Developing software to monitor respiratory rate using wearable sensors

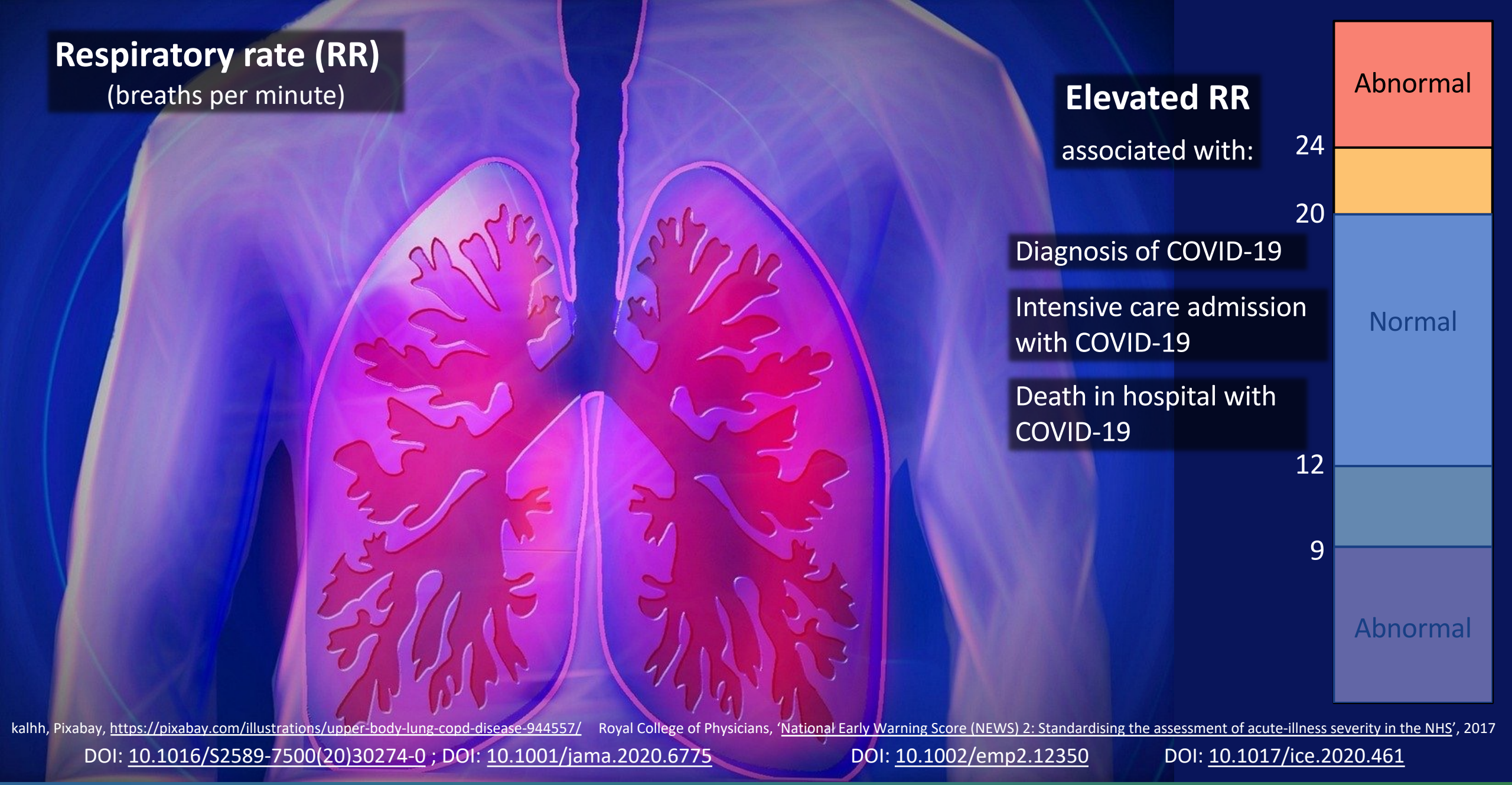
Dr Peter H. Charlton

University of Cambridge

City, University of London

Slides available at: https://doi.org/10.5281/zenodo.6413093 (CC BY 4.0)

Respiratory rate (RR)
(breaths per minute)



Elevated RR
associated with:

- Diagnosis of COVID-19
- Intensive care admission with COVID-19
- Death in hospital with COVID-19

kalhh, Pixabay, https://pixabay.com/illustrations/upper-body-lung-copd-disease-944557/ Royal College of Physicians, 'National Early Warning Score (NEWS) 2: Standardising the assessment of acute-illness severity in the NHS', 2017

DOI: 10.1016/S2589-7500(20)30274-0 ; DOI: 10.1001/jama.2020.6775 DOI: 10.1002/emp2.12350 DOI: 10.1017/ice.2020.461

Peter Charlton, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Face_mask_for_respiratory_monitoring.jpg (CC BY 4.0)
Peter Charlton, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Chest_band.jpg (CC BY 4.0)
Peter Charlton, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Oral_nasal_cannula.jpg (CC BY 4.0) Peter Charlton, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Max_Health_Band.jpg (CC BY 4.0)

Aim: To develop and validate algorithms to estimate respiratory rate from signals provided by wearables.

Respiratory rate software

Vision for software

Pressing questions

gcasasola, pxhere, https://pxhere.com/en/photo/1457247 (CC0)

Brother UK, https://www.flickr.com/photos/brother-uk/31501281284/in/photostream/ (CC BY 2.0)

StockSnap, Pixabay, https://pixabay.com/photos/code-coding-programming-html-2558224/

Respiratory rate software for wearables

Aim: to develop and validate algorithms to estimate respiratory rate from signals provided by wearables.

Understanding the state-of-the-art

Literature review. Research questions.

Developing a toolbox of algorithms

Implementation. Verification. Dissemination.

Assessment

Healthy volunteers. Hospital patients. Clinical application.

Future work

Toolbox refinement. Assessment in daily life. Evaluation.

Respiratory rate software for wearables

Aim: to develop and validate algorithms to estimate respiratory rate from signals provided by wearables.

Understanding the state-of-the-art

Literature review. Research questions.

Developing a toolbox of algorithms

Implementation. Verification. Dissemination.

Assessment

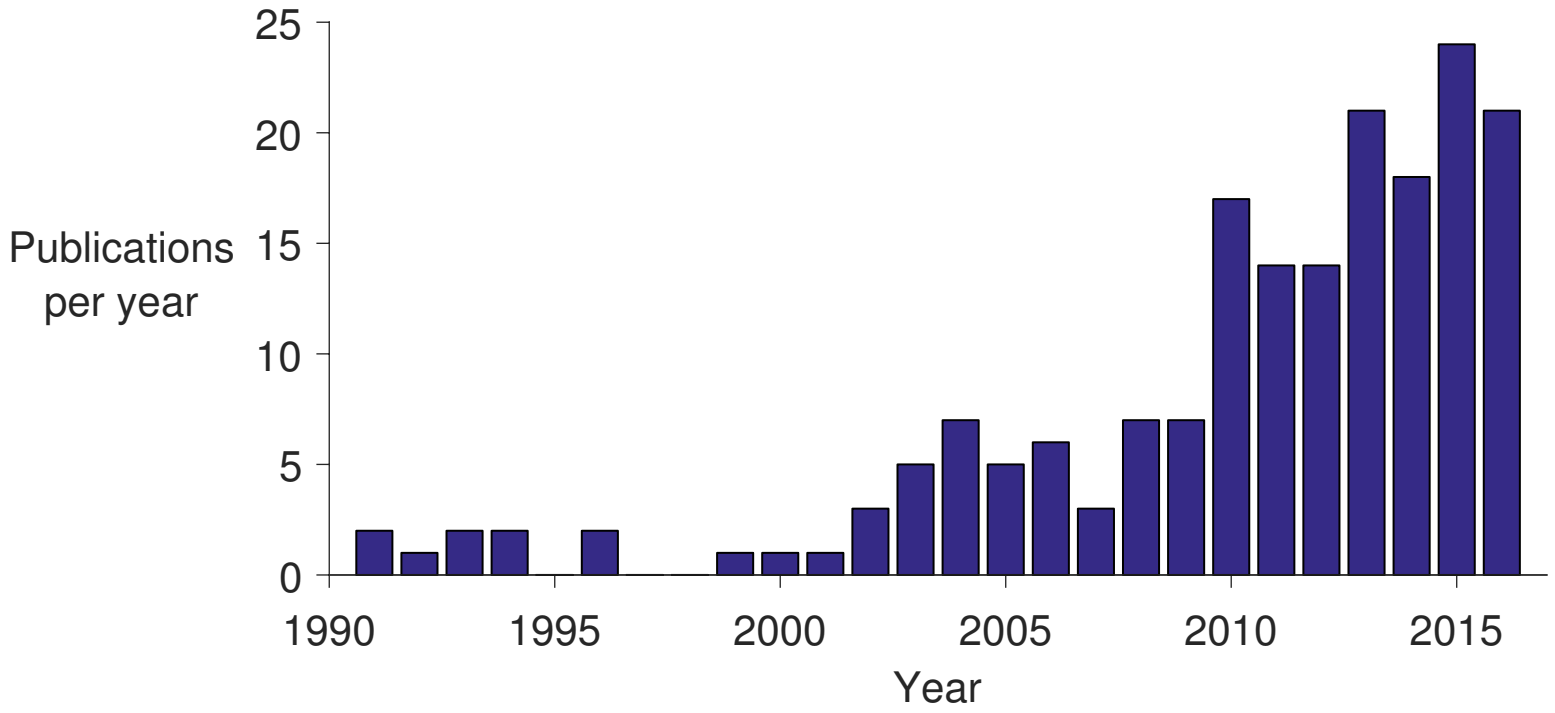
Healthy volunteers. Hospital patients. Clinical application.

Future work

Toolbox refinement. Assessment in daily life. Evaluation.

