
# Equitable Photoplethysmography in Wearables: Accurate Data for All

Dr Peter H. Charlton

University of Cambridge

City, University of London

Photo by Luke Chesser on Unsplash

Undiagnosed disease in UK:

0.4 mill — atrial fibrillation

1.4 mill — obstructive sleep apnea

5.5 mill — hypertension

Knauert M et al., Clinical consequences and economic costs of untreated obstructive sleep apnea syndrome, World J Otorhinolaryngol Head Neck Surg, 2015

Public Health England, Atrial fibrillation prevalence estimates in England: Application of recent population estimates of AF in Sweden, 2015


Photo by Luke Chesser on Unsplash


St. Thomas' Hospital
St. Thomas' Hospital

(artistic license – this heart rate is fictional)

"**Equity** is the absence of unfair, avoidable or remediable differences among groups of people …"

World Health Organisation, 'Healthy equity', https://www.who.int/health-topics/health-equity, 2024. *Accessed 24-Sept-2024.*

“**Equity** is the absence of unfair, avoidable or remediable differences among groups of people …”

**remediable**: capable of being corrected

**unfair**: without favouritism or discrimination

*[Oxford English dictionary]*

**groups of people:** “… whether those groups are defined socially, economically, demographically, or geographically or by other dimensions of inequality (e.g. sex, gender, ethnicity, disability, or sexual orientation).”

World Health Organisation, ‘Healthy equity’, https://www.who.int/health-topics/health-equity, 2024. *Accessed 24-Sept-2024.*

Examples from signal processing algorithms:

"**Equity** is the absence of unfair, avoidable or remediable differences among groups of people …"

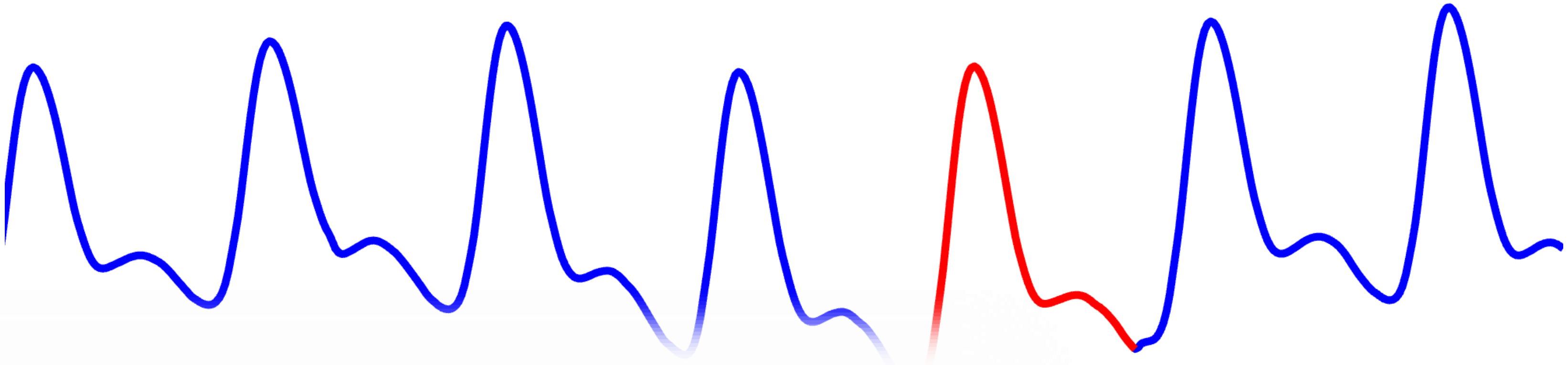
**unfair**: *e.g.* training an algorithm on a select group without accounting for other groups

**remediable**: *e.g.* specifying constants which are not suitable across all groups

**avoidable:** *e.g.* using a suboptimal algorithm when other algorithms would perform better across groups

# PPG beat detection:

**Adult:**

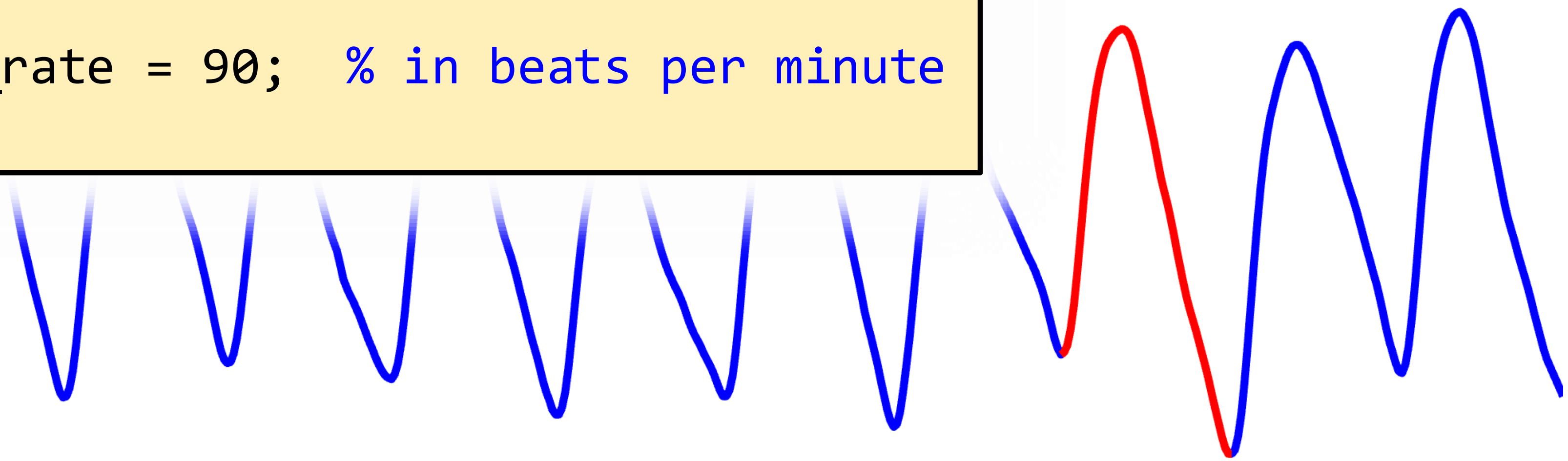


Heart rate: ~97 bpm

```
%% Assumptions

typical_heart_rate = 90;  % in beats per minute
```

**Neonate:**

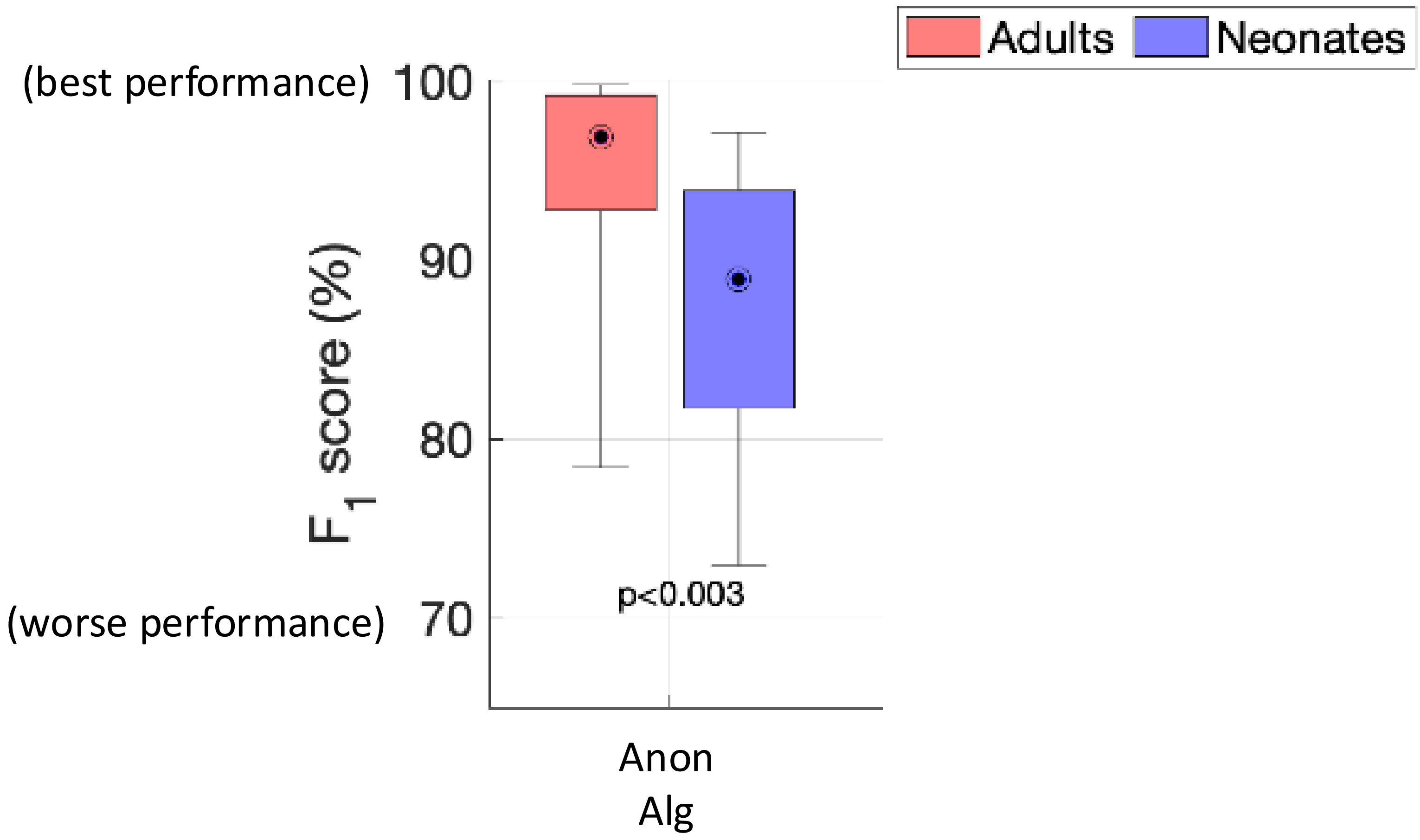


Heart rate: ~150 bpm

PPG beat detection:

```
%% Assumptions

typical_heart_rate = 90;  % in beats per minute
```



PPG beat detection:

```
%% Assumptions

typical_heart_rate = 90;  % in beats per minute
```

"**Equity** is the absence of unfair, avoidable or remediable

differences among groups of people …"

**remediable**: could we improve performance across groups by modifying this constant?

**unfair**: *e.g.* training an algorithm on a select group without diverse subjects?

**unfair**: could we improve performance by re-training on data consisting of other groups

**avoidable:** *e.g.* using a suboptimal algorithm when better algorithms would perform better across groups?

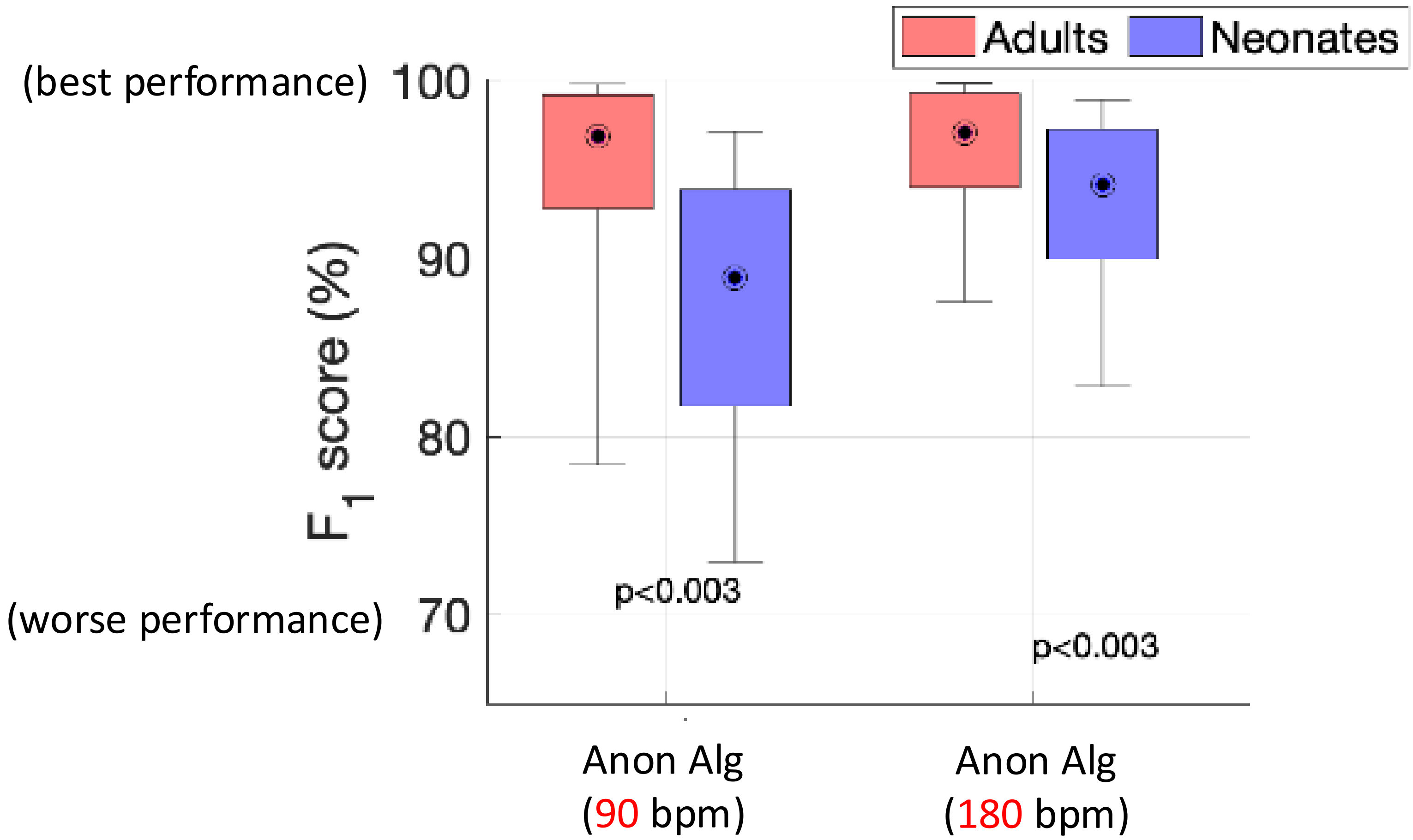
**avoidable:** could an alternative algorithm provide better performance across different groups

World Health Organisation, 'Healthy equity', https://www.who.int/health-topics/health-equity, 2024. *Accessed 24-Sept-2024.*

PPG beat detection:

```
%% Assumptions

typical_heart_rate = 180;   % in beats per minute
```



PPG beat detection:

```
%% Assumptions

typical_heart_rate = 90;  % in beats per minute
```

"**Equity** is the absence of unfair, avoidable or remediable differences among groups of people …"

**unfair**: algorithm was trained on adults to identify a typical heart rate of 90 bpm

**remediable**: could we improve performance across groups by modifying this constant?

**avoidable:** could use an alternative algorithm which performs better across different groups

World Health Organisation, 'Healthy equity', https://www.who.int/health-topics/health-equity, 2024. *Accessed 24-Sept-2024.*

