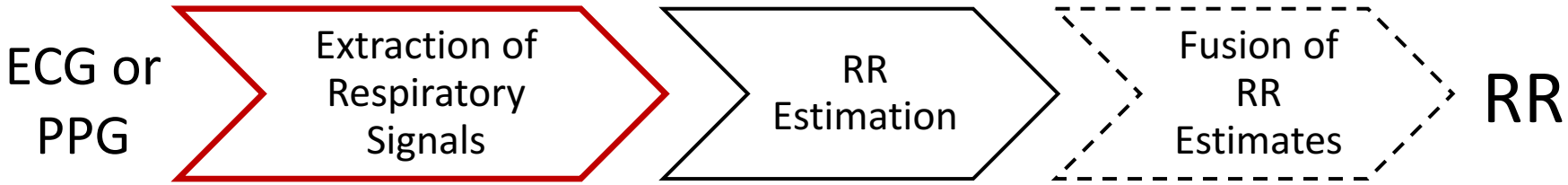
Prior Work

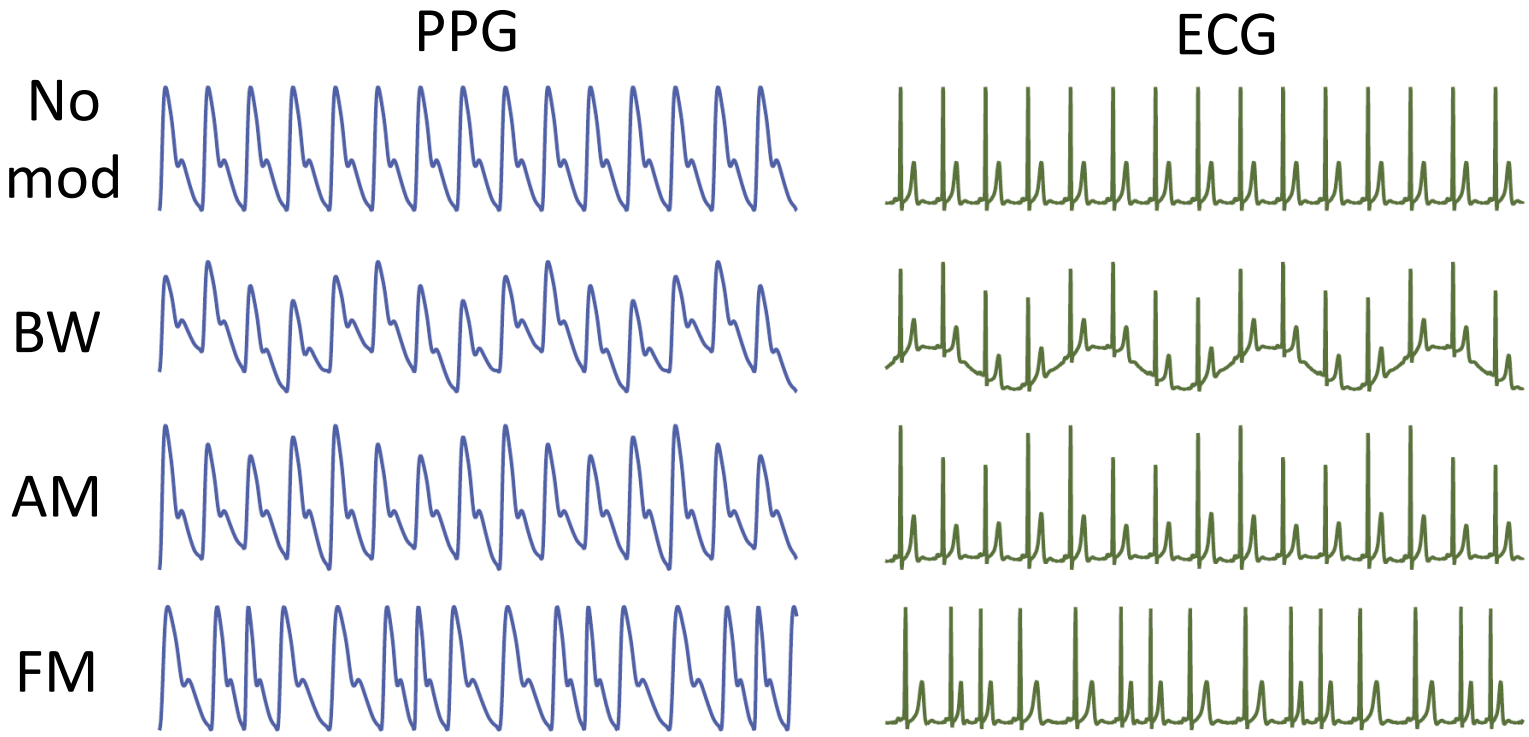


Structure of Algorithms

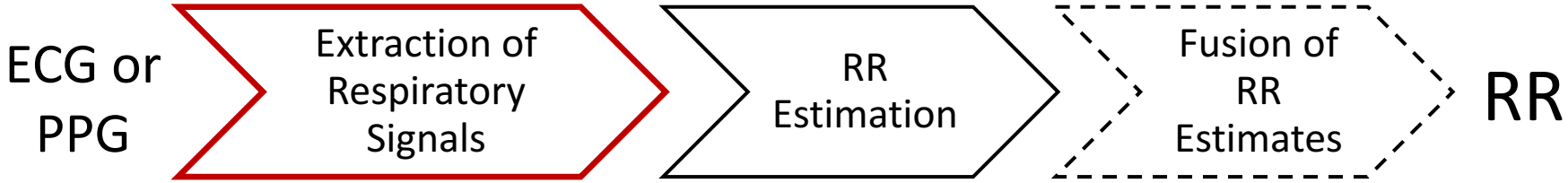


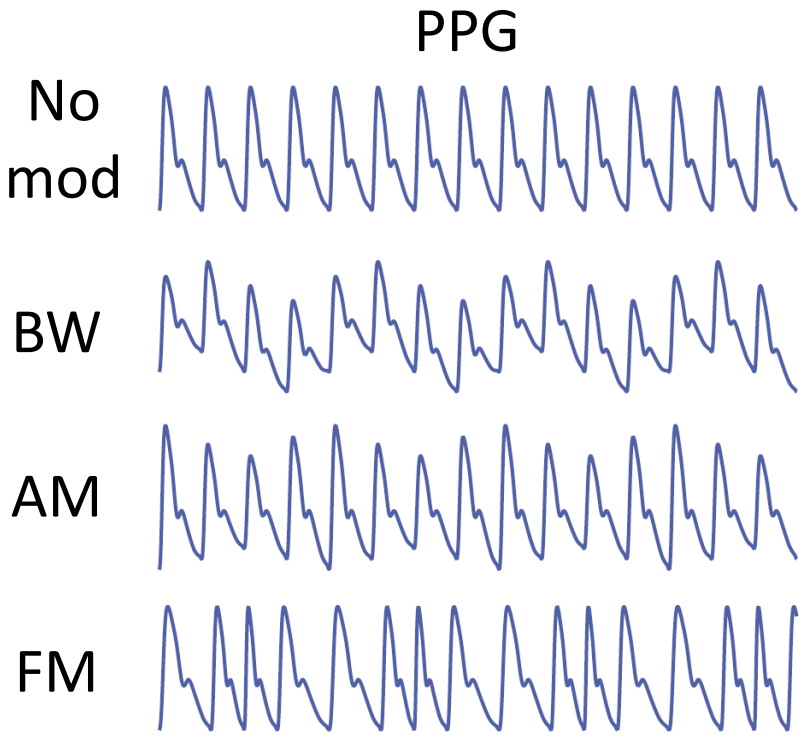
Structure of Algorithms



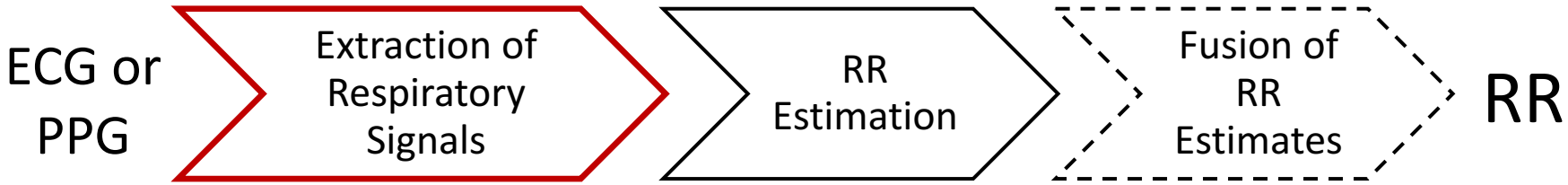


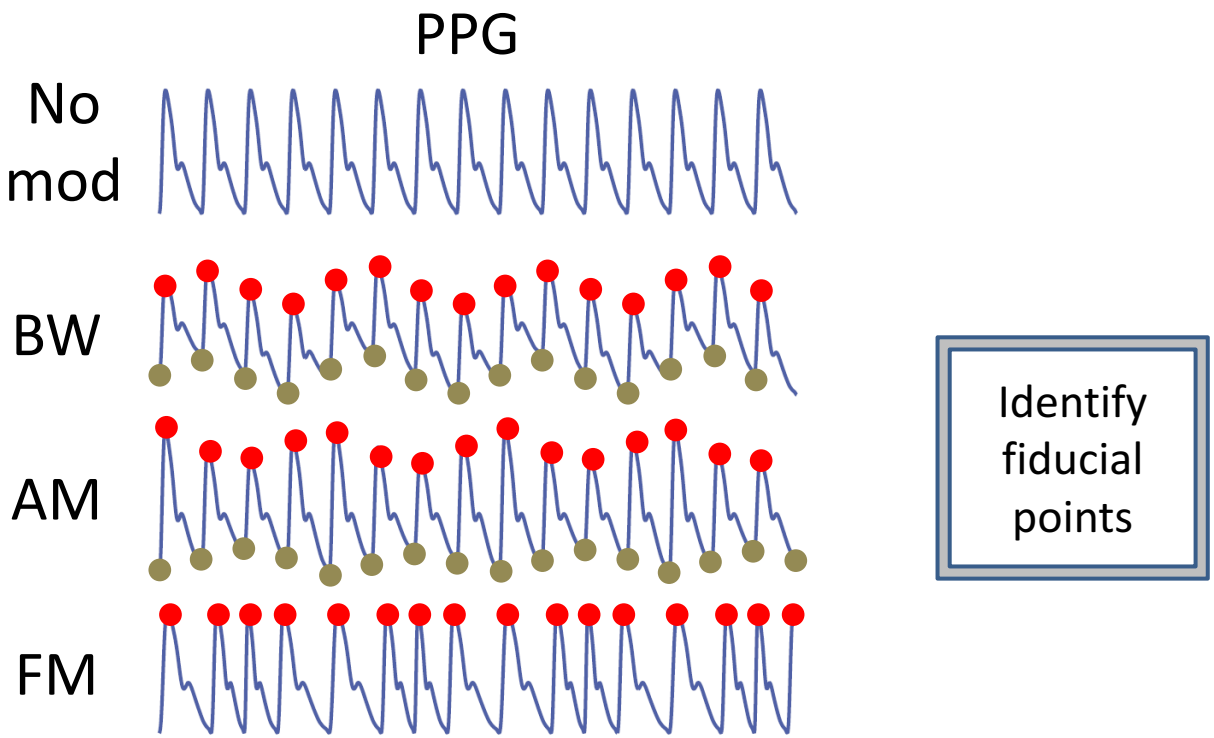
Structure of Algorithms



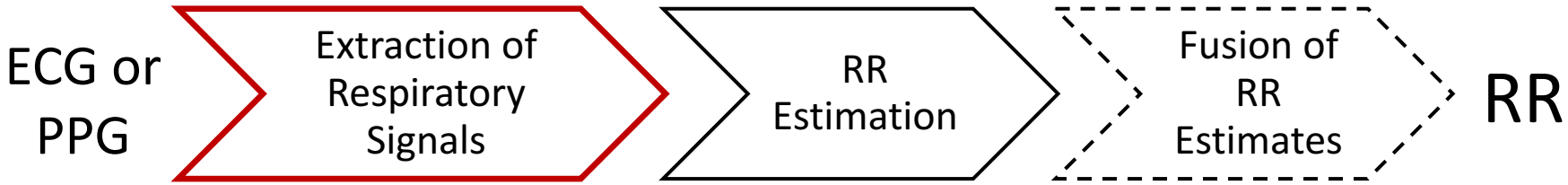


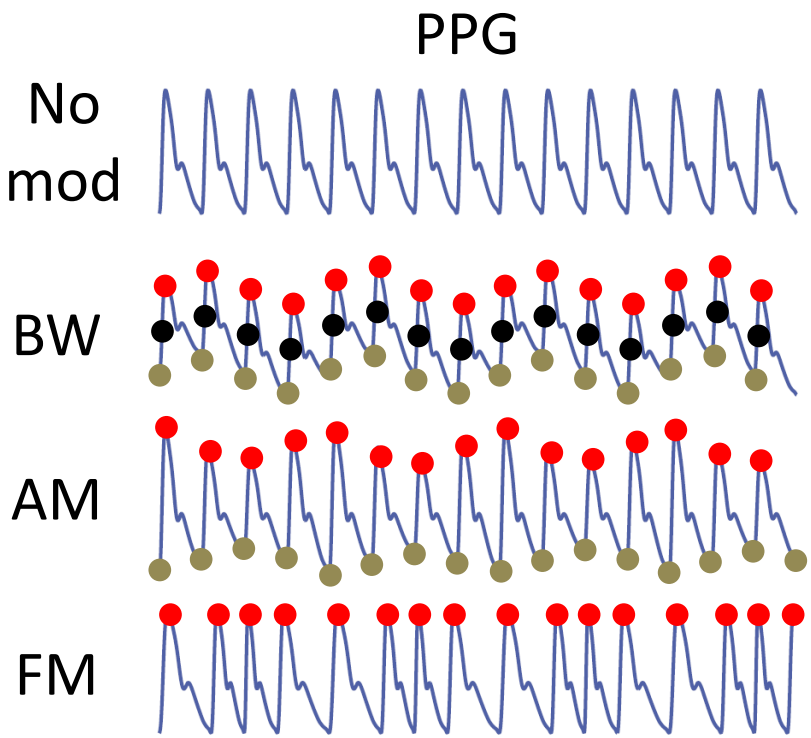
Structure of Algorithms