Literature review

Respiratory rate algorithms have been described in >196 publications

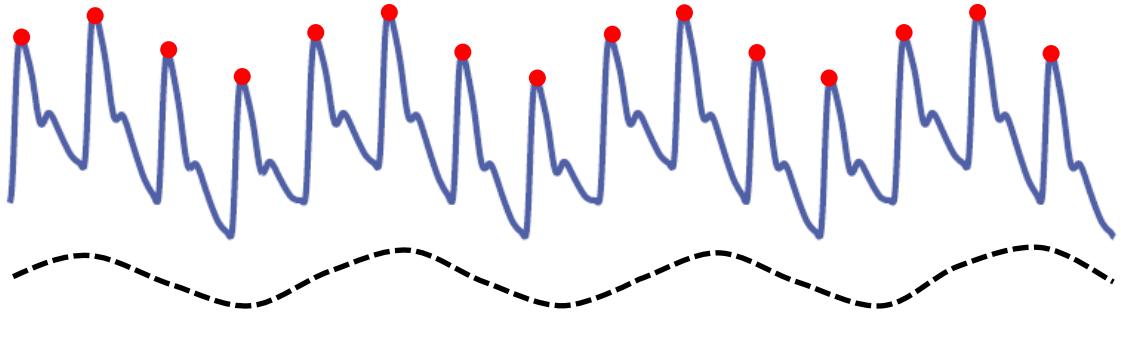


Charlton P.H. *et al.*, IEEE RBME, 2018: 10.1109/RBME.2017.2763681 (CC BY 4.0)

How respiratory rate algorithms work

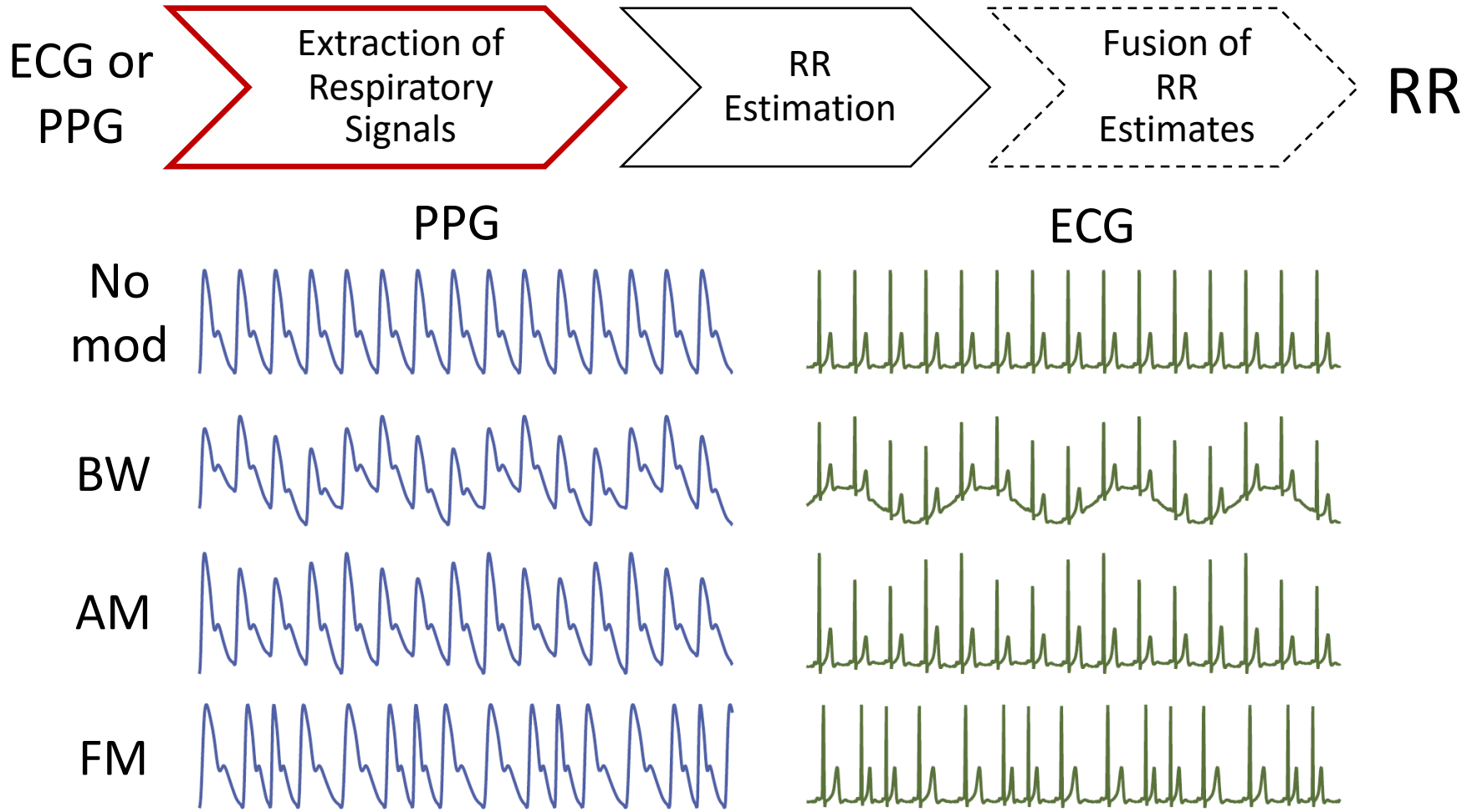
Respiratory rate estimated from either the optical signal measured by wearables (PPG):

Optical signal (photoplethysmogram, PPG):

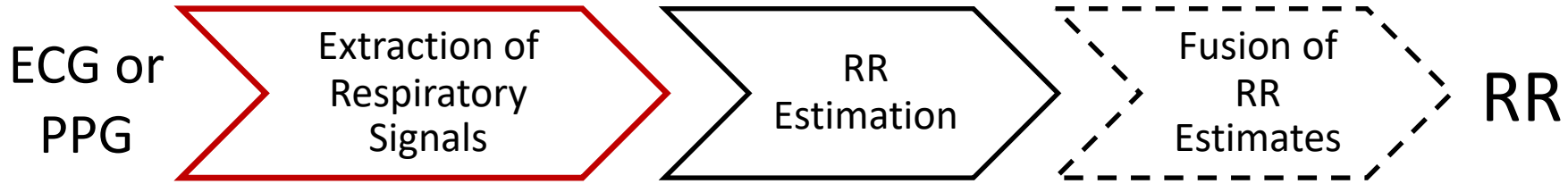


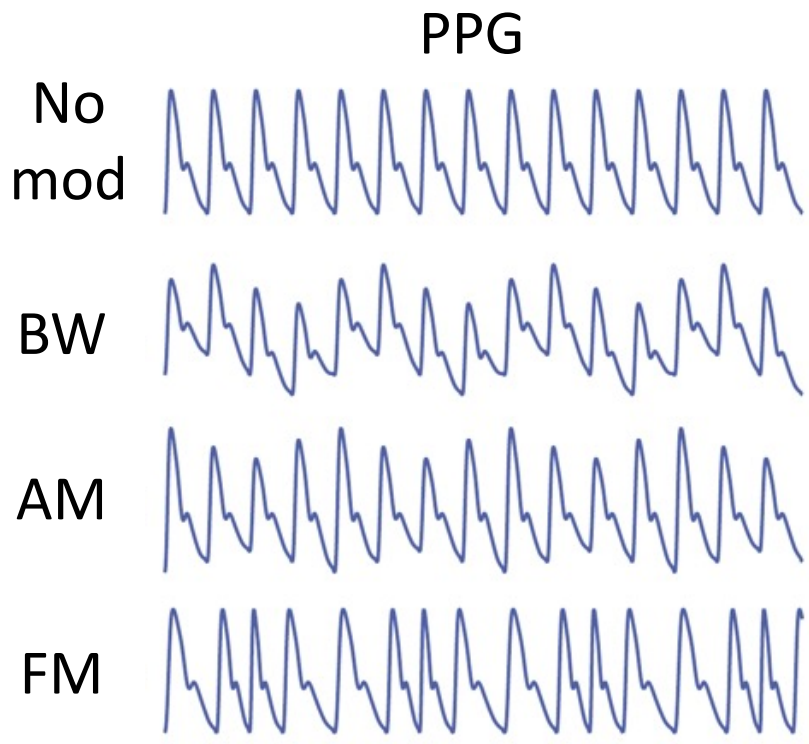
… or the electrocardiogram (ECG)