PPG beat detection:

```
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typical_heart_rate = 90;  % in beats per minute
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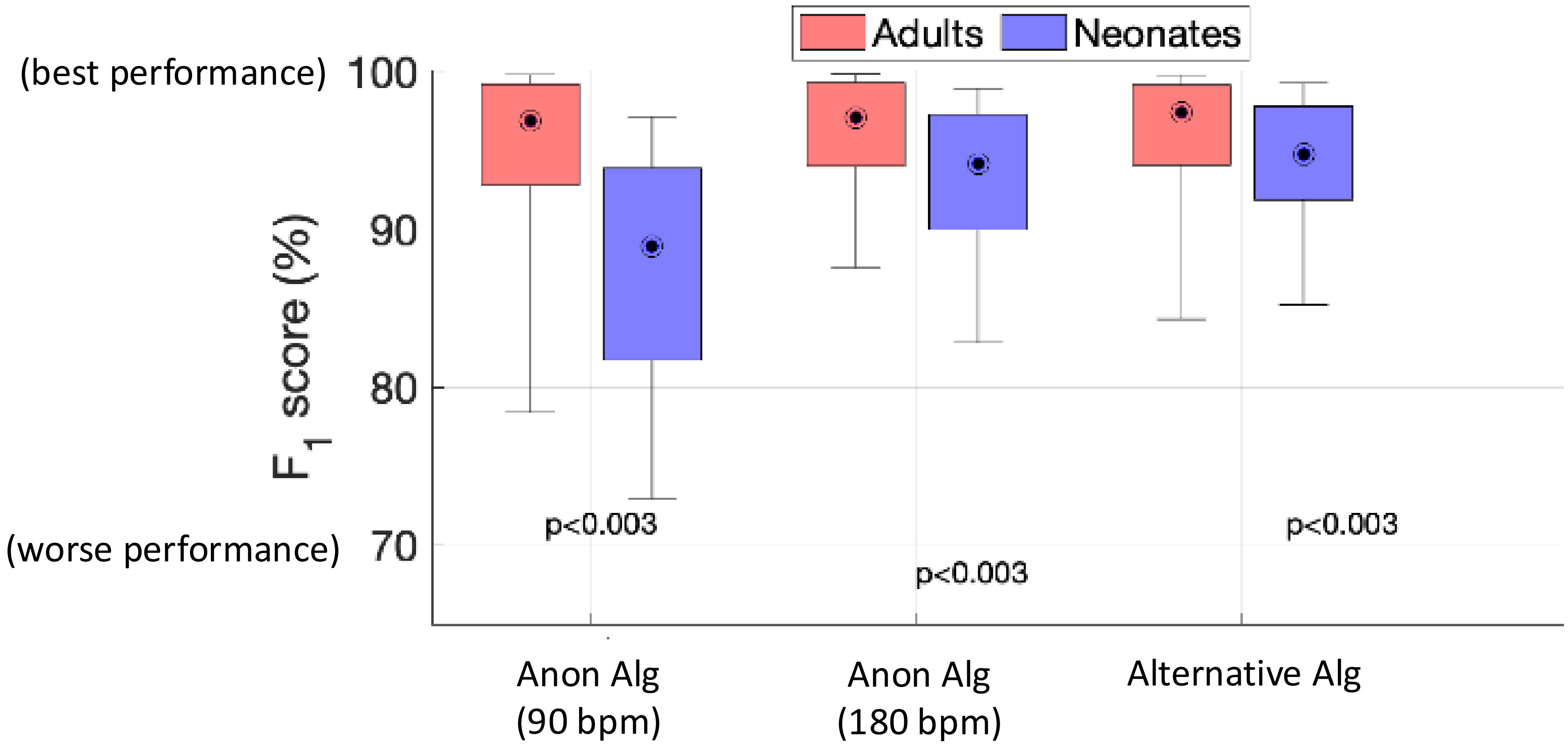
# PPG beat detection:



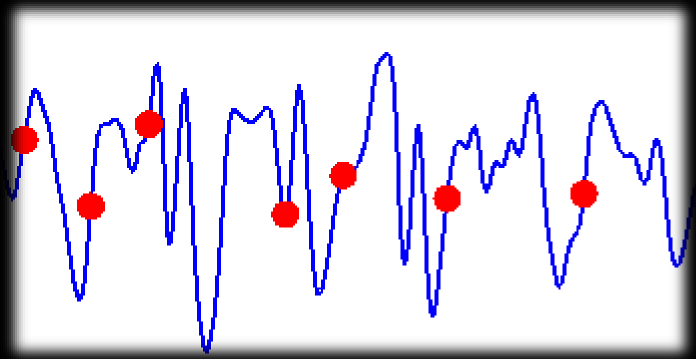
“**Equity** is the absence of unfair, avoidable or remediable differences among groups of people …”

Many, many factors contribute to equity, *e.g.*

- Performance of wearables
- Acceptability of wearables

**1. Introduction to wearables**

**2. Our contributions**



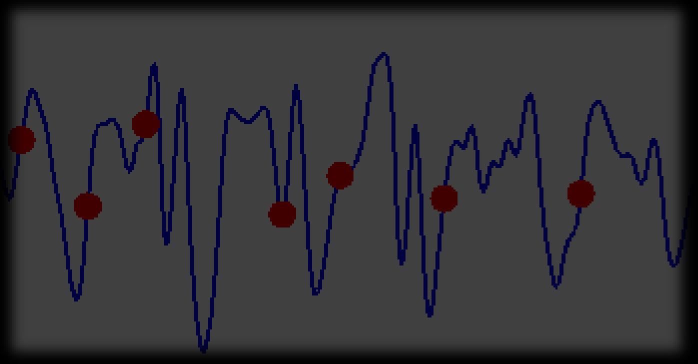
**3. Perspectives**

Photo by Luke Chesser on Unsplash

Photo by Dario Valenzuela on Unsplash

**1. Introduction to wearables**

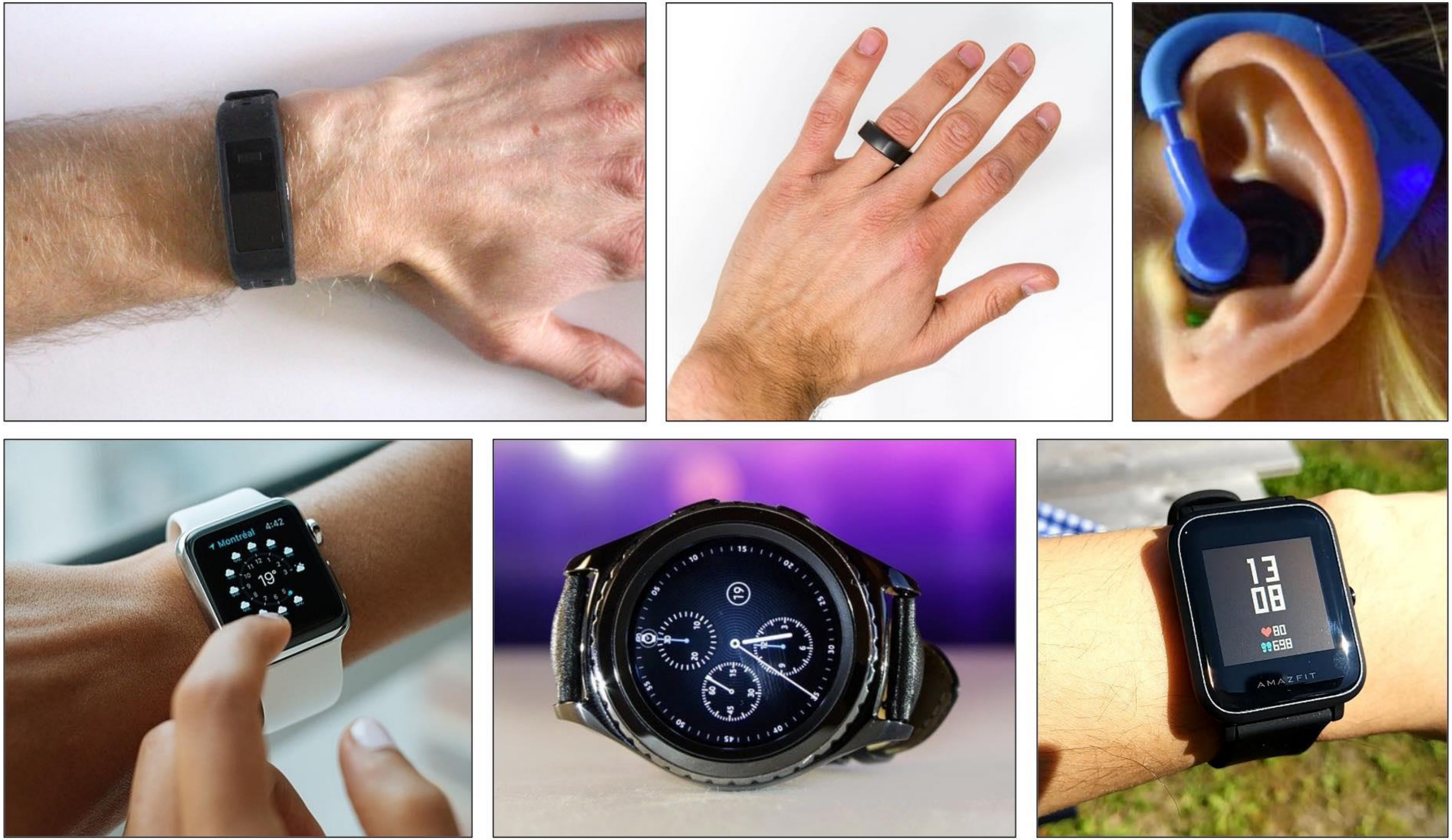

**2. Our contributions**



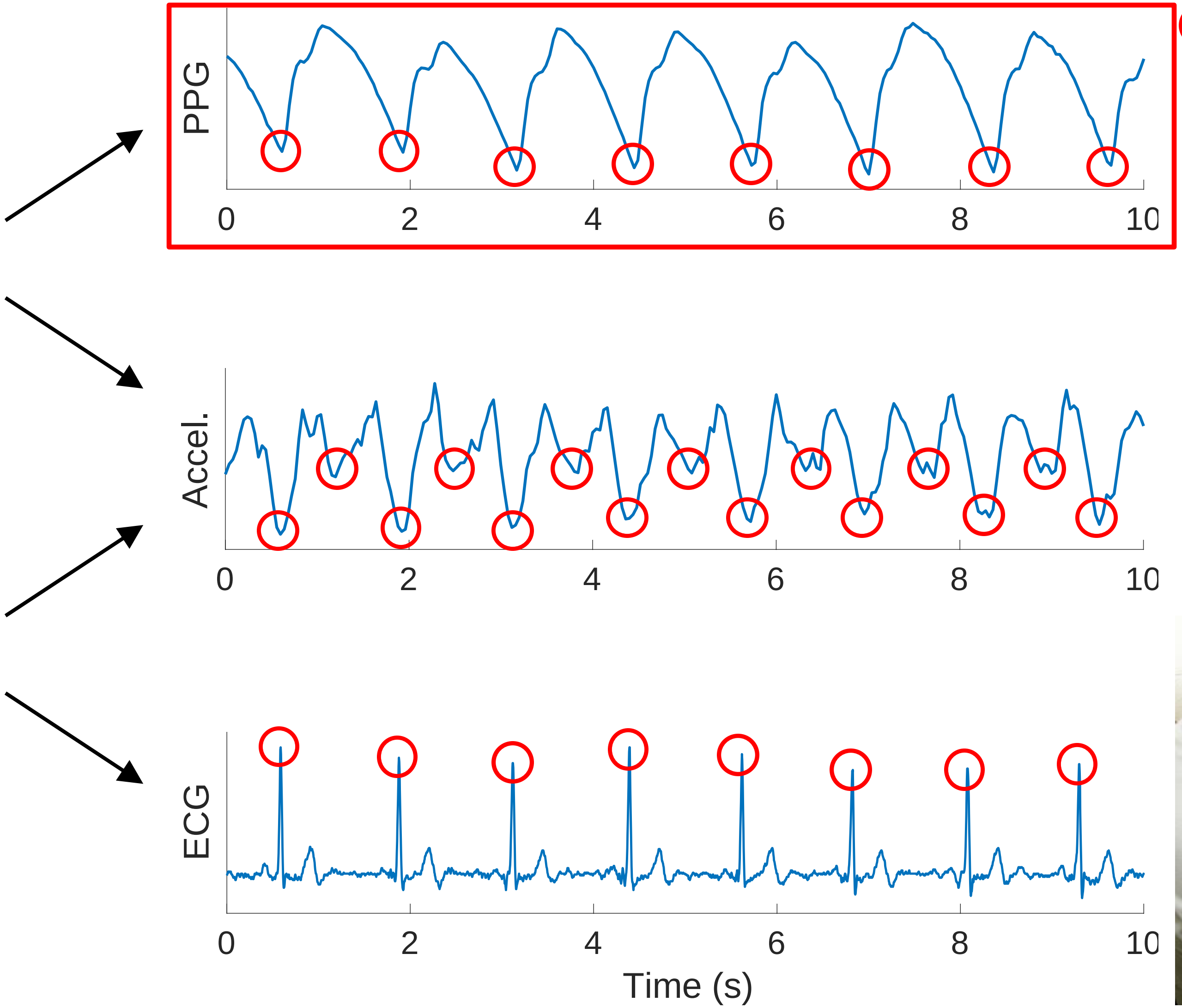
**3. Perspectives**

Photo by Luke Chesser on Unsplash

Photo by Dario Valenzuela on Unsplash

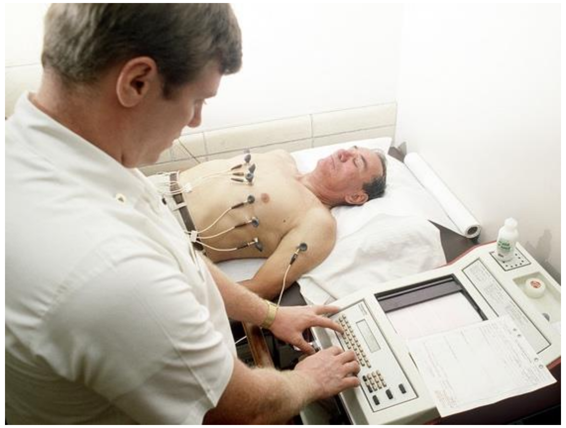

Montréal
4:42
19°
13
08
80
698
AMAZFIT

A **Fitness tracker** which acquires photoplethysmography (PPG) and accelerometry (Accel.) signals




**Pulse waves** used to:
- estimate heart rate
- identify an irregular pulse

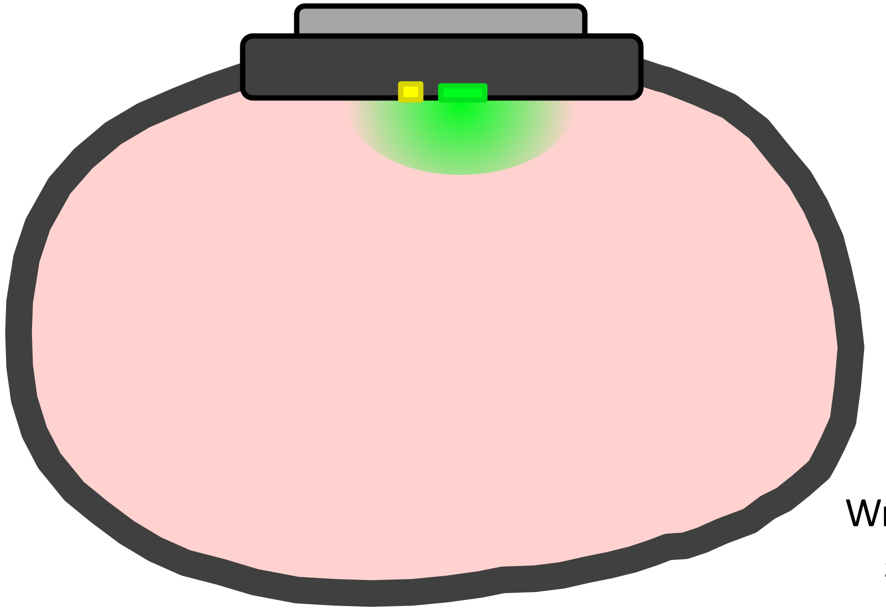
**Steps** used to:
- estimate step count



A **Smartwatch** which acquires electrocardiography (ECG) and accelerometry (Accel.) signals

# The Photoplethysmogram

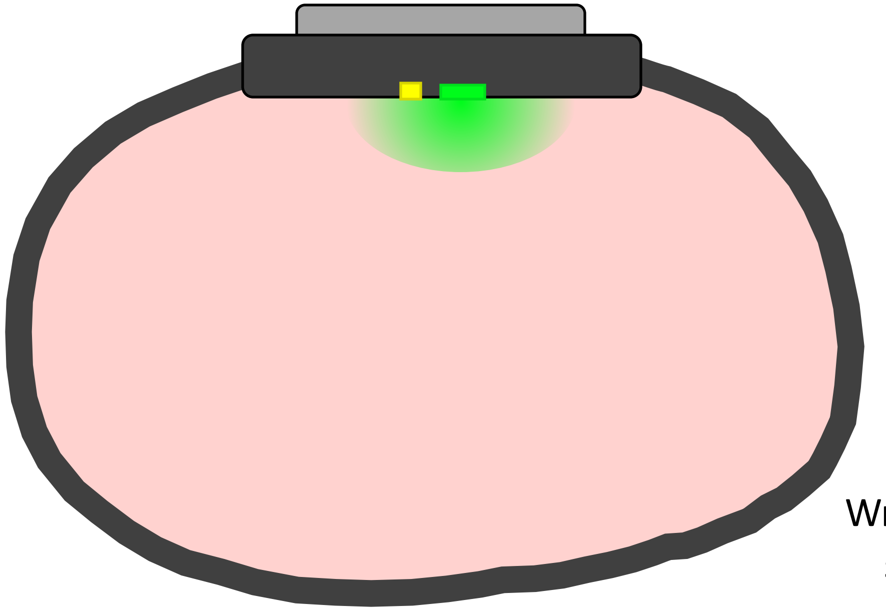
Photoplethysmogram (PPG) Sensor



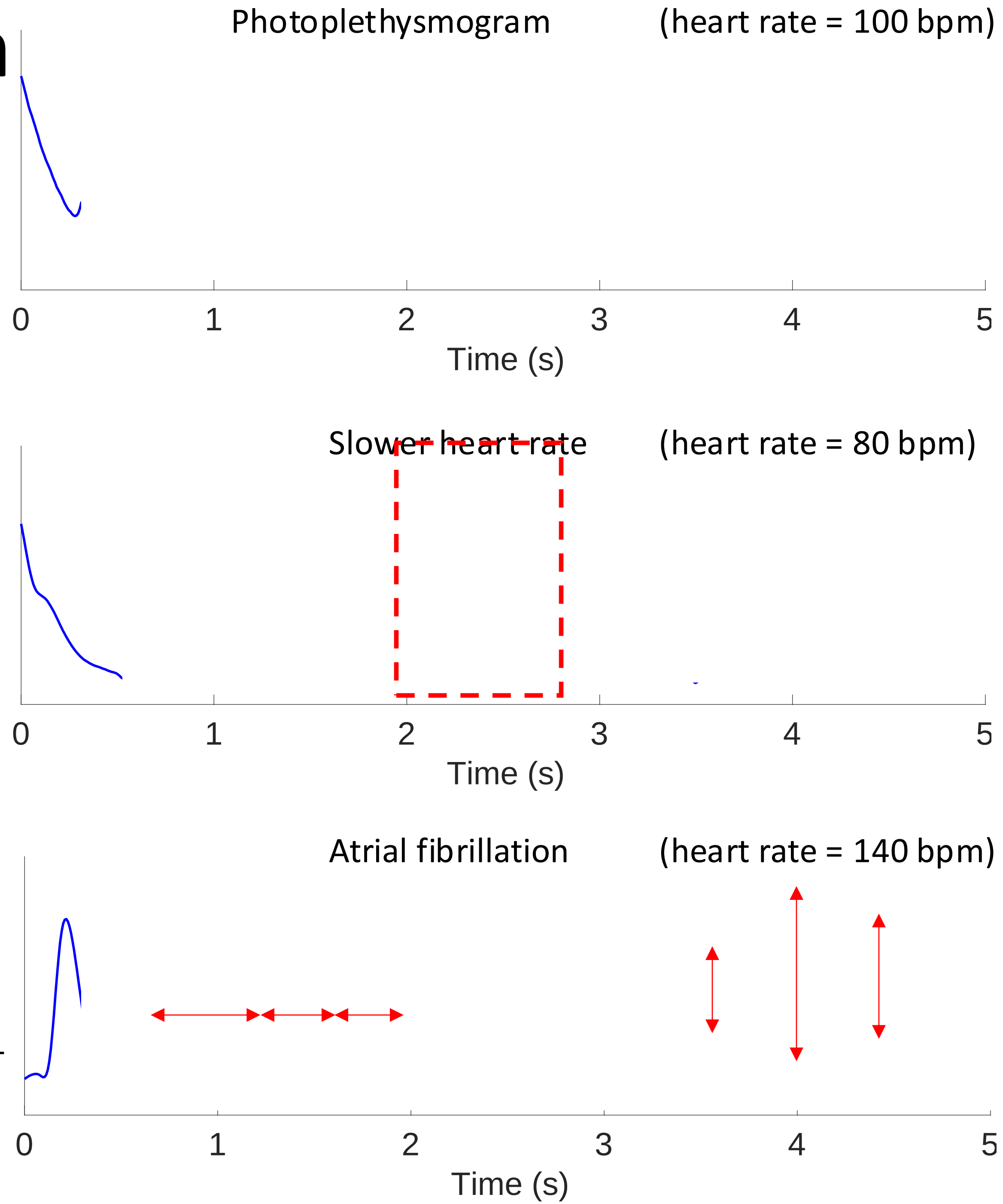
Wrist cross-section

# The Photoplethysmogram

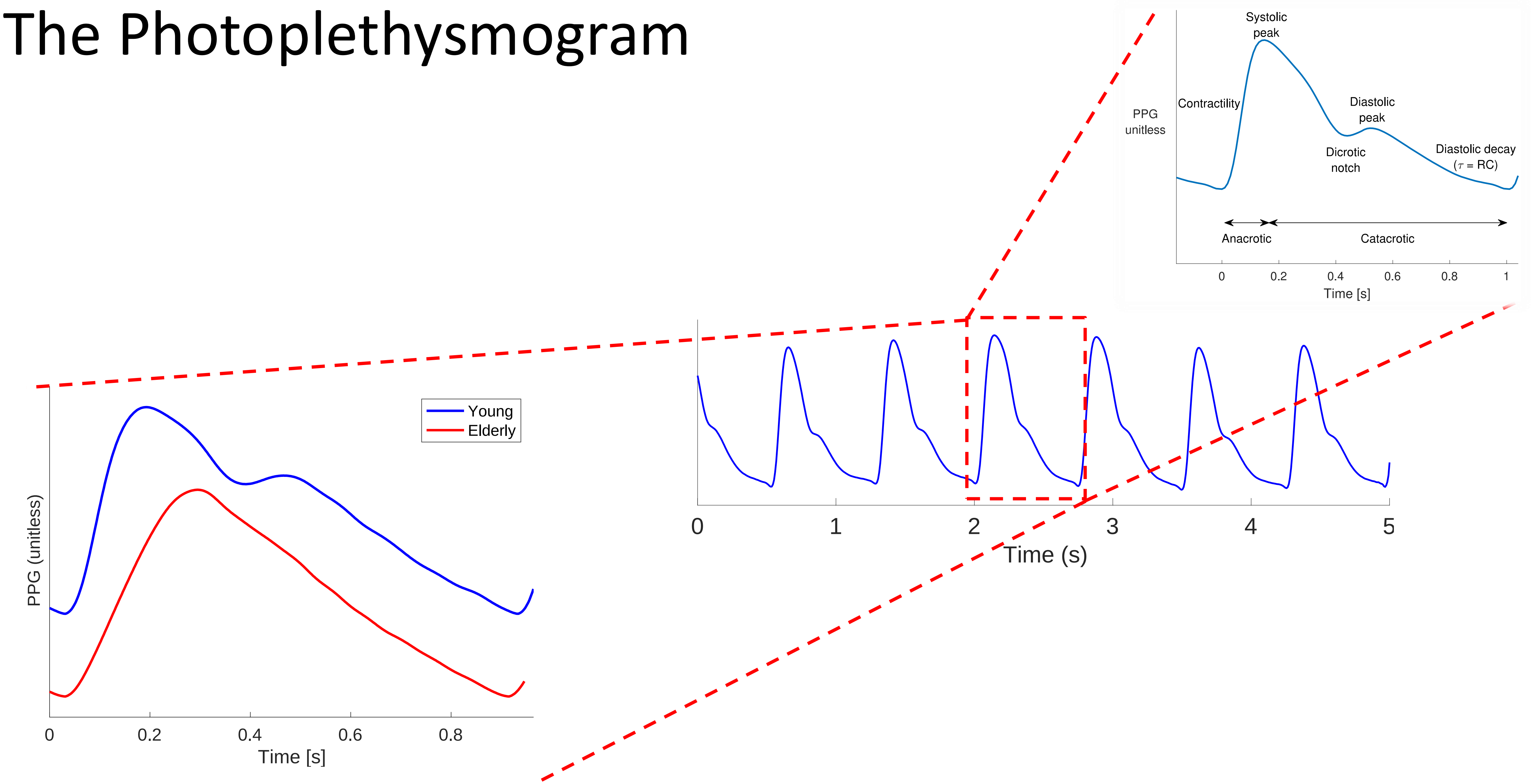
Photoplethysmogram (PPG) Sensor



Wrist cross-section



# The Photoplethysmogram




Charlton PH *et al.*, Wearable photoplethysmography for cardiovascular monitoring, Proc. IEEE, 2022. https://doi.org/10.1109/JPROC.2022.3149785 (CC BY 4.0)

Peter Charlton, PhD Thesis (CC BY 4.0)

# Further Reading on Wearable Photoplethysmography

Broad overview:

Charlton P.H. *et al.*, **The 2023 wearable photoplethysmography roadmap**, *Phys Meas*, 2023, https://doi.org/10.1088/1361-6579/acead2

Review article:

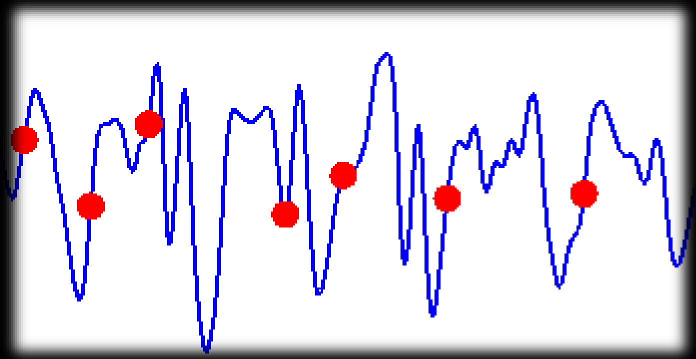
Charlton P.H. *et al.*, **Wearable Photoplethysmography for Cardiovascular Monitoring**, Proc. *IEEE*, 2022, https://doi.org/10.1109/JPROC.2022.3149785

Textbook chapter:

Charlton P.H. and Marozas V., **Wearable photoplethysmography devices**, *Photoplethysmography*, 2021, https://doi.org/10.1016/B978-0-12-823374-0.00011-6

1. Introduction to wearables


2. Our contributions



3. Perspectives

Photo by Luke Chesser on Unsplash