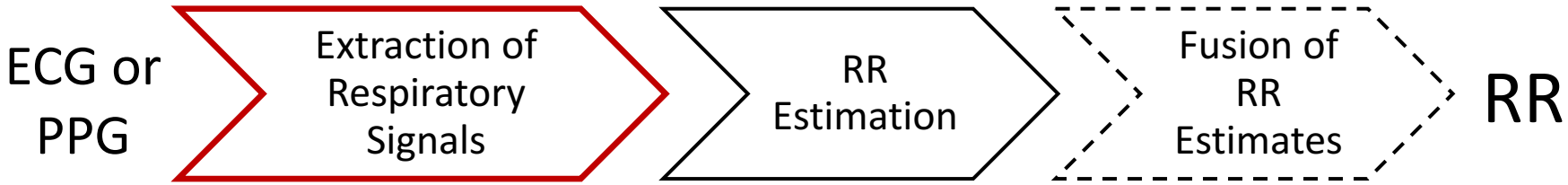
Structure of Algorithms

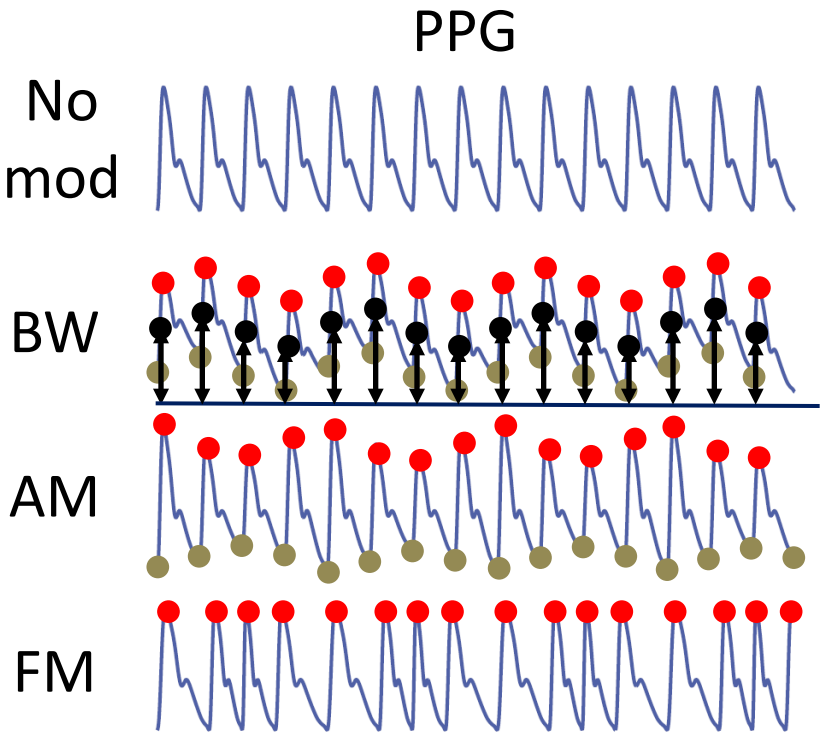




Find baseline

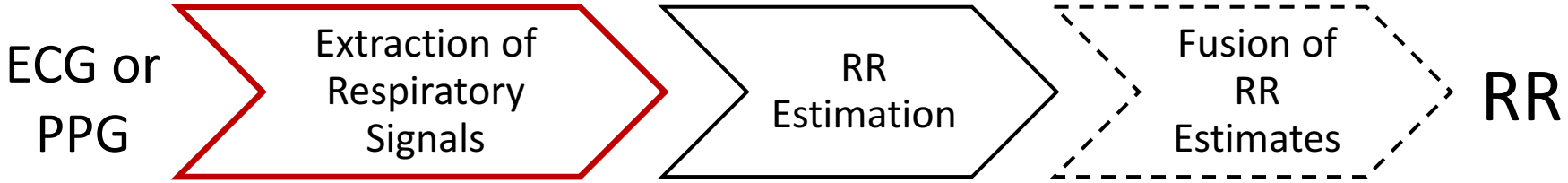
Structure of Algorithms

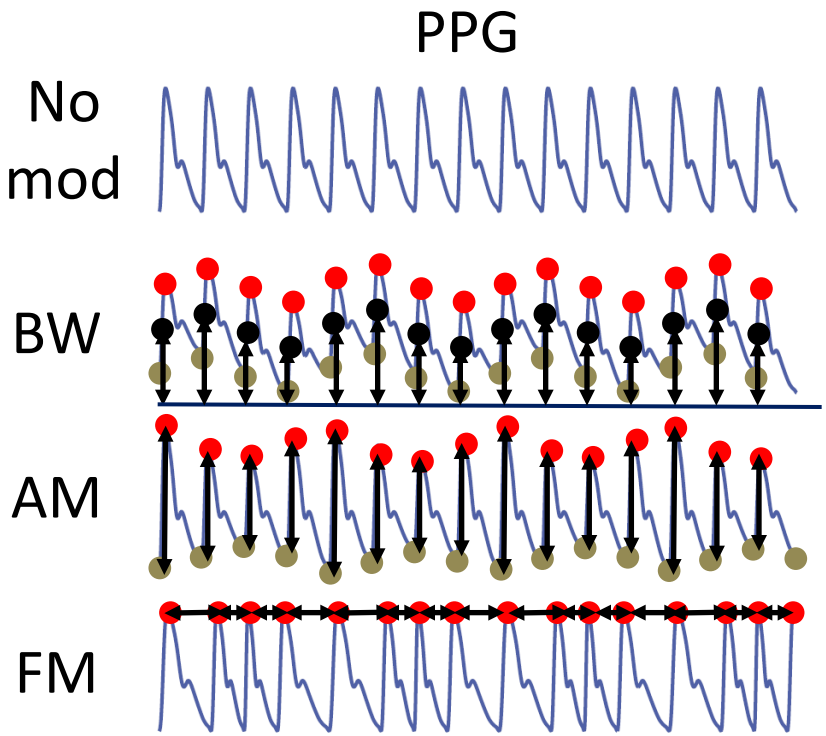




Find baseline

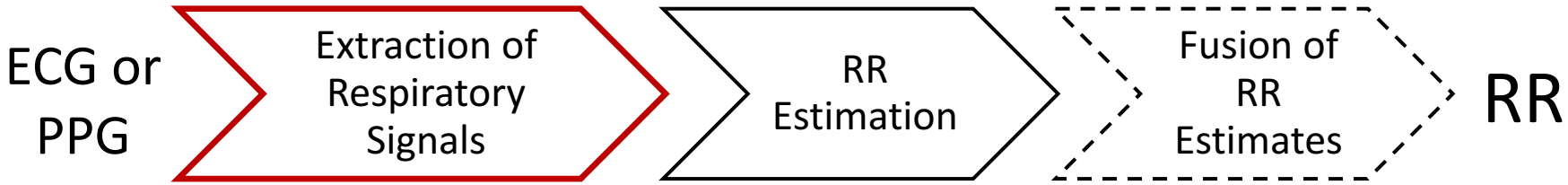
Structure of Algorithms

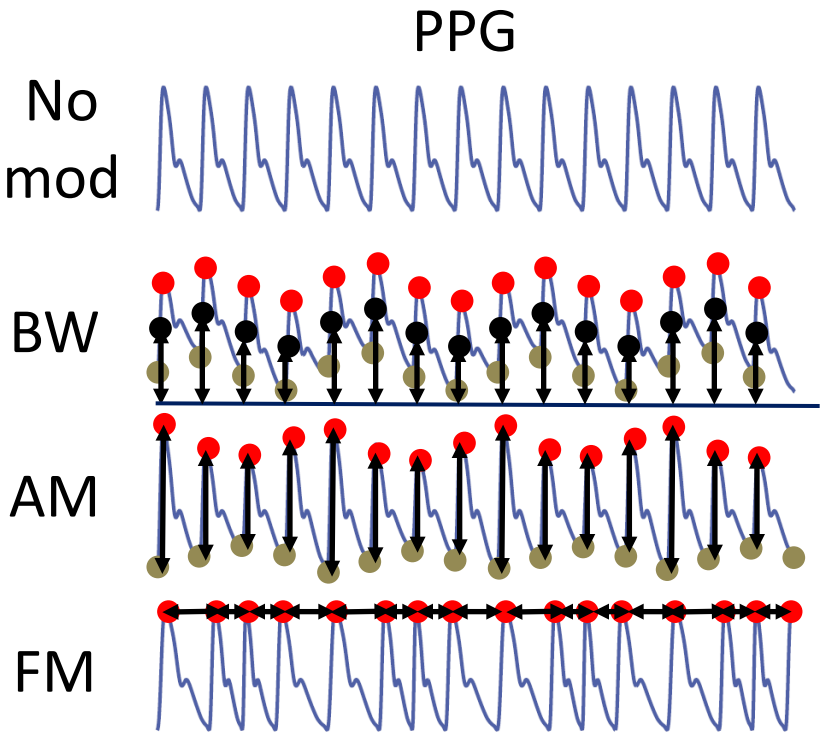


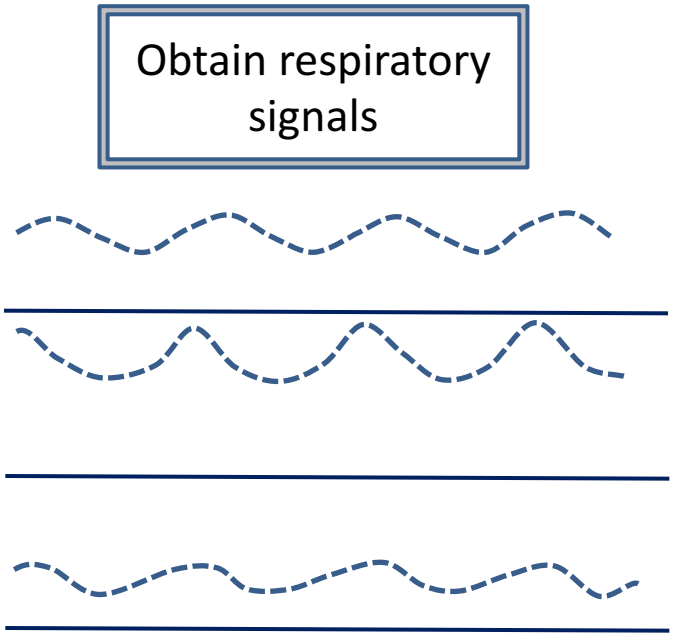


Measure amplitudes and intervals