Structure of Algorithms

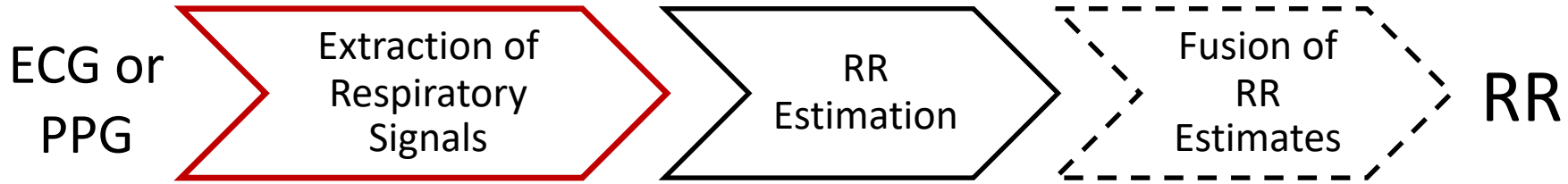


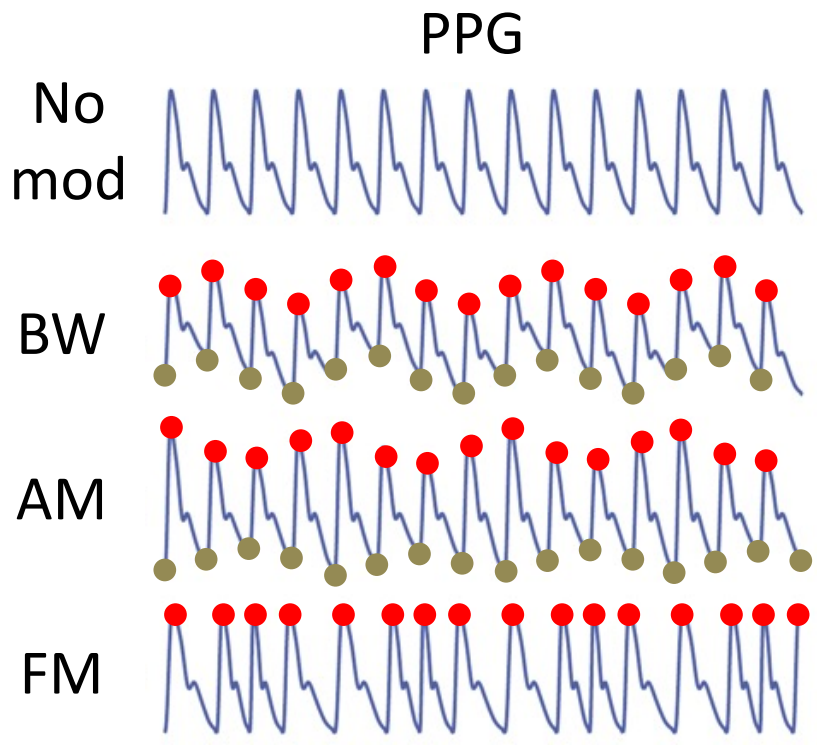
Structure of Algorithms





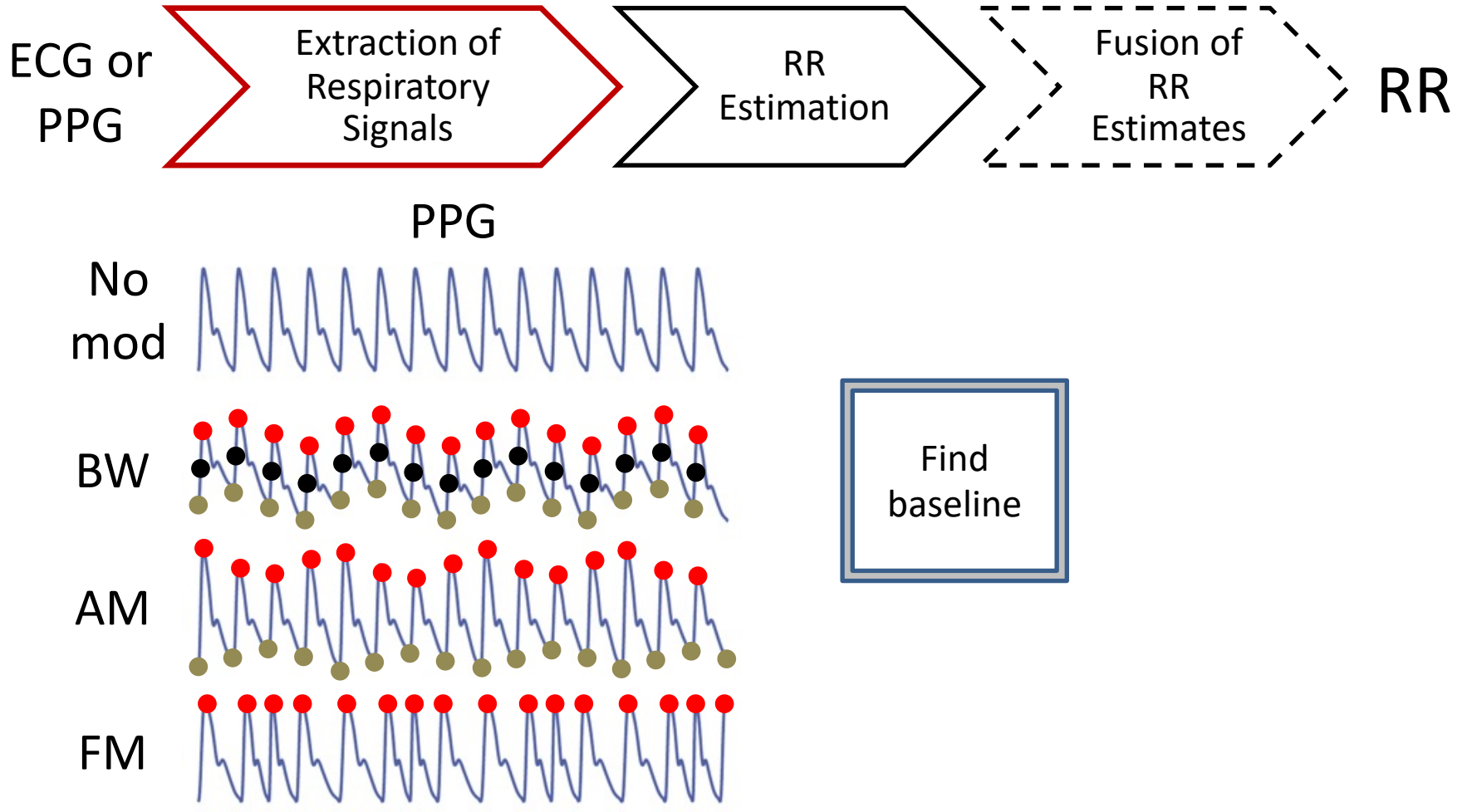
Structure of Algorithms



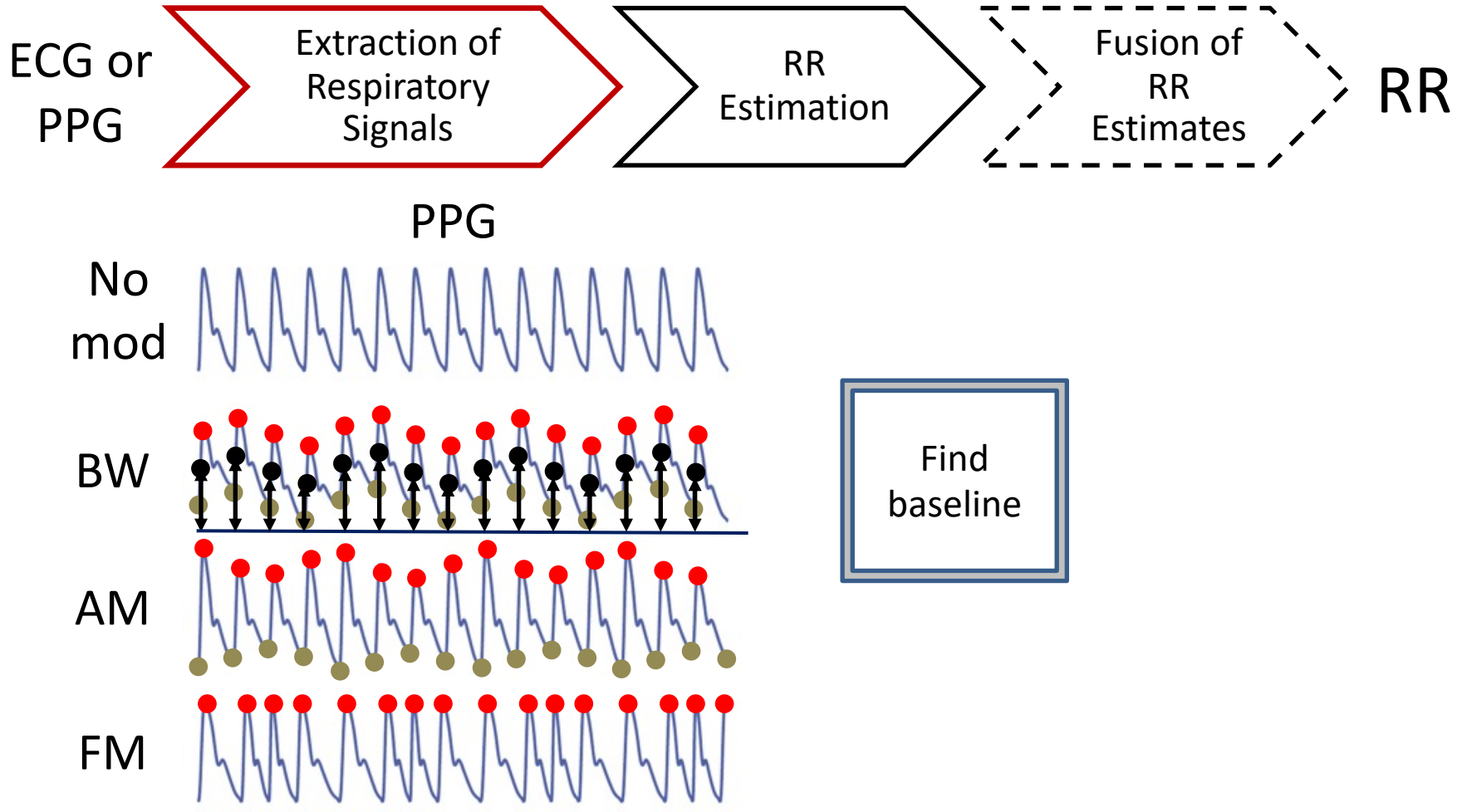


Identify fiducial points

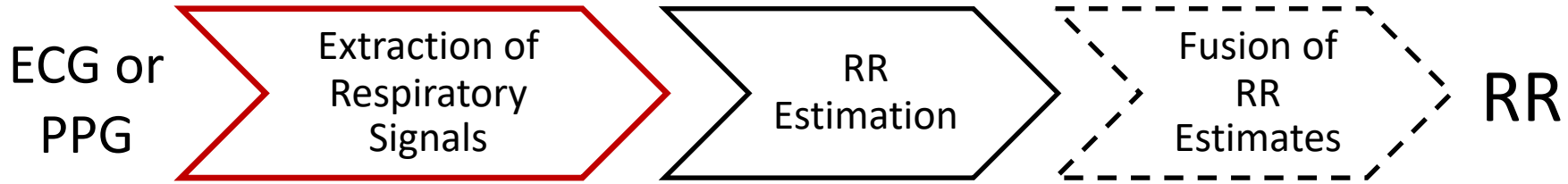
Structure of Algorithms

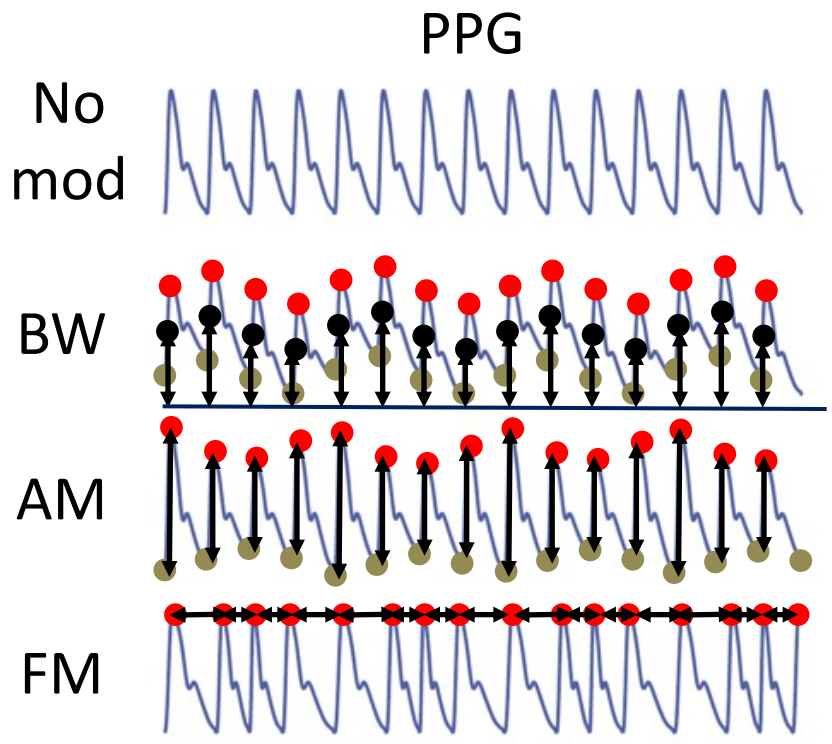


Structure of Algorithms



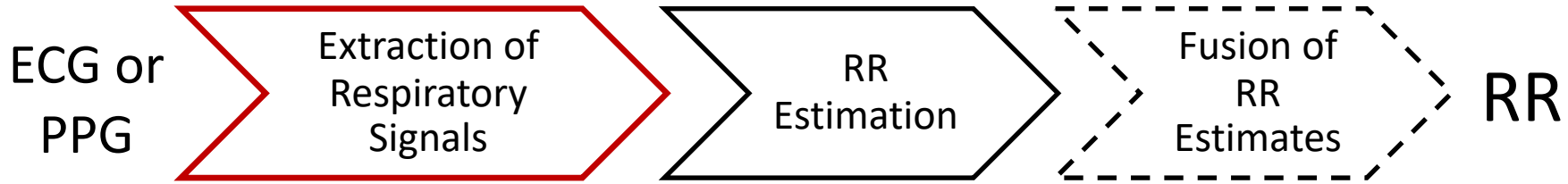
Structure of Algorithms

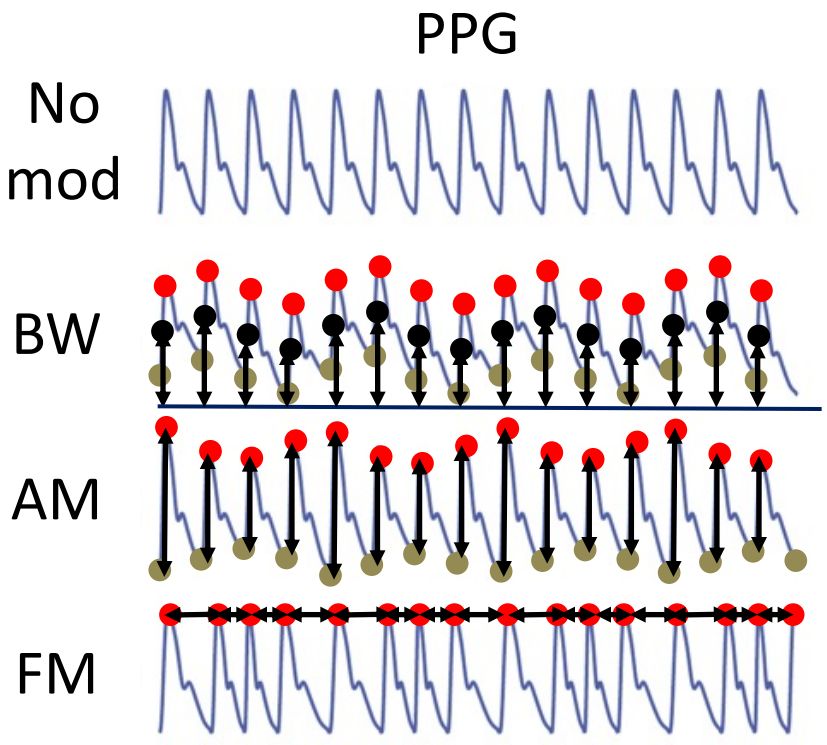


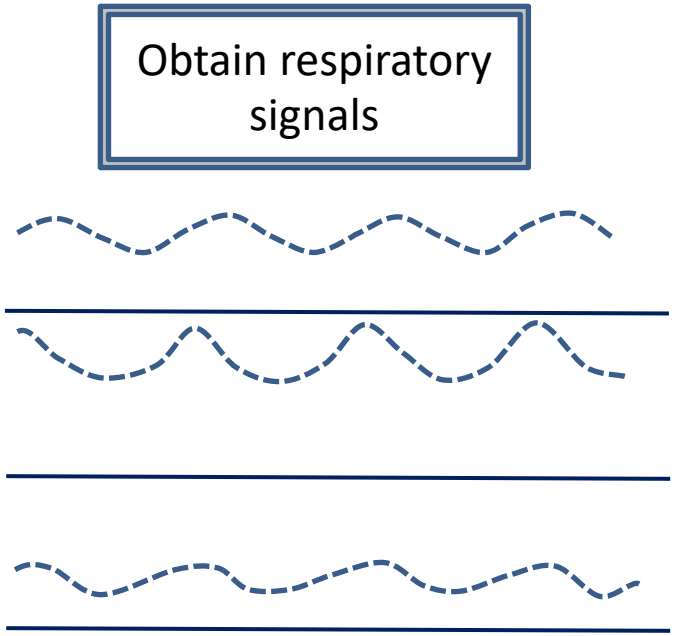


Measure amplitudes and intervals

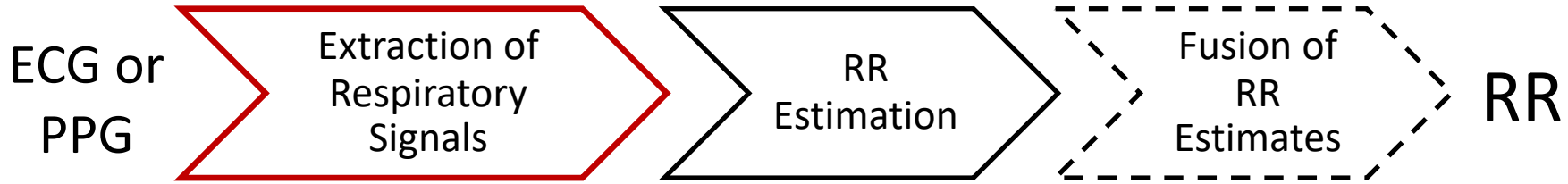