Photo by Dario Valenzuela on Unsplash

**If atrial fibrillation was adequately treated in England:**

**2,000** — **Lives saved p.a.**

**7,000** — **Strokes prevented**

**425,000** — **Additional diagnoses**

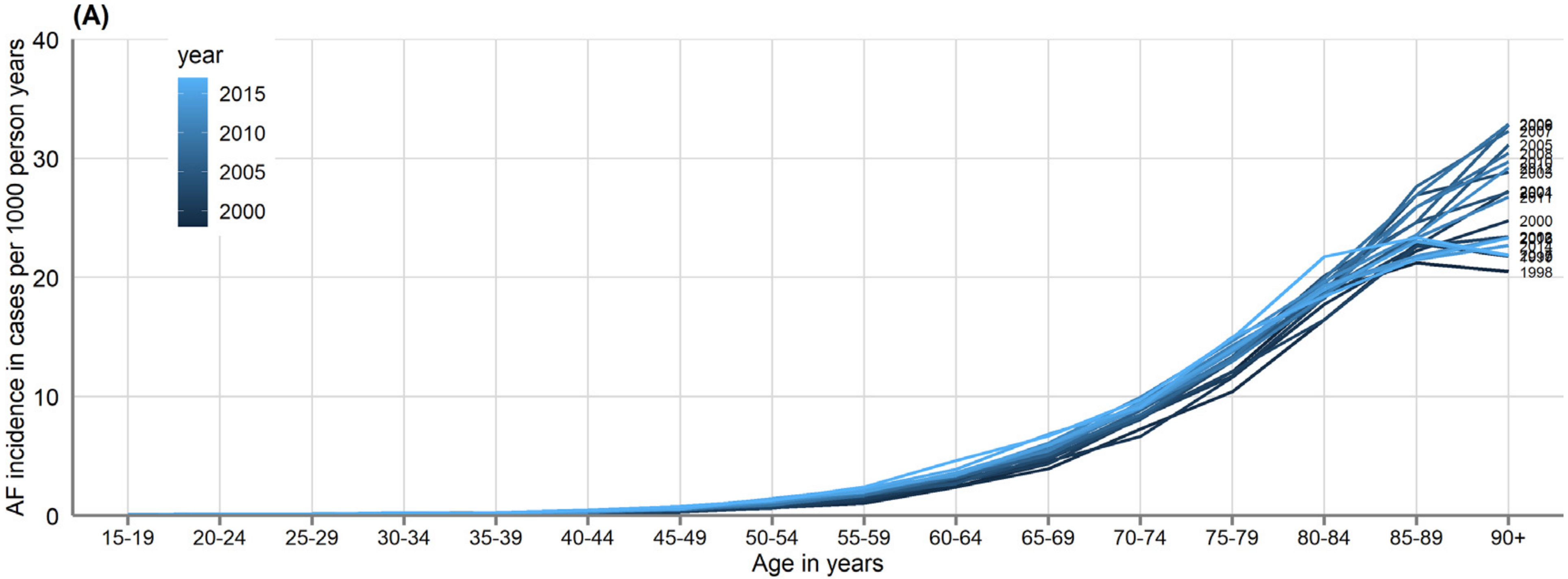
Stroke Association, "State of the Nation," 2017.
Public Health England, "Atrial fibrillation prevalence estimates in England …", 2015.

Pexels, https://pixabay.com/photos/man-heartache-chest-pain-hurt-pain-1846050/ (Pixabay Licence)

# Target population and target setting

**Older adults because:**

- AF incidence increases with age




*From primary and secondary electronic health records of 3.4 million individuals in England*

**In daily life because:**

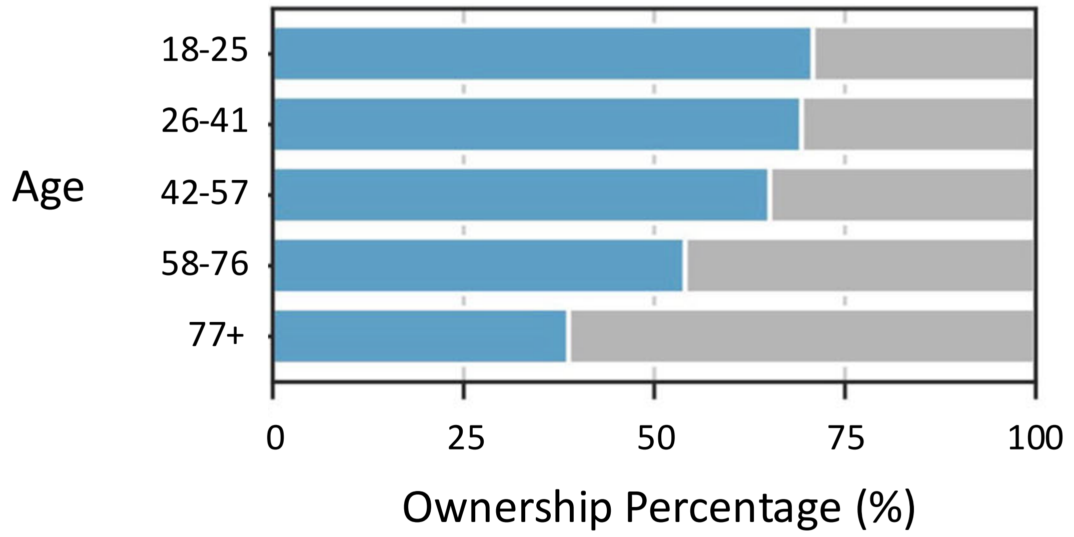
- AF can occur infrequently

Wu J *et al.*, 'Temporal trends and patterns in atrial fibrillation incidence: A population-based study of 3.4 million Individuals',
https://doi.org/10.1016/j.lanepe.2022.100395 (CC BY 4.0)

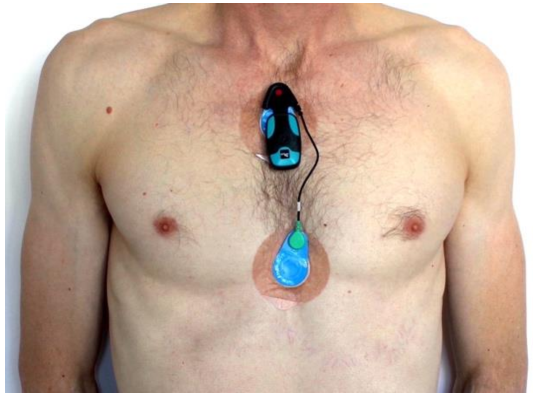
# Smartwatch ownership

Not everyone has a smartwatch, particularly older adults

*An electronic survey of 1,368 patient advisory group members:*




Shandhi MH et al., ‘Assessment of ownership of smart devices and the acceptability of digital health data sharing’, https://doi.org/10.1038/s41746-024-01030-x (CC BY 4.0)



SAFER
wearables study

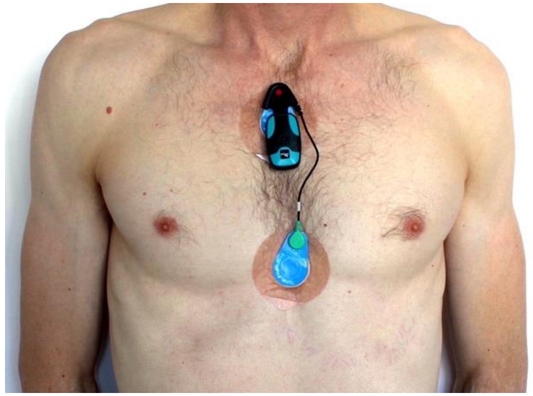
**Aim:** Assess performance and acceptability of wearables for detecting atrial fibrillation (AF)

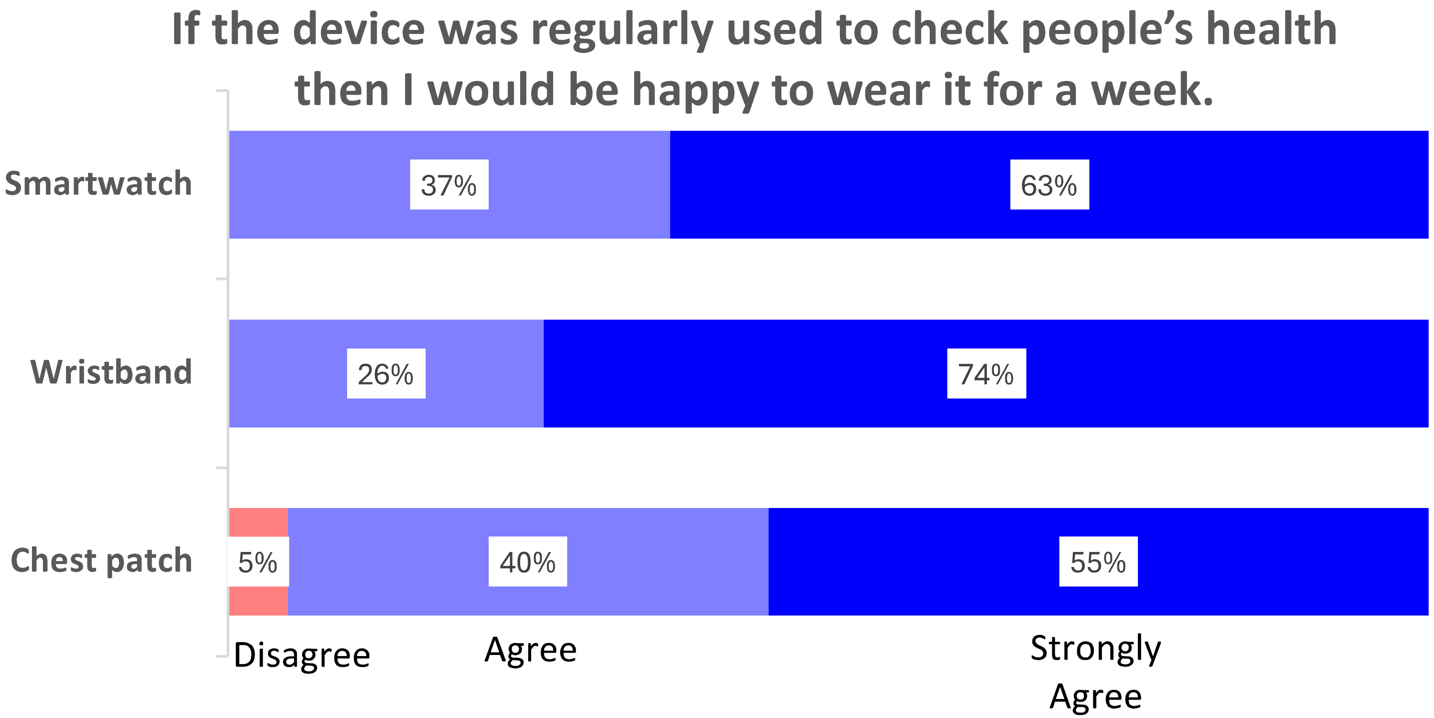
**Methods:**

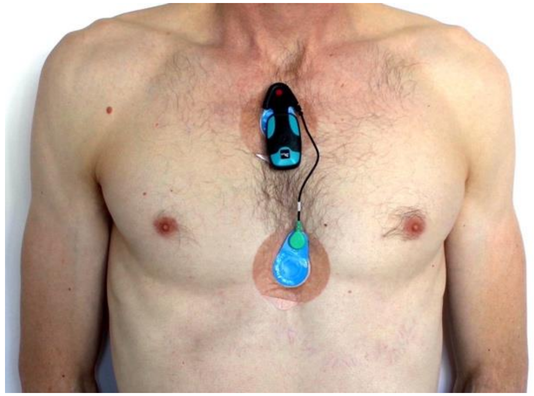
- In 130 older adults, aged 65+, half of whom have AF
- Two wrist-worn devices: smartwatch, wristband
- Reference ECG chest patch
- Questionnaire

**Progress:**

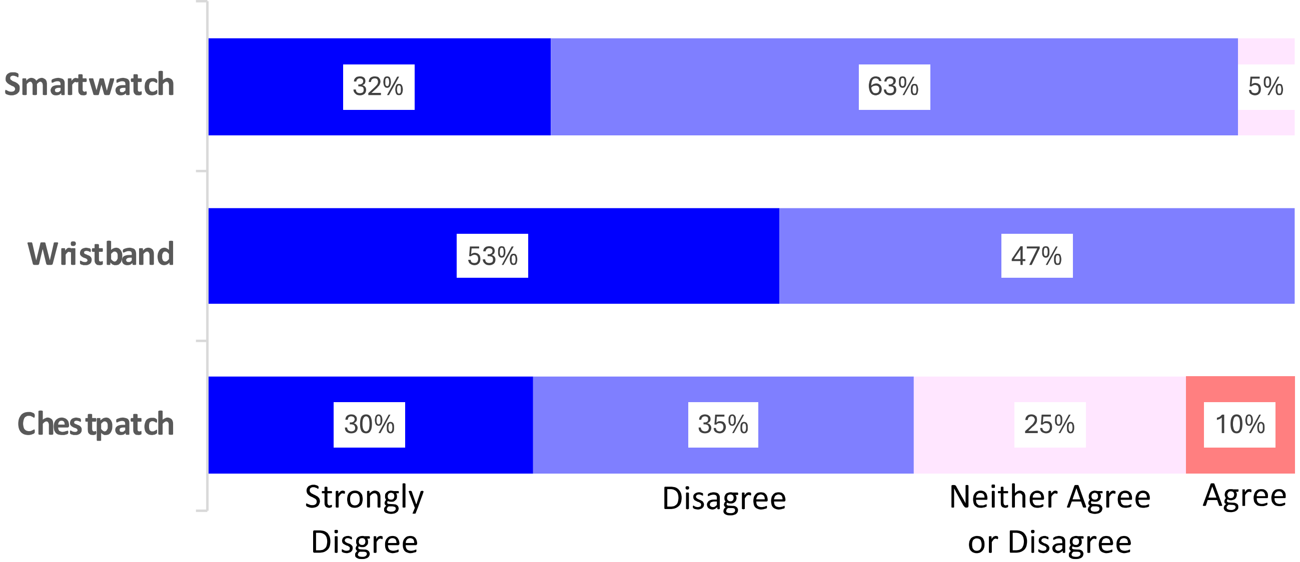
- 21 out of 130 participants to date.



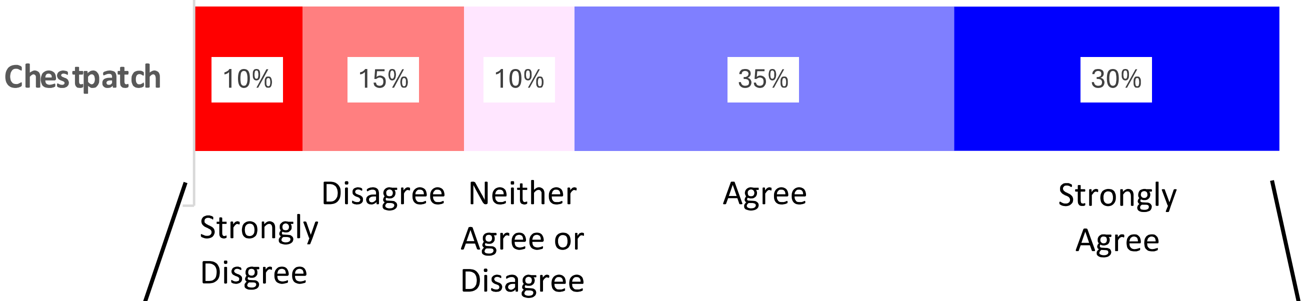

If the device was regularly used to check people's health then I would be happy to wear it for a week.
Smartwatch
37%
63%
Wristband
26%
74%
Chest patch
5%
40%
55%
Disagree
Agree
Strongly Agree



## The device was uncomfortable



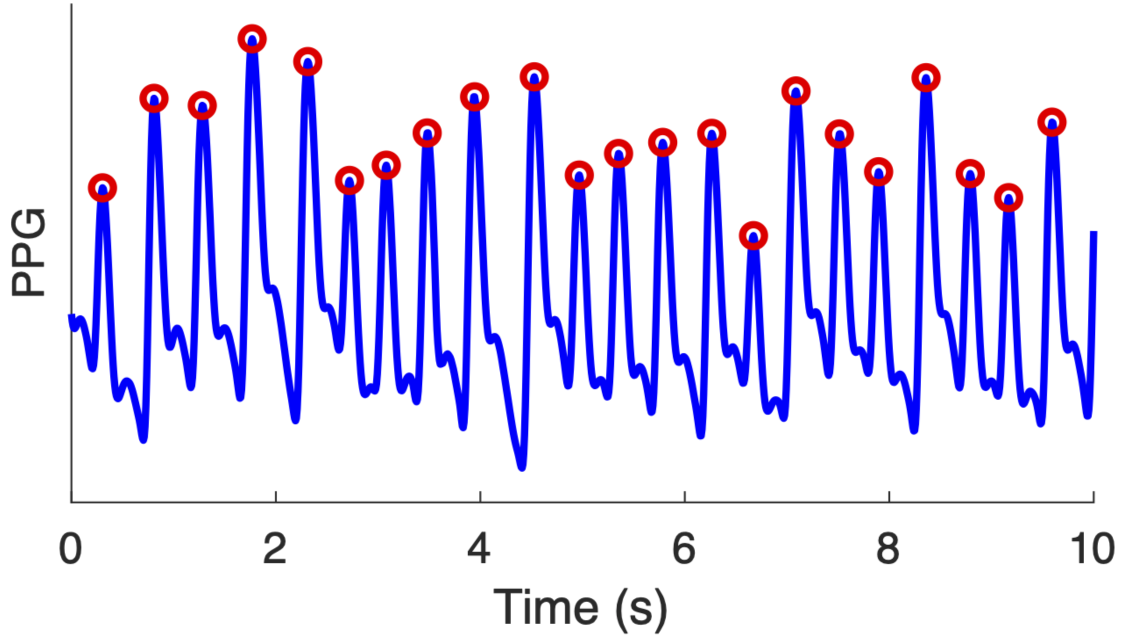

## The sticky dots on my chest didn’t bother me.




*“looked as though I'd been attacked with an octopus with a round ring”*

*"I forget that's there”*

# Benchmarking photoplethysmogram beat detectors



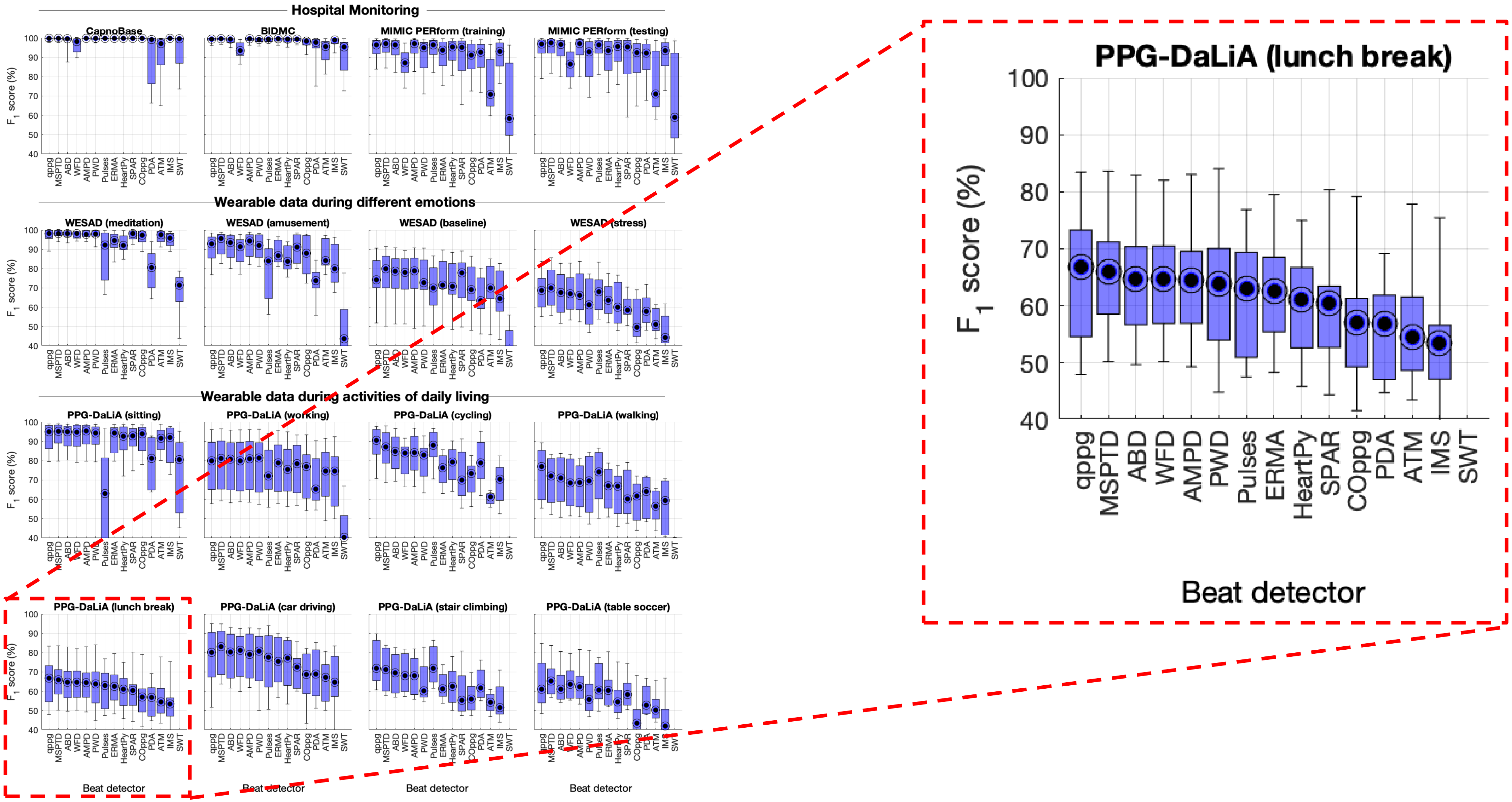

**Aim:** To identify the best algorithm to detect heart beats in photoplethysmography signals.

**Methods:**

- Fifteen open-source beat detection algorithms