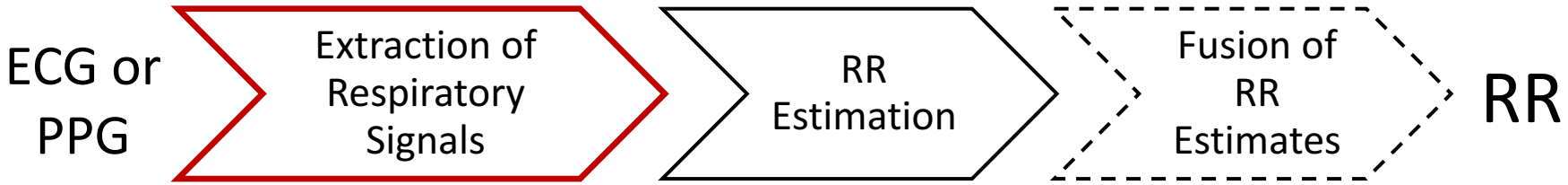
Structure of Algorithms

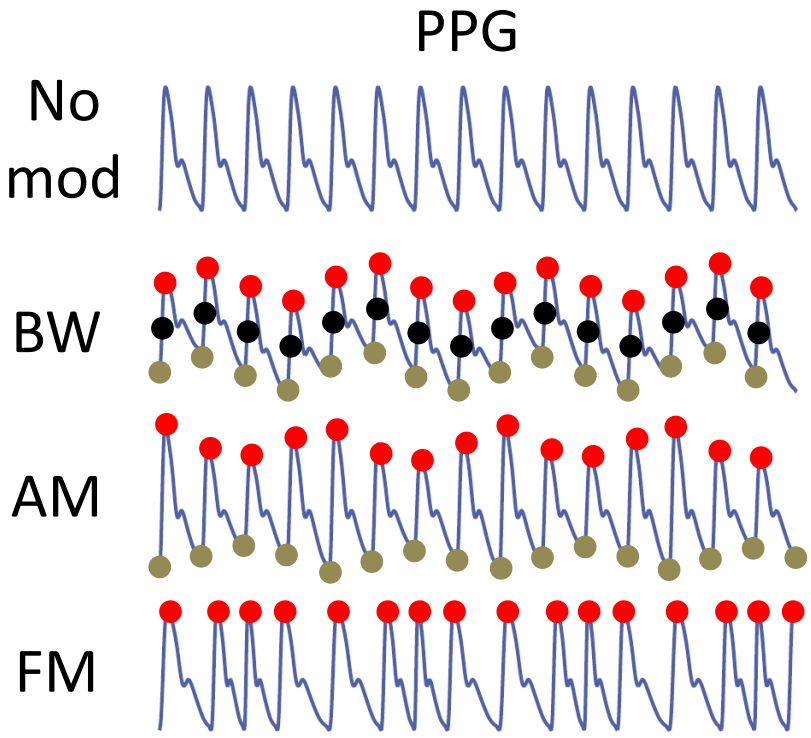




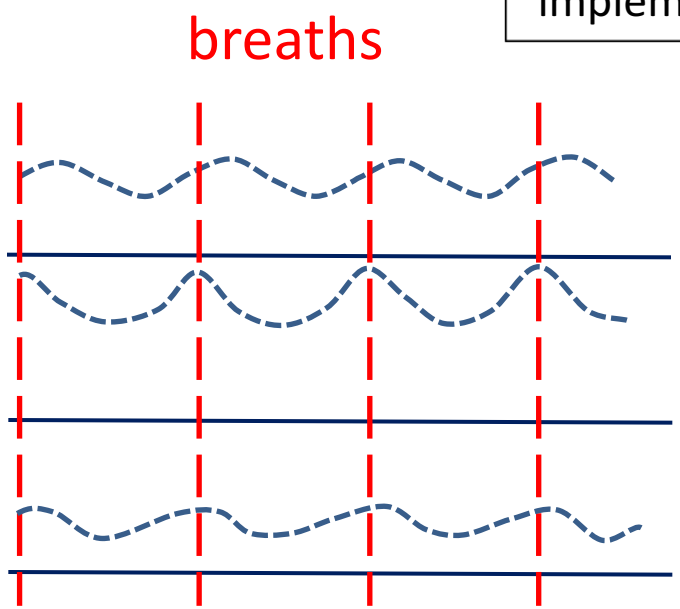


Structure of Algorithms

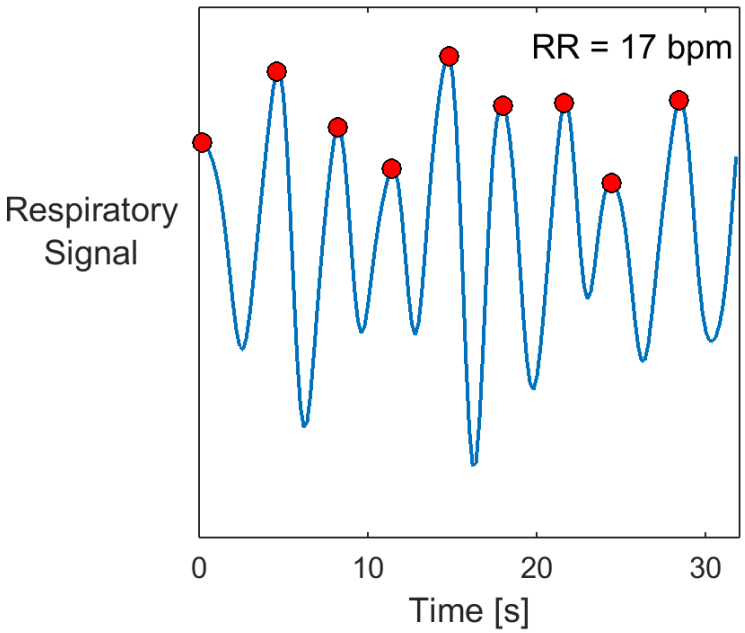


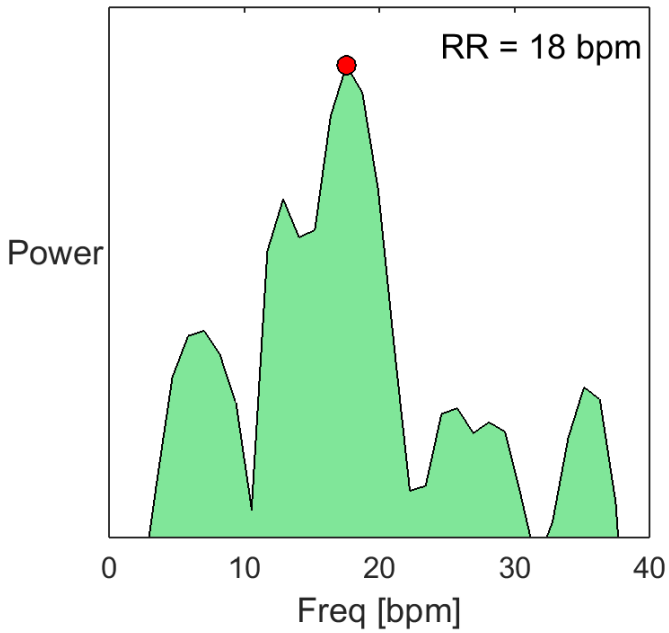


14 techniques implemented



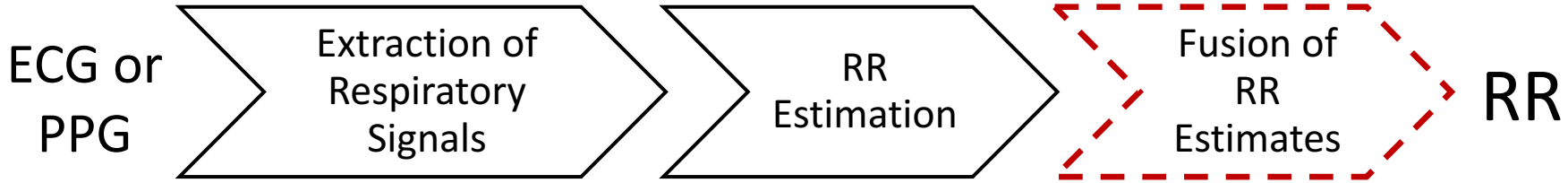
Structure of Algorithms

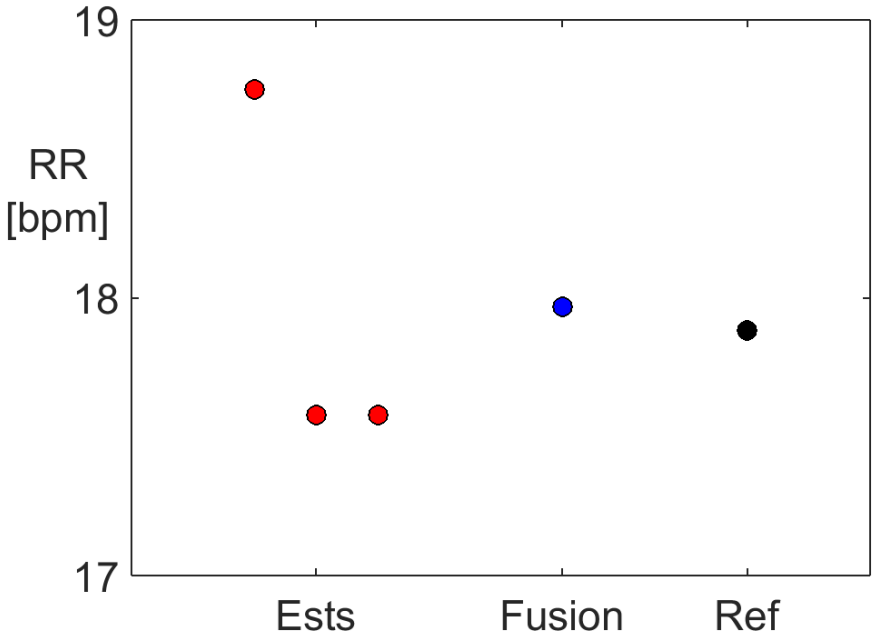




12 techniques implemented

