Wearable photoplethysmography devices for health monitoring

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Slides available at: https://doi.org/10.5281/zenodo.7301839 (CC BY 4.0)

Every 30 mins in UK:

6 hospital admissions

10 deaths

€500,000 healthcare costs

BHF Statistics Factsheet – UK, 2020: https://www.bhf.org.uk/what-we-do/our-research/heart-statistics

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

- Vascular age
- Arrhythmias
- Oxygen saturation
- Sleep assessment
- Energy expenditure
- Blood pressure
- Respiratory rate
- Heart rate
- Stress level
- VO2 max

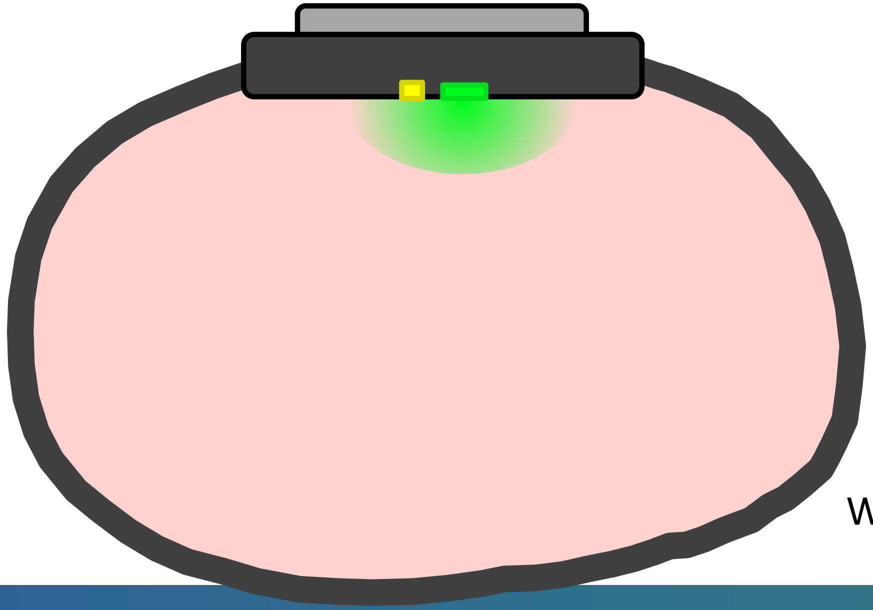
Infectious diseases
Fitness tracking
Biometric authentication
CV risk prediction
Health insurance
Clinical deterioration
Menstrual cycle
Vascular age
Chronic kidney disease
Mental stress
Pre-eclampsia
Sleep monitoring
Seizure detection
Obstructive sleep apnea
Orthostatic hypotension
Atrial fibrillation
Asthma
Heart failure
COPD
Sepsis


St. Thomas' Hospital
St. Thomas' Hospital


♡119
(artistic licence – the device didn’t show this heart rate)

The Photoplethysmogram

Photoplethysmogram (PPG) Sensor



Wrist cross-section

The Photoplethysmogram

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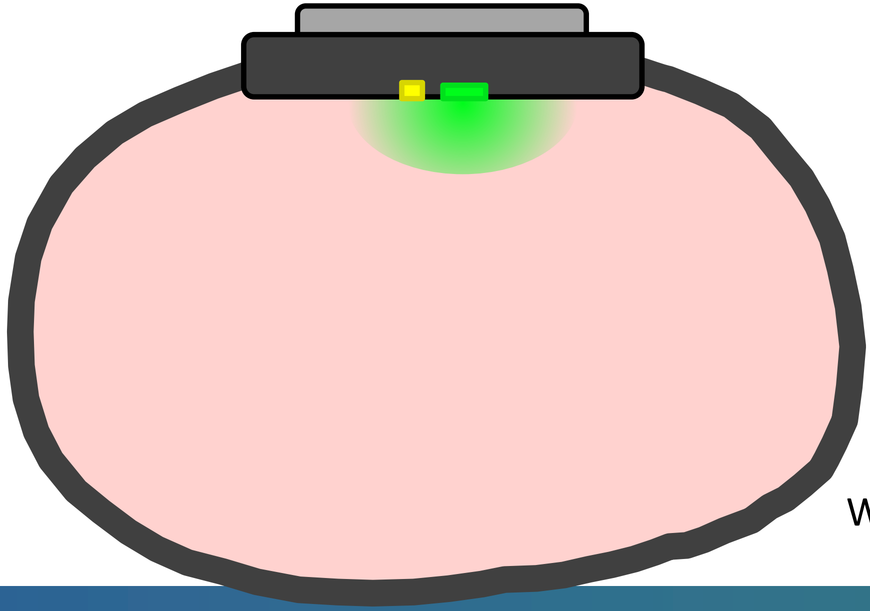
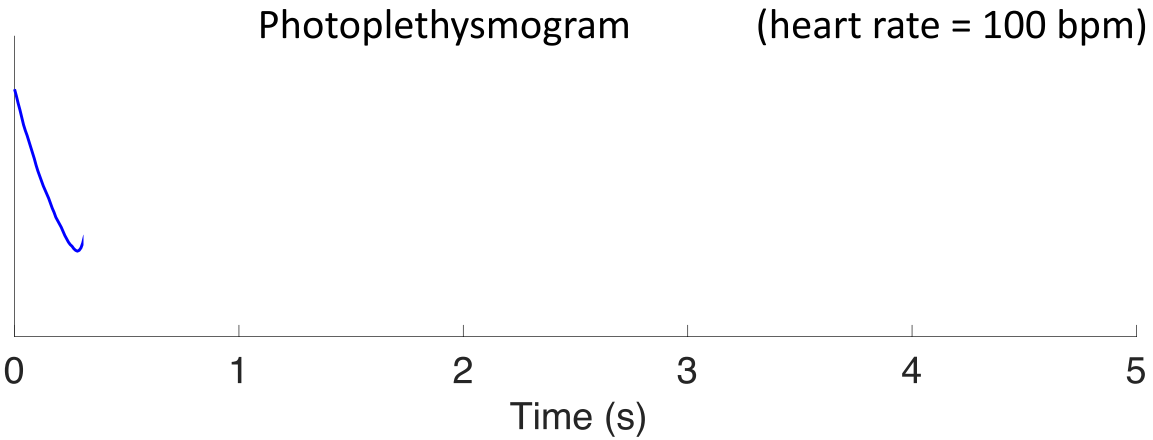
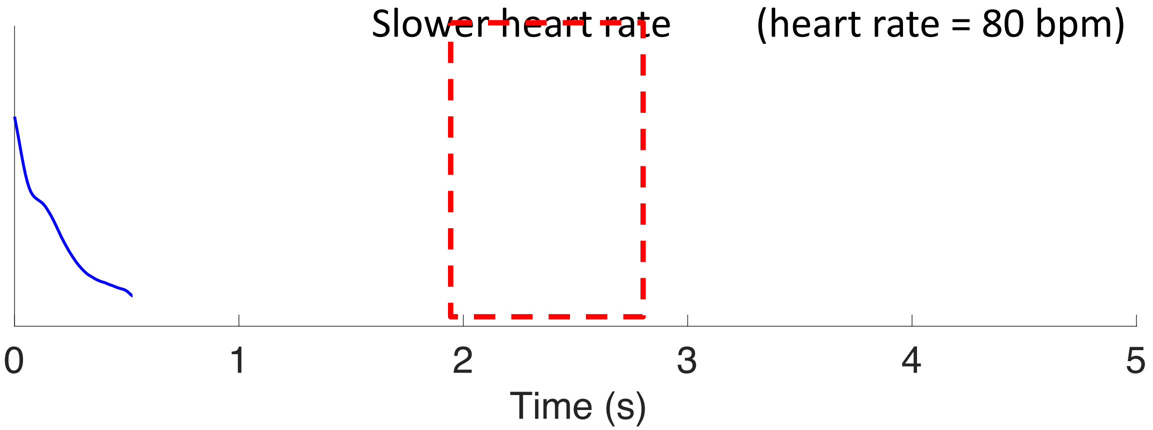
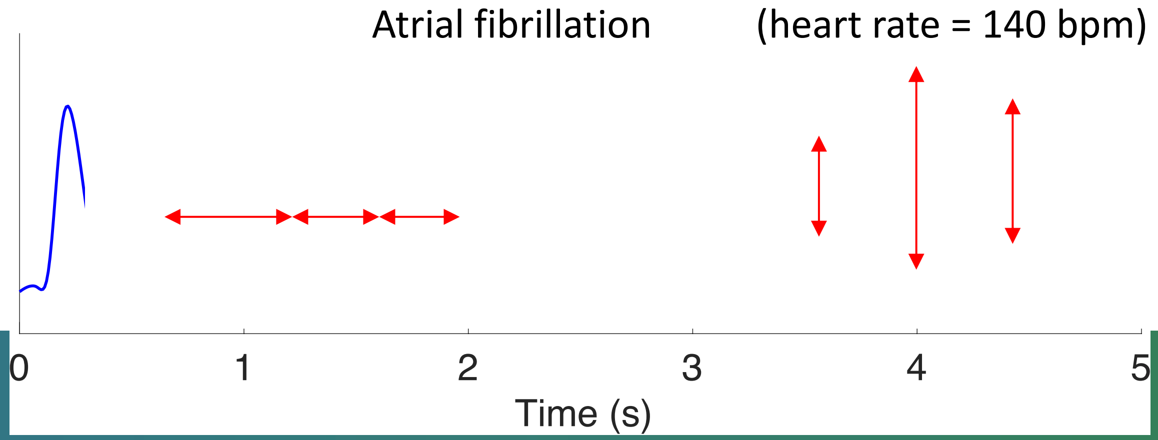