- Assessed against electrocardiogram-derived heartbeats
- On eight datasets.

Charlton PH *et al.*, Detecting beats in the photoplethysmogram: benchmarking open-source algorithms, Phys Meas., 2022. https://doi.org/10.1088/1361-6579/ac826d (CC BY 4.0)

# Benchmarking photoplethysmogram beat detectors

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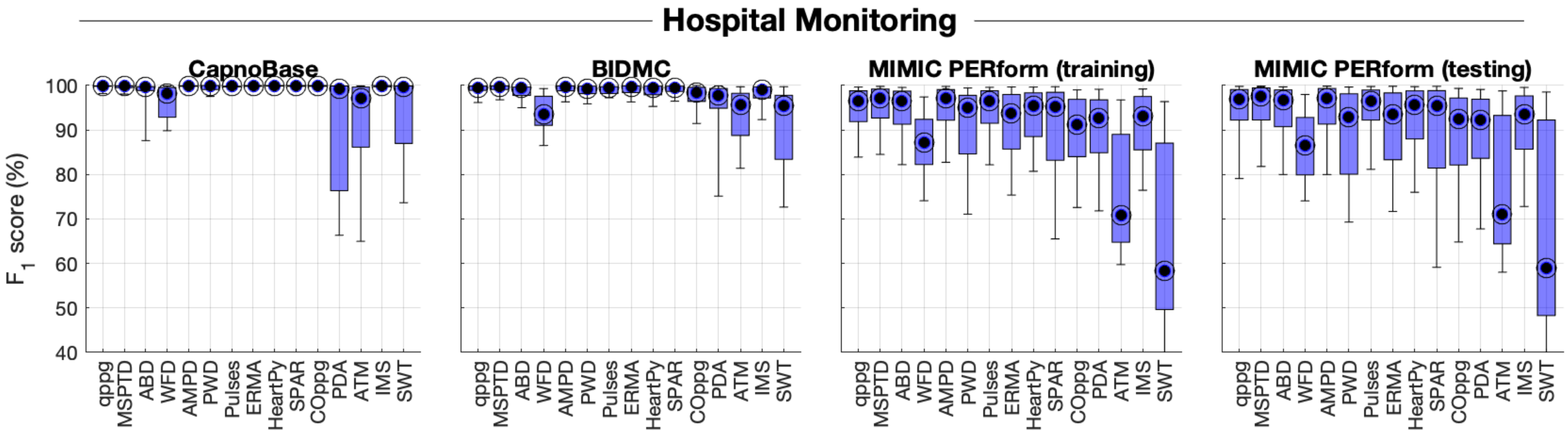
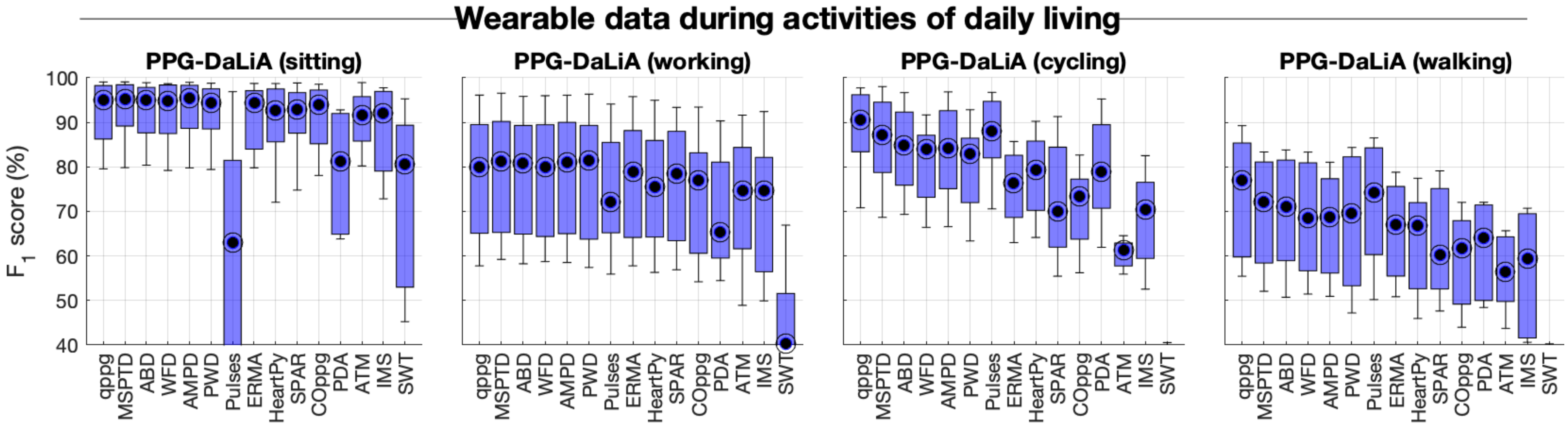



Eight beat detectors performed well at rest in the absence of movement

- F1 scores of >=90% on hospital data and wearable data

# Benchmarking photoplethysmogram beat detectors




Eight beat detectors performed well at rest in the absence of movement

- F1 scores of >=90% on hospital data and wearable data

Their performance was poorer during exercise:

- F1 scores of 55%–91%

Charlton PH *et al.*, Detecting beats in the photoplethysmogram: benchmarking open-source algorithms, Phys Meas., 2022. https://doi.org/10.1088/1361-6579/ac826d (CC BY 4.0)

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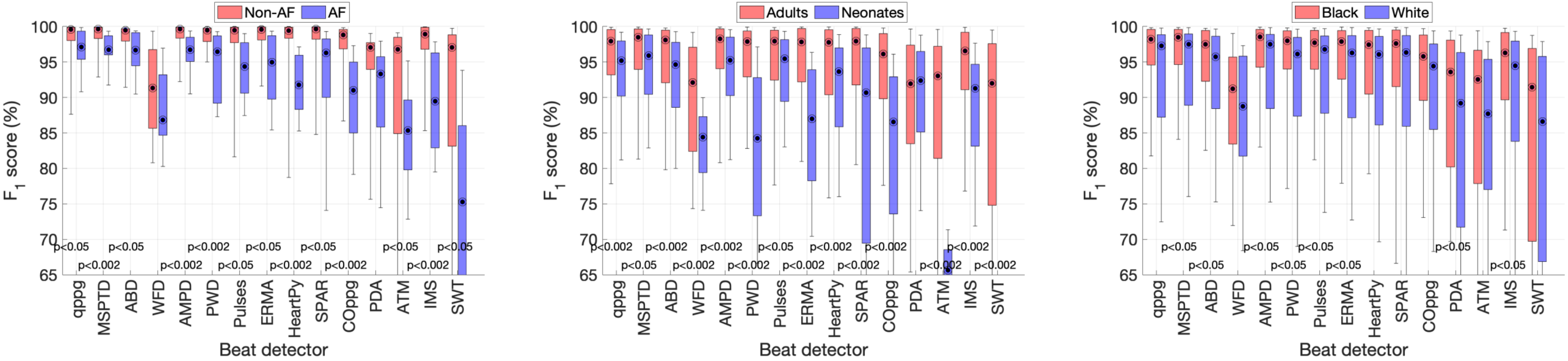



Eight beat detectors performed well at rest in the absence of movement

- F1 scores of >=90% on hospital data and wearable data

Their performance was poorer during exercise:

- F1 scores of 55%–91%

Performance was:

- Poorer in AF
- Poorer in neonates than adults
- Not associated with ethnicity (Black compared with White)

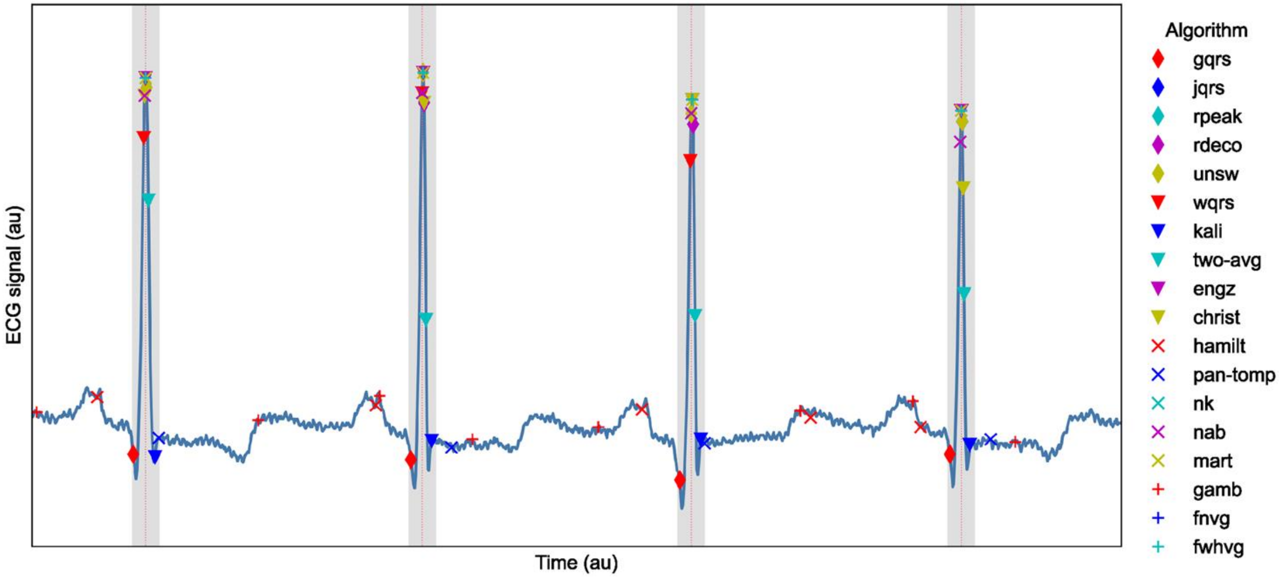
Concluded that ‘MSPTD’ and ‘qppg’ performed best, although this is somewhat subjective.

Charlton PH *et al.*, Detecting beats in the photoplethysmogram: benchmarking open-source algorithms, Phys Meas., 2022. https://doi.org/10.1088/1361-6579/ac826d (CC BY 4.0)

# Using photoplethysmography to prompt single-lead ECG


Photo by Luke Chesser on Unsplash

# Benchmarking ECG beat detectors



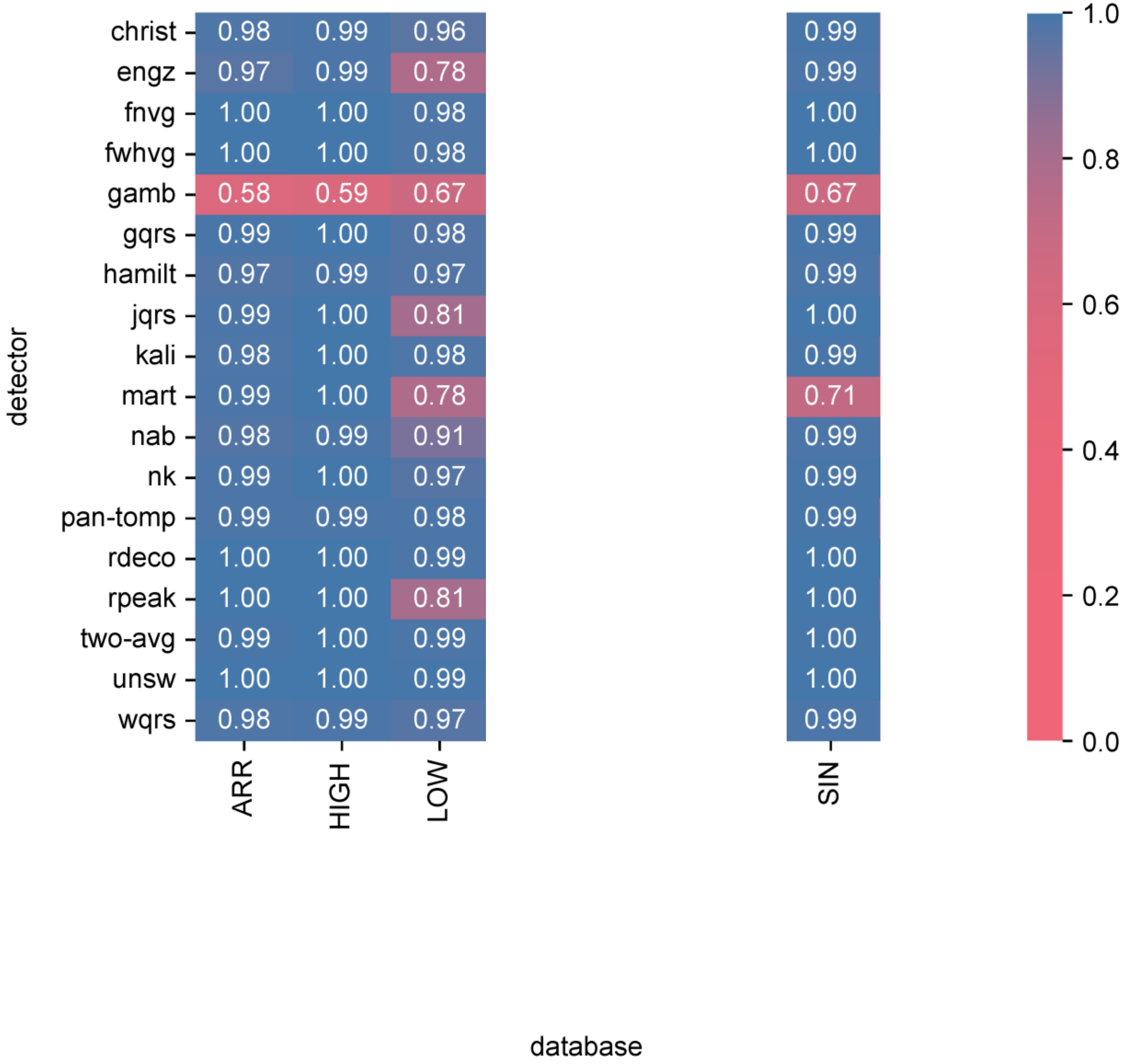

**Aim:** To identify the best-performing open-source QRS detector for use with telehealth ECGs

**Methods:**

- 18 open-source beat detection algorithms
- Assessed against manual annotations
- On six datasets.
- Performance expressed as F1-score (ranges from 0 to 1, with 1 being best).

Kristof F *et al.*, QRS detection in single-lead, telehealth electrocardiogram signals: Benchmarking open-source algorithms, *PLOS Digital Health*, 2024.
https://doi.org/10.1371/journal.pdig.0000538 (CC BY 4.0)

# Benchmarking ECG beat detectors




**Results:**

Using ‘F1 score ≥0.96’ as the criteria for determining whether an algorithm performed well:

- 12 algorithms performed well on ECGs collected under clinical supervision.
- Fewer performed well on telehealth ECGs:
  - Five performed well on the TELE dataset
  - Six performed well on high-quality SAFER data
  - Performance was poorer on low-quality SAFER data.

Kristof F *et al.*, QRS detection in single-lead, telehealth electrocardiogram signals: Benchmarking open-source algorithms, *PLOS Digital Health*, 2024.
https://doi.org/10.1371/journal.pdig.0000538 (CC BY 4.0)

# Respiratory rate (RR)
(breaths per minute)

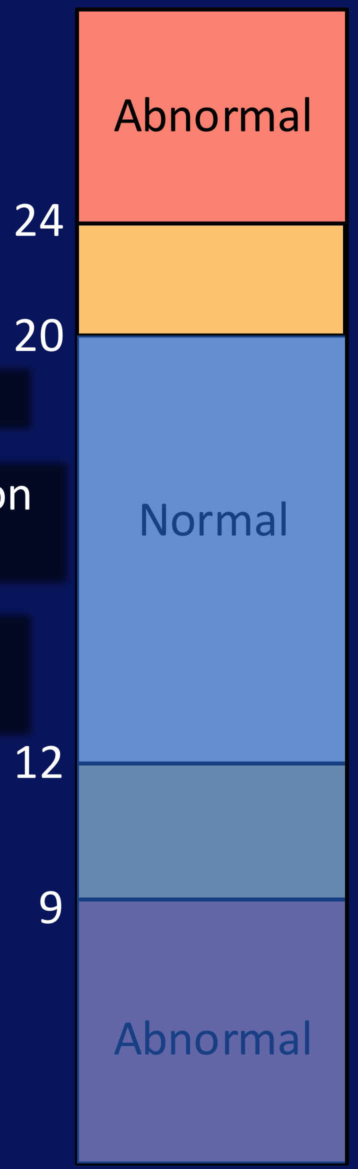
**Elevated RR**

associated with:

Diagnosis of COVID-19

Intensive care admission with COVID-19

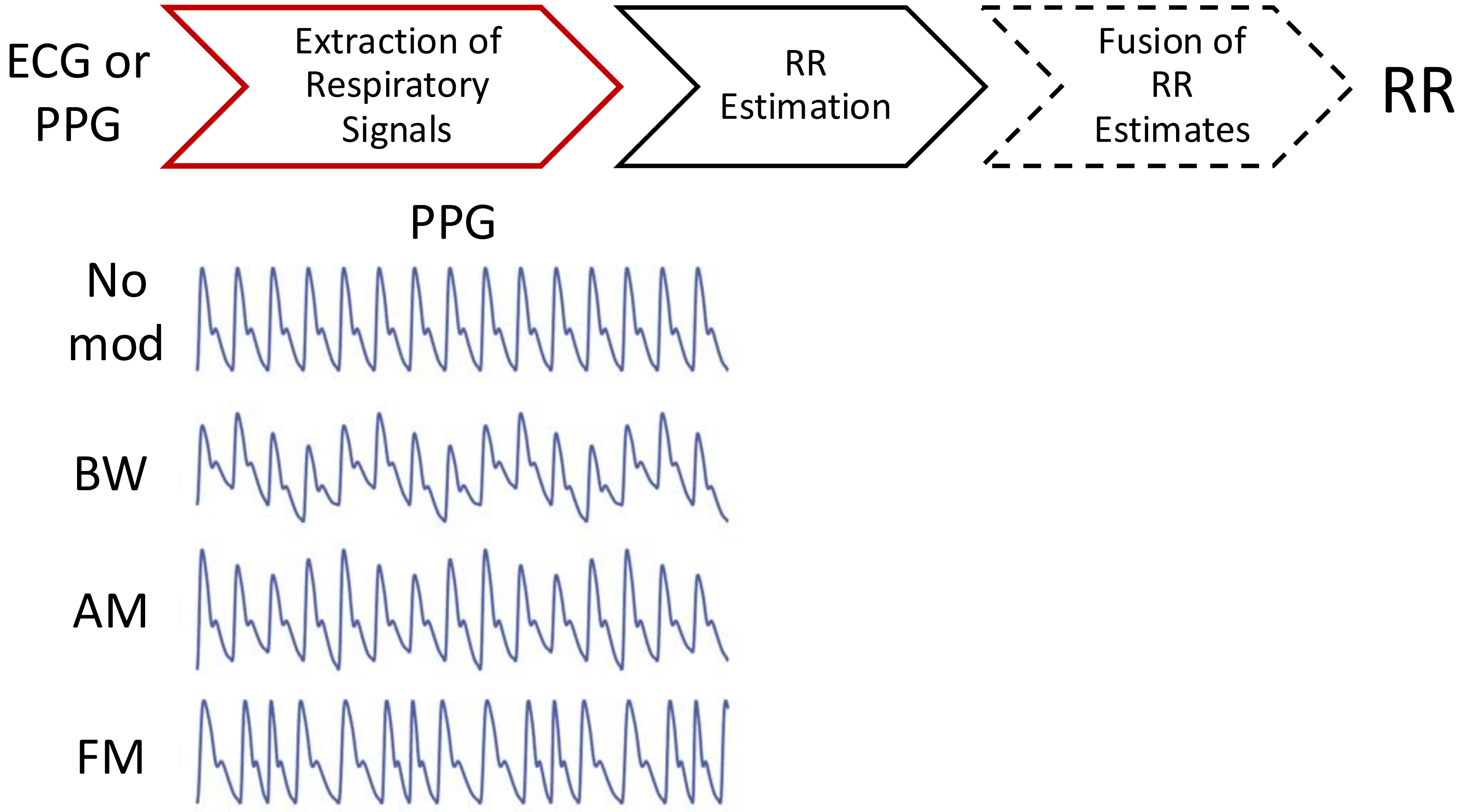
Death in hospital with COVID-19




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

# Structure of Algorithms



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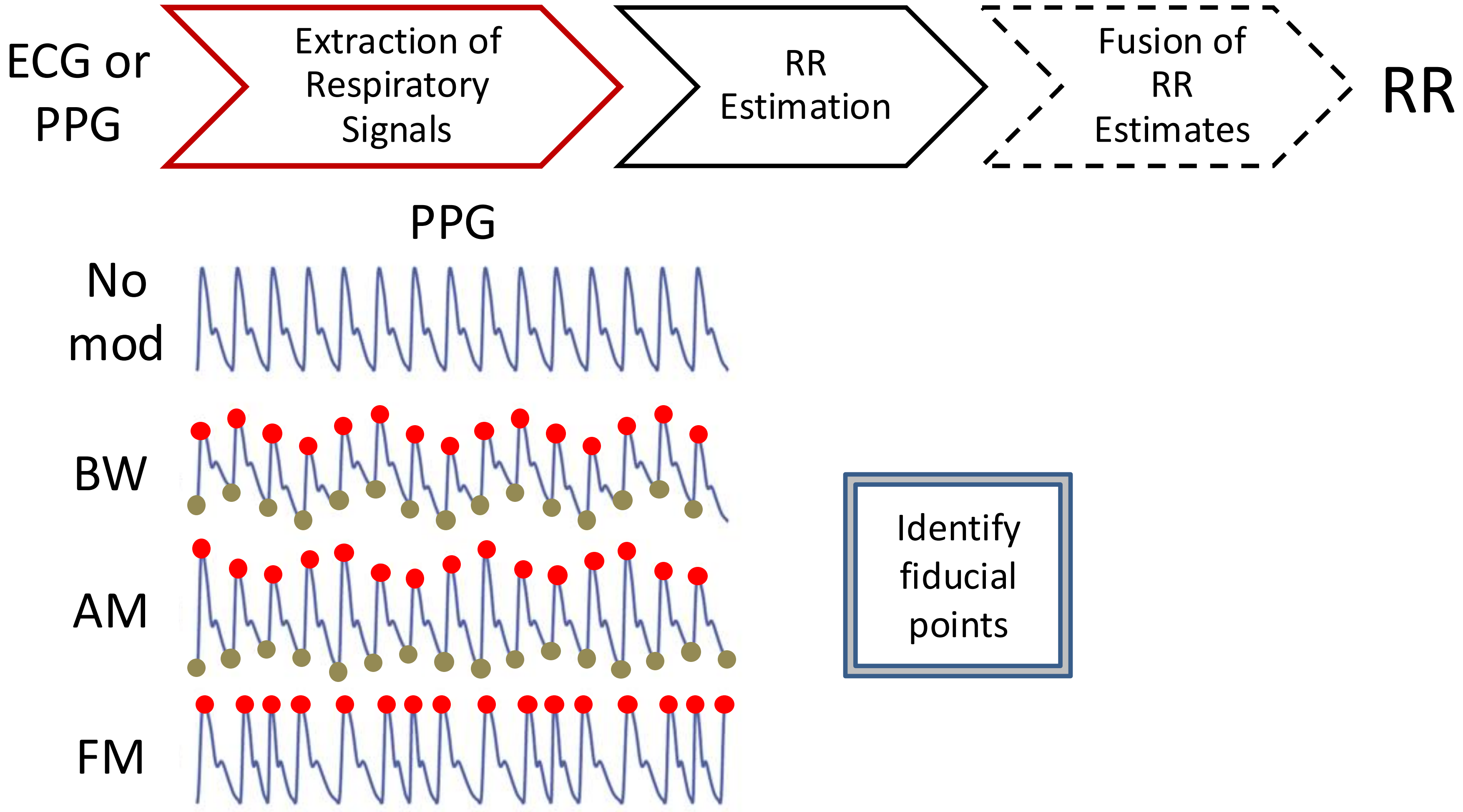

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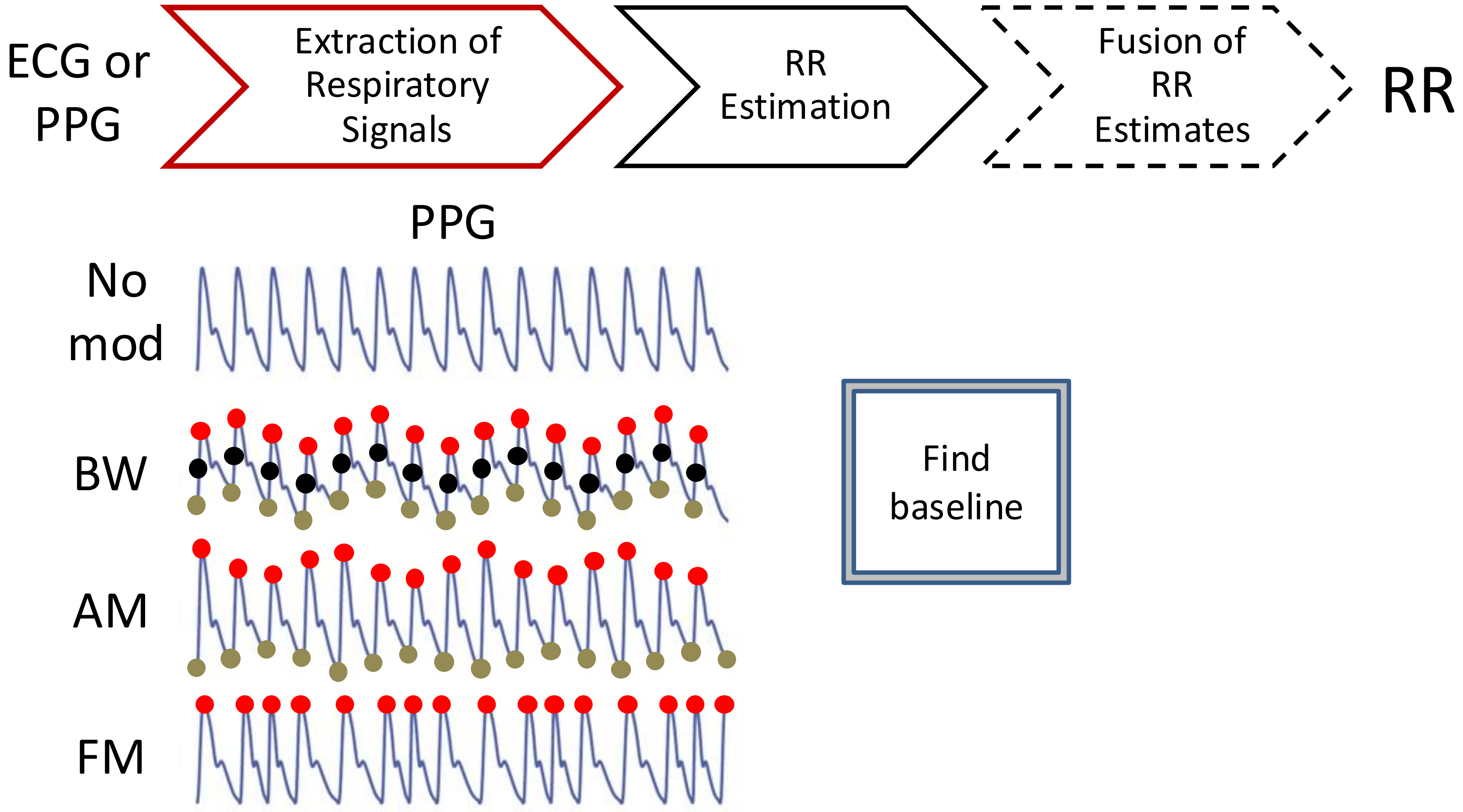

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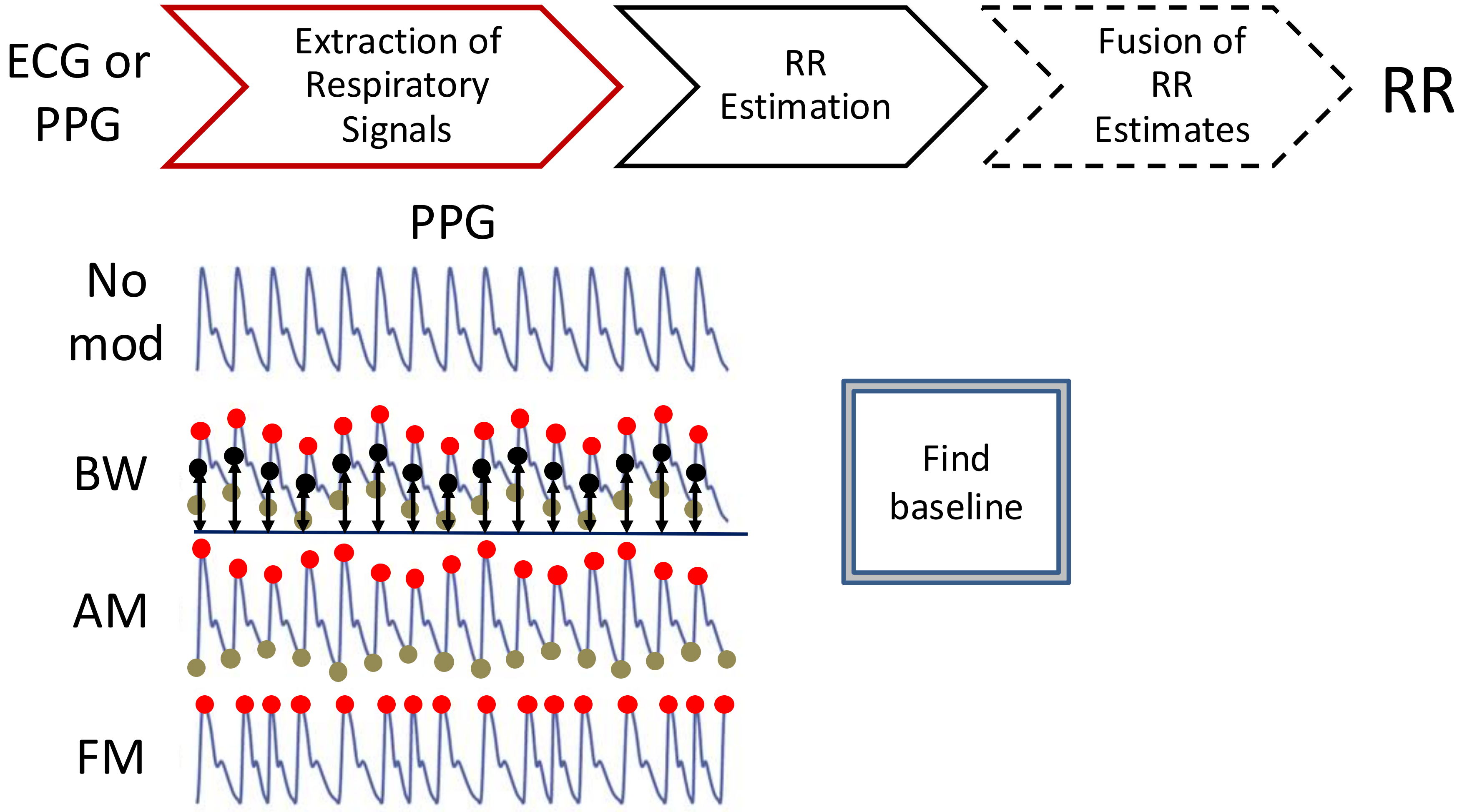

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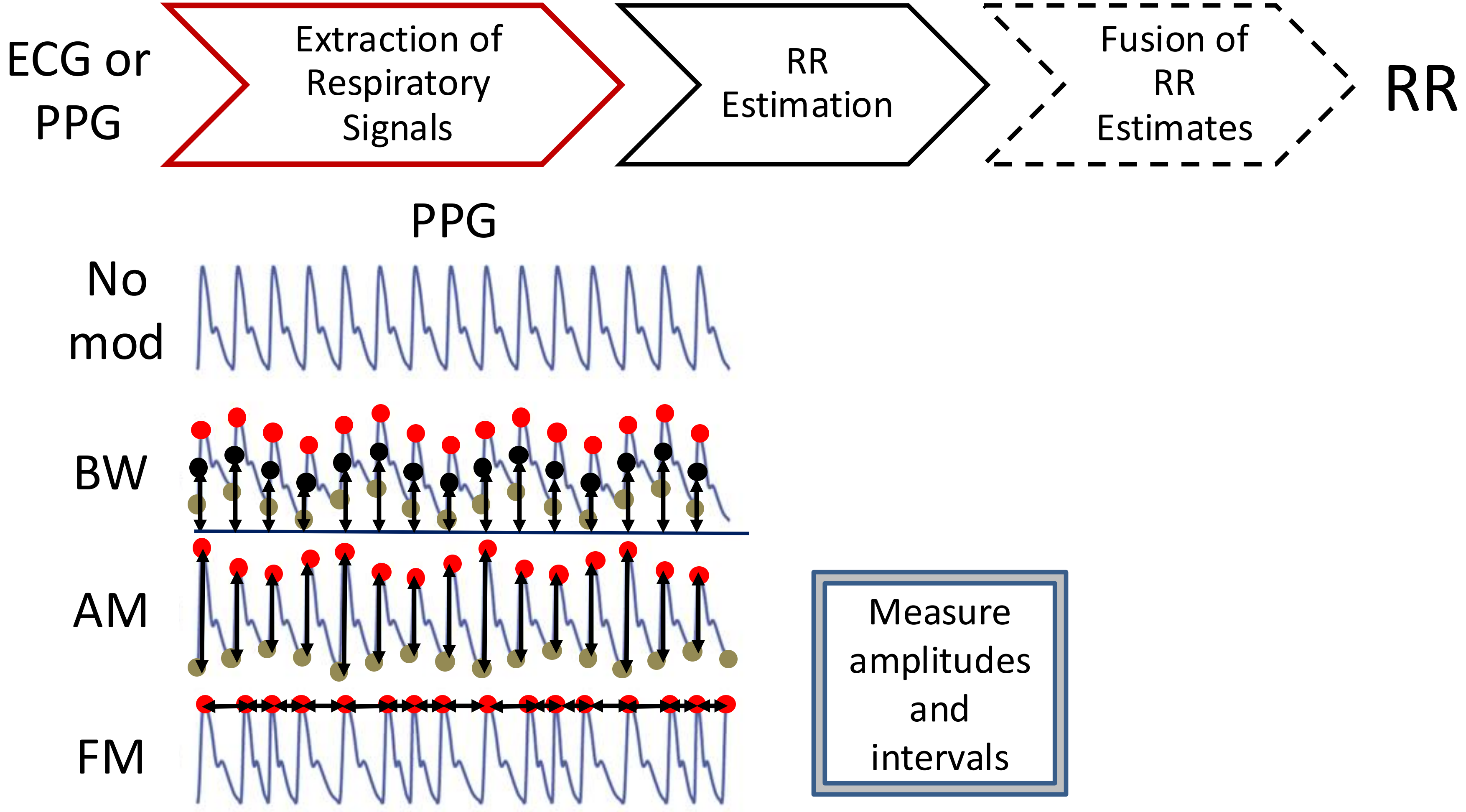

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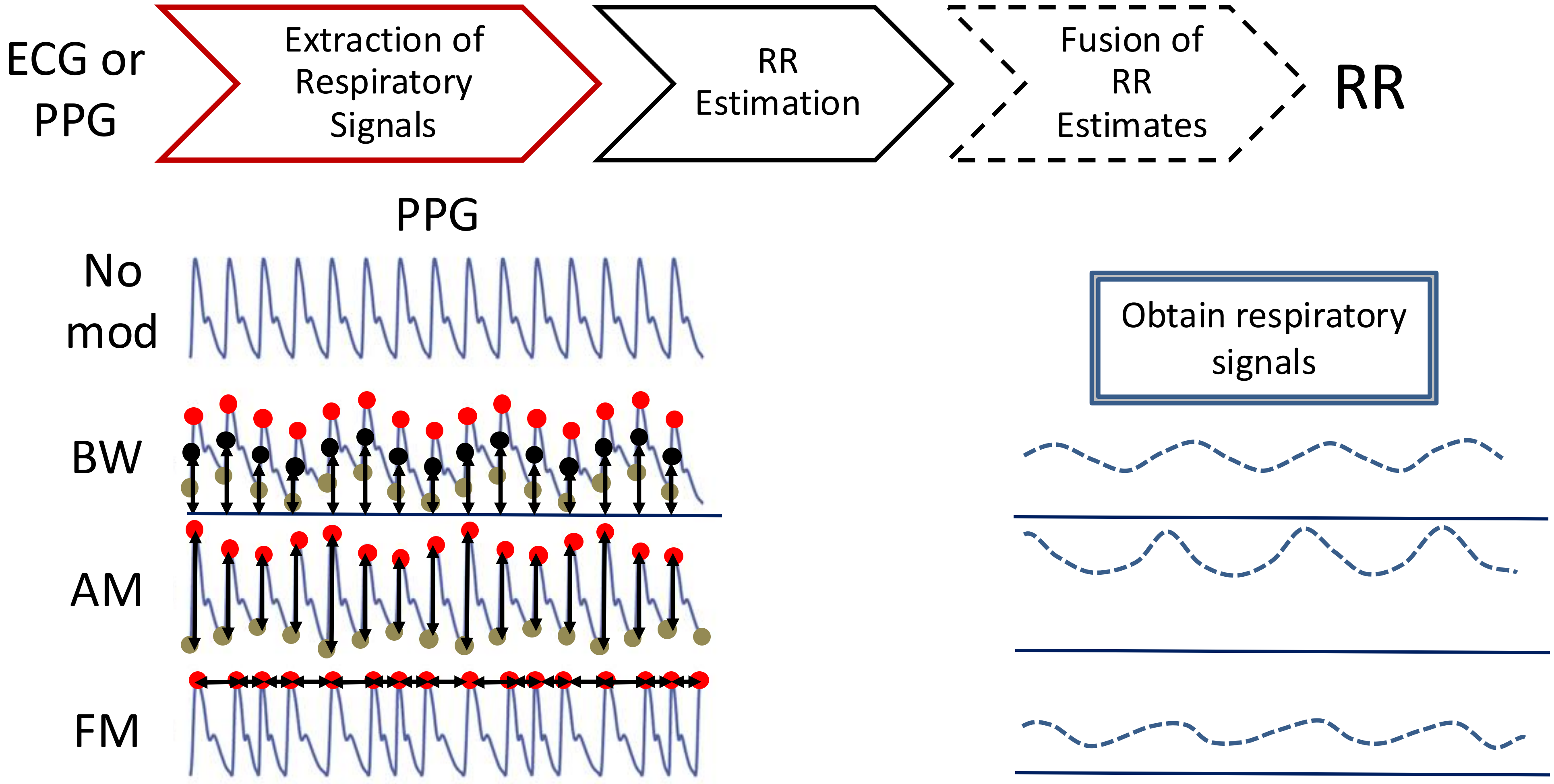

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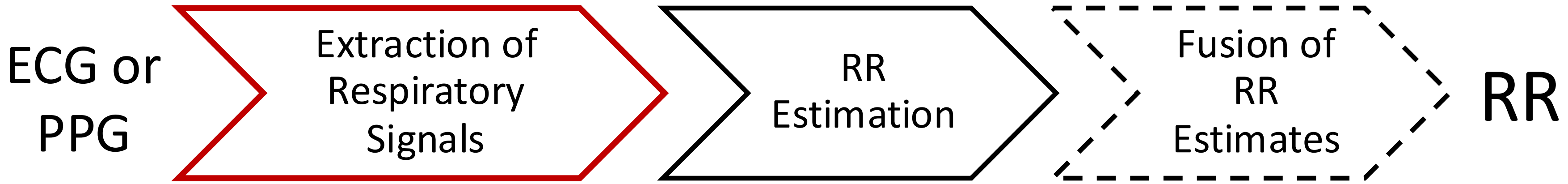


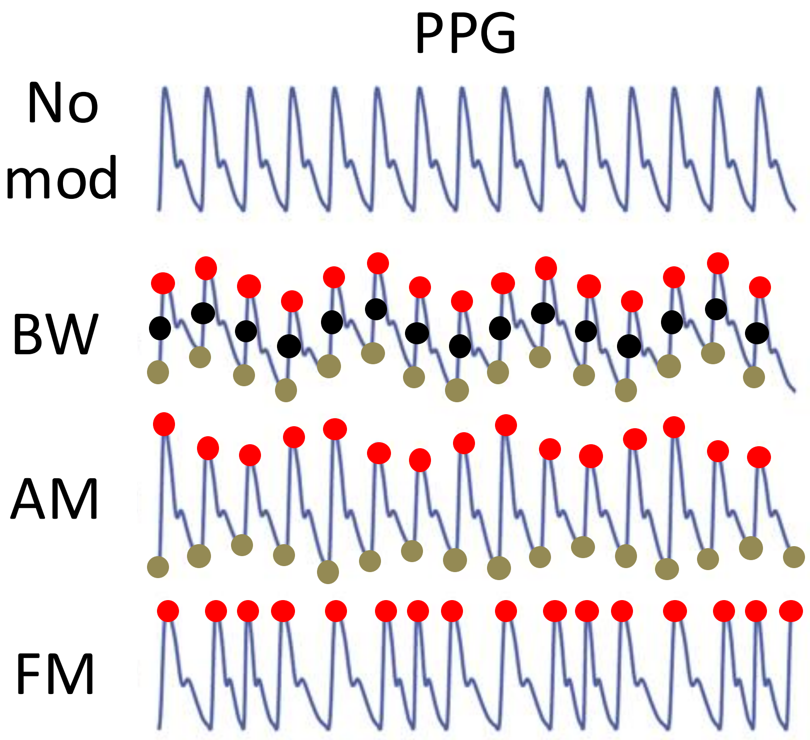


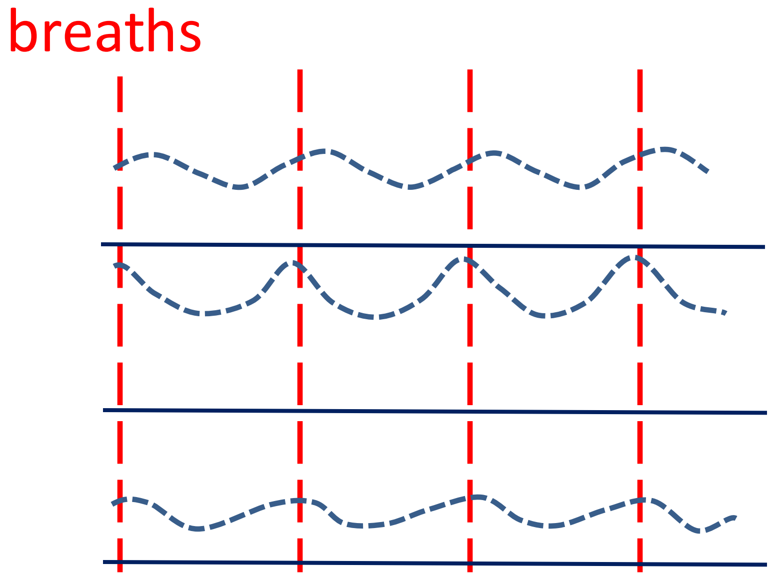

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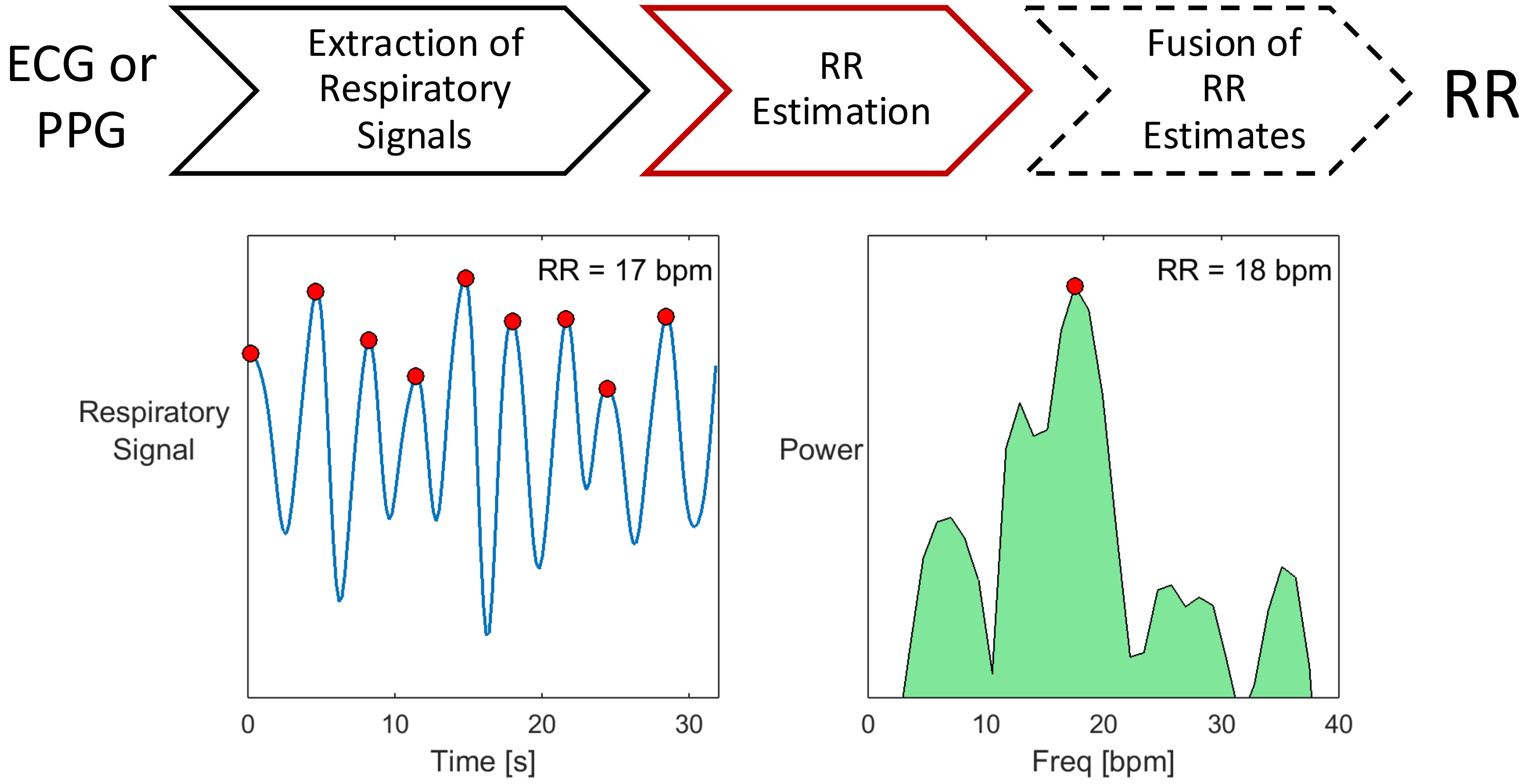


Source: [Charlton PH. Zenodo, 2018](). [CC BY 4.0]()

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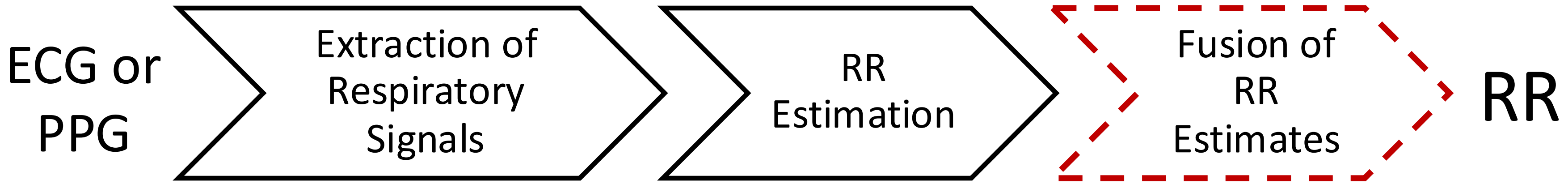
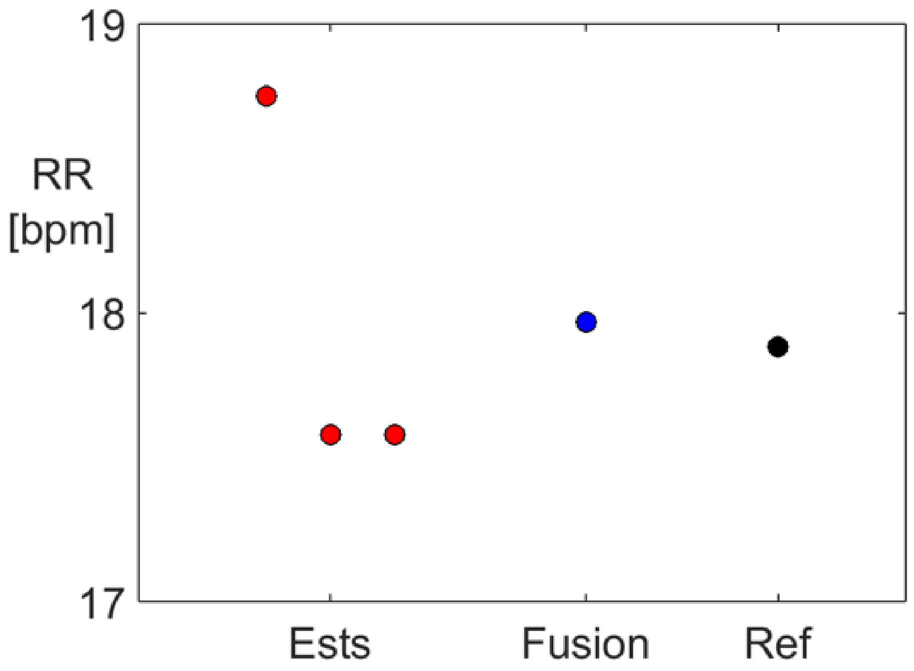
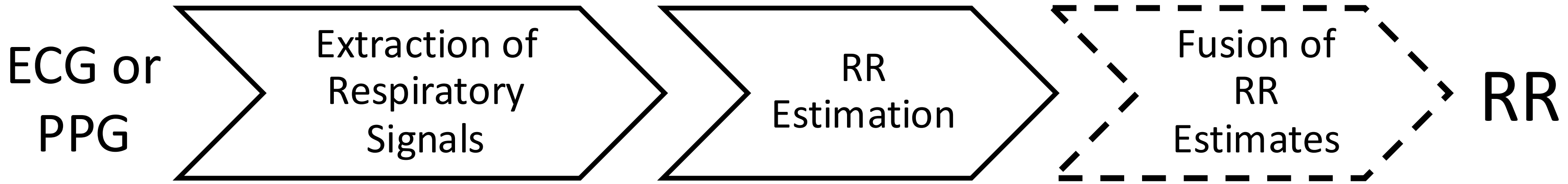


# Implementing Algorithms




BW
AM
FM
Peak amplitudes
Onset amplitudes
…

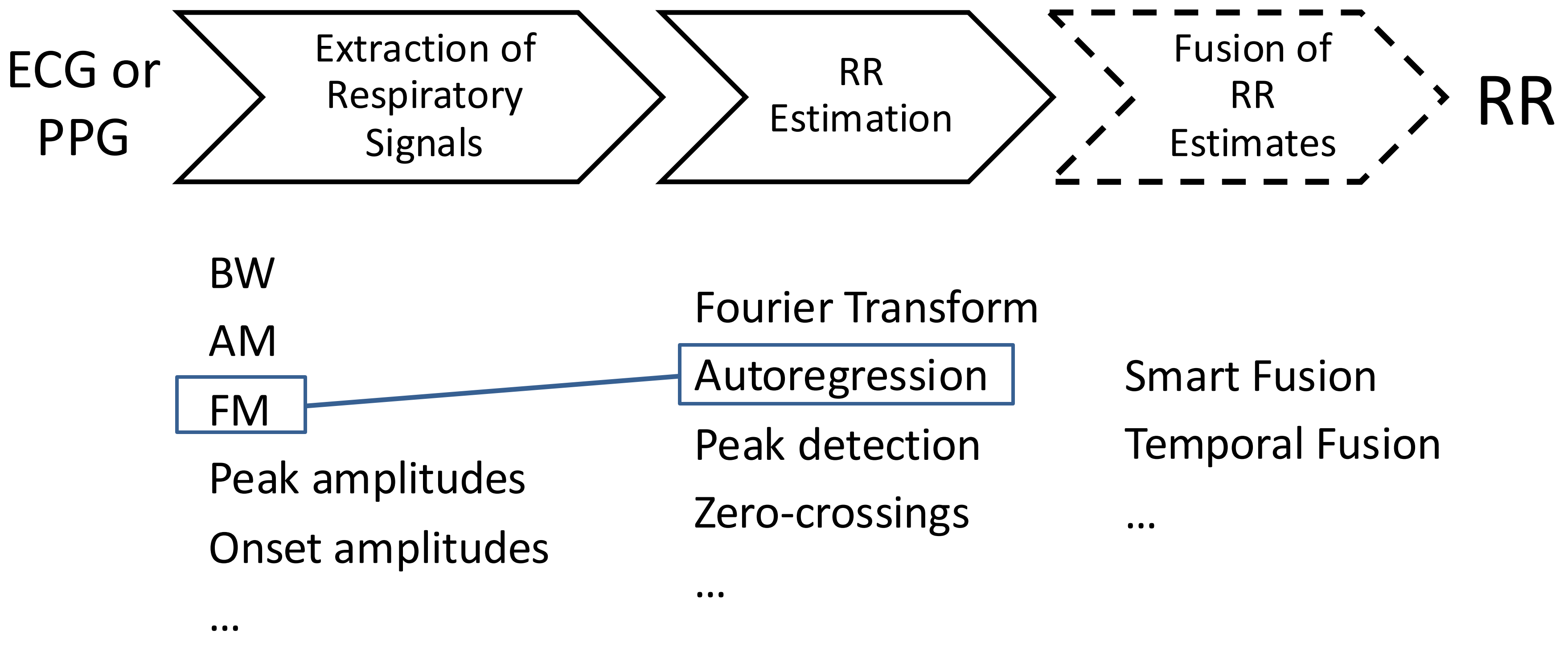
Fourier Transform
Autoregression
Peak detection
Zero-crossings
…

Smart Fusion
Temporal Fusion
…

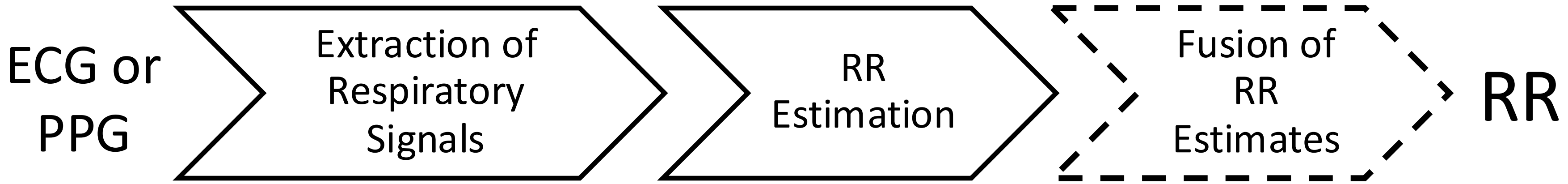
*Further reading:*

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](https://doi.org/10.1109/RBME.2017.2763681)

# Implementing Algorithms



# Implementing Algorithms

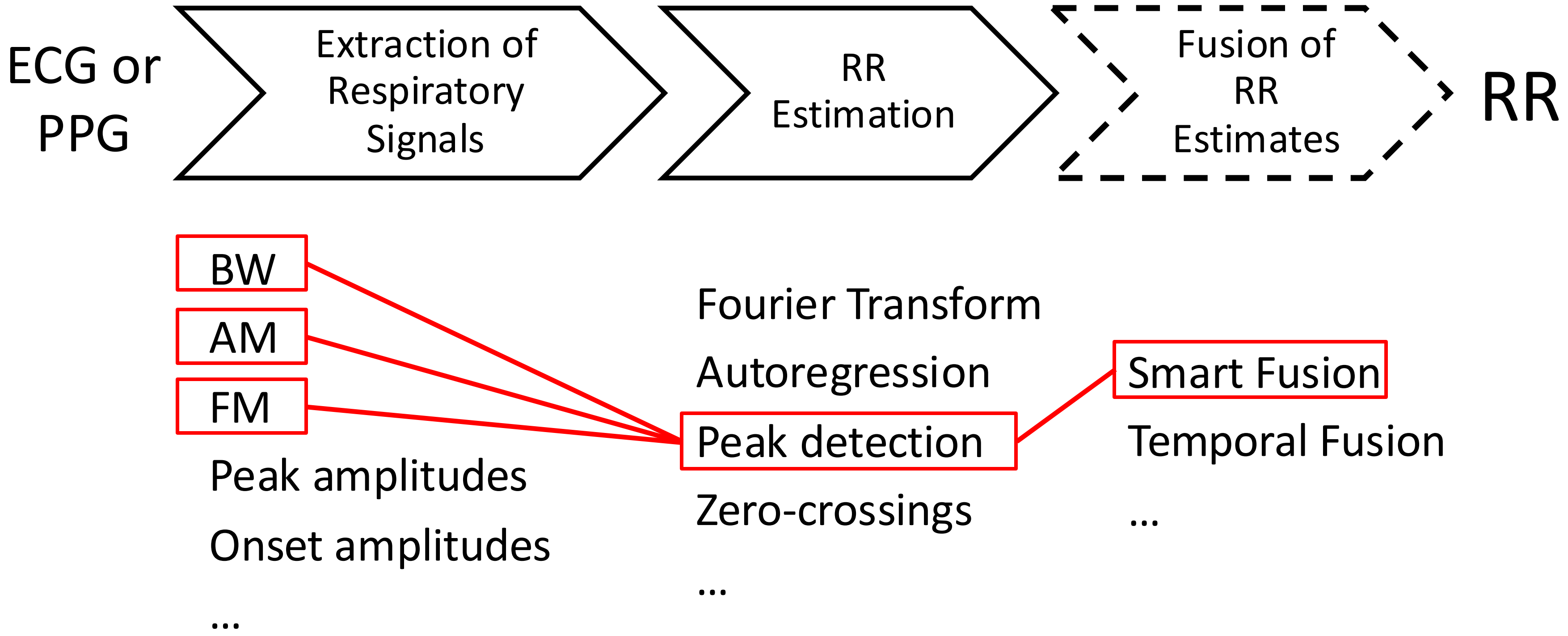



- BW
- AM
- FM
- Peak amplitudes
- Onset amplitudes
- …

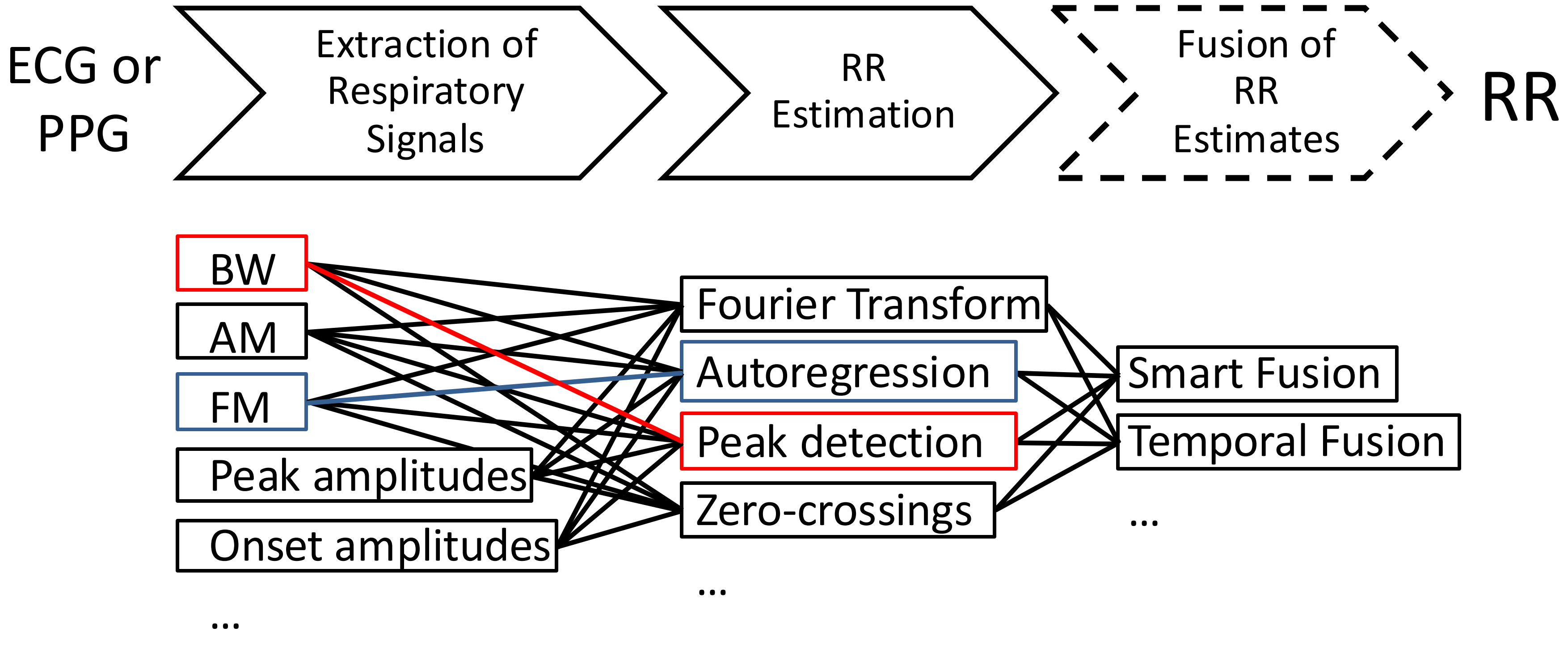
- Fourier Transform
- Autoregression
- Peak detection
- Zero-crossings
- …

- Smart Fusion
- Temporal Fusion
- …

# Implementing Algorithms



# Implementing Algorithms



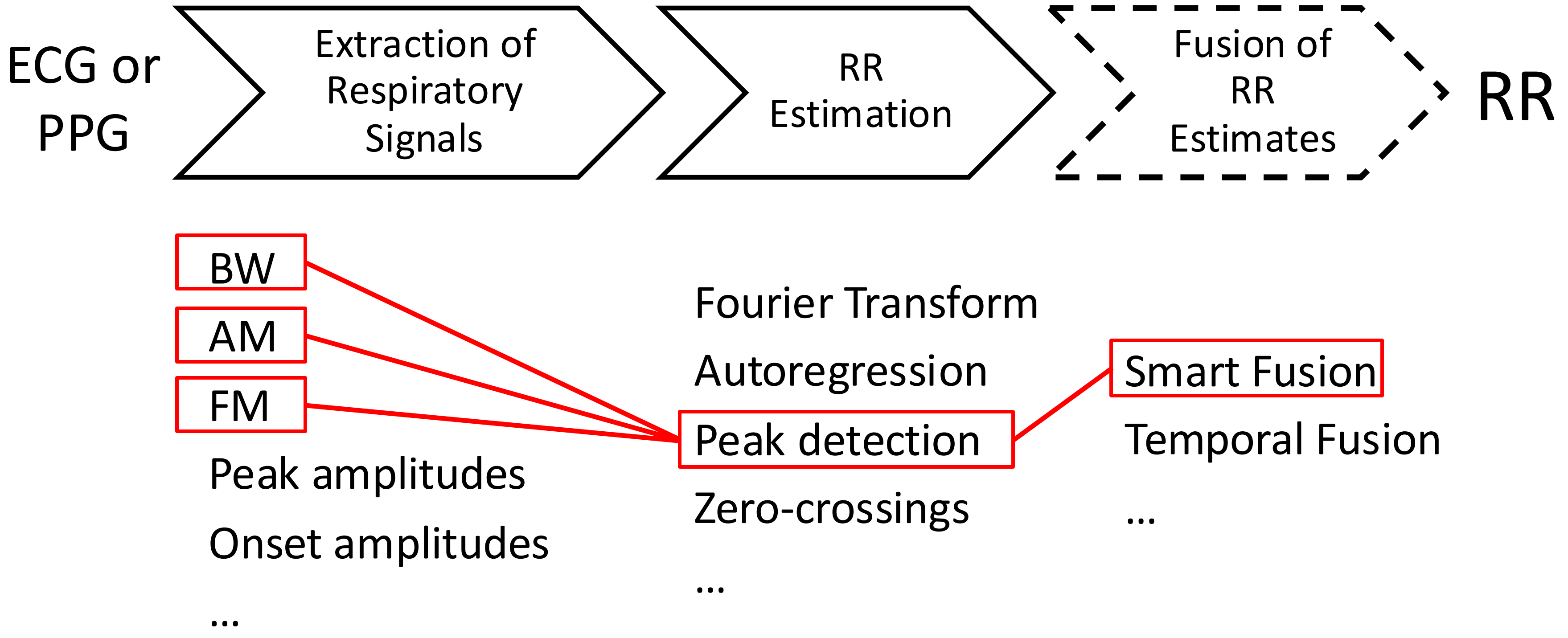

14 techniques