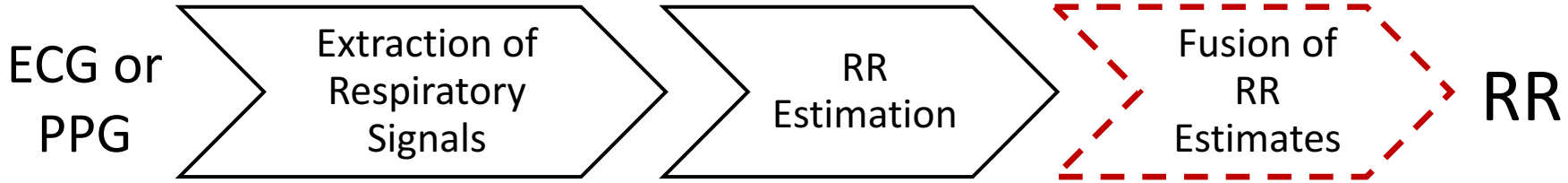
Structure of Algorithms

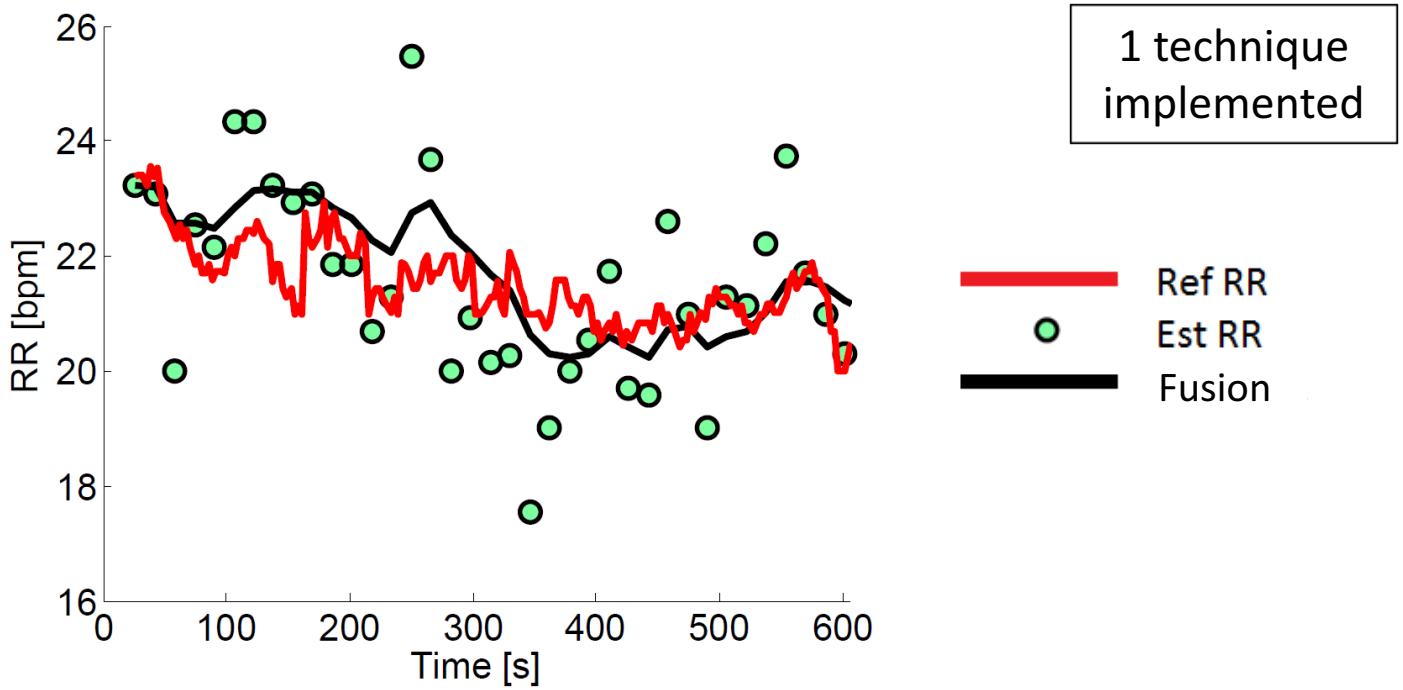




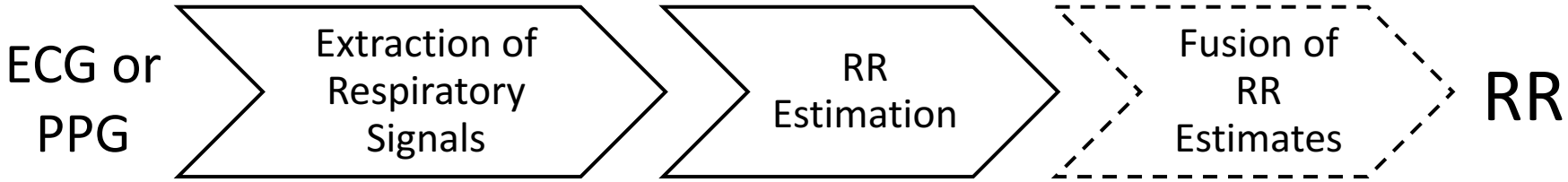
4 techniques implemented

Structure of Algorithms





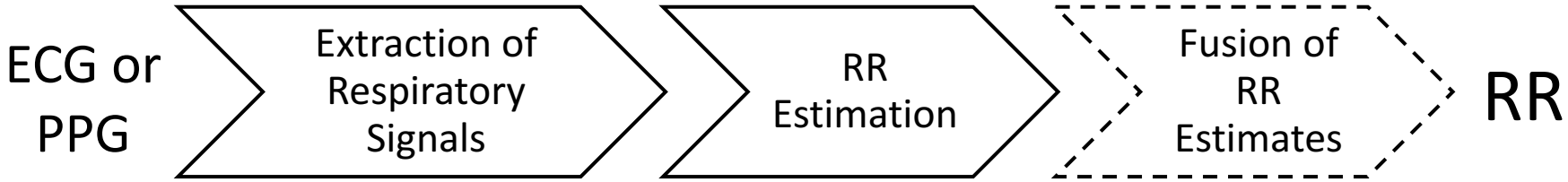
Constructing Algorithms

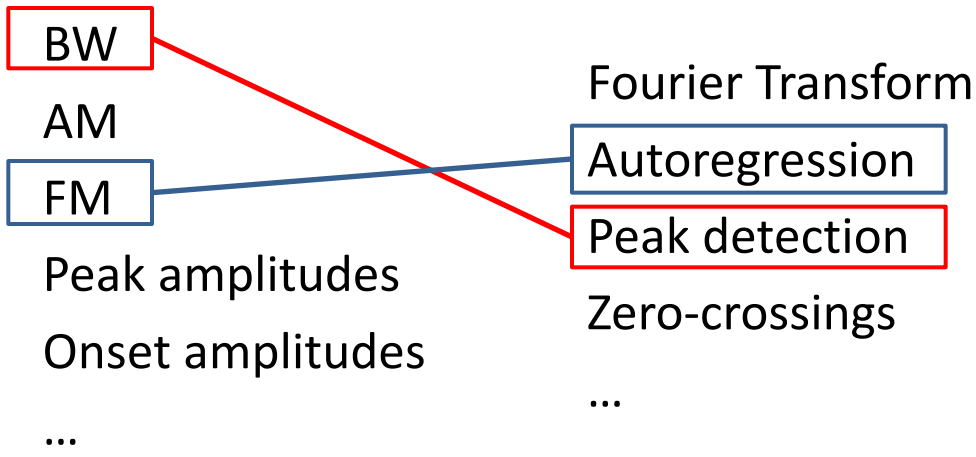


BW
AM
FM
Peak amplitudes
Onset amplitudes
…

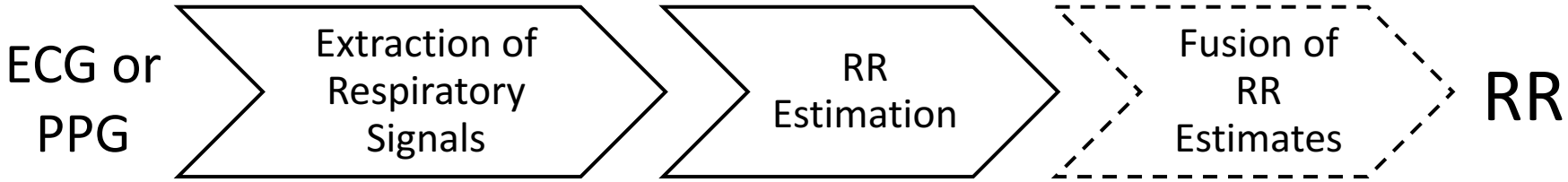
Fourier Transform
Autoregression
Peak detection
Zero-crossings
…