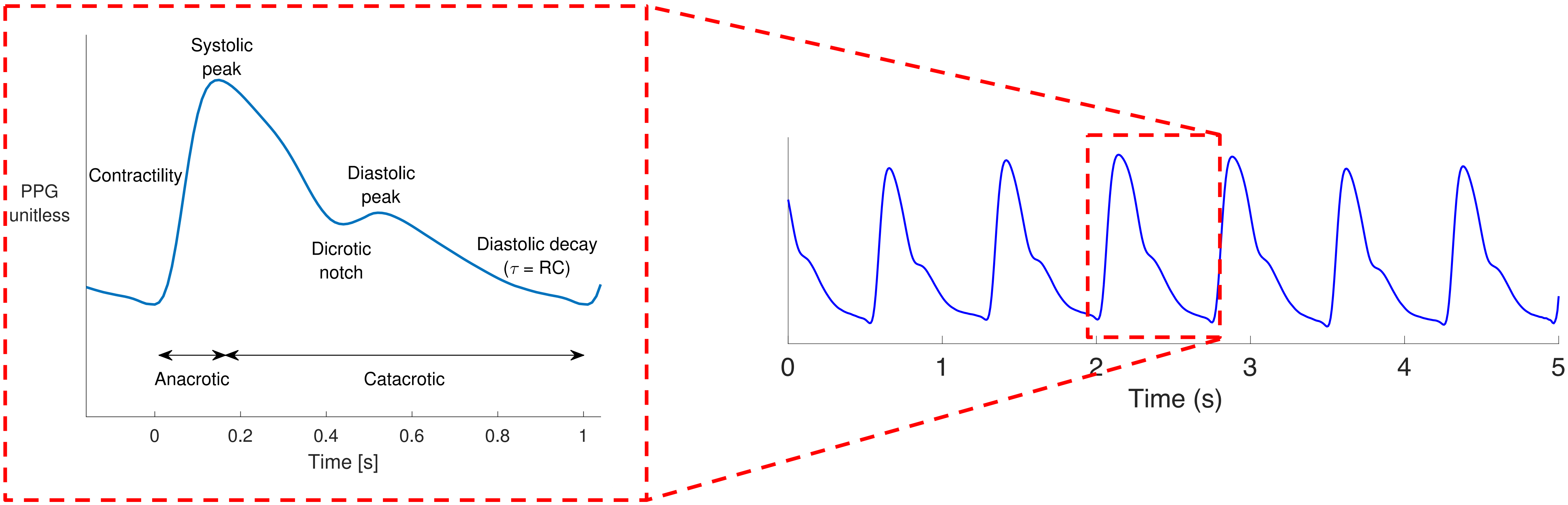
Wrist cross-section



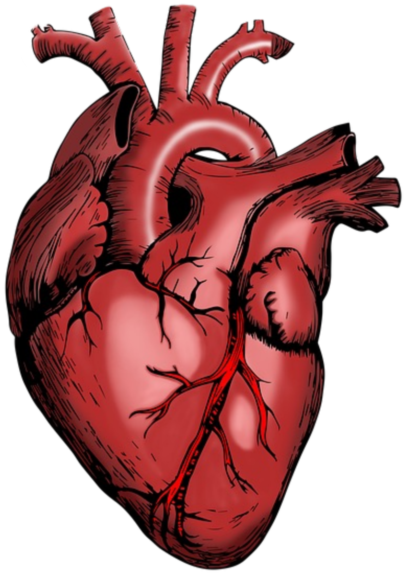




The Photoplethysmogram



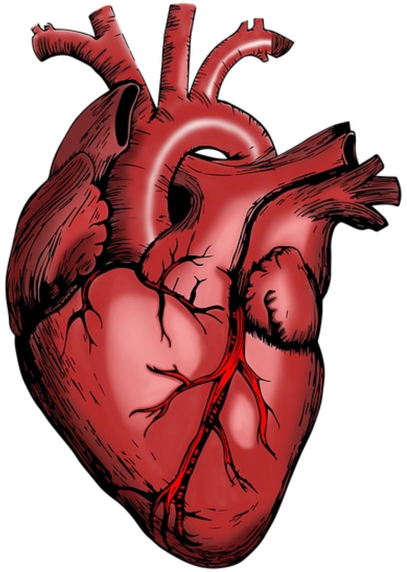
Applications



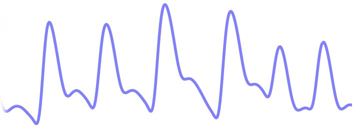
Research and Development

Challenges

Applications



Research and Development

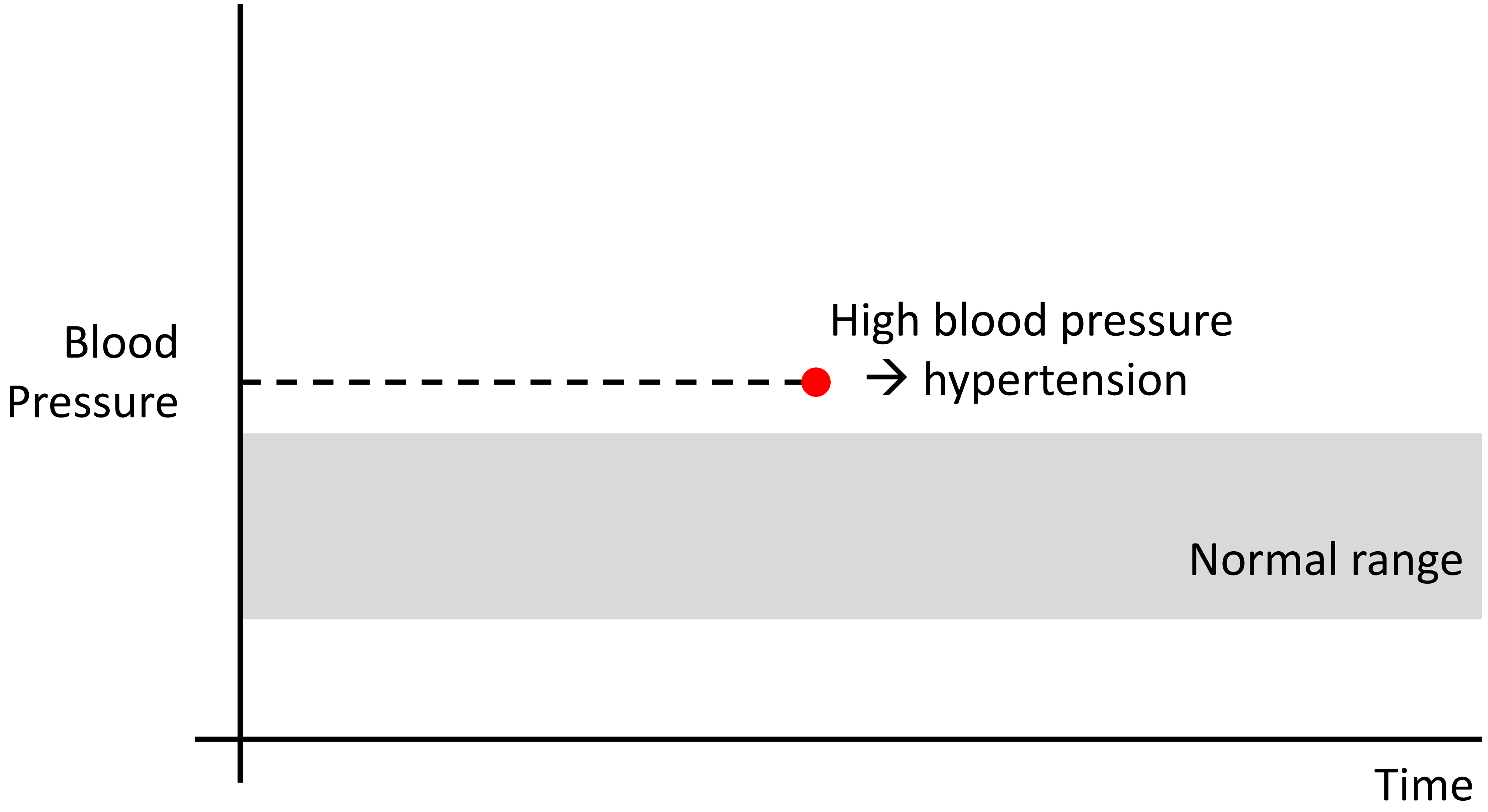


Challenges

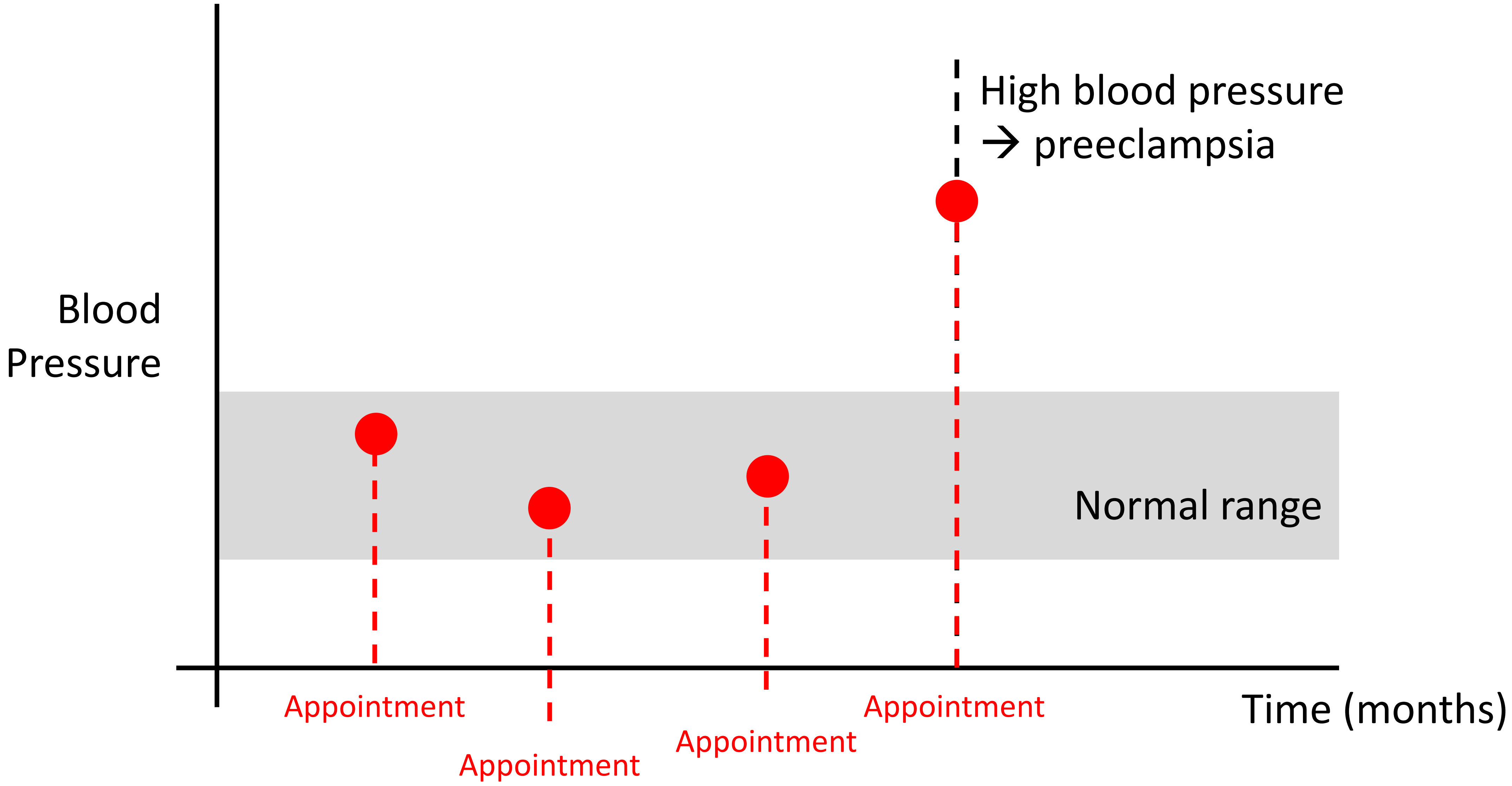
cardiovascular monitoring


Blood
Pressure
Time

Identifying hypertension in a middle-aged man:



Identifying early signs of preeclampsia in a pregnant woman:



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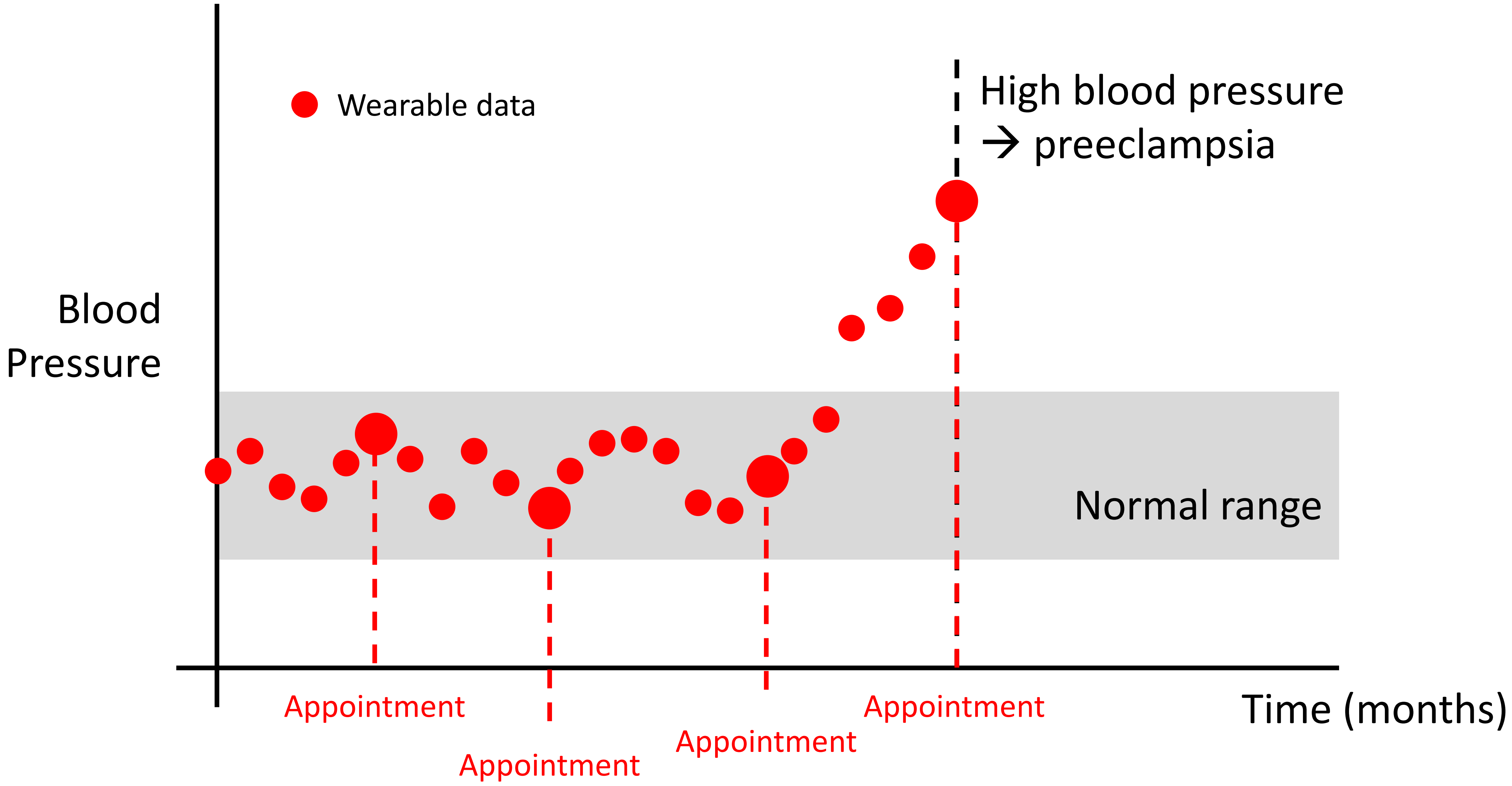
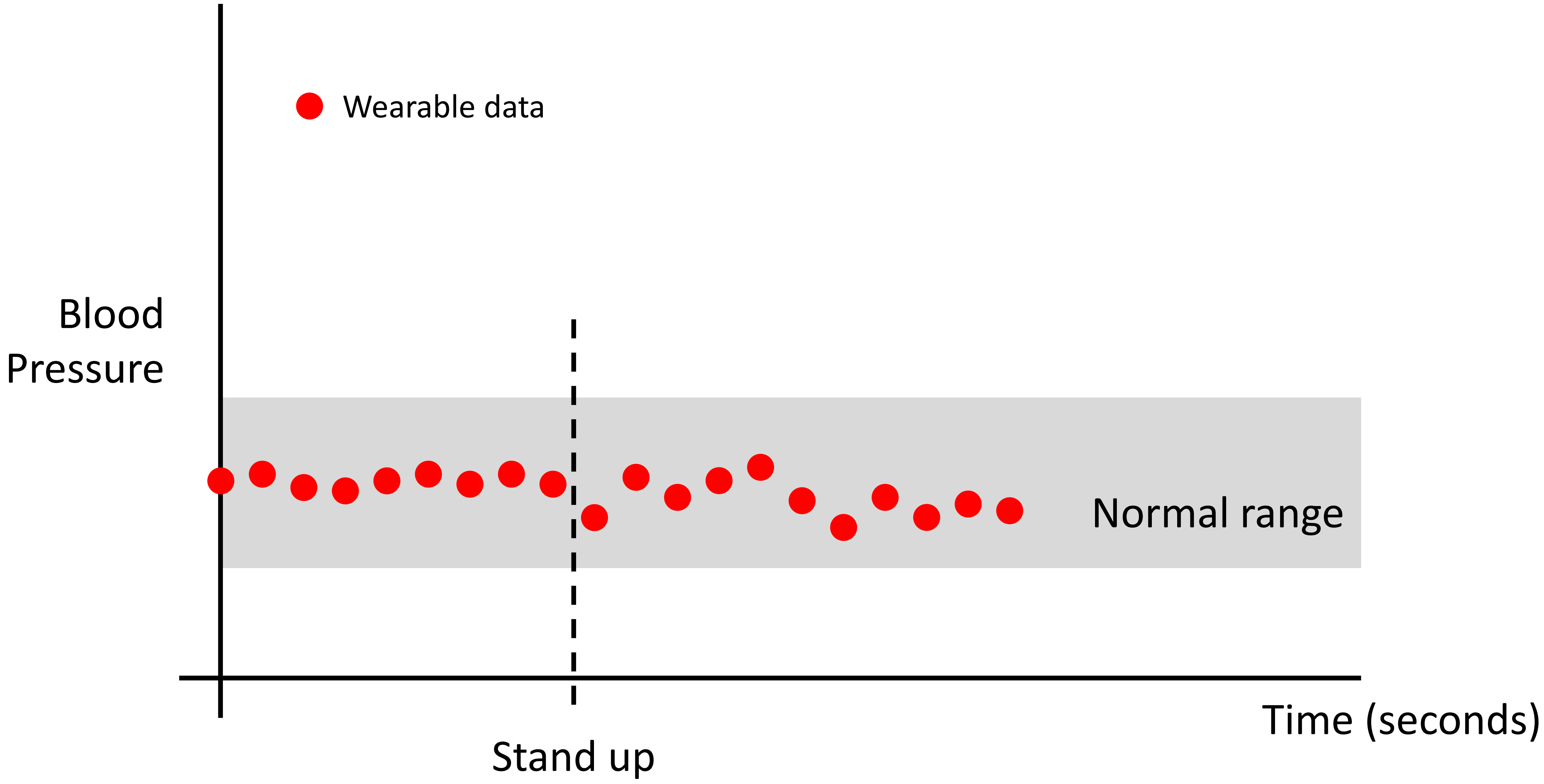
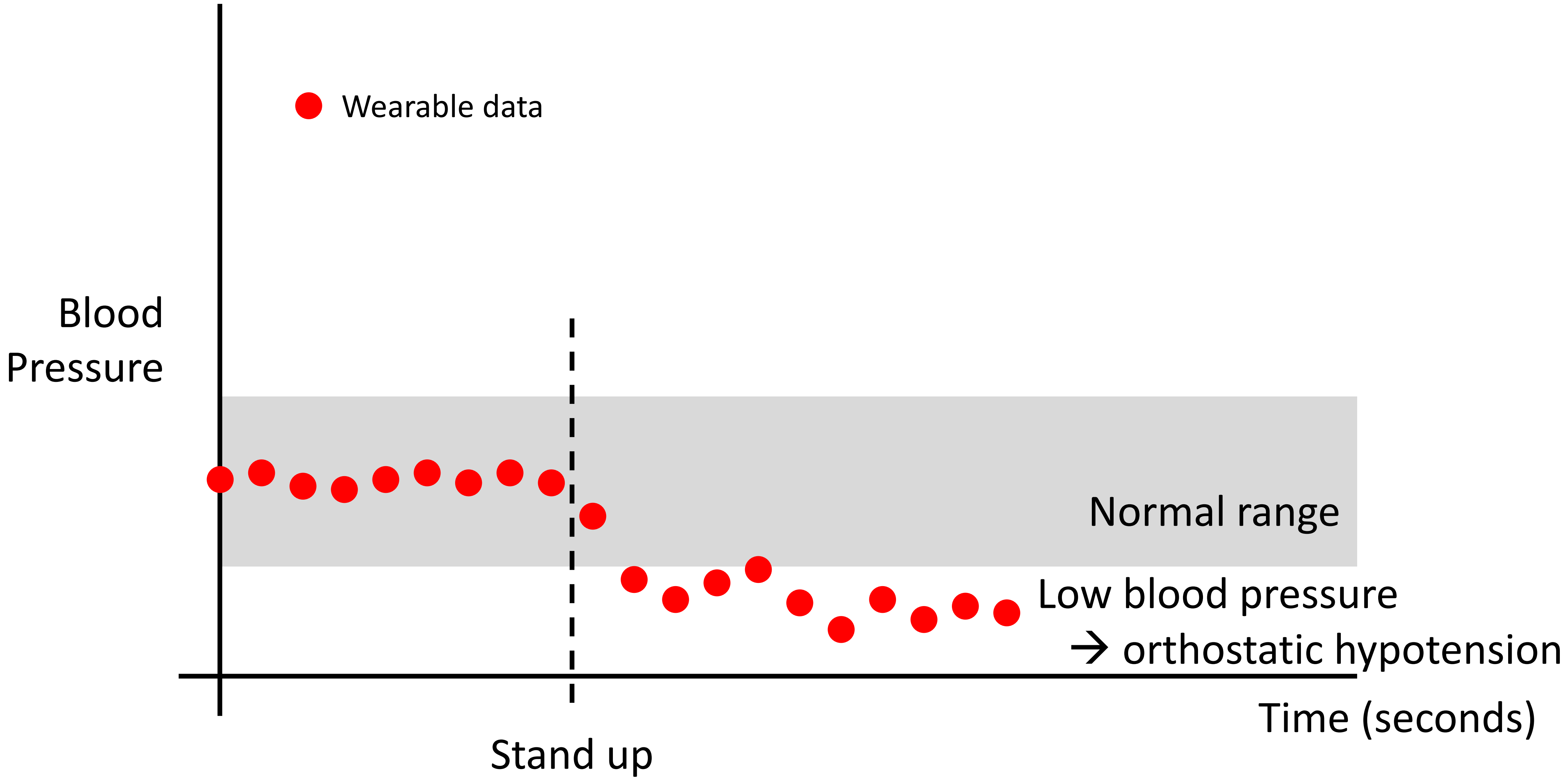