12 techniques

5 techniques

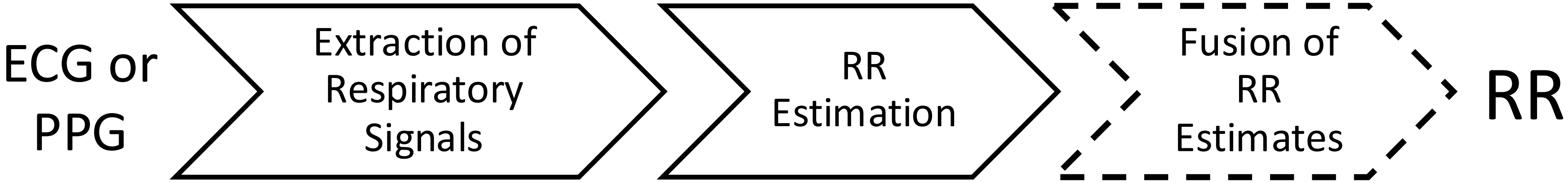
370 algorithms

# The winner…




… on young subjects

# The strength of respiratory modulations

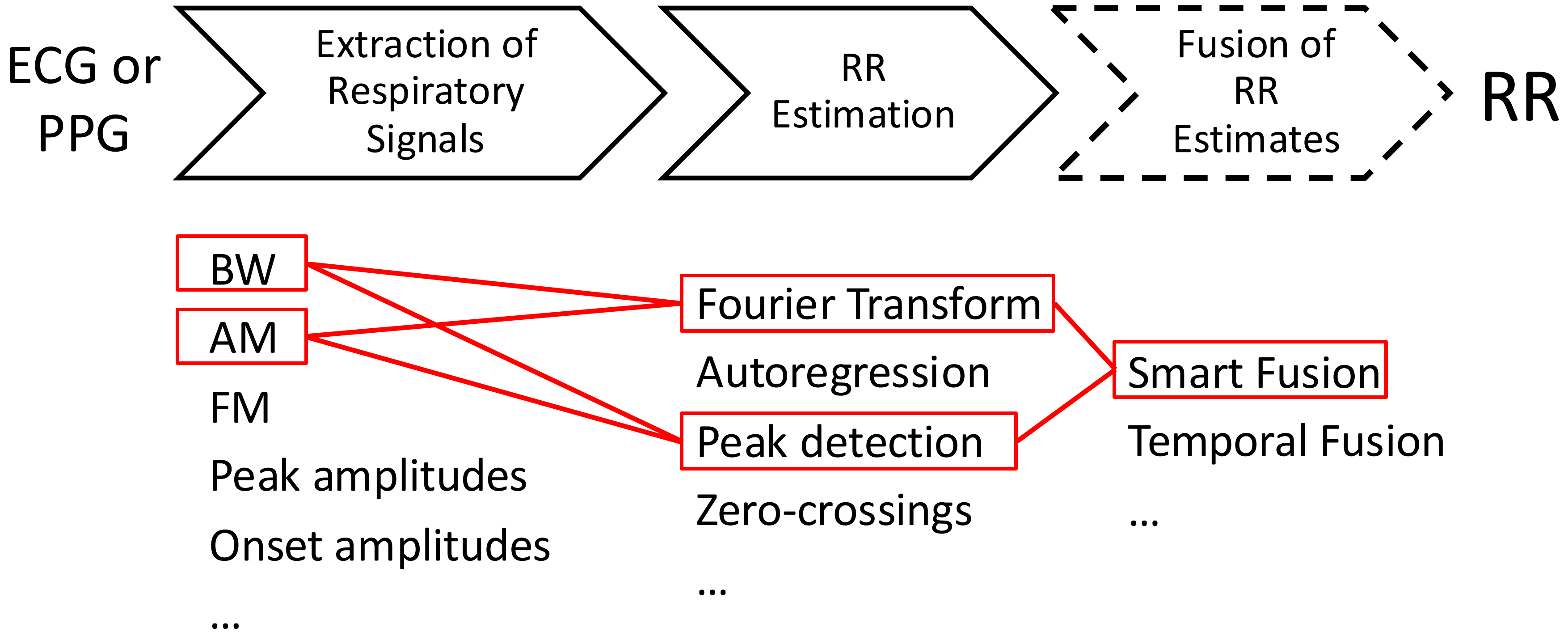



BW
AM
FM
Peak amplitudes
Onset amplitudes
…

| Respiratory modulation | Strength (CC): Young adults | Strength (CC): Older adults |
|---|---|---|
| BW | 0.48 (0.35 – 0.56) | 0.49 (0.36 – 0.63) |
| AM | 0.48 (0.39 – 0.57) | 0.47 (0.35 – 0.57) |
| FM | 0.64 (0.50 – 0.73) | 0.38 (0.32 – 0.55) |

Charlton PH *et al.*, Extraction of respiratory signals from the electrocardiogram and photoplethysmogram: technical and physiological determinants, Phys Meas., 2017. https://doi.org/10.1088/1361-6579/aa670e

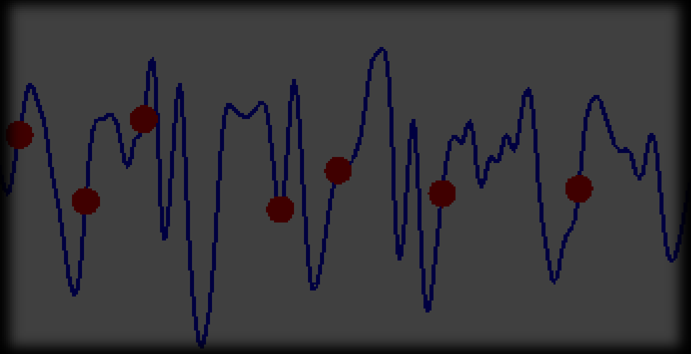
# The (revised) winner…




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

1. Introduction to wearables

2. Our contributions



3. Perspectives

Photo by Luke Chesser on Unsplash

Photo by Dario Valenzuela on Unsplash

# Perspectives

**Areas for inequity:**

- Many, many potential sources of inequity for wearables. See:
  - D. M. Kaplan, M. Greenleaf, and W. A. Lam, ‘Wear With Care: A Call for Empirical Investigations of Adverse Outcomes of Consumer Health Wearables’, *Mayo Clinic Proceedings: Digital Health*, vol. 1, no. 3, pp. 413–418, Sep. 2023, doi: 10.1016/j.mcpdig.2023.06.014.

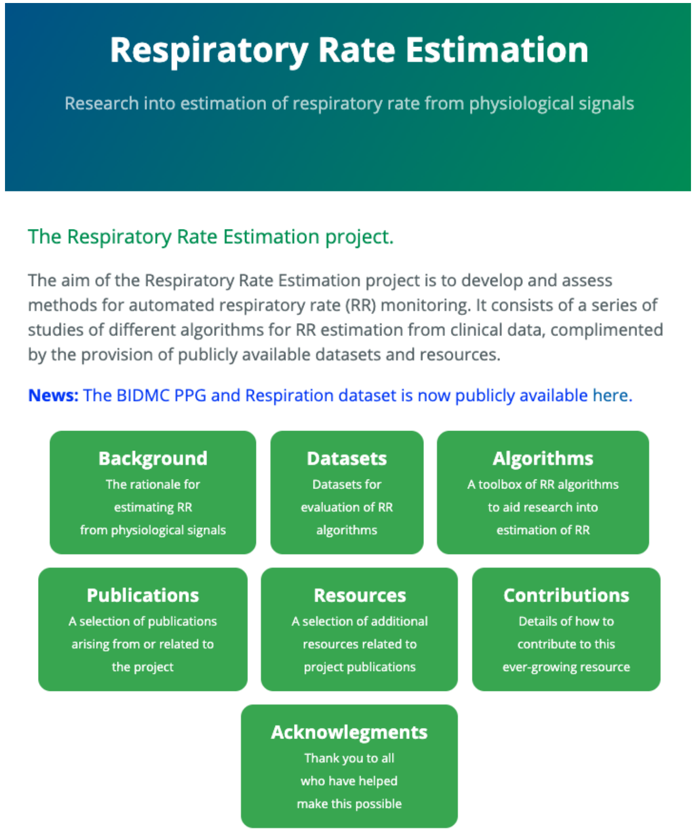
**Equity in academic research: Open science**

- In my academic role, I value sharing our work. *e.g.*

# Open science

- Providing open-source toolboxes of algorithms

MATLAB Toolbox

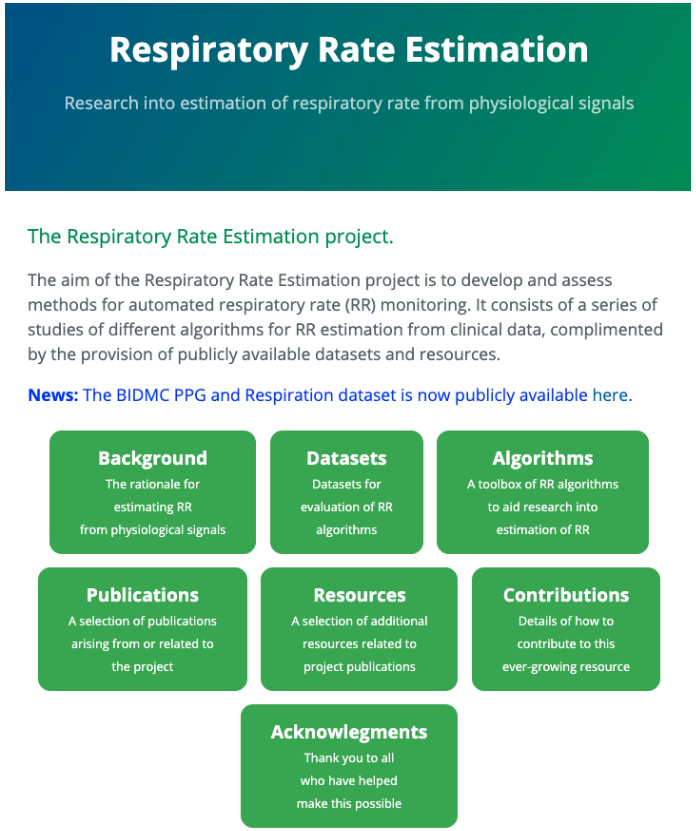



https://peterhcharlton.github.io/RRest

# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use

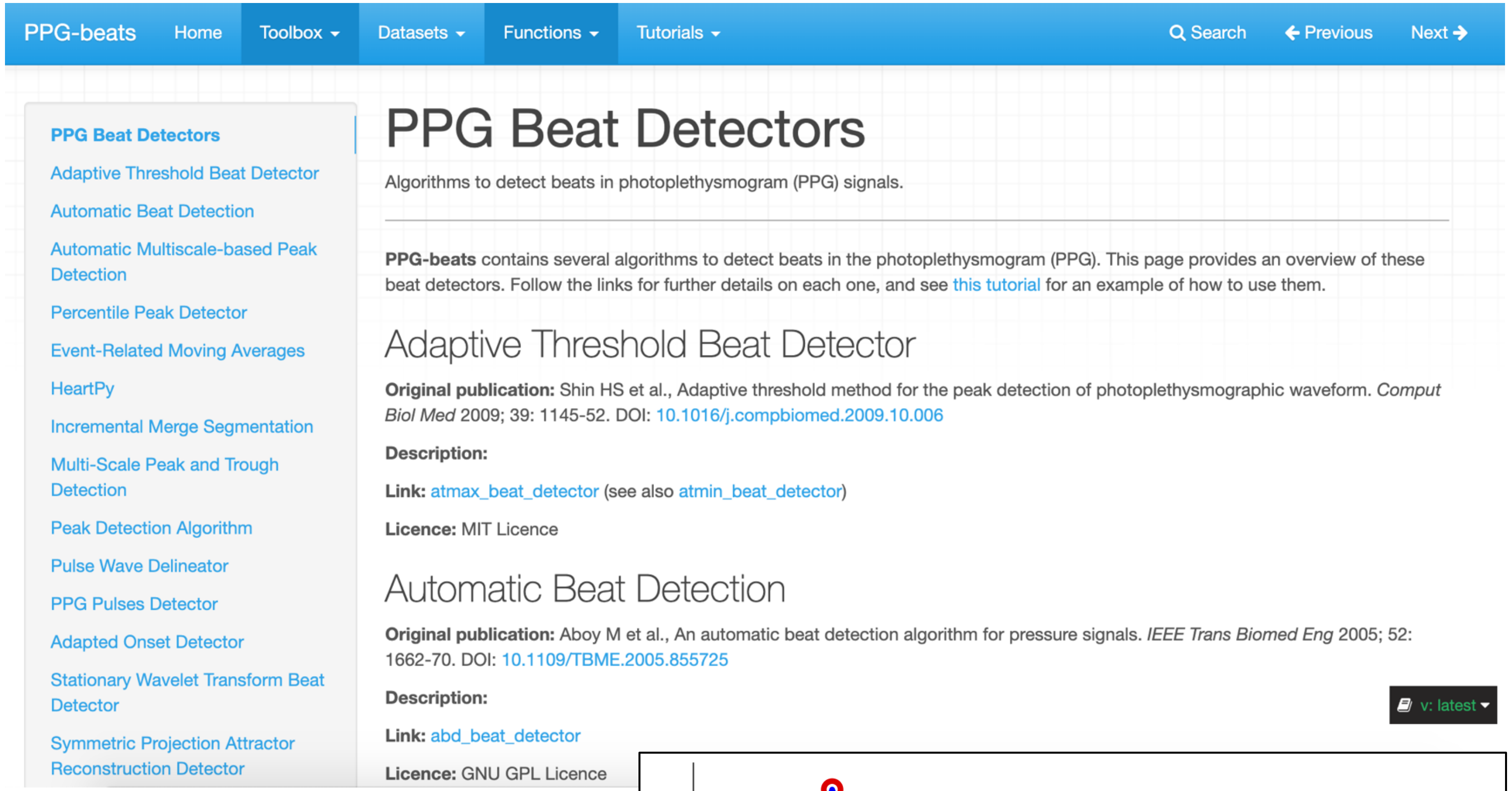
MATLAB Toolbox



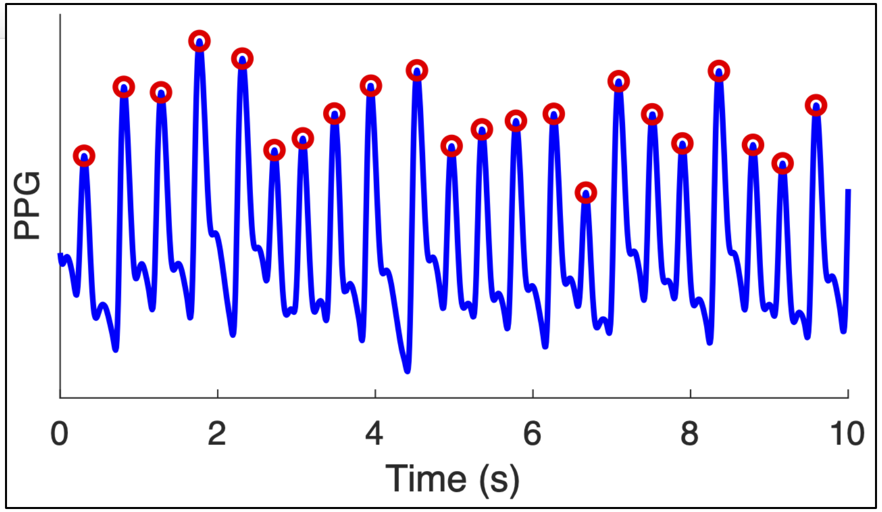

https://peterhcharlton.github.io/RRest

# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use

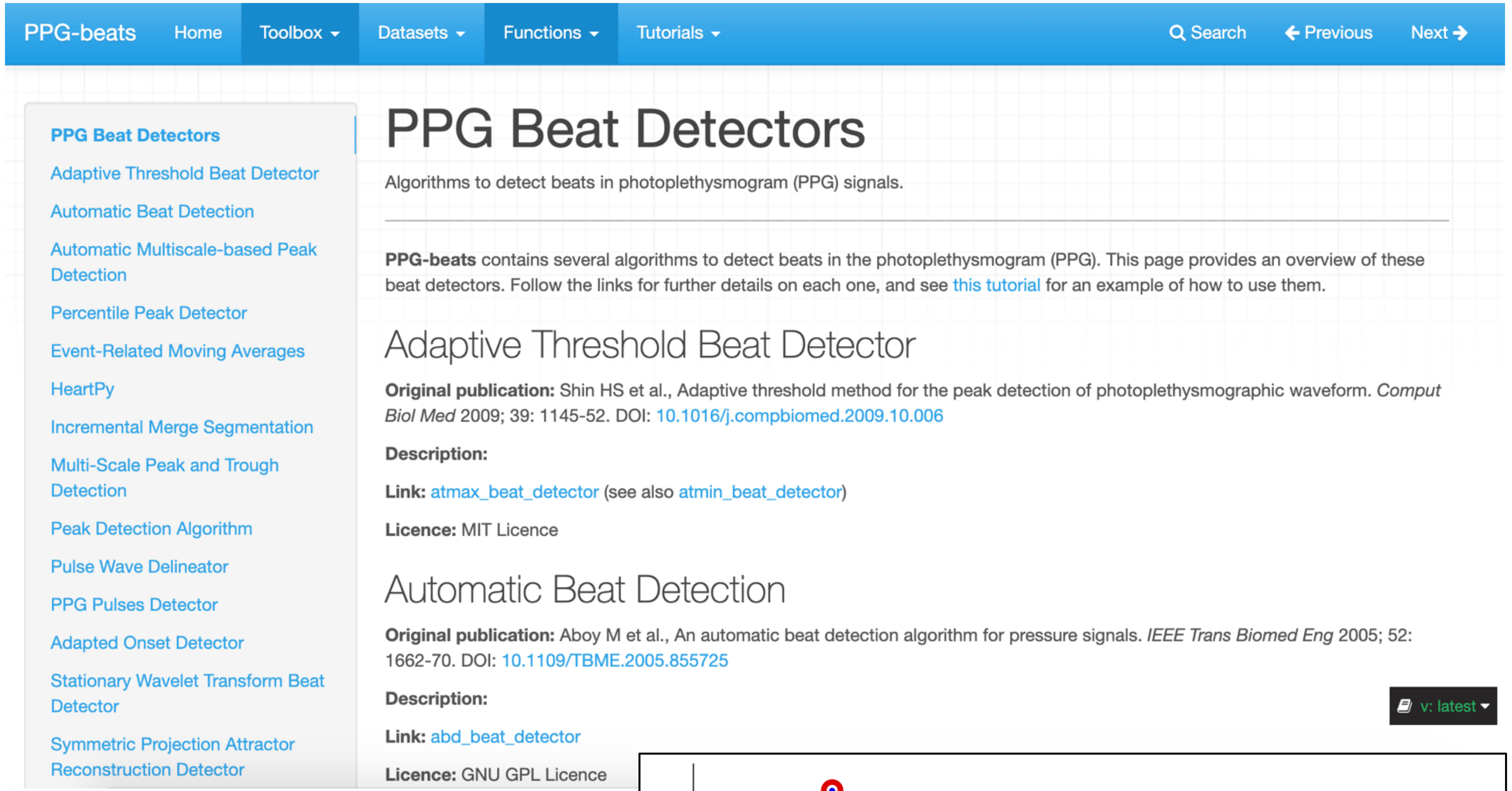



https://ppg-beats.readthedocs.io/



# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language

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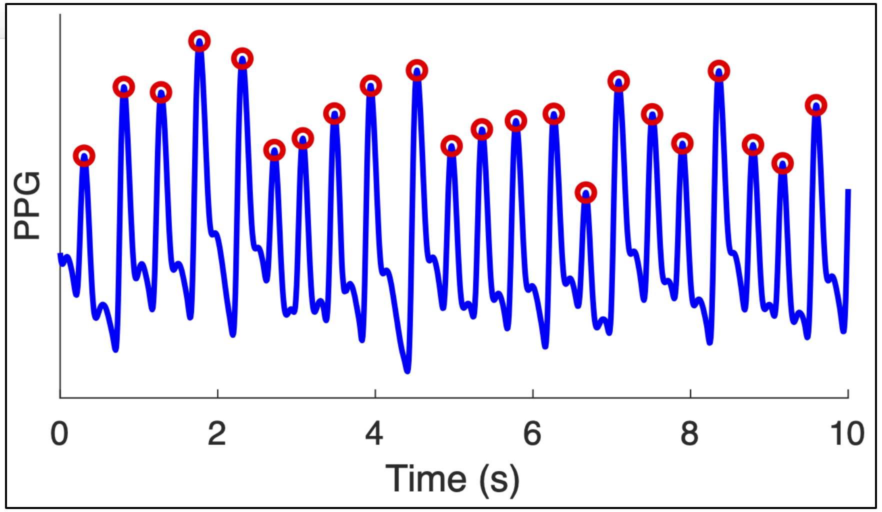
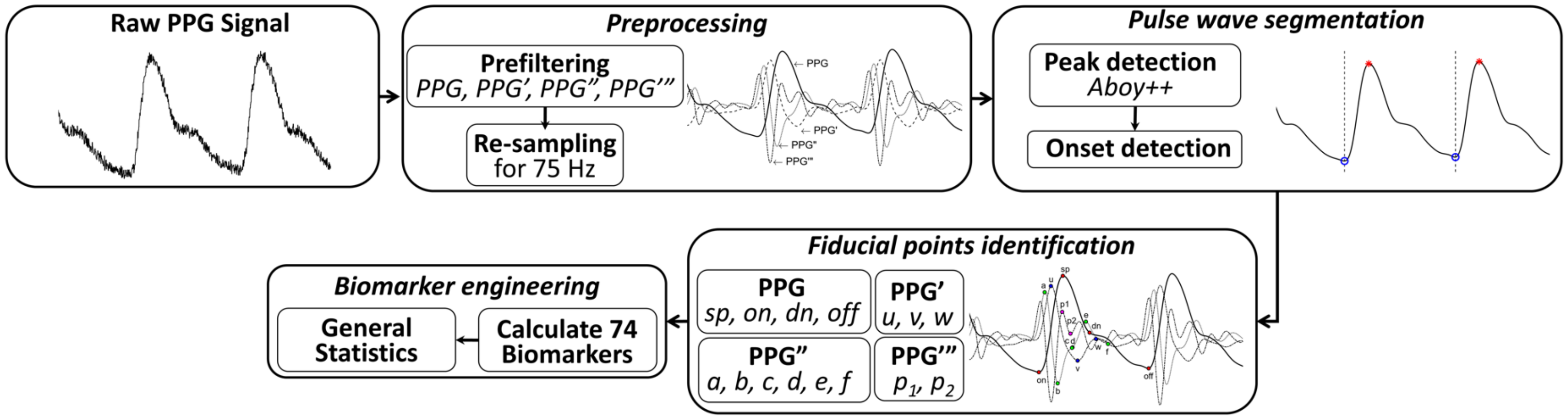


# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language

***pyPPG toolbox***

A toolbox for finger photoplethysmogram (PPG) analysis, including beat detection, fiducial point detection, and comprehensive assessment of standard biomarkers.

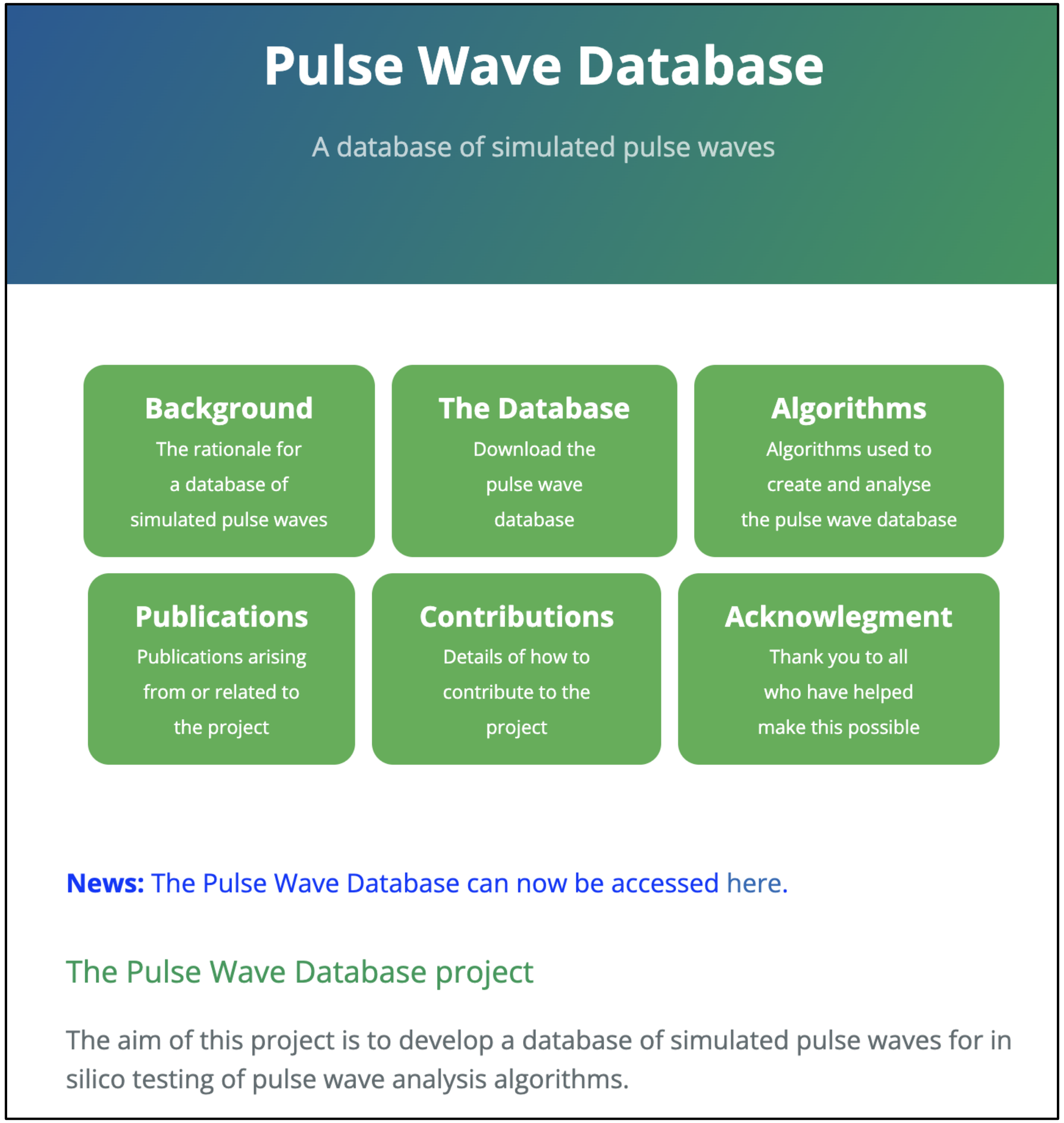



https://pyppg.readthedocs.io/

# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language