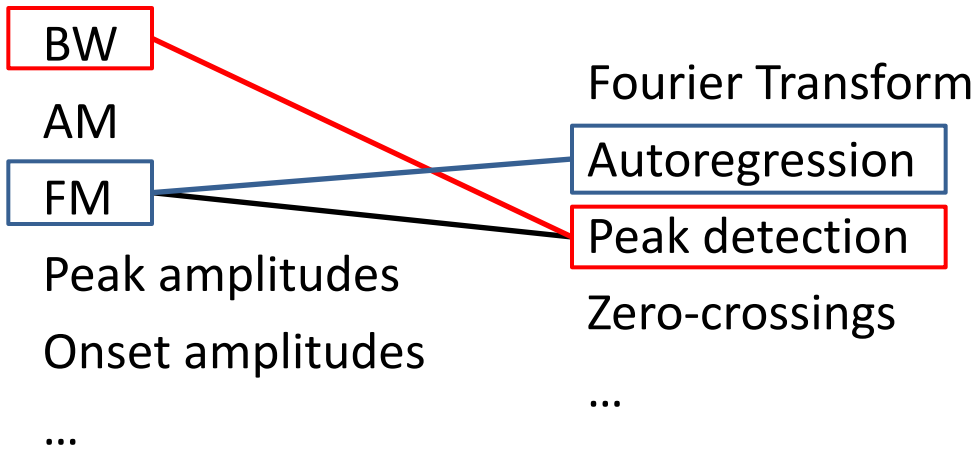
Constructing Algorithms



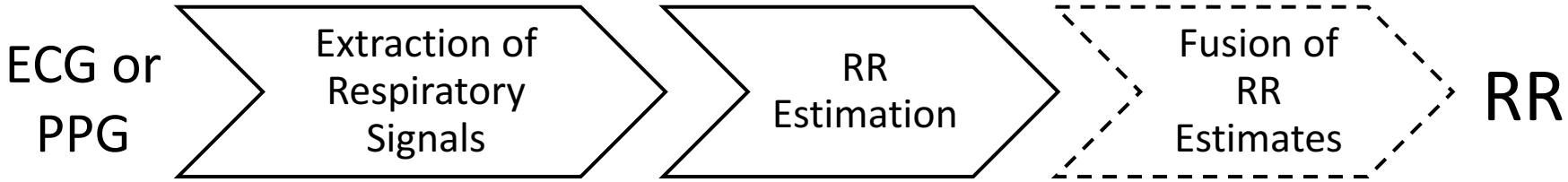


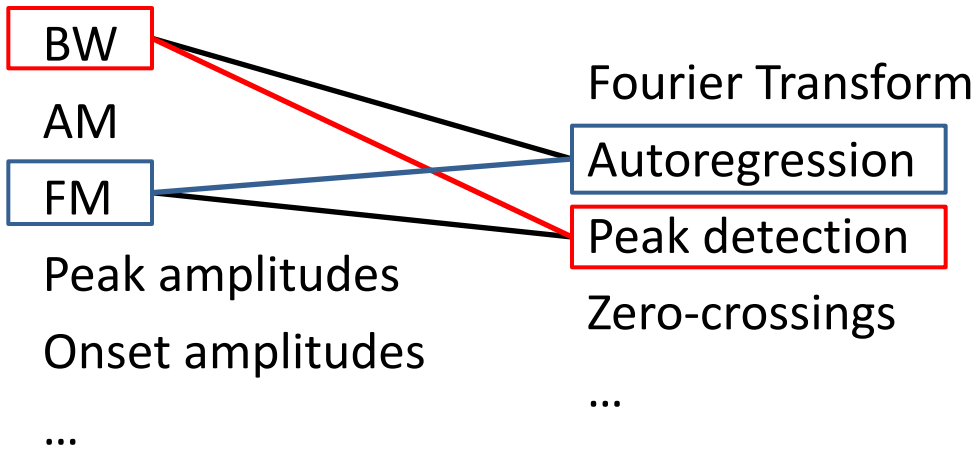
Constructing Algorithms



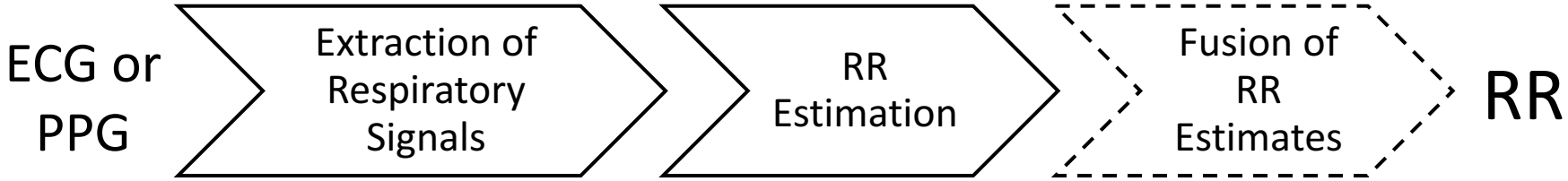


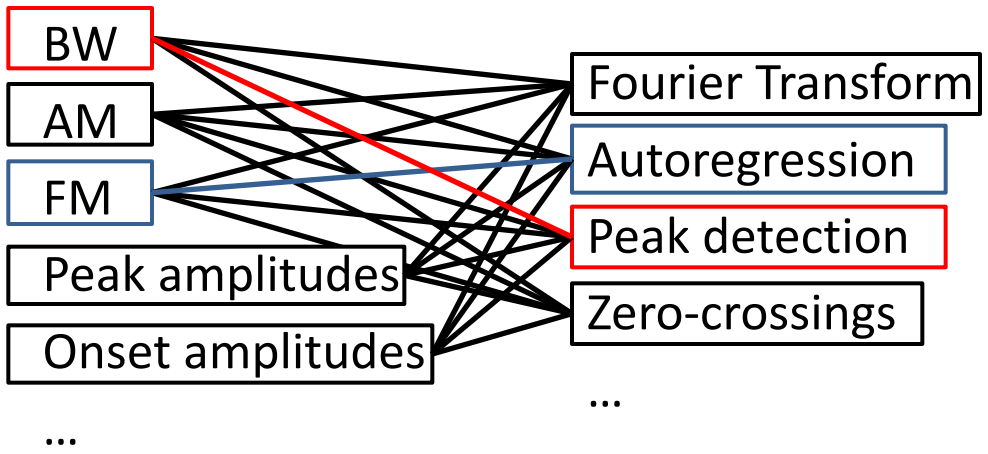
Constructing Algorithms



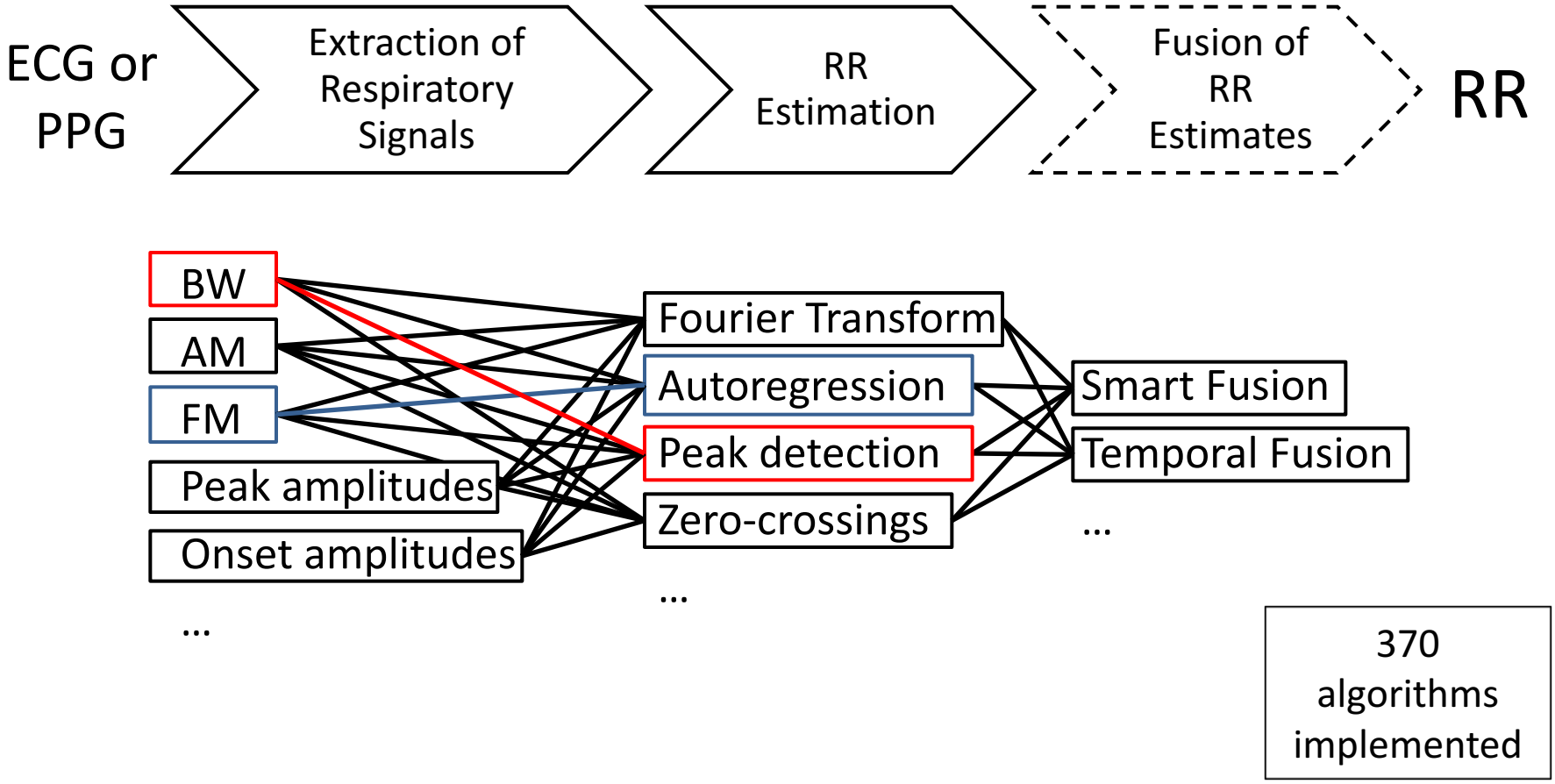


Constructing Algorithms

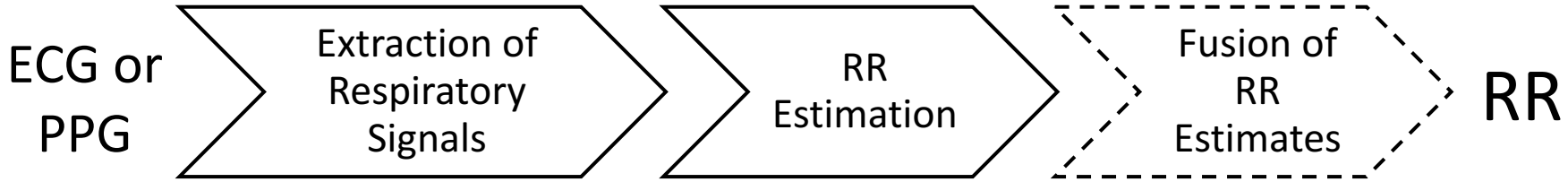




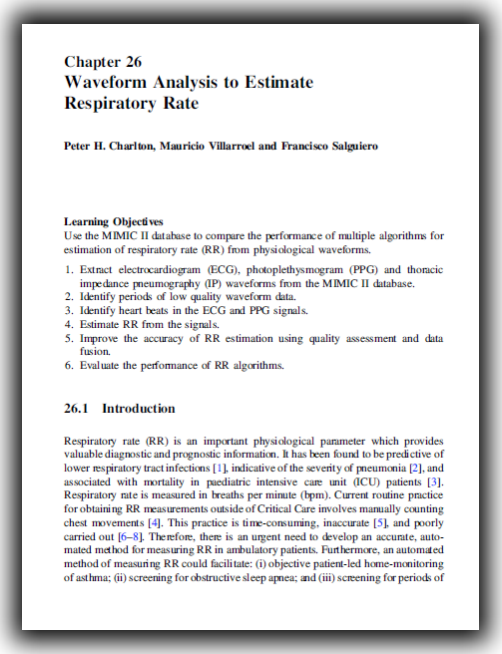
Constructing Algorithms



Toolbox of Algorithms



Publicly available [here](#)



Chapter 26
Waveform Analysis to Estimate Respiratory Rate

Peter H. Charlton, Mauricio Villarroel and Francisco Salguiero

Learning Objectives
Use the MIMIC II database to compare the performance of multiple algorithms for estimation of respiratory rate (RR) from physiological waveforms.

1. Extract electrocardiogram (ECG), photoplethysmogram (PPG) and thoracic impedance pneumography (IP) waveforms from the MIMIC II database.
2. Identify periods of low quality waveform data.
3. Identify heart beats in the ECG and PPG signals.
4. Estimate RR from the signals.
5. Improve the accuracy of RR estimation using quality assessment and data fusion.
6. Evaluate the performance of RR algorithms.

26.1 Introduction

Respiratory rate (RR) is an important physiological parameter which provides valuable diagnostic and prognostic information. It has been found to be predictive of lower respiratory tract infections [1], indicative of the severity of pneumonia [2], and associated with mortality in paediatric intensive care unit (ICU) patients [3]. Respiratory rate is measured in breaths per minute (bpm). Current routine practice for obtaining RR measurements outside of Critical Care involves manually counting chest movements [4]. This practice is time-consuming, inaccurate [5], and poorly carried out [6–8]. Therefore, there is an urgent need to develop an accurate, automated method for measuring RR in ambulatory patients. Furthermore, an automated method of measuring RR could facilitate: (i) objective patient-led home-monitoring of asthma; (ii) screening for obstructive sleep apnea; and (iii) screening for periods of

Charlton P.H. *et al.* **Waveform analysis to estimate respiratory rate**, in *Secondary Analysis of Electronic Health Records*, Springer, pp.377-390, 2016.
DOI: 10.1007/978-3-319-43742-2_26 .

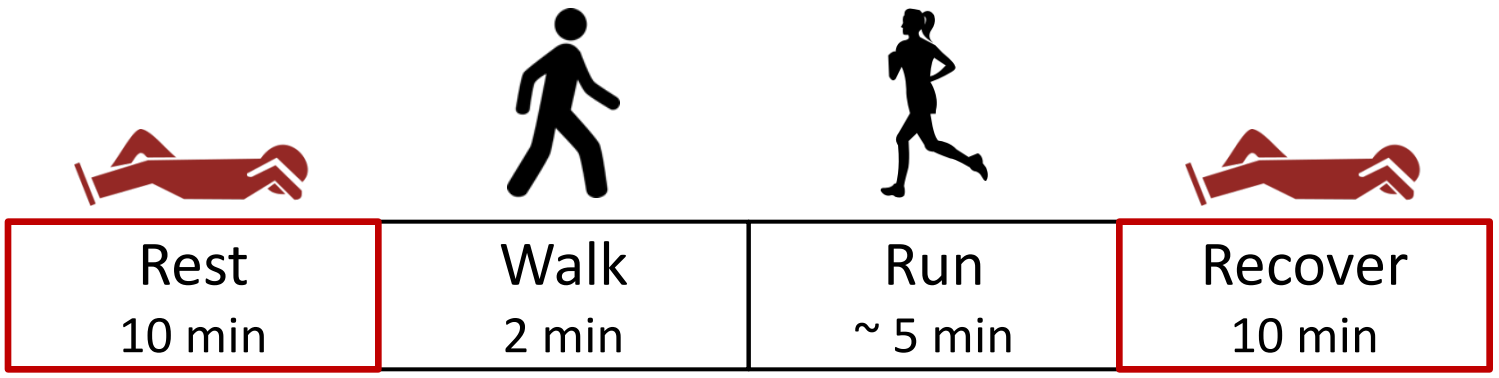
Methods

Verification of Implementations

- Synthetic ECG and PPG with simulated RR modulation
  - HR: 30-200 bpm
  - RR: 4-60 bpm
- 314 (85%) of algorithms accurate
- Failures caused by two techniques which were removed