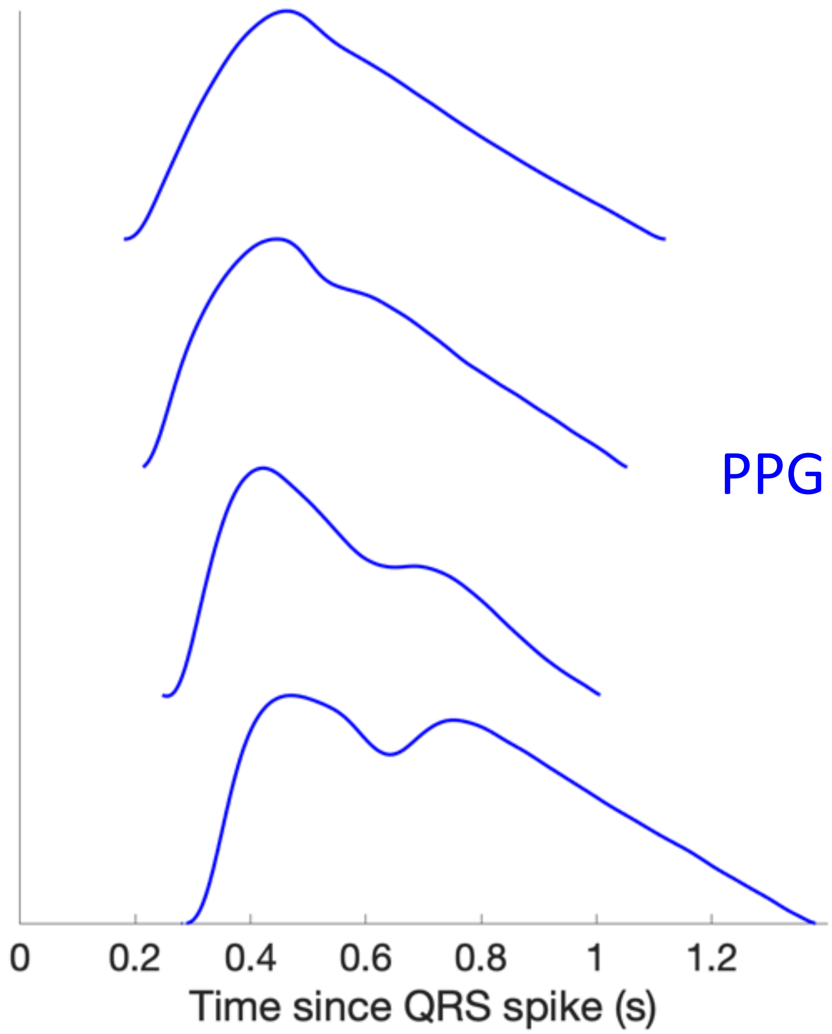
Identifying orthostatic hypotension in an older adult, indicating risk of falls:



Identifying orthostatic hypotension in an older adult, indicating risk of falls:



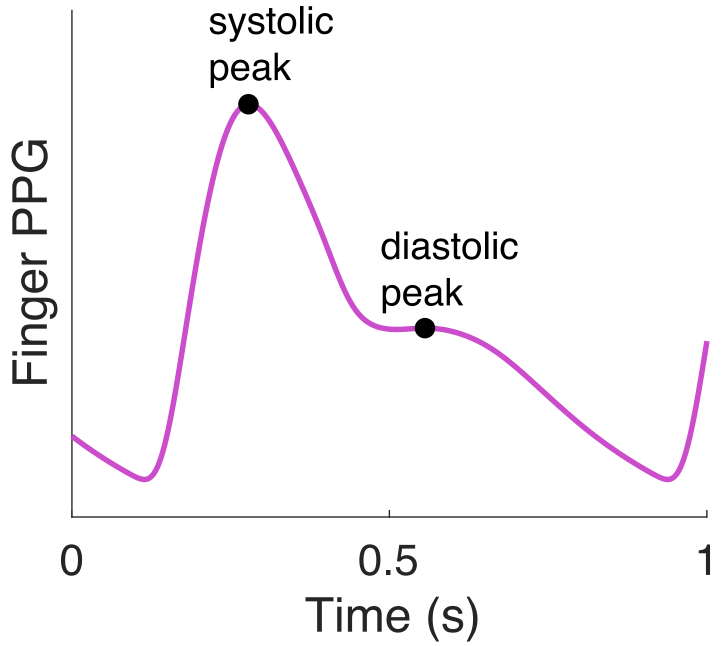
Pulse wave shape changes with blood pressure:



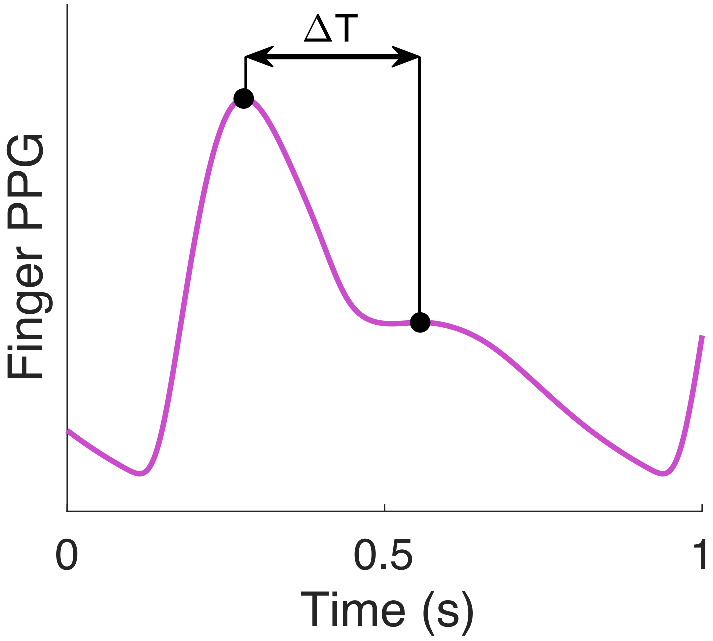
PPG pulse waves

Estimating blood pressure from a single PPG signal

i) Identify fiducial points



ii) Extract pulse wave feature



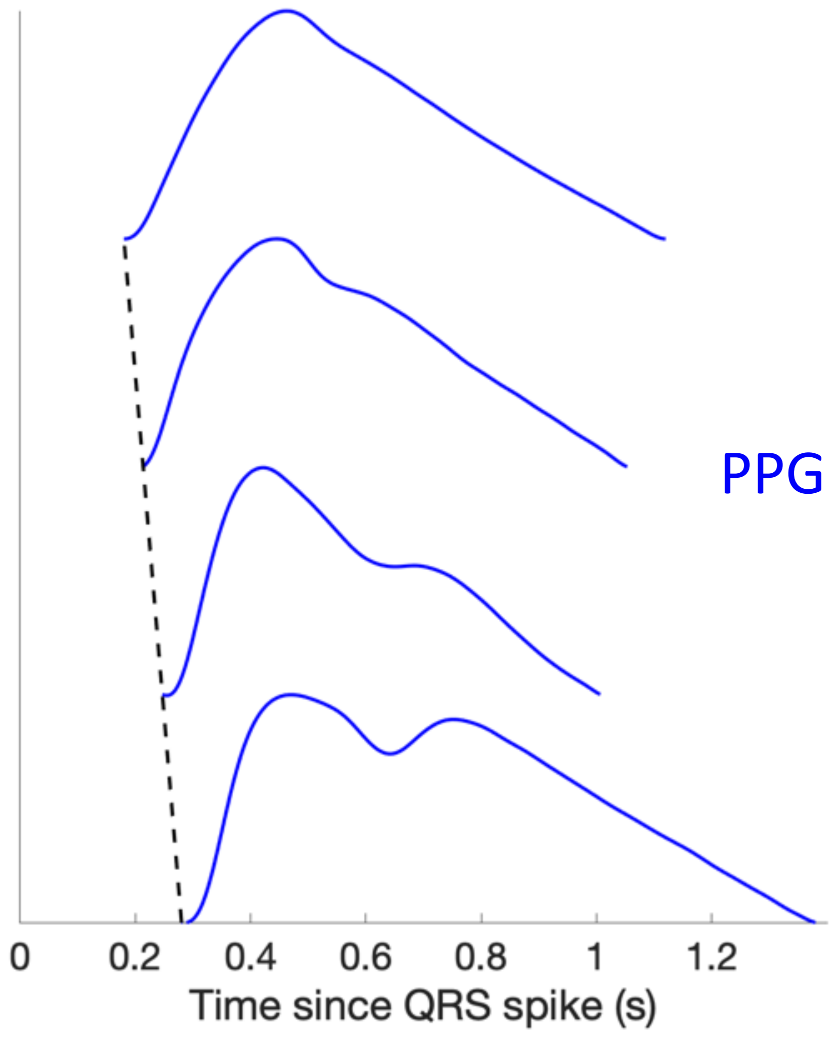
iii) Estimate BP

e.g. estimate systolic blood pressure,

$$SBP = \alpha \, . \, \Delta T + \beta$$

from the time delay (ΔT)

Pulse wave timing changes with blood pressure:

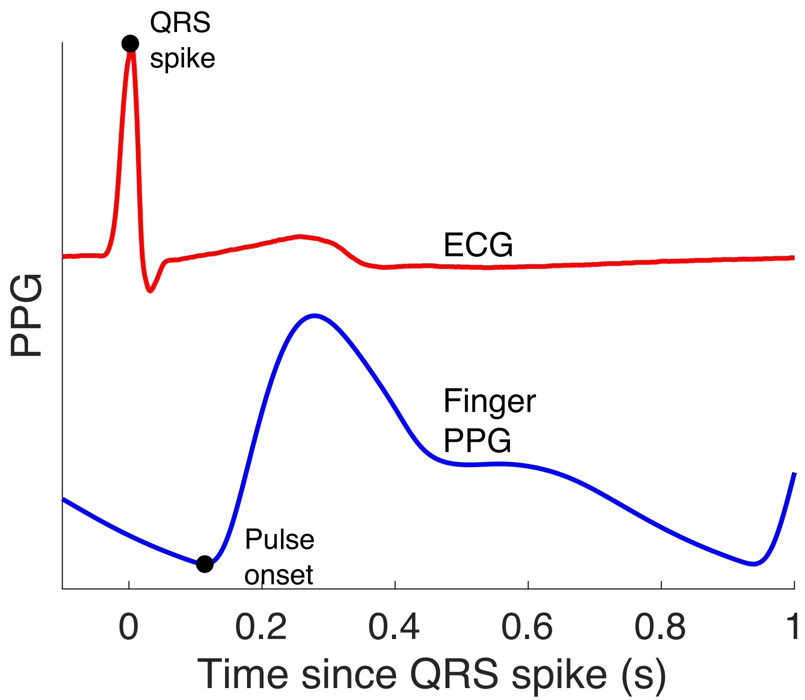


PPG pulse waves

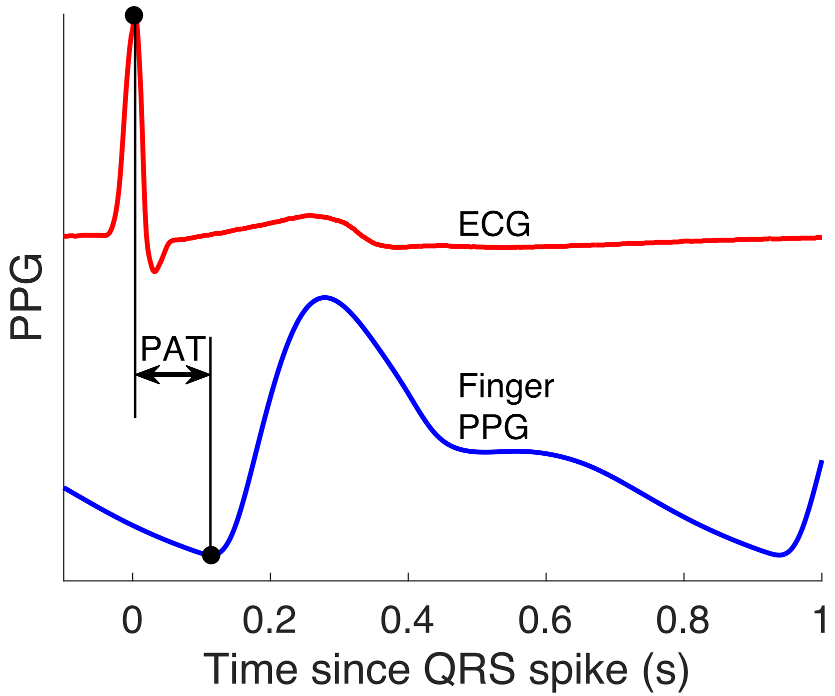
Data from the Vortal dataset (with artistic licence)