- Providing open datasets

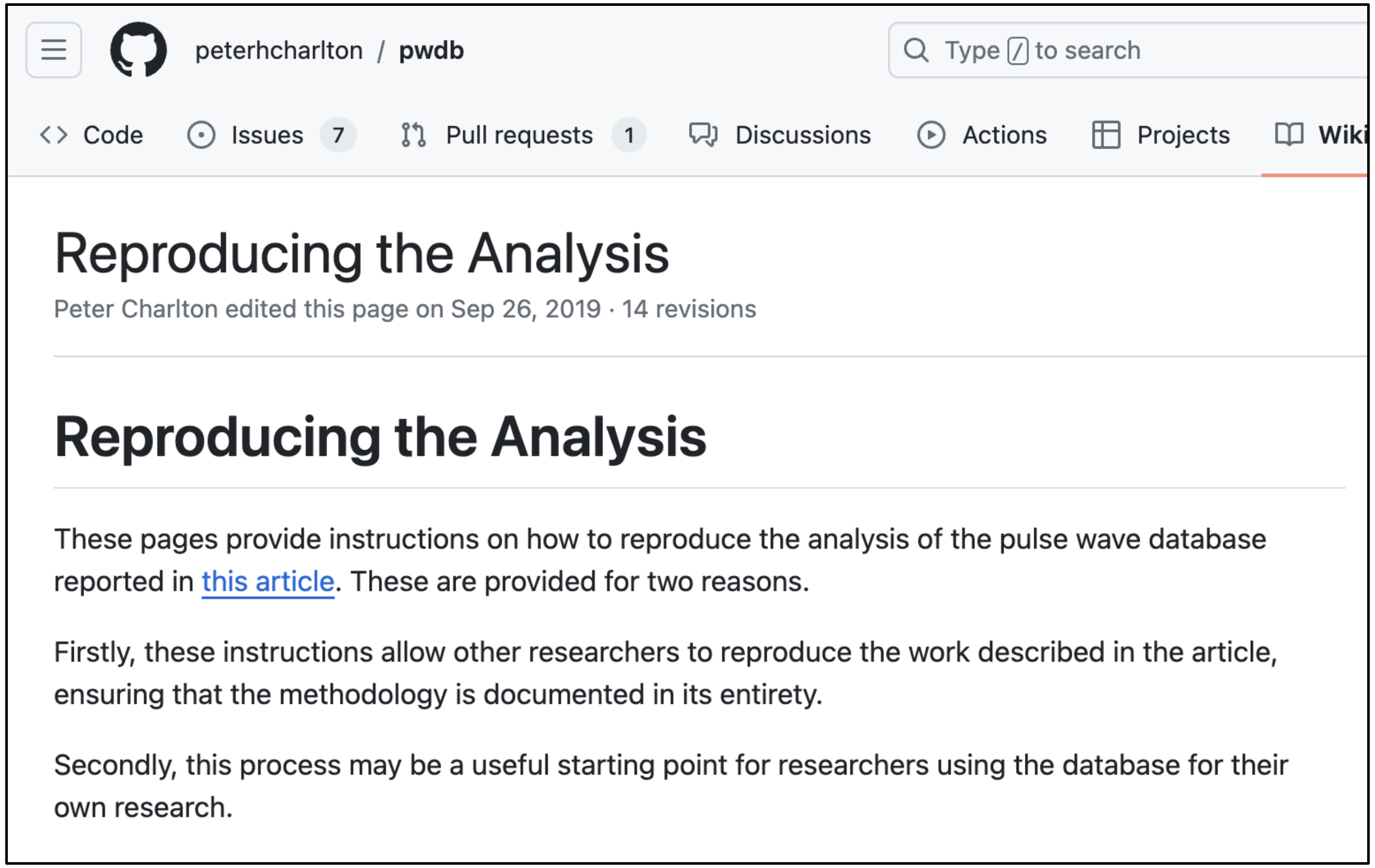



https://peterhcharlton.github.io/pwdb

Charlton PH *et al.*, Modeling arterial pulse waves in healthy aging: a database for in silico evaluation of hemodynamics and pulse wave indexes, AJP Heart Circ, 2019. https://doi.org/10.1152/ajpheart.00218.2019 

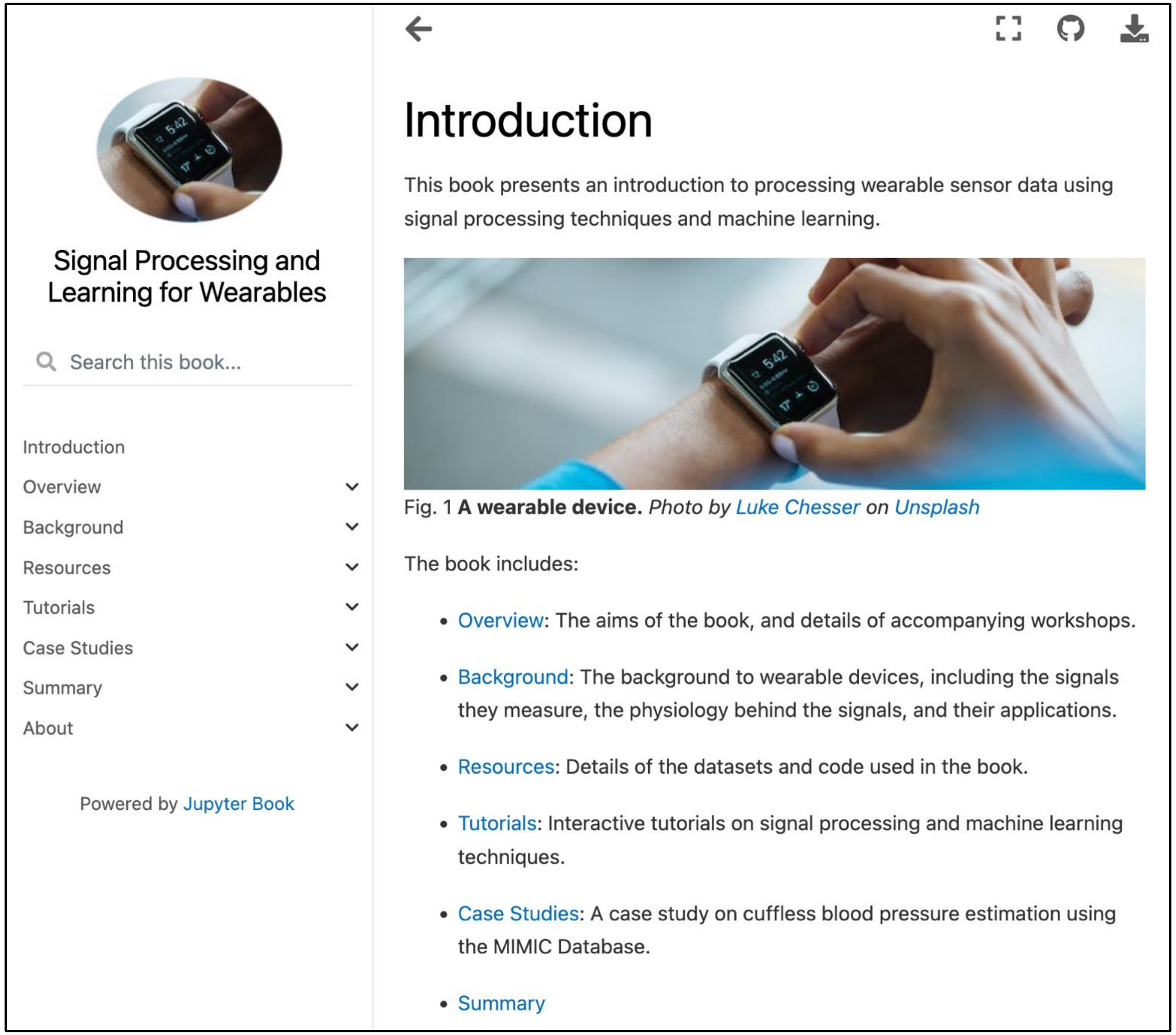
# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language
- Providing open datasets
- Reproducible research



# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language
- Providing open datasets
- Reproducible research
- Educational resources



Signal Processing and Learning for Wearables

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# Introduction

This book presents an introduction to processing wearable sensor data using signal processing techniques and machine learning.

Fig. 1 **A wearable device.** *Photo by Luke Chesser on Unsplash*

The book includes:

- Overview: The aims of the book, and details of accompanying workshops.
- Background: The background to wearable devices, including the signals they measure, the physiology behind the signals, and their applications.
- Resources: Details of the datasets and code used in the book.
- Tutorials: Interactive tutorials on signal processing and machine learning techniques.
- Case Studies: A case study on cuffless blood pressure estimation using the MIMIC Database.
- Summary

https://peterhcharlton.github.io/bsp-book/

# Open science

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language
- Providing open datasets
- Reproducible research
- Educational resources
- Open access publications

**Peter Charlton** Home Projects Publications News Talks Resources Students CV

## Overview

This new textbook, titled *Photoplethysmography*, is due to be published in late 2021. Several experts in the field have contributed to the textbook, which is intended to provide a comprehensive summary of the theory, principles and technology of photoplethysmography.

## Sample Chapters

The following sample chapters are available:

1. **Photoplethysmography signal processing and synthesis**: A comprehensive overview of signal processing techniques for the photoplethysmogram signal.
2. **Wearable photoplethysmography devices**: A comprehensive overview of the state-of-the-art of wearable photoplethysmography devices.

## Link to Published Version

The published version of the textbook is available here, and can be previewed here. (Note that some of the images in the preview version are in black and white, whereas the sample chapters above contain full colour images.)