Structure of Algorithms

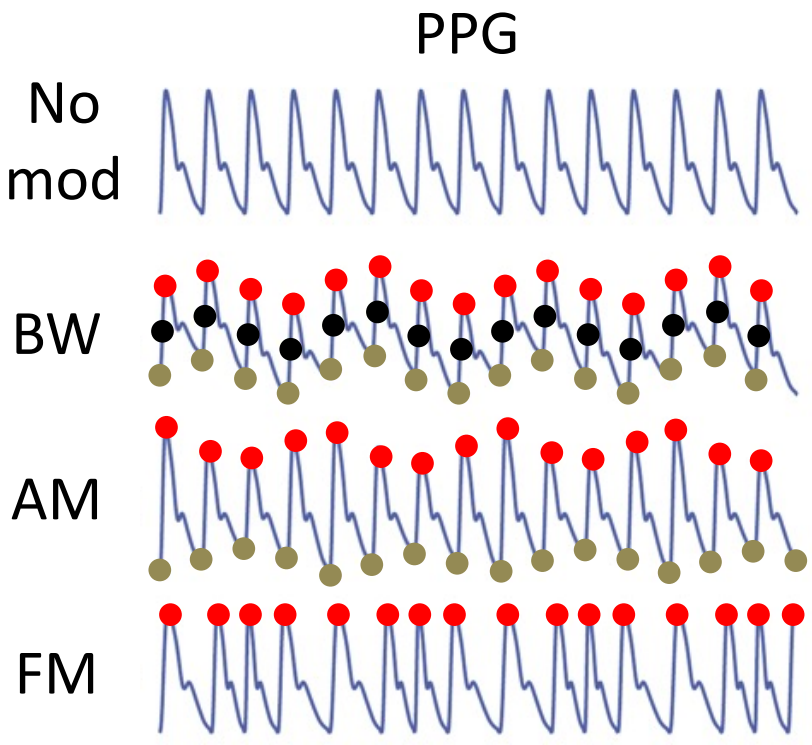


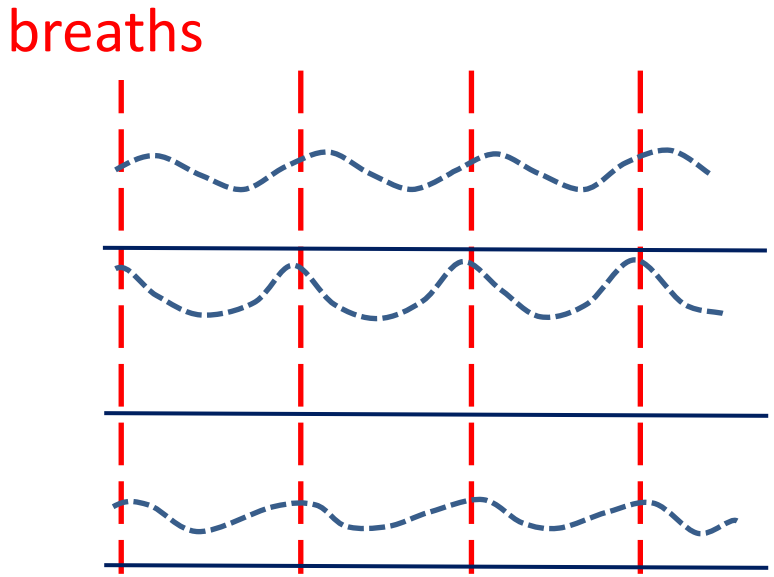




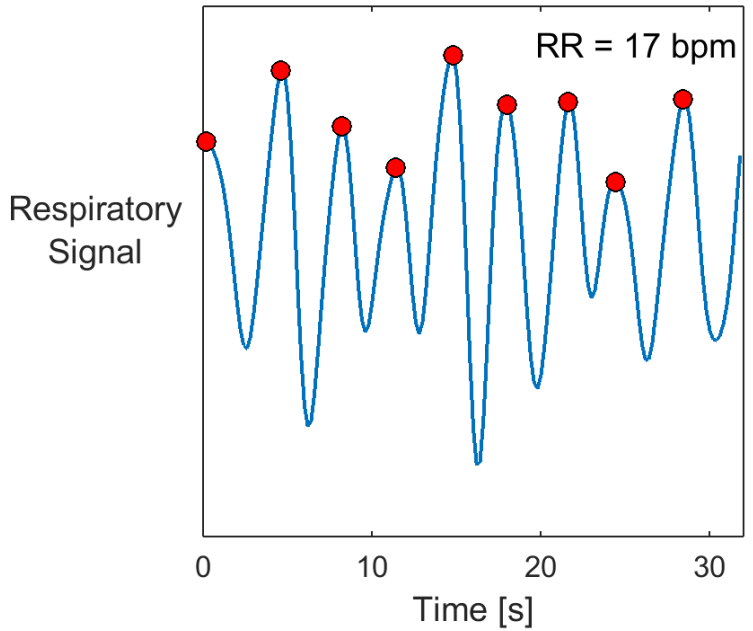
Structure of Algorithms



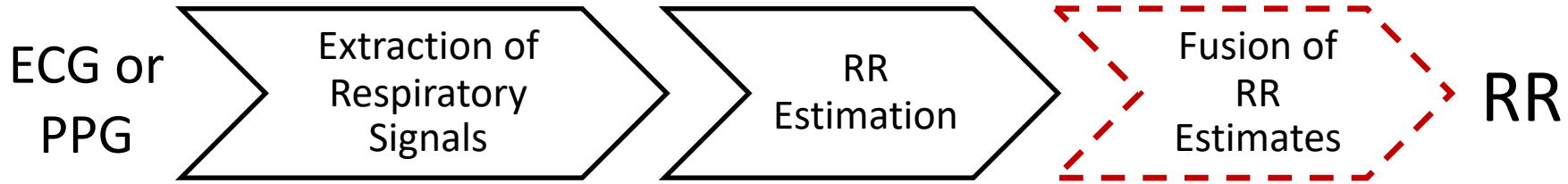


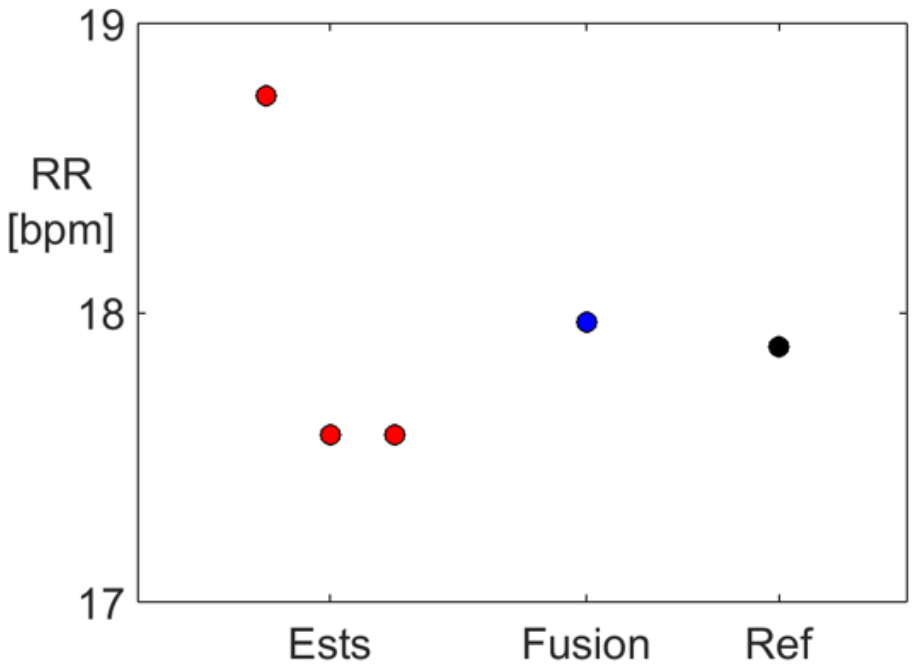


Structure of Algorithms



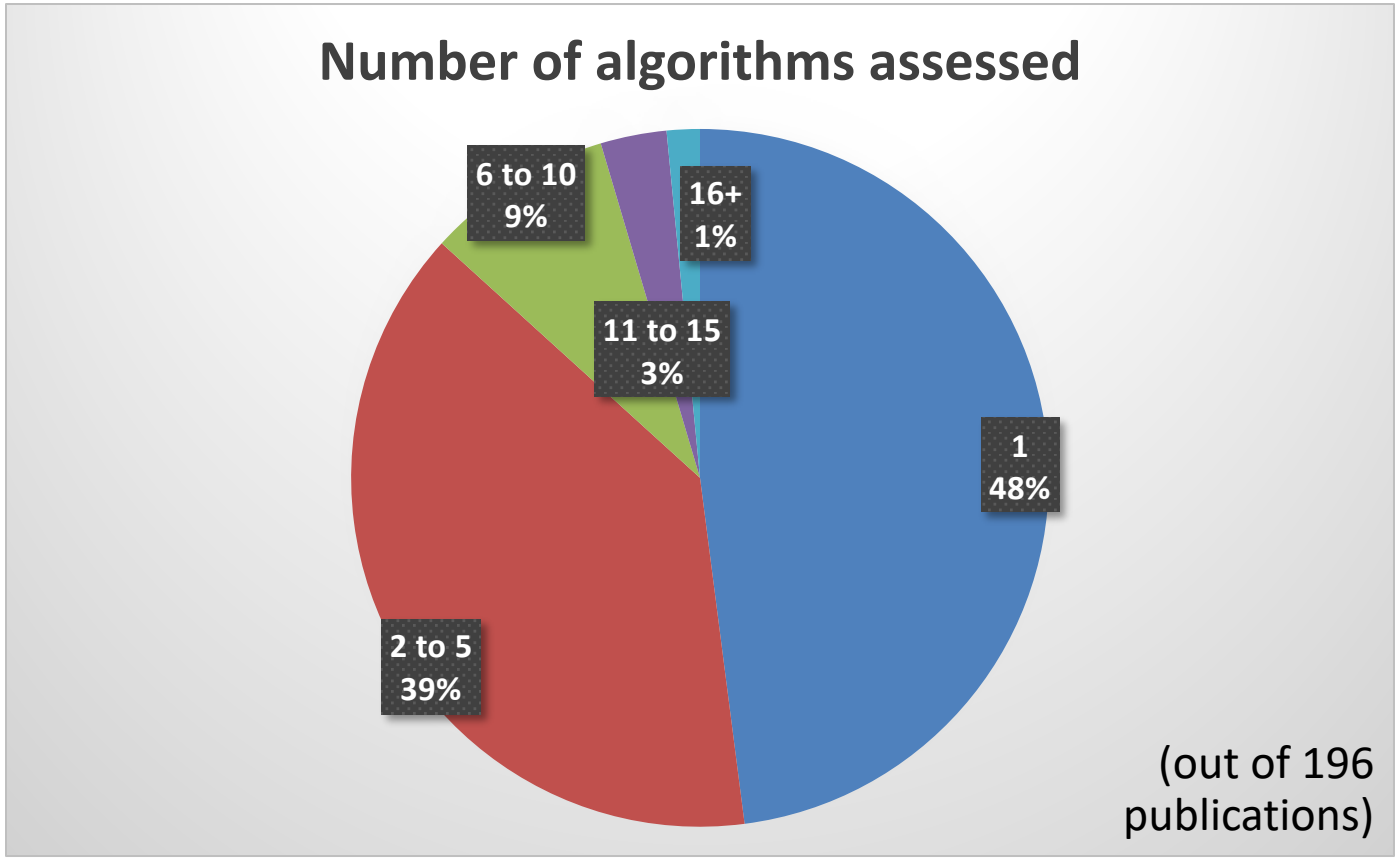
Structure of Algorithms





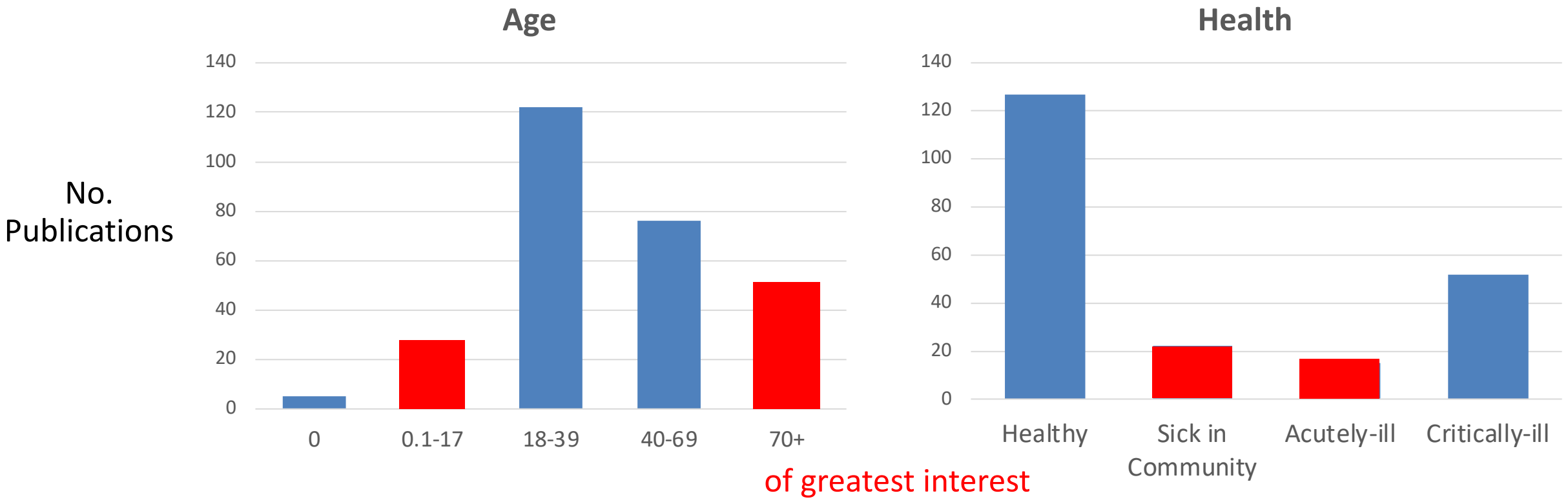
Literature review

Previous studies mostly focused on developing novel algorithms, rather than comparing algorithms:



Literature review

Previous studies primarily used data from young adults, and healthy subjects, rather than assessing performance in the target setting:



Research questions

1. How well do respiratory rate algorithms perform in the target setting?
2. Which algorithm performs best?
3. Is it clinically useful?

Respiratory rate software for wearables

Aim: to develop and validate algorithms to estimate respiratory rate from signals provided by wearables.

Understanding the state-of-the-art

Literature review. Research questions.

Developing a toolbox of algorithms

Implementation. Verification. Dissemination.

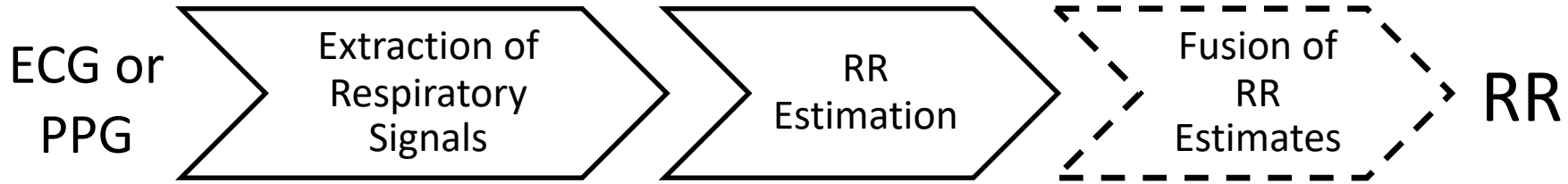
Assessment

Healthy volunteers. Hospital patients. Clinical application.