Estimating blood pressure from PPG and electrocardiogram (ECG) signals

i) Identify QRS and pulse onset



ii) Extract pulse arrival time



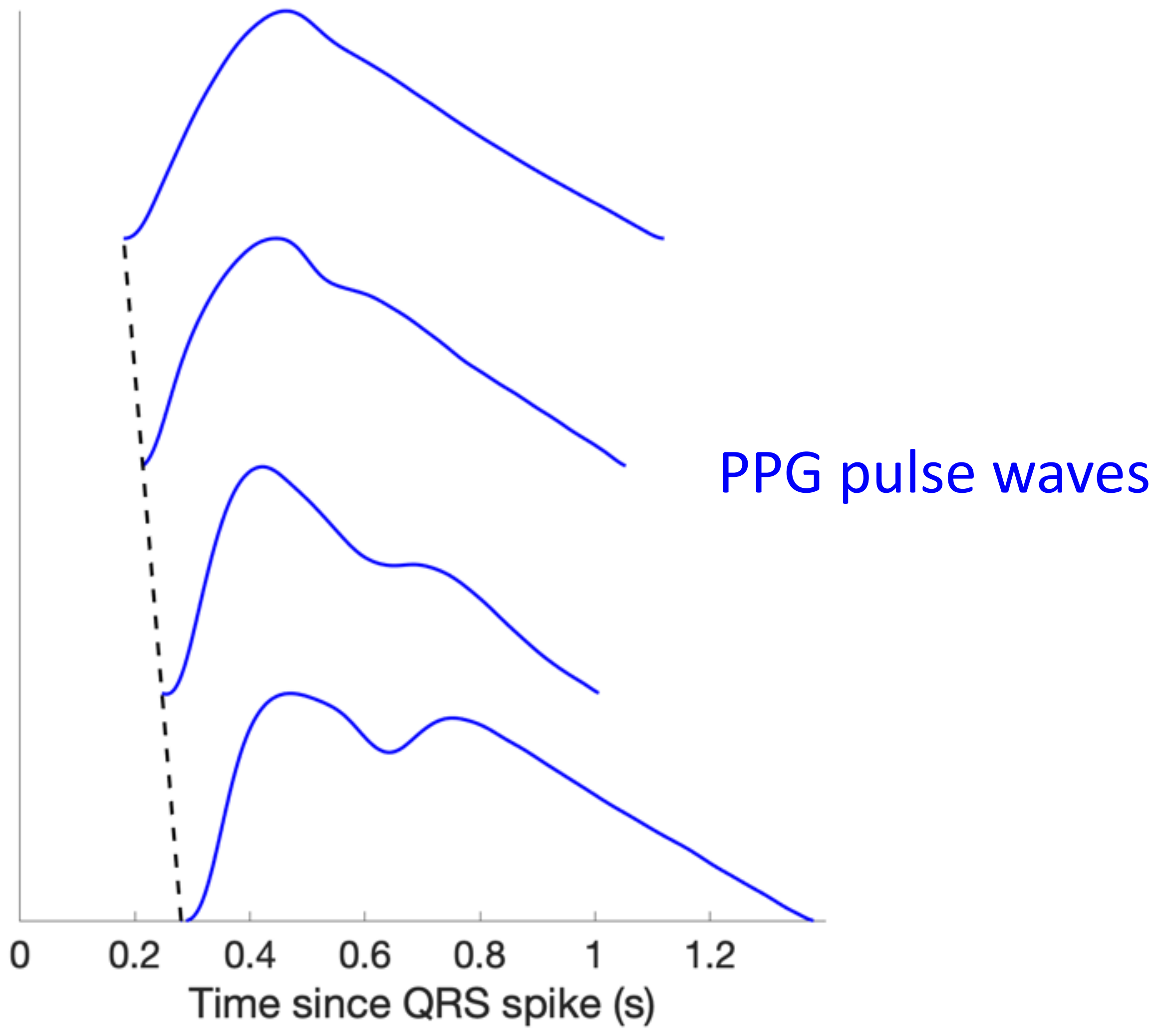
iii) Estimate BP

e.g. estimate systolic blood pressure,

$$SBP = \alpha \cdot \Delta T + \beta$$

from the pulse arrival time (PAT)

Pulse wave shape and timing change with blood pressure:



Data from the Vortal dataset (with artistic licence)

Aortic stiffness:

Ageing — ~ 10% increase per decade

Disease — *e.g.* Diabetes, Heart failure

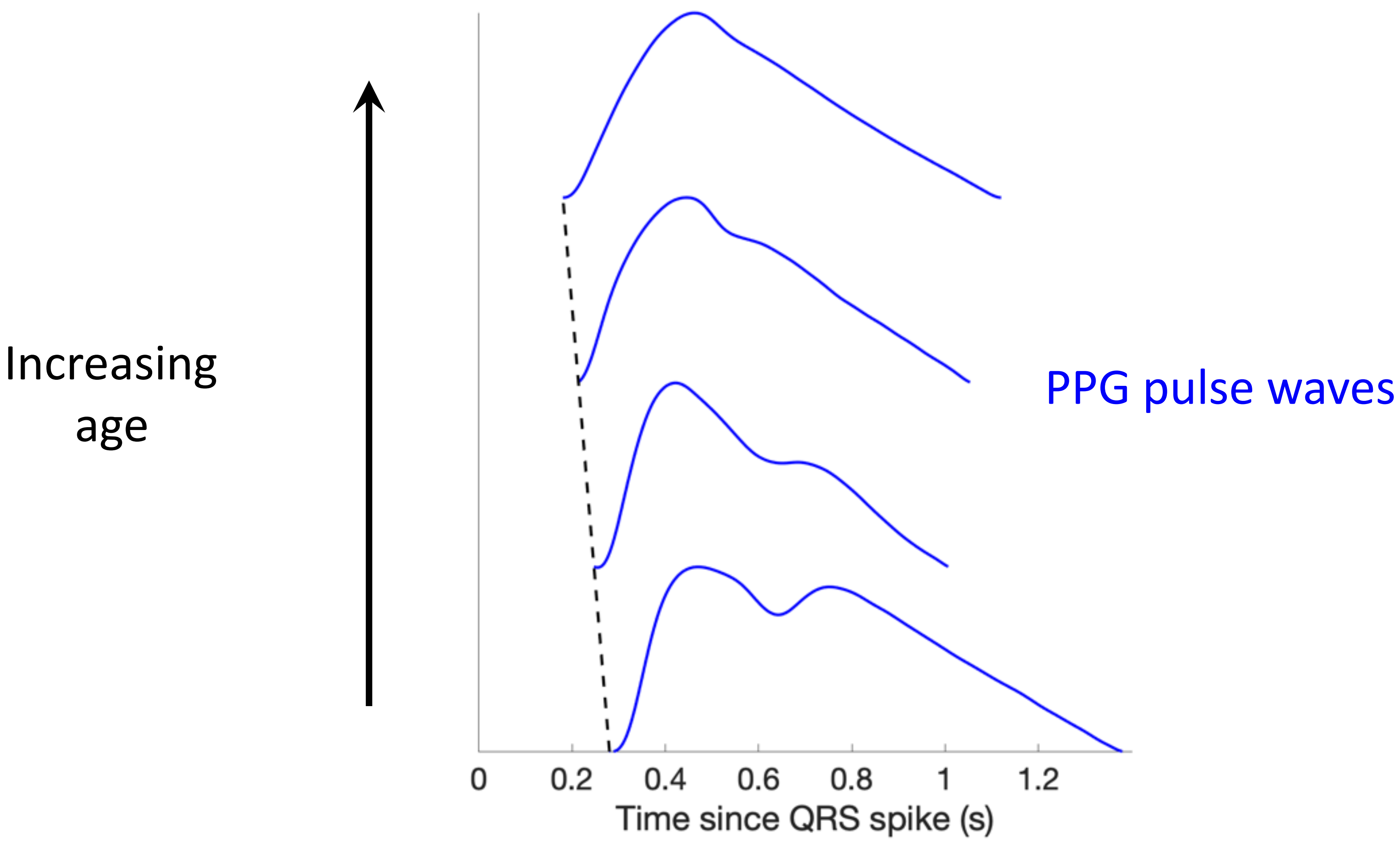
Predictor — CV events, Mortality

Vascular ageing

Benetos A, Am J Hypertens, 2002.
Vlachopoulos C *et al.*, "JACC", 2010.