atrial fibrillation · cardiovascular monitoring · photoplethysmography · SAFER Wearables Study · wearables

https://peterhcharlton.github.io

# Open science: an example

- Providing open-source toolboxes of algorithms
  - Ease of use
  - Programming language
- Providing open datasets
- Reproducible research
- Educational resources
- Open access publications

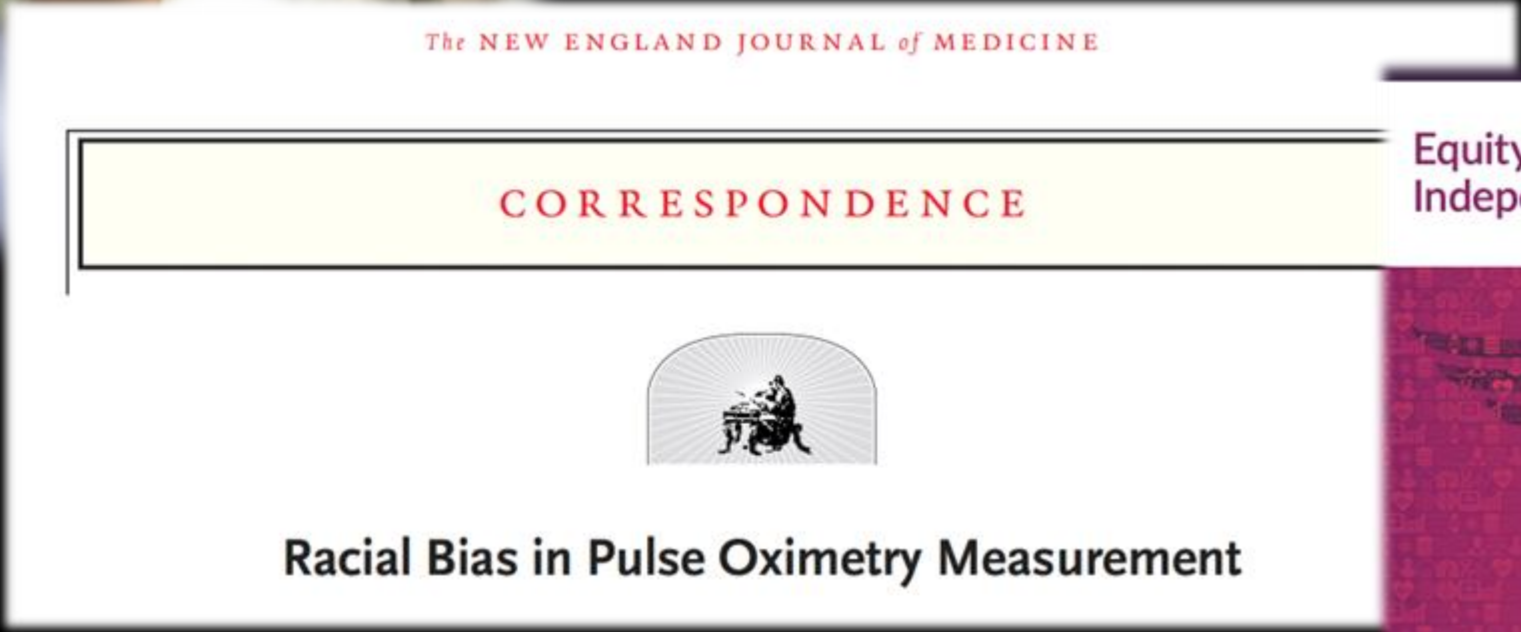
qppg

- Openly available
- GNU GPL Licence
- Highly efficient

MSPTD

- Openly available
- MIT Licence
- Less efficient

MSPTDfast


The NEW ENGLAND JOURNAL of MEDICINE

CORRESPONDENCE

Racial Bias in Pulse Oximetry Measurement


Sjoding MW *et al.*, NEJM, 2020, https://doi.org/10.1056/NEJMc2029240
Photo by Syed Ali on Unsplash

Equity in medical devices: independent review,,GOV.UK, 2024,
https://www.gov.uk/government/publications/equity-in-medical-devices-independent-review-final-report (OGL 3.0)

## With thanks to…

Prof Jonathan Mant

Prof Panicos Kyriacou

The SAFER Research Team

University of Cambridge

City, University of London

King’s College London

British Heart Foundation

NIHR

EPSRC

… and many, many others

Photoplethysmography is now widely used in wearable devices, with many potential applications.

Photoplethysmography-based wearables have shown great promise in certain applications such as detecting atrial fibrillation.

However, there is much work to do to ensure the potential benefits of photoplethysmography are available to all, making photoplethysmography-based devices as reliable as a climbing rope.

# Equitable Photoplethysmography in Wearables: Accurate Data for All


Dr Peter H. Charlton

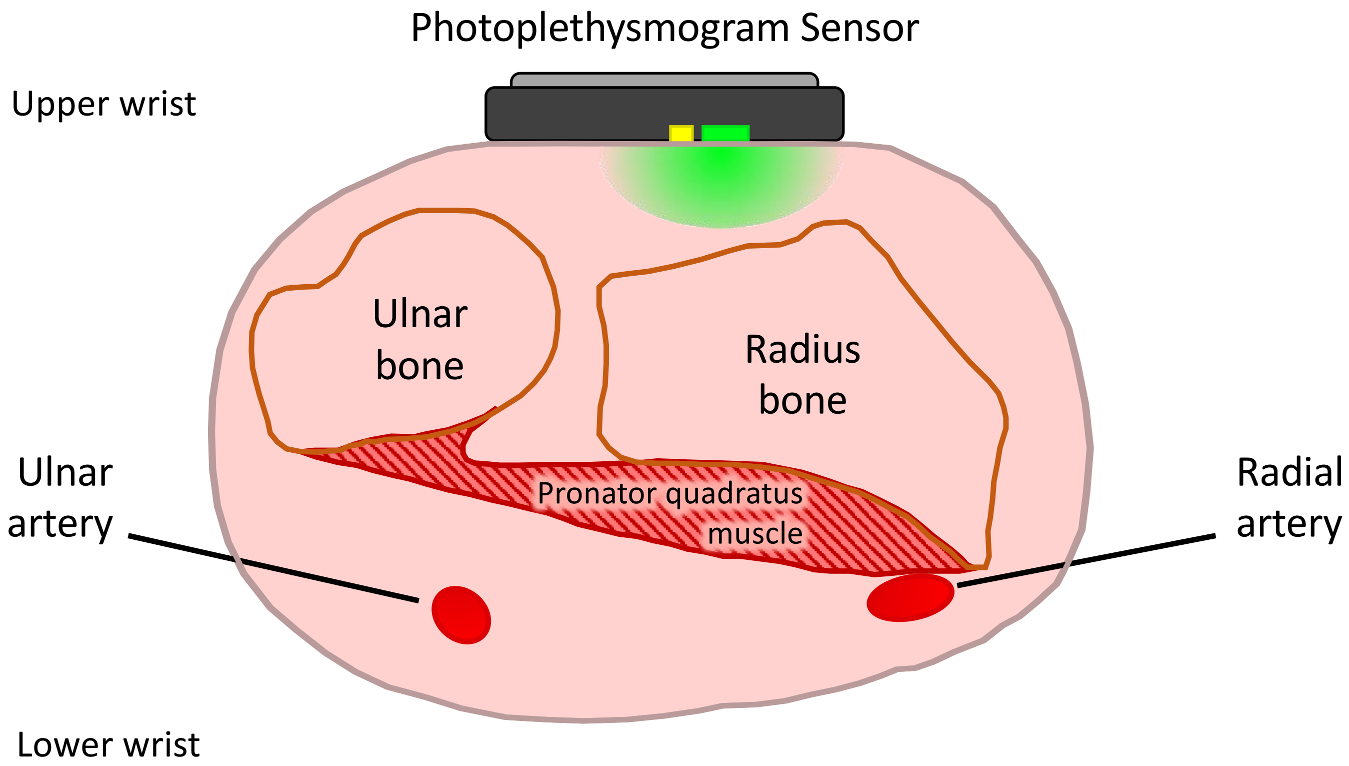
https://peterhcharlton.github.io

pc657@cam.ac.uk


Slides available at: https://doi.org/10.5281/zenodo.13833790 (CC BY 4.0)

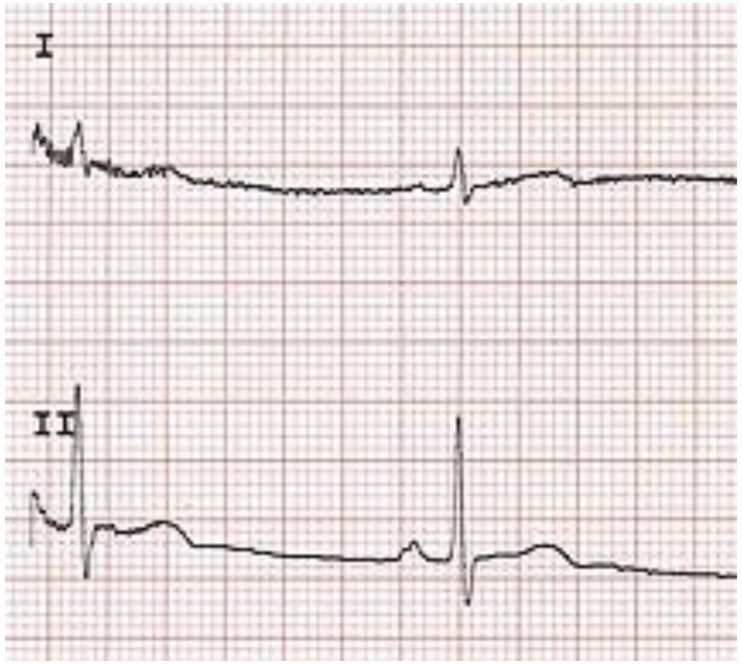
# Wrist photoplethysmography: limitations

Photoplethysmogram (PPG) Sensor




Charlton PH *et al.*, Wearable photoplethysmography for cardiovascular monitoring, Proc. IEEE, 2022. https://doi.org/10.1109/JPROC.2022.3149785 (CC BY 4.0)
Adapted from: H. Gray, Anatomy of the Human Body, W. H. Lewis, Ed., 2nd ed. New York, NY, USA: Lea and Febiger, 1918

# Single-lead ECG: limitations




- Dry electrodes
- Recorded without clinical supervision
- Lead I

"Sinus P waves are usually most prominently seen in leads II and V1"

Meek S and Morris F, 'ABC of clinical electrocardiography: Introduction. II—basic terminology', https://doi.org/10.1136/bmj.324.7335.470