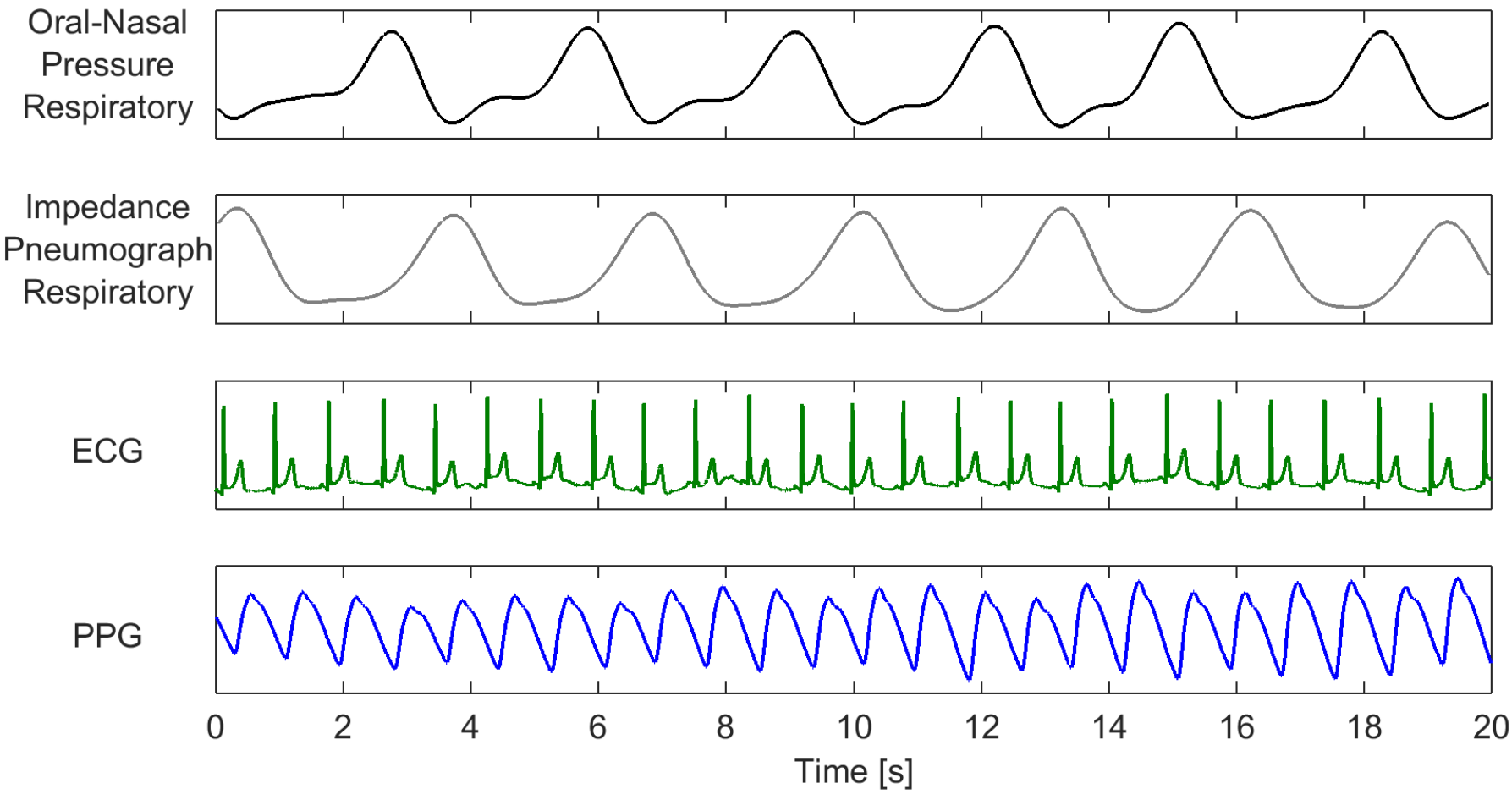
Participants

- Aged 18 to 40
- Free of comorbidities affecting cardiac, respiratory or autonomic nervous systems
- Range of RR generated by asking subjects to exercise

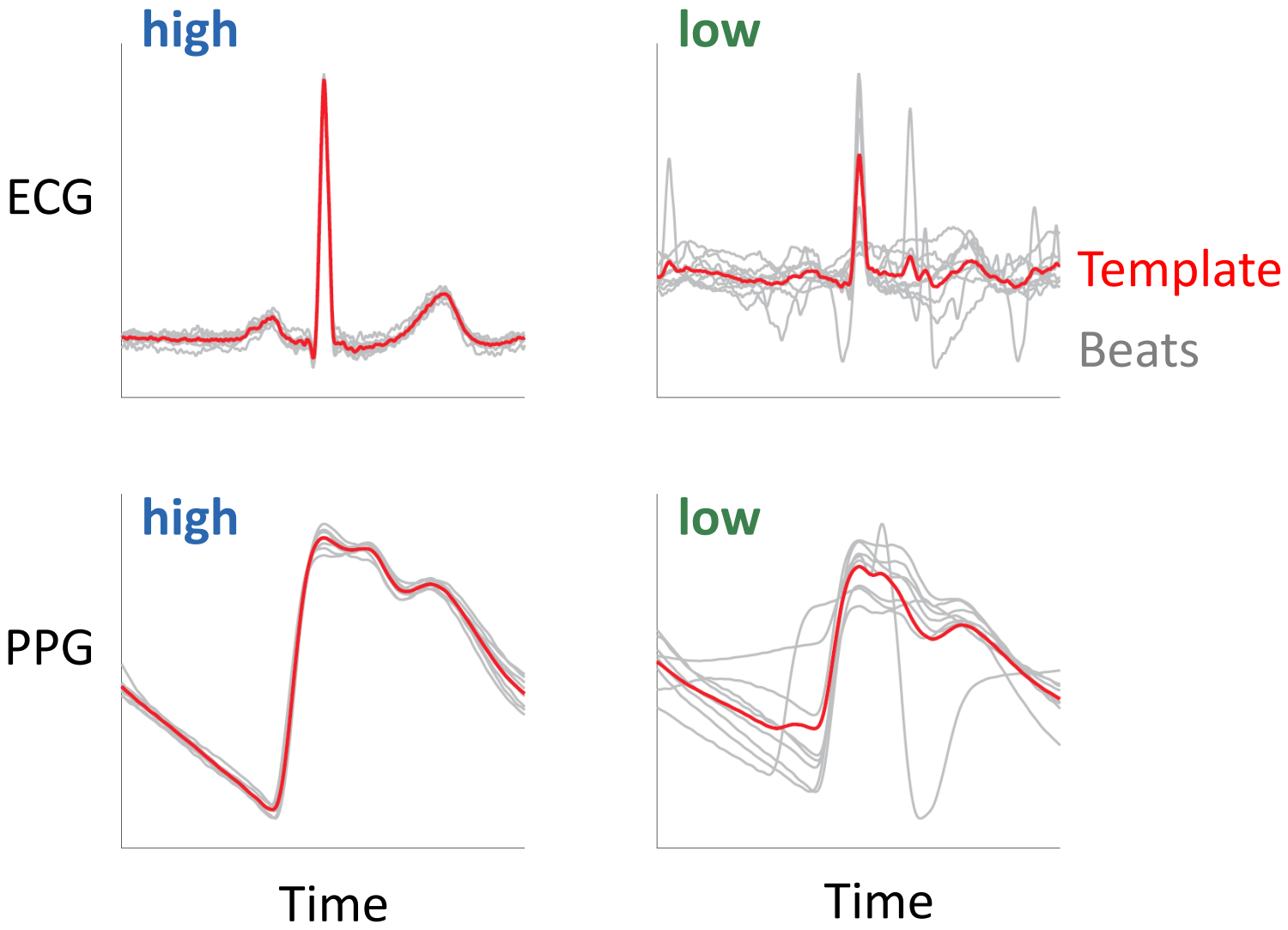


National Clinical Trial 01472133

Signals

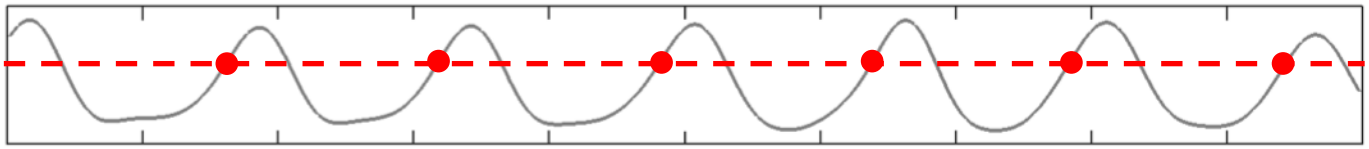

Oral-Nasal
Pressure
Respiratory
Impedance
Pneumograph
Respiratory
ECG
PPG
0
2
4
6
8
10
12
14
16
18
20
Time [s]

Signal Quality



Reference RRs

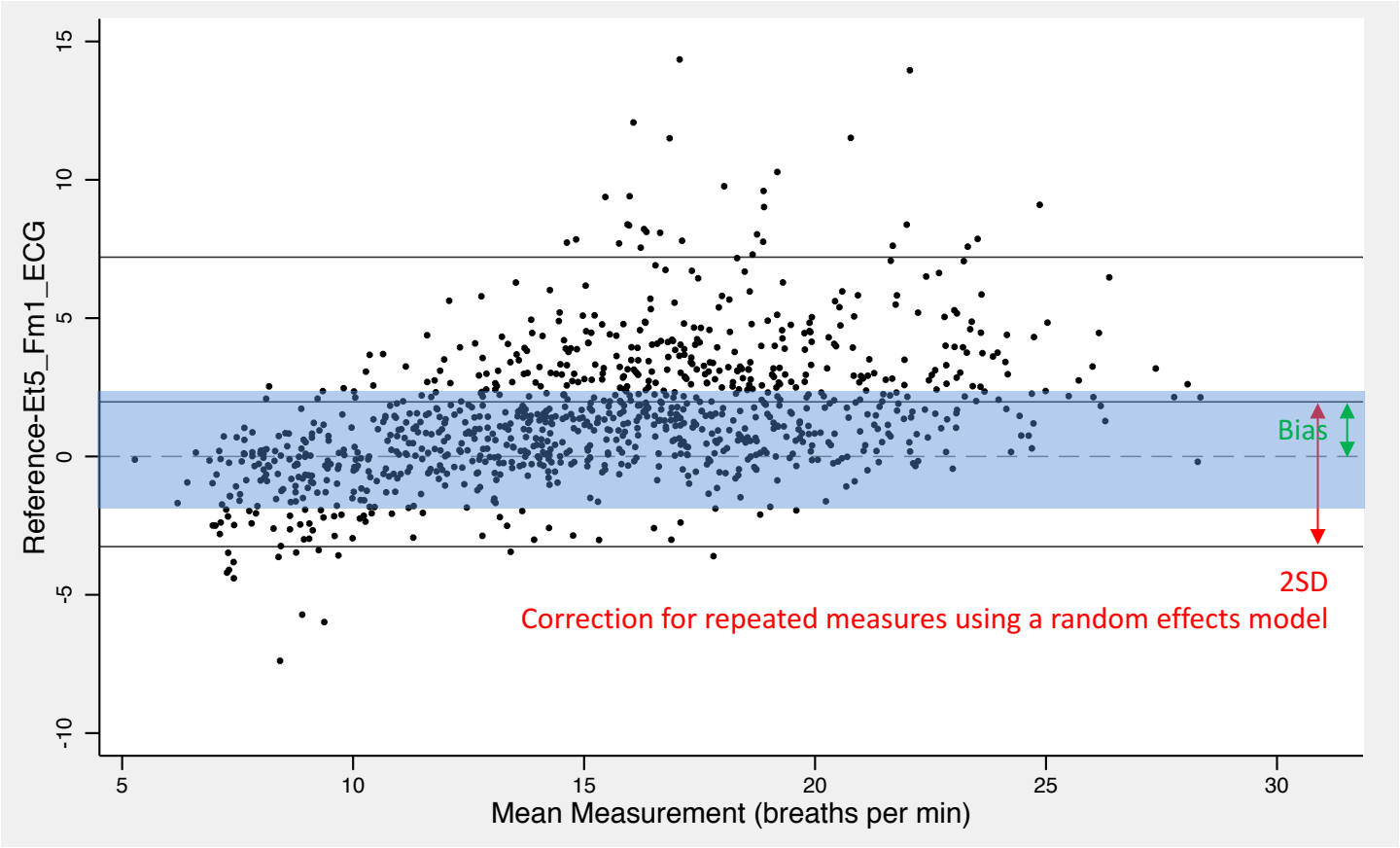
- Positive-gradient crossings detected from oro-nasal pressure signal
- Algorithm verified by comparison with manually annotated breaths



Statistics

- Consistent interpretation in different populations
- Intuitive interpretation conducive to decision making
- Separates bias from precision
  - Trends are more important than absolute values
  - If error is caused by a constant bias can be corrected by calibration

Statistics



Ranked algorithms by 2SD, followed by bias.