Qimono, Pixabay (Pixabay Licence)

Changes in pulse waves with vascular ageing:



Data from the Vortal dataset (with artistic licence)

From a recent review:

- The indicators of vascular ageing most commonly assessed from the PPG in research:

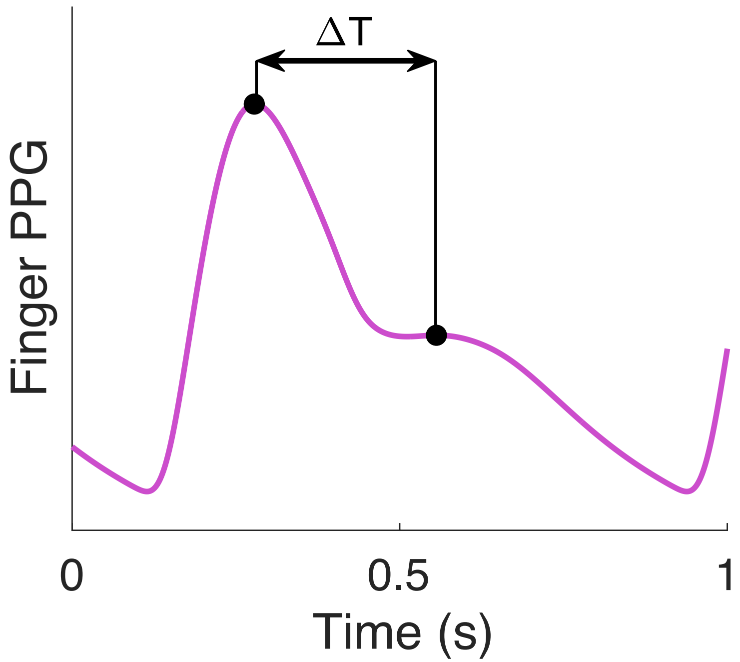
- Blood pressure (vast majority of articles)
- Arterial stiffness (few)
- Atherosclerosis (inc. peripheral arterial disease) (very few)

Adapted from Charlton et al. (2022), Assessing hemodynamics from the photoplethysmogram (CC BY 4.0)

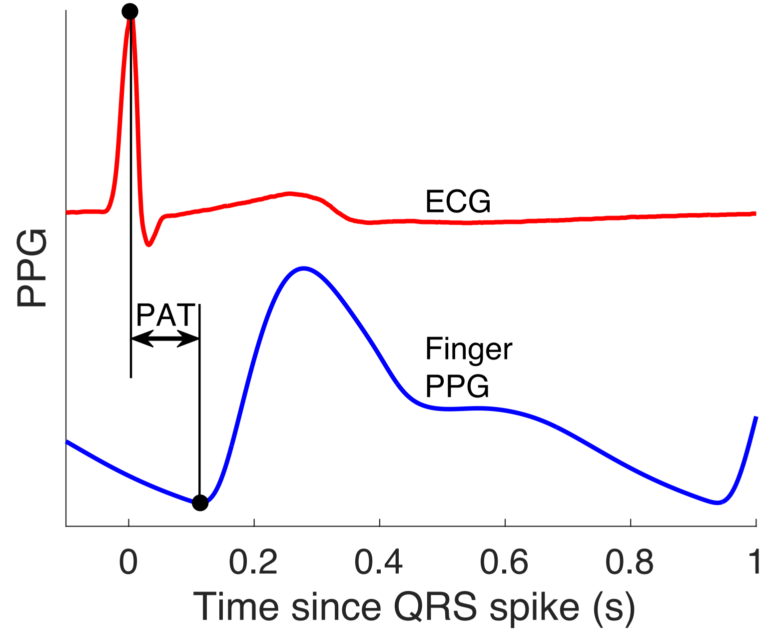
From a recent review:

- Three approaches to using the PPG to assess vascular ageing:

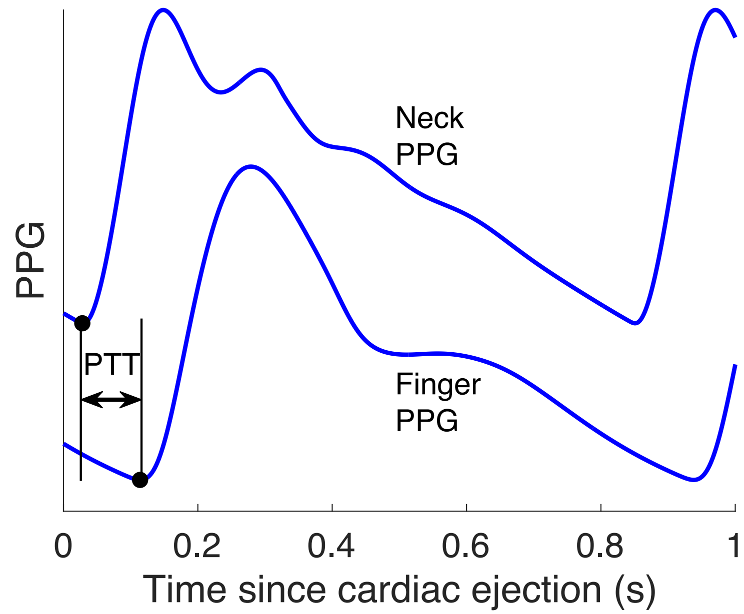
1. Single PPG



2. PPG and ECG



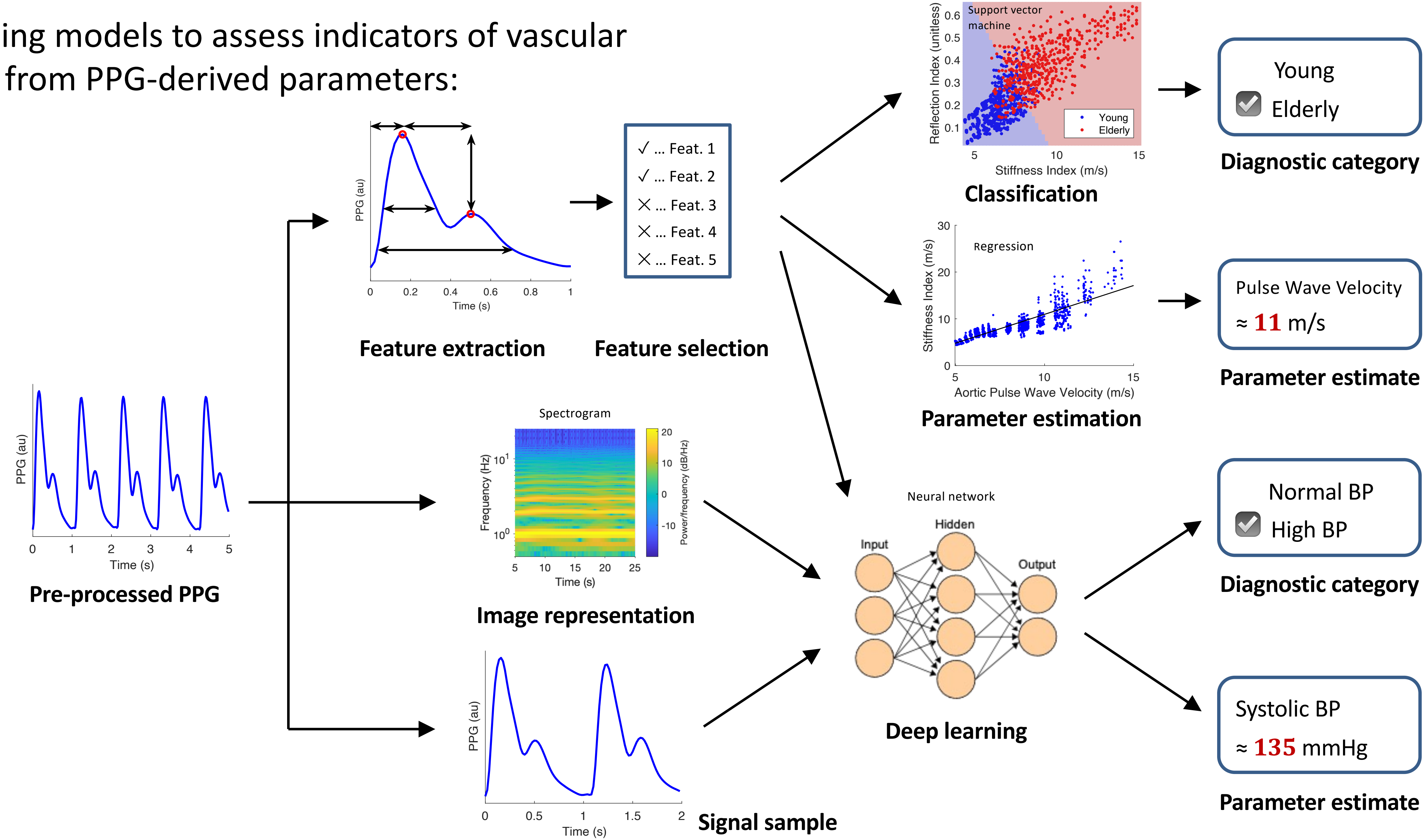
3. Multiple PPGs



How do we estimate a parameter such as blood pressure from these measurements?

Adapted from Charlton et al. (2022), Assessing hemodynamics from the photoplethysmogram (CC BY 4.0)

- Using models to assess indicators of vascular age from PPG-derived parameters:



Charlton PH *et al.*, Wearable photoplethysmography for cardiovascular monitoring, Proc. IEEE, 2022. (CC BY 4.0)

From a recent review:

- How has the performance of PPG-derived parameters of vascular age been assessed?