Future work

Toolbox refinement. Assessment in daily life. Evaluation.

Implementing Algorithms



BW
AM
FM
Peak amplitudes
Onset amplitudes
…

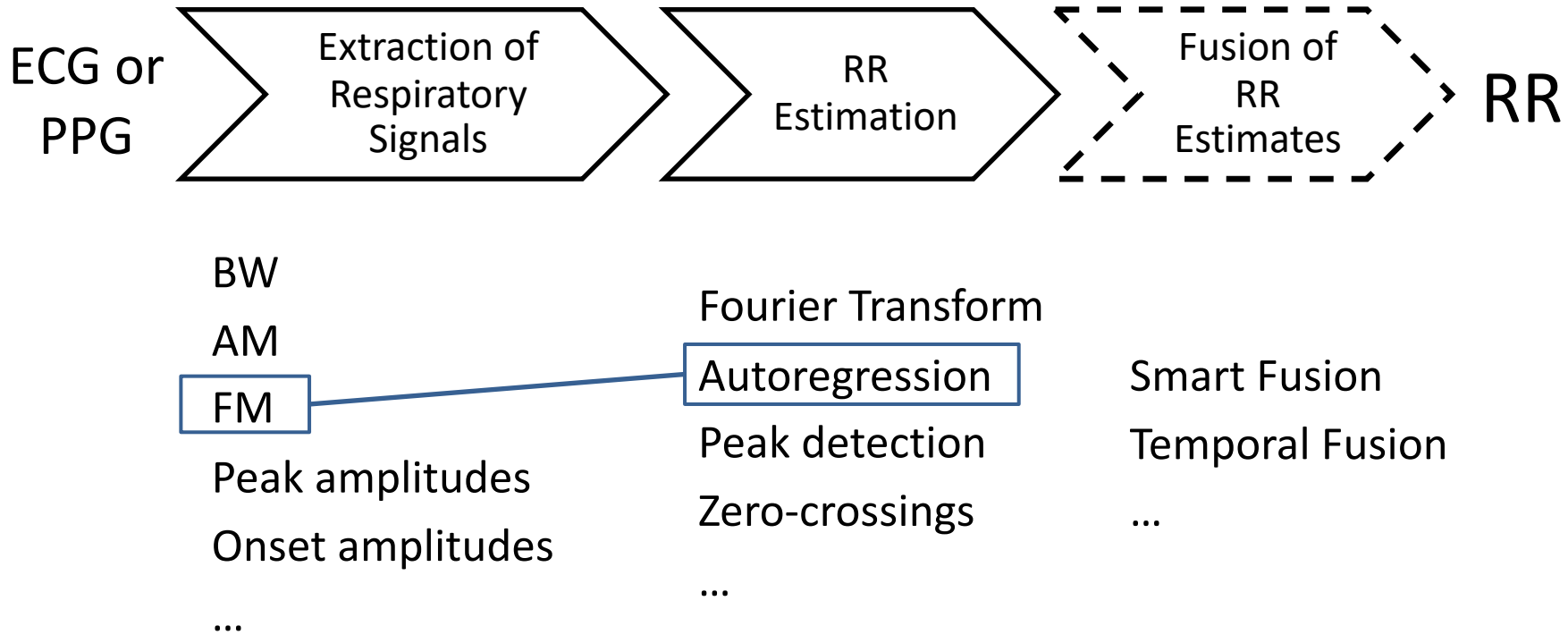
Fourier Transform
Autoregression
Peak detection
Zero-crossings
…

Smart Fusion
Temporal Fusion
…

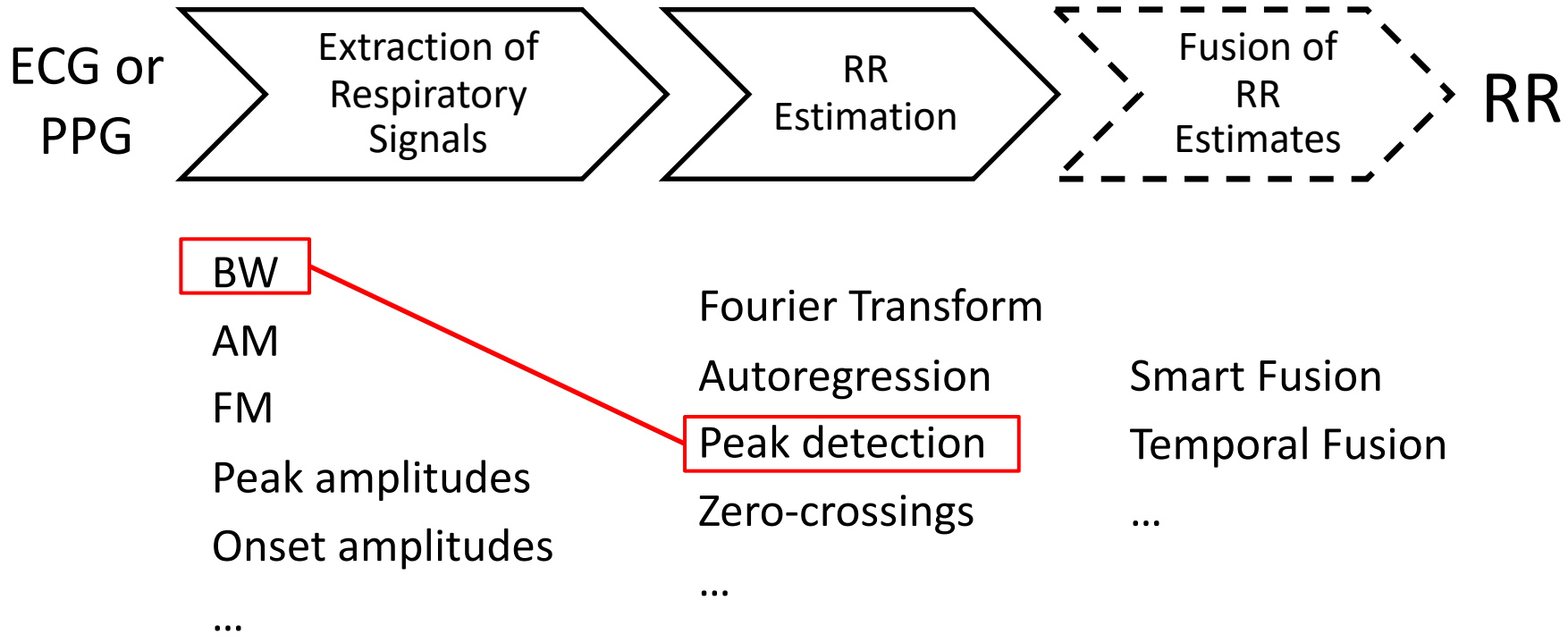
Further reading:

Charlton PH *et al.*, Breathing rate estimation from the electrocardiogram and photoplethysmogram: a review. *IEEE Rev. Biomed. Eng.* **2018**, *11*, 2–20. doi:10.1109/RBME.2017.2763681