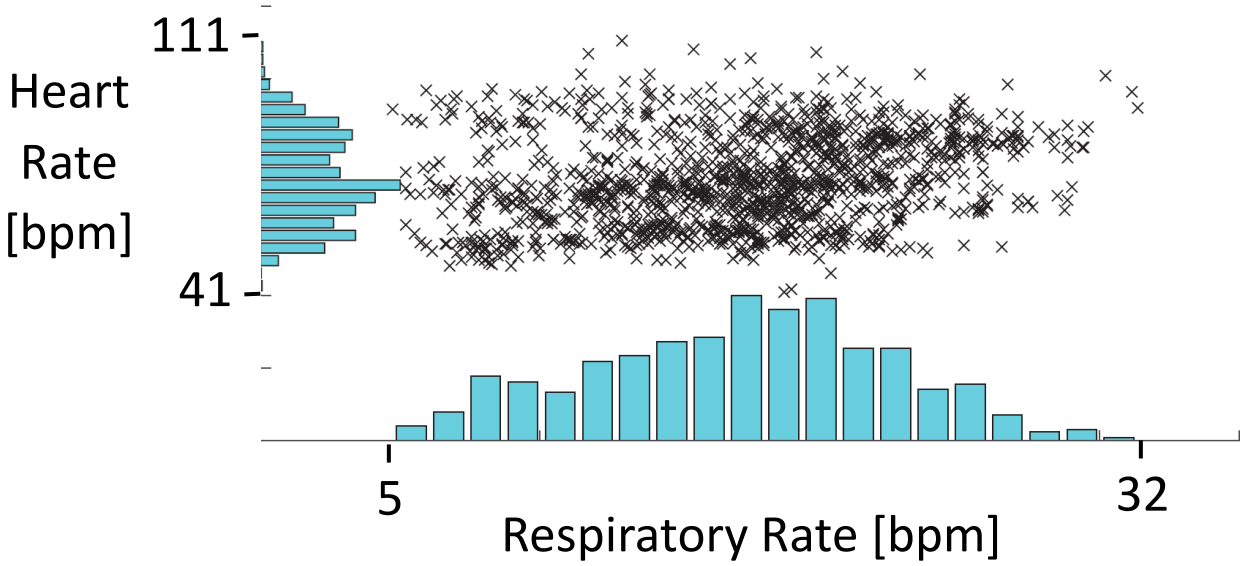
Results

Dataset

- 39 subjects
  - Age: 29 (26, 32)
  - BMI: 23 (21, 26)
  - 54% female
- ≈ 36 windows per subject

Dataset

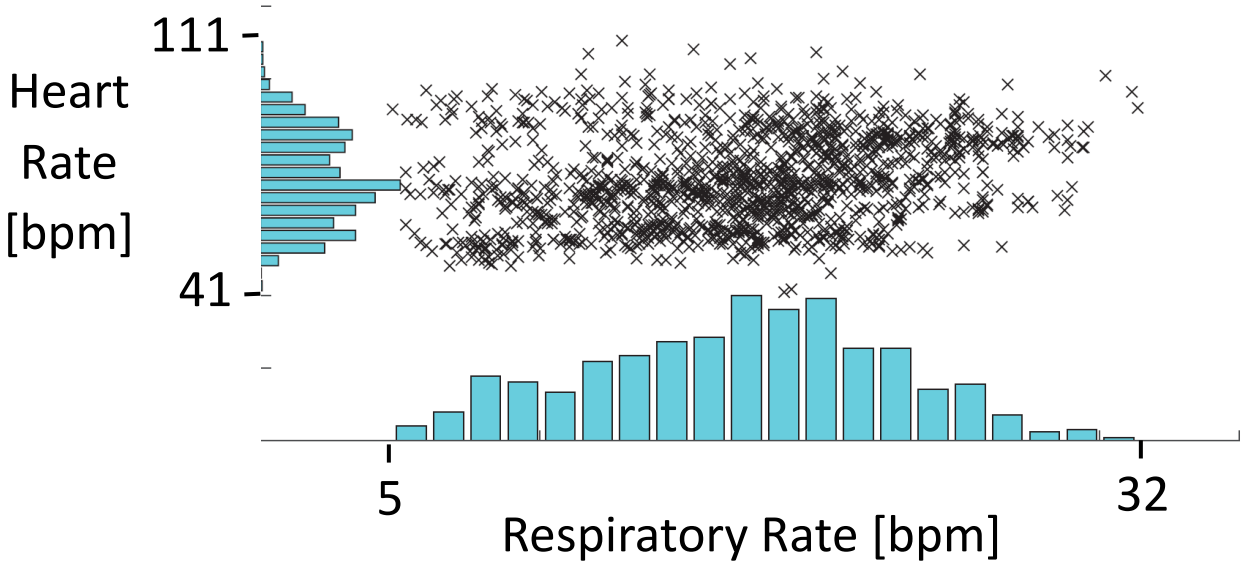
- 39 subjects
  - Age: 29 (26, 32)
  - BMI: 23 (21, 26)
  - 54% female
- ≈ 36 windows per subject



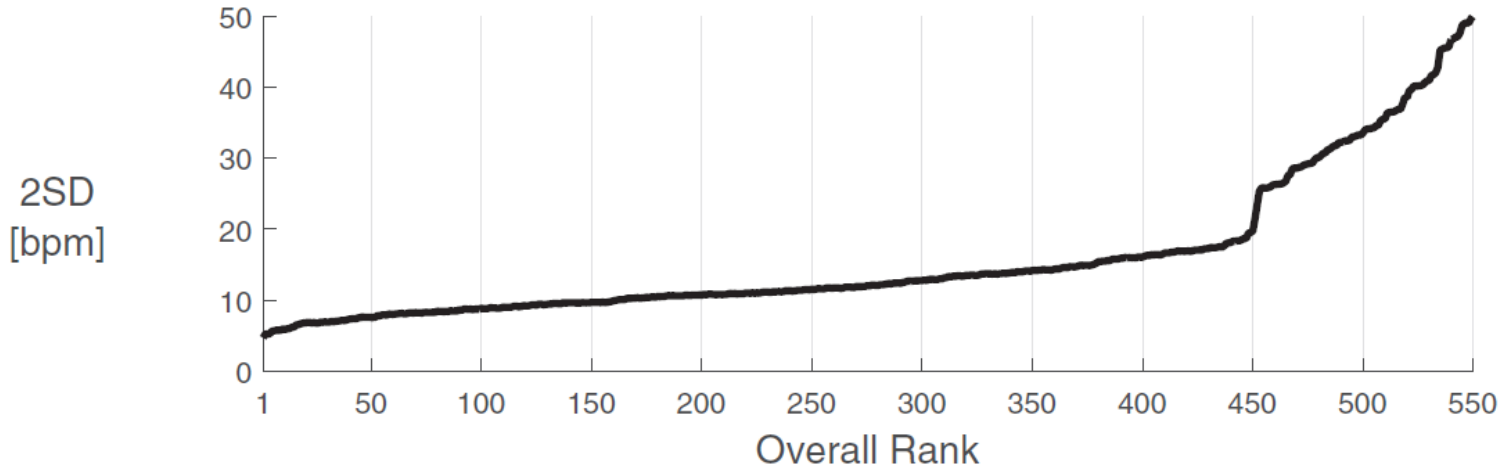
Dataset

- 39 subjects
  - Age: 29 (26, 32)
  - BMI: 23 (21, 26)
  - 54% female
- ≈ 36 windows per subject