Studies:

- Mostly in healthy adults
- Small sample sizes
- Range of reference indicators of vascular age
- Range of statistics

Adapted from Charlton et al. (2022), Assessing hemodynamics from the photoplethysmogram (CC BY 4.0)

From a recent review:

- How well do PPG-derived parameters of vascular age perform in comparison to reference indicators?

Studies:

- Pulse wave velocity: Moderate correlations between PPG-derived and reference pulse wave velocity (or pulse transit time)
- Blood pressure: Very few studies meet required precision
- Peripheral arterial disease: PPG-derived parameters useful

Adapted from Charlton et al. (2022), Assessing hemodynamics from the photoplethysmogram (CC BY 4.0)

From a recent review:

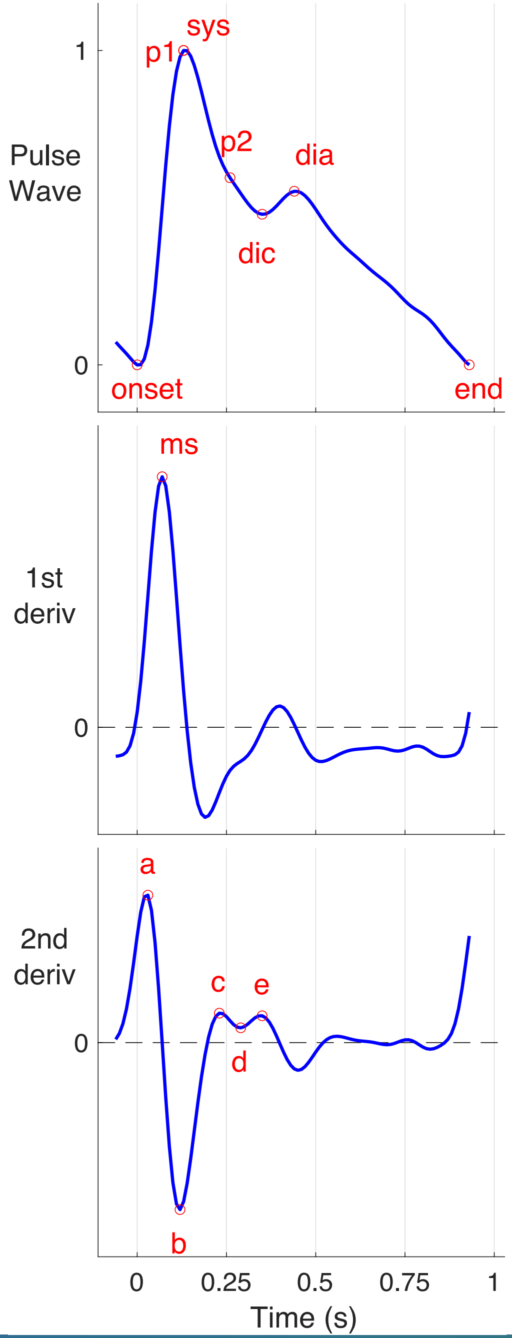
- What is the potential clinical utility of PPG-derived parameters of vascular age?

Much of the evidence relates to:

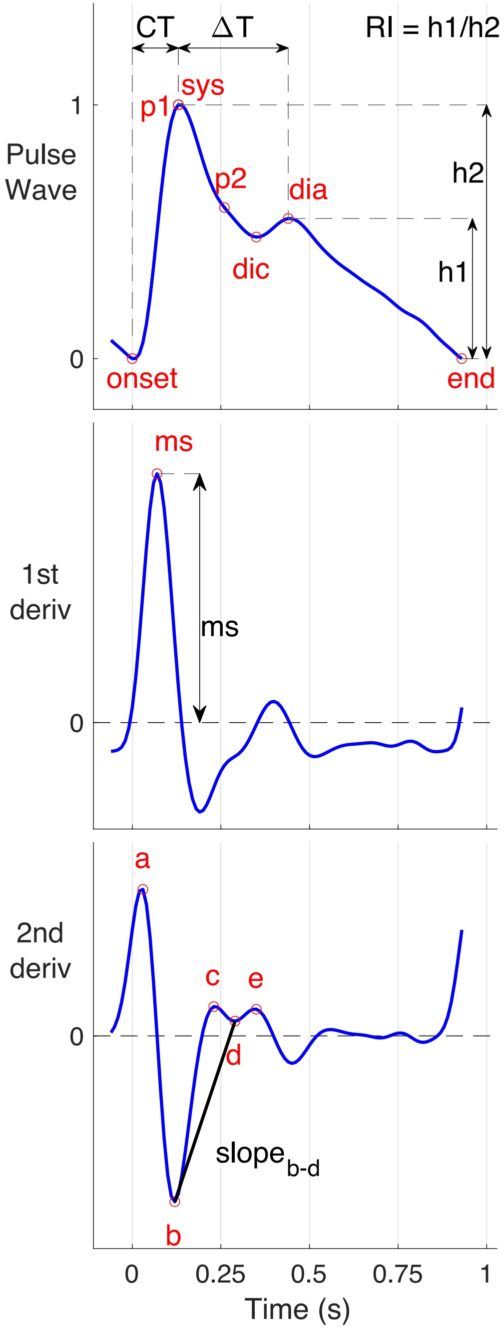
- Identifying peripheral arterial disease
- Identifying diabetes
- Cardiovascular risk prediction

Adapted from Charlton et al. (2022), Assessing hemodynamics from the photoplethysmogram (CC BY 4.0)

Identify fiducial points:



Extract pulse wave features:

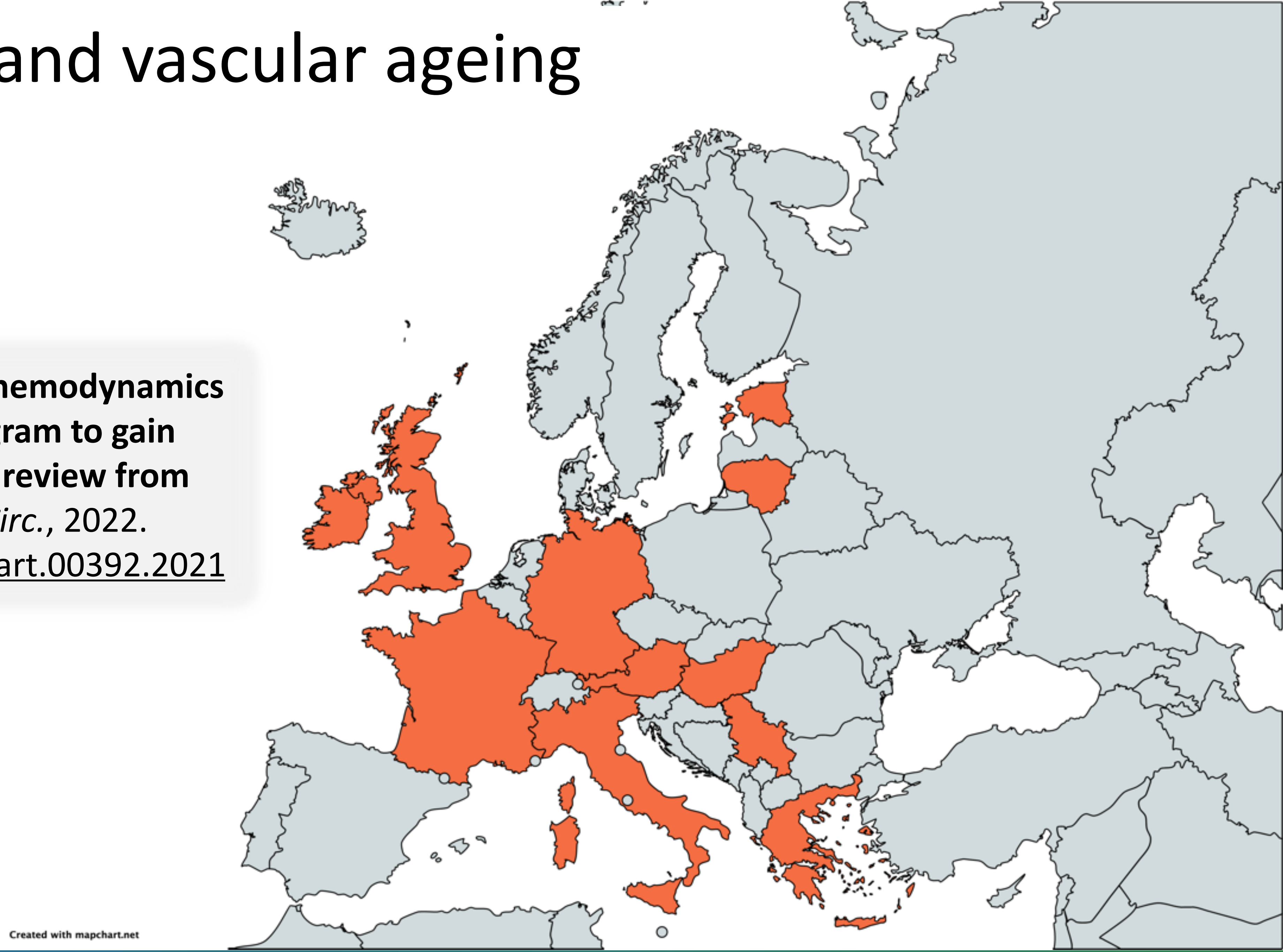