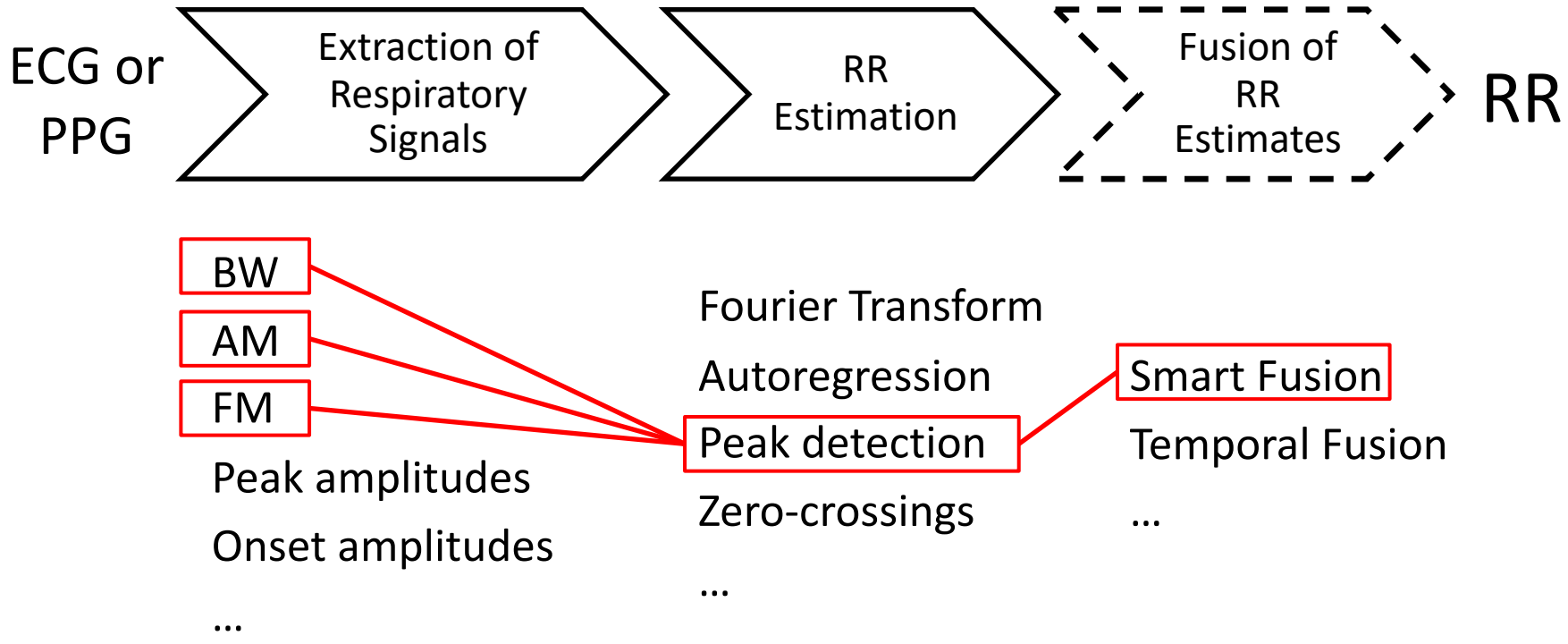
Implementing Algorithms



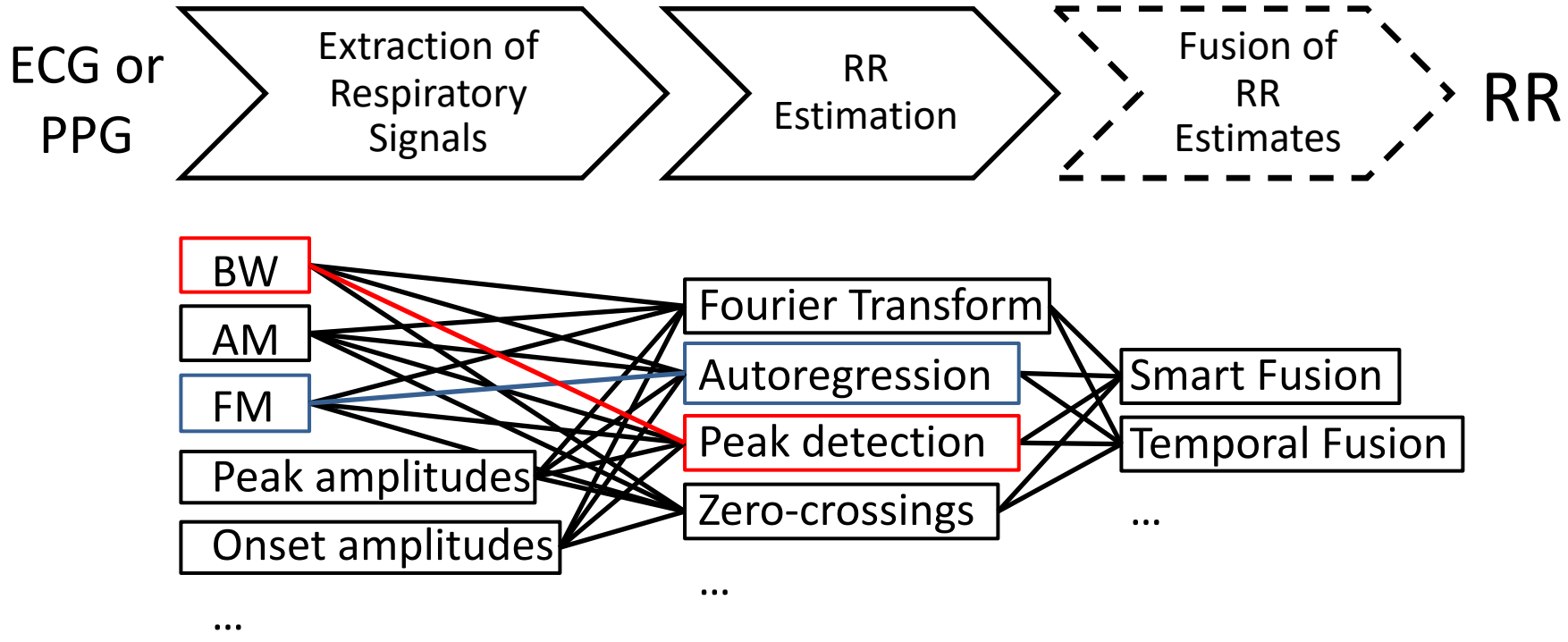
Implementing Algorithms



Implementing Algorithms

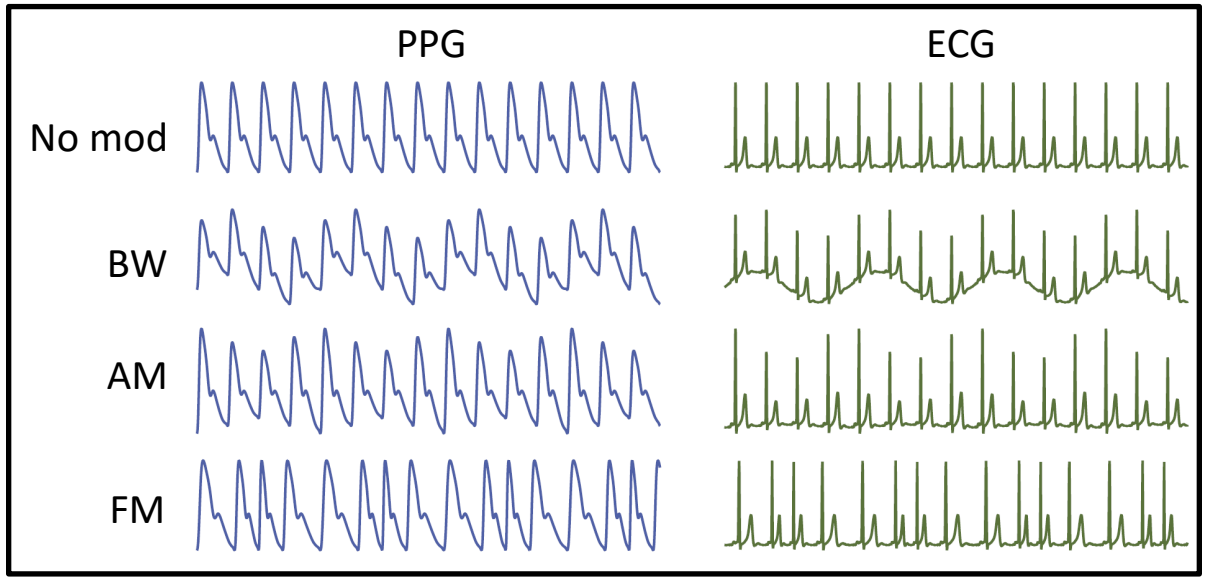


Implementing Algorithms



Verifying Algorithms

- Simulated data
- Range of heart rates
- Range of respiratory rates
- Two techniques resulted in inaccurate algorithms, so were removed
- 314 (85%) of algorithms deemed to be accurate



Disseminating Algorithms

MATLAB Toolbox

https://peterhcharlton.github.io/RRest

> 2,500 downloads

- Algorithms within an assessment framework
  - Helpful for designing and assessing new techniques
  - Not so helpful for using algorithms in devices
- Matlab
  - Widely used in academia
  - Costly
- Open-source
  - GNU GPL
- GitHub
  - Developed over time
  - Little maintenance recently
- Publicised on:
  - Personal website
  - Mathworks File Exchange
  - Youtube

Respiratory rate software for wearables

Aim: to develop and validate algorithms to estimate respiratory rate from signals provided by wearables.

Understanding the state-of-the-art

Literature review. Research questions.

Developing a toolbox of algorithms

Implementation. Verification. Dissemination.

Assessment

Healthy volunteers. Hospital patients. Clinical application.

Future work

Toolbox refinement. Assessment in daily life. Evaluation.

Performance of best algorithm

Input signal	Performance, expressed as limits of agreement (breaths per minute)		
	Healthy laboratory data	Benchmark clinical data	Real-world clinical data
ECG	-4.4 to 4.8	-5.1 to 4.5	-9.8 to 7.4
PPG	-6.5 to 5.9	-3.3 to 2.9	-7.3 to 7.7

The algorithms can produce large errors, which would be clinically significant when compared to the normal RR range of 12-20 bpm.

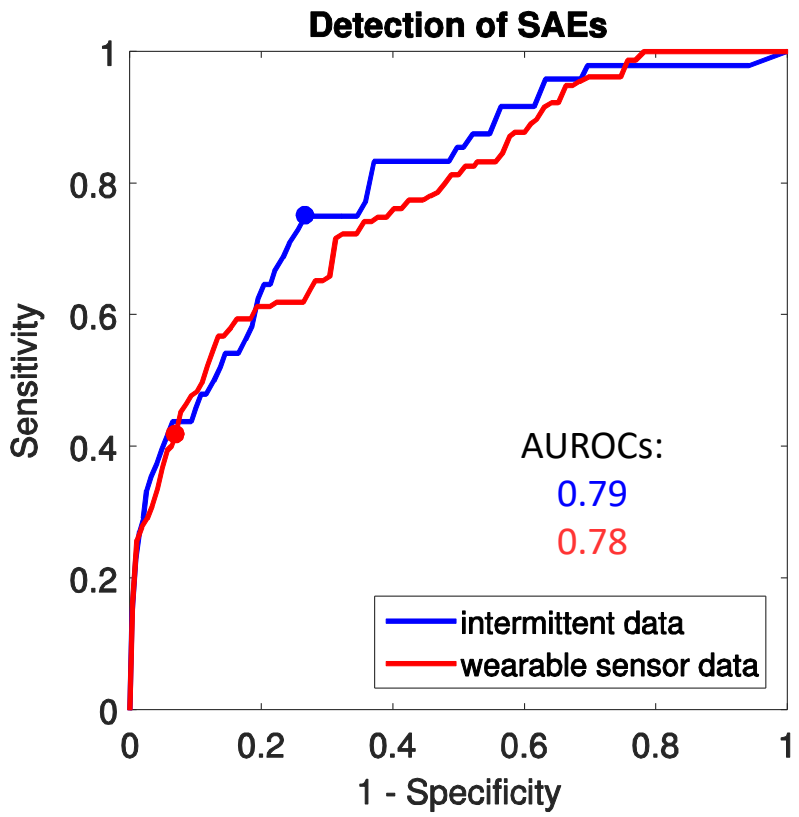
Charlton PH, Continuous respiratory rate monitoring to detect clinical deteriorations using wearable sensors, PhD Thesis, 2017.