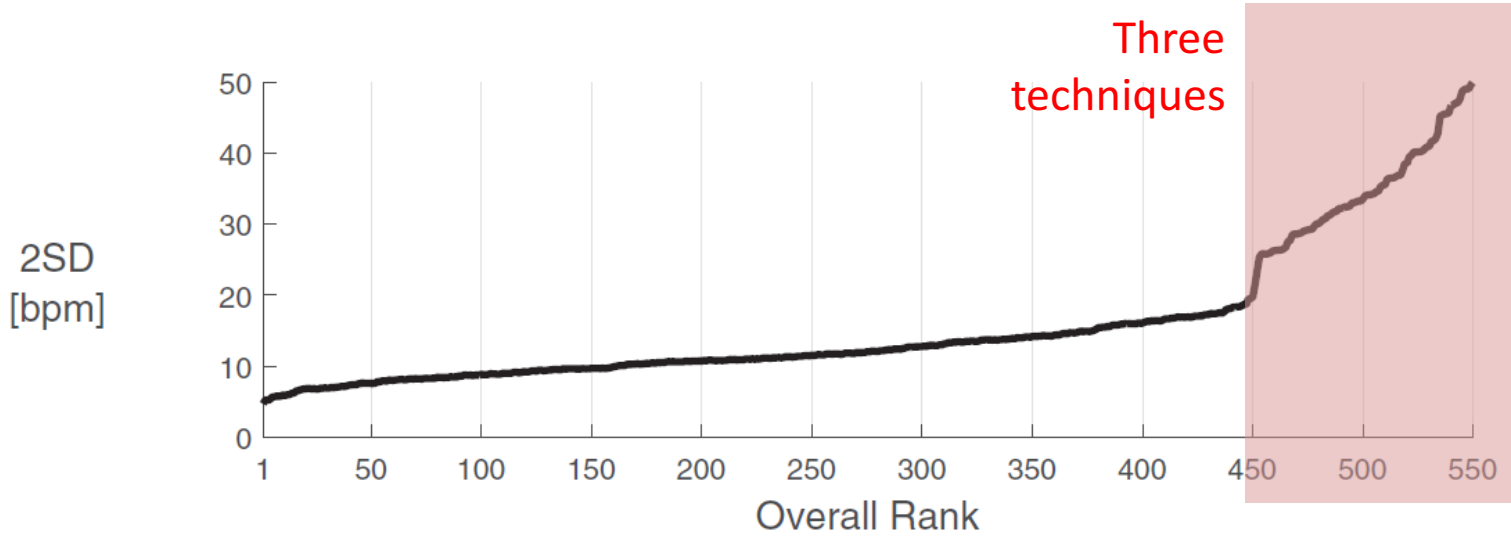
Publicly available here



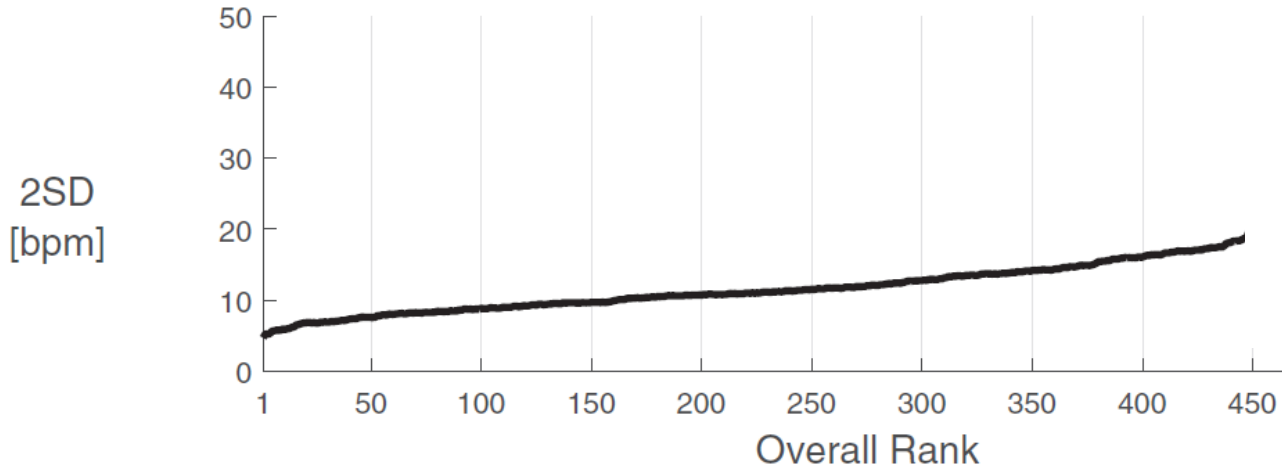
Performance of Algorithms



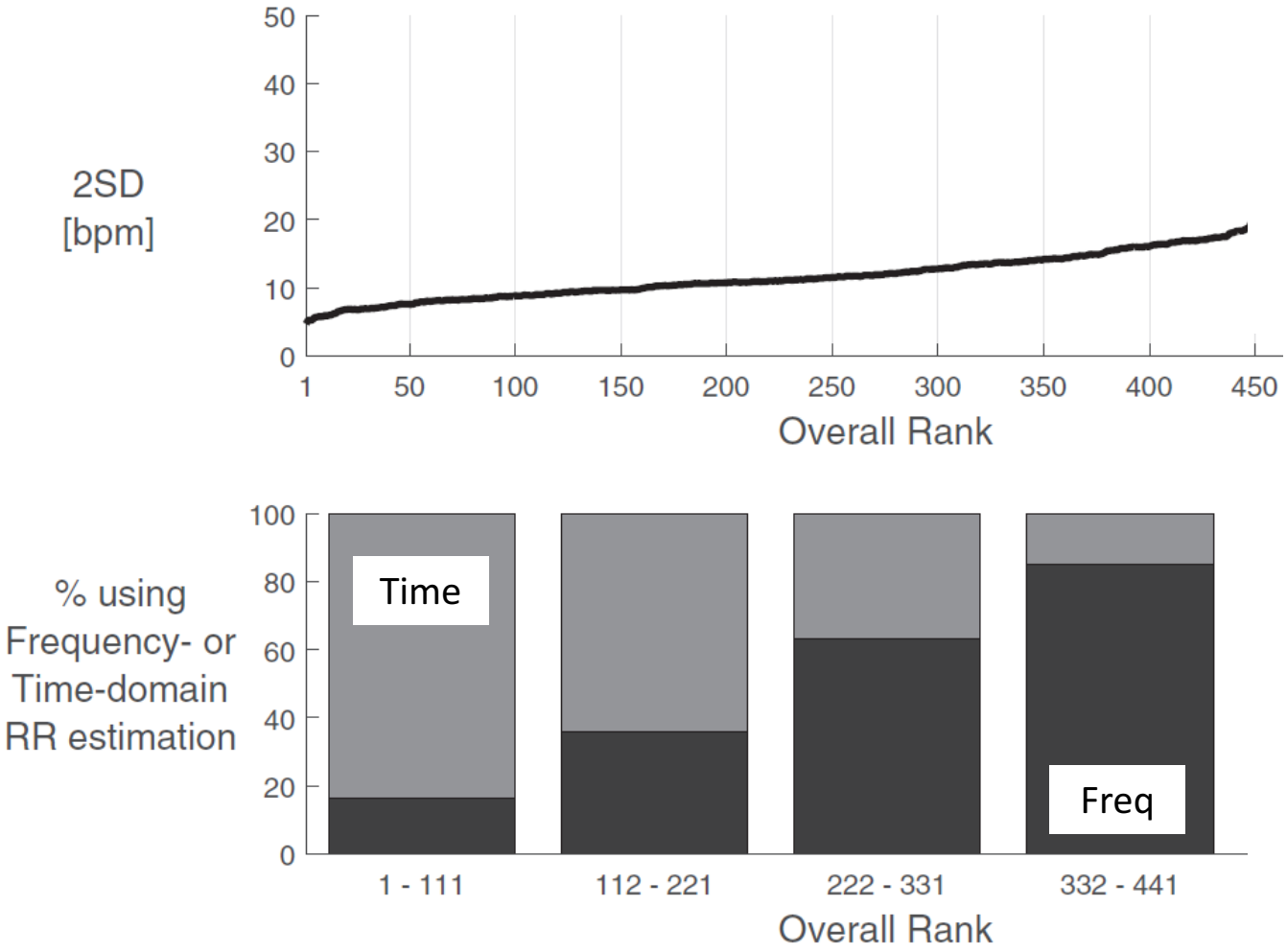
Performance of Algorithms



Performance of Algorithms



Performance of Algorithms



Best Algorithms

Signal	Rank	2SD [bpm]	RR Estimation	Modulation Fusion?	Temporal Fusion?
Clinical (IP)	5	5.4			
ECG	1	4.7	Time	✓	
	2	5.2	Time	✓	
	3	5.2	Time	✓	
	4	5.3	Time	✓	
	6	5.6	Time		
PPG	15	6.2	Time	✓	
	17	6.5	Time	✓	
	35	7.0	Time	✓	✓
	46	7.5	Time		✓
	48	7.6	Time		✓

Same Algorithm

ECG vs PPG

- Significant difference in 2SD (median):
  - ECG: 11.6 bpm
  - PPG: 12.4 bpm
- 64% of algorithms more precise on ECG
- Different physiological mechanisms

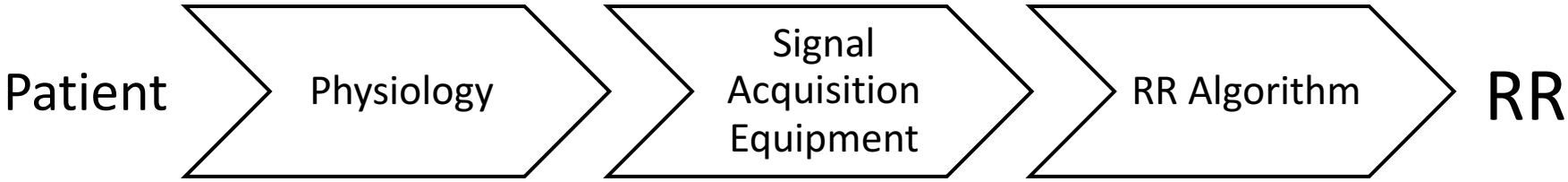
Discussion

Limitations

- Not all algorithms implemented
- Invite contributions
- Statistics based on normally distributed errors
- Cannot extrapolate to other scenarios

Future Work

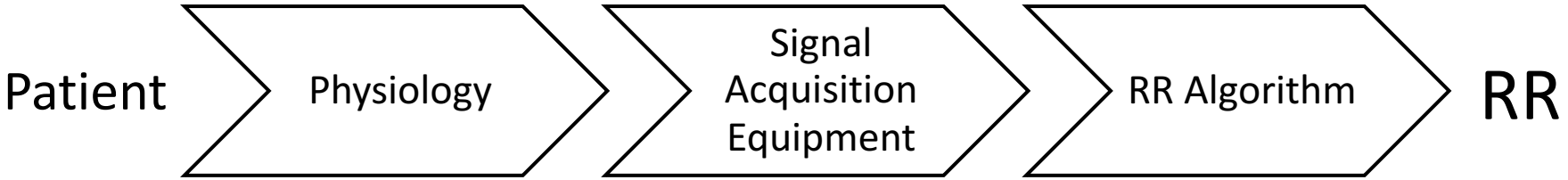
Investigate effects of:



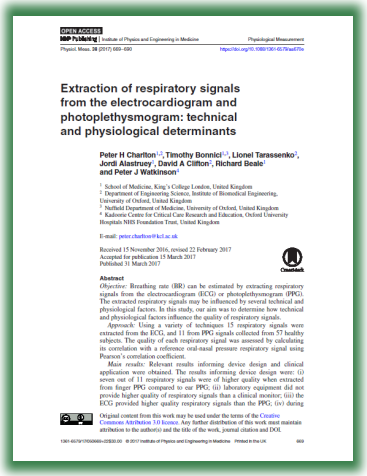
Physiology	Signal Acquisition Equipment	RR Algorithm
Age	Signal Fidelity	*This paper*
Disease	Filtering	
Arrhythmias	Noise	

Future Work

Investigate effects of:



Physiology	Signal Acquisition Equipment	RR Algorithm
Age	Signal Fidelity	*This paper*
Disease	Filtering	
Arrhythmias	Noise	



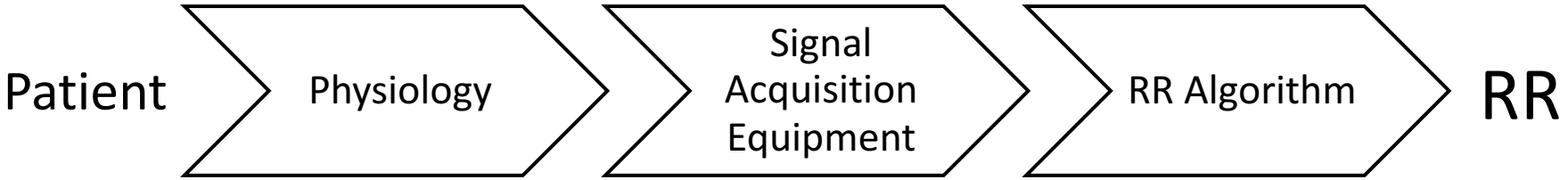
Extraction of respiratory signals from the electrocardiogram and photoplethysmogram: technical and physiological determinants

Peter H Charlton[1,2], Timothy Bonnici[1,3], Lionel Tarassenko[3], Jordi Alastruey[1], David A Clifton[3], Richard Beale[1] and Peter J Watkinson[1]

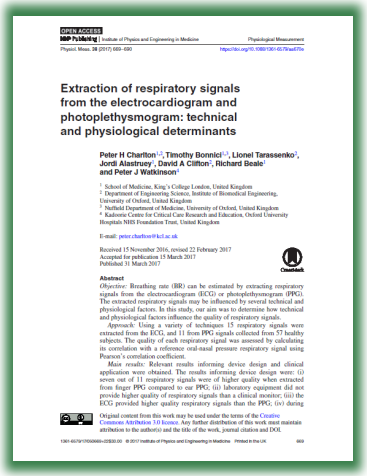
Charlton P.H. *et al.* **Extraction of respiratory signals from the electrocardiogram and photoplethysmogram: technical and physiological determinants**, *Physiological Measurement*, 37(4), 2016. DOI: 10.1088/1361-6579/aa670e . CC BY 3.0 Licence

Future Work

Investigate effects of:



Physiology	Signal Acquisition Equipment	RR Algorithm
Age	Signal Fidelity	*This paper*
Disease	Filtering	
Arrhythmias	Noise	



Extraction of respiratory signals from the electrocardiogram and photoplethysmogram: technical and physiological determinants

Peter H Charlton[1,2], Timothy Bonnici[2,3], Lionel Tarassenko[3], Jordi Alastruey[1], David A Clifton[3], Richard Beale[4] and Peter J Watkinson[4]

Charlton P.H. *et al.* **Extraction of respiratory signals from the electrocardiogram and photoplethysmogram: technical and physiological determinants**, *Physiological Measurement*, 37(4), 2016. DOI: 10.1088/1361-6579/aa670e . CC BY 3.0 Licence

Conclusions

- 314 algorithms assessed under ideal conditions
- According to these results …
  - time-domain RR estimation, and
  - fusion of estimates

    … resulted in superior performance.
- Four ECG-based algorithms comparable to clinical standard
- ECG preferable to PPG
- Toolbox of algorithms and dataset publicly available

Acknowledgments

The authors are grateful to …

Data collection:

J Brooks, I Schelcher, R Yang, K Lei and J Smith

Algorithm implementations:

M Pimentel and C Orphanidou

Statistical analysis:

J Birks and S Gerry

Funders:

EPSRC, NIHR, Wellcome Trust, Royal Academy of Engineering

The views expressed are those of the authors and not necessarily those of the EPSRC, NHS, NIHR, Department of Health, Wellcome Trust, or Royal Academy of Engineering.

A complete list of acknowledgments is available here.

Additional Acknowledgments

Thanks also to:

- Jason Long for Cayman Theme which inspired this presentation template
- Open Clipart for some of the images in this presentation

Source:

References and Resources

Charlton P.H. and Bonnici T. *et al.* **An assessment of algorithms to estimate respiratory rate from the electrocardiogram and photoplethysmogram**, *Physiological Measurement*, 37(4), 2016.
DOI: 10.1088/0967-3334/37/4/610 . CC BY 3.0 Licence

An assessment of algorithms to estimate respiratory rate from the electrocardiogram and photoplethysmogram

Peter H Charlton[1,2,3], Timothy Bonnici[1,4,3], Lionel Tarassenko[2], David A Clifton[2], Richard Beale[1] and Peter J Watkinson[3]

[1] School of Medicine, King's College London, UK
[2] Department of Engineering Science, Institute of Biomedical Engineering, University of Oxford, UK
[3] Kadoorie Centre for Critical Care Research and Education, John Radcliffe Hospital, UK
[4] Nuffield Department of Medicine, University of Oxford, UK

E-mail: peter.charlton@gstt.nhs.uk

Received 21 January 2016
Accepted for publication 4 February 2016
Published 30 March 2016

Abstract

Over 100 algorithms have been proposed to estimate respiratory rate (RR) from the electrocardiogram (ECG) and photoplethysmogram (PPG). As they have never been compared systematically it is unclear which algorithm performs the best.

Our primary aim was to determine how closely algorithms agreed with a gold standard RR measure when operating under ideal conditions. Secondary aims were: (i) to compare algorithm performance with IP, the clinical standard for continuous respiratory rate measurement in spontaneously breathing patients; (ii) to compare algorithm performance when using ECG and PPG; and (iii) to provide a toolbox of algorithms and data to allow future researchers to conduct reproducible comparisons of algorithms.

Algorithms were divided into three stages: extraction of respiratory signals, estimation of RR, and fusion of estimates. Several interchangeable techniques were implemented for each stage. Algorithms were assembled using all possible combinations of techniques, many of which were novel. After verification on simulated data, algorithms were tested on data from healthy participants. RRs derived from ECG, PPG and IP were compared to

[5] Contributed equally to this work.

0967-3334/16/040610+17$33.00 © 2016 Institute of Physics and Engineering in Medicine Printed in the UK

Part of the **Respiratory Rate Estimation Project** at:

http://peterhcharlton.github.io/RRest/

The **dataset** is available here.

The **algorithms** and user manual are available here.

The complete **table of results** is in the Supplementary Material

A complete list of **references** is available here.