Assessing clinical utility

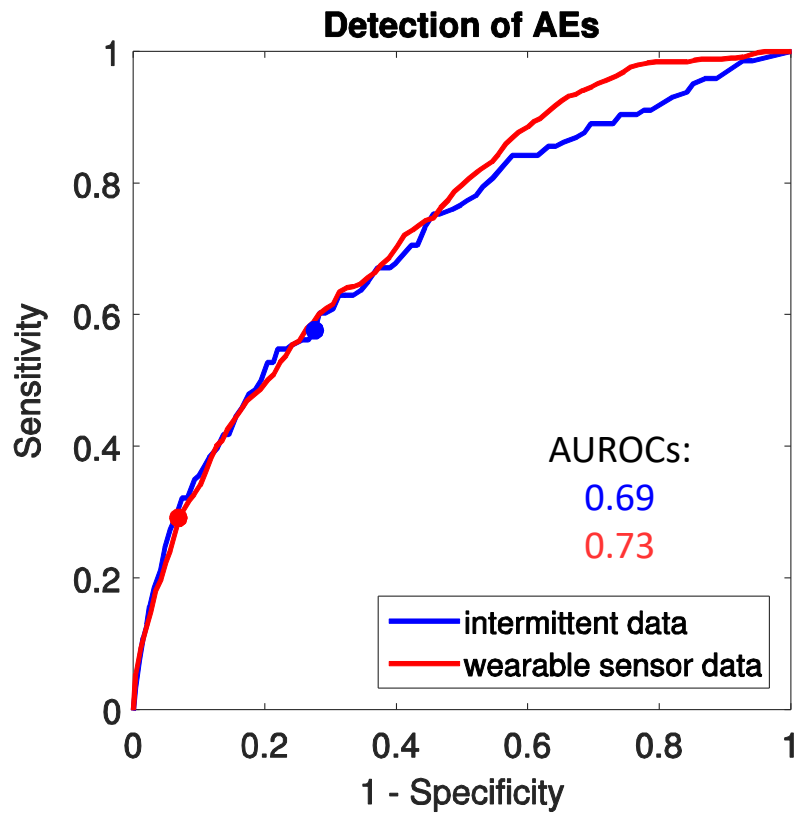
- 184 patients recovering from cardiac surgery on ambulatory ward
- Monitored continuously with wearable sensor for approx. 4 days
- Clinical deteriorations noted:
  - *136 patients didn't deteriorate*
  - *37 had a 'minor' deterioration (e.g. infection, arrhythmia)*
  - *11 had a 'severe' deterioration (e.g. readmission to critical care, cardiac arrest, death)*
- Continuous respiratory rates calculated from ECG signal
- Assessed predictive value of early warning scores when calculated using:
  - *Routine manual observations (every 4-6 hours)*
  - *Wearable data (near continuous)*

Assessing clinical utility

Detecting serious deteriorations



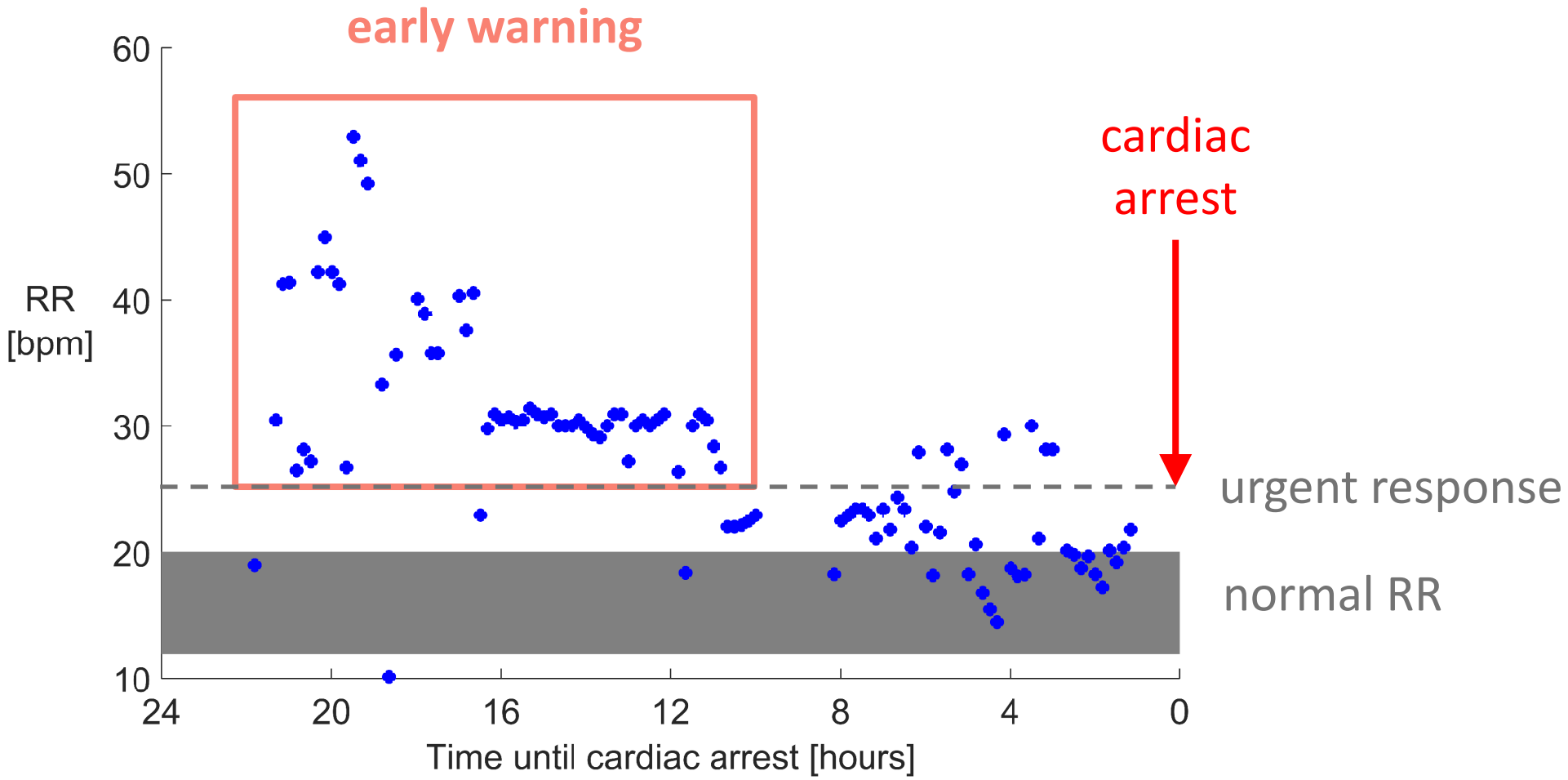
Detecting minor deteriorations



The algorithms could potentially be used for unobtrusive RR monitoring to predict clinical deteriorations with similar accuracy to current clinical practice .

Assessing clinical utility

ECG-derived RRs every 10 mins on hospital ward



Respiratory rate software for wearables

Aim: to develop and validate algorithms to estimate respiratory rate from signals provided by wearables.

Understanding the state-of-the-art

Literature review. Research questions.

Developing a toolbox of algorithms

Implementation. Verification. Dissemination.

Assessment

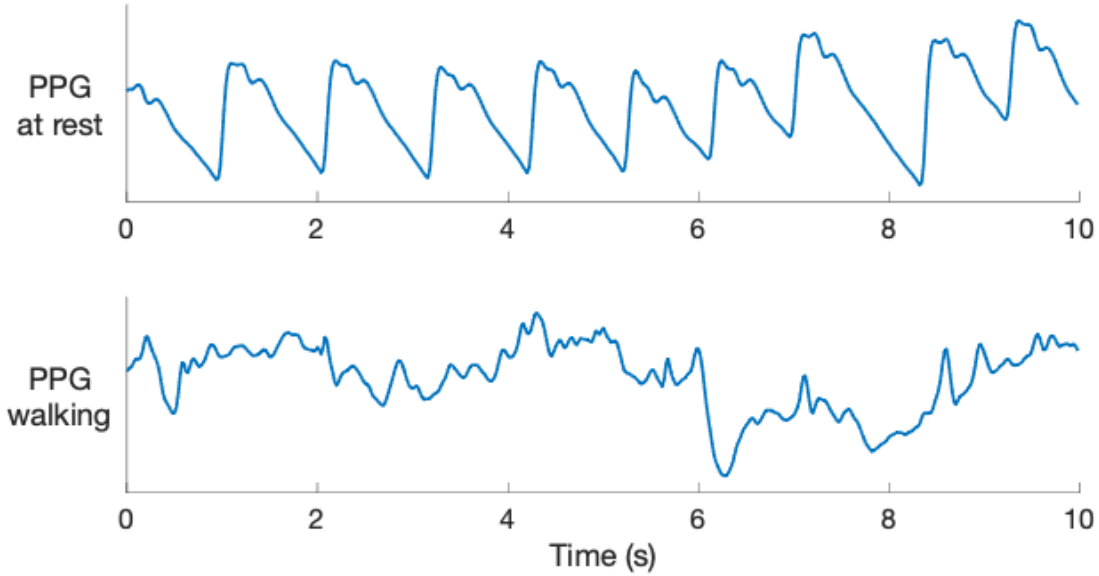
Healthy volunteers. Hospital patients. Clinical application.

Future work

Toolbox refinement. Assessment in daily life. Evaluation.

Future Work

- Implement novel techniques designed to handle lower quality signals
- Assess performance in daily life
- Perform comprehensive evaluation of performance across different settings



Respiratory rate software

Vision for software

Pressing questions

gcasasola, pxhere, https://pxhere.com/en/photo/1457247 (CC0)

Brother UK, https://www.flickr.com/photos/brother-uk/31501281284/in/photostream/ (CC BY 2.0)

StockSnap, Pixabay, https://pixabay.com/photos/code-coding-programming-html-2558224/

Vision for biomedical signal processing software

1. To establish best approaches to key physiological signal processing tasks.
2. To implement these approaches in software suitable for use in devices.
3. To assess the utility of these approaches: validation, and utility for defined applications.

This is discussed further in:

Charlton P.H. *et al.*, **Establishing best practices in photoplethysmography signal acquisition and processing**, *[Under Review]*, 2022

Respiratory rate software

gcasasola, pxhere, https://pxhere.com/en/photo/1457247 (CC0)

Vision for software

Brother UK, https://www.flickr.com/photos/brother-uk/31501281284/in/photostream/ (CC BY 2.0)

Pressing questions

StockSnap, Pixabay, https://pixabay.com/photos/code-coding-programming-html-2558224/

Pressing questions

Creating universal signal processing software

1. Is it possible to create software which would work well across different device / sensor designs, and for different clinical / consumer applications?
2. What protocols should be used for validation?
3. Could such software be approved for universal use?

Disseminating software

4. What coding language?
5. What accompanying materials are required? *e.g.* documentation, test examples.

Encouraging others to use the software and contribute

6. How to form an active community and maintain the software?
7. What additional resources would help? *e.g.* datasets
8. How to encourage innovation? *e.g.* challenges, leaderboards

With thanks to…

Tim Bonnici

Richard Beale

David Clifton

Lionel Tarassenko

Peter Watkinson

Marco Pimentel

Jordi Alastruey

Guy’s and St Thomas’ NHS Foundation Trust

King’s College London

University of Cambridge

EPSRC

British Heart Foundation

This project has demonstrated the potential utility of software to monitor RR using wearable sensors. Further work should assess algorithms in daily life.

A vision was presented to establish best approaches to key physiological signal processing tasks, implement them in software, and assess their utility.

It is not yet clear whether such software could be like a climbing rope:

- highly reliable
- validated
- suitable for different users and settings

Developing software to monitor respiratory rate using wearable sensors

Dr Peter H. Charlton

https://peterhcharlton.github.io

pete@oxon.org

For further reading see:

https://peterhcharlton.github.io/RRest

Charlton P.H. *et al.*, **Breathing rate estimation from the electrocardiogram and photoplethysmogram: a review**, *IEEE RBME*, 2018, https://doi.org/10.1109/RBME.2017.2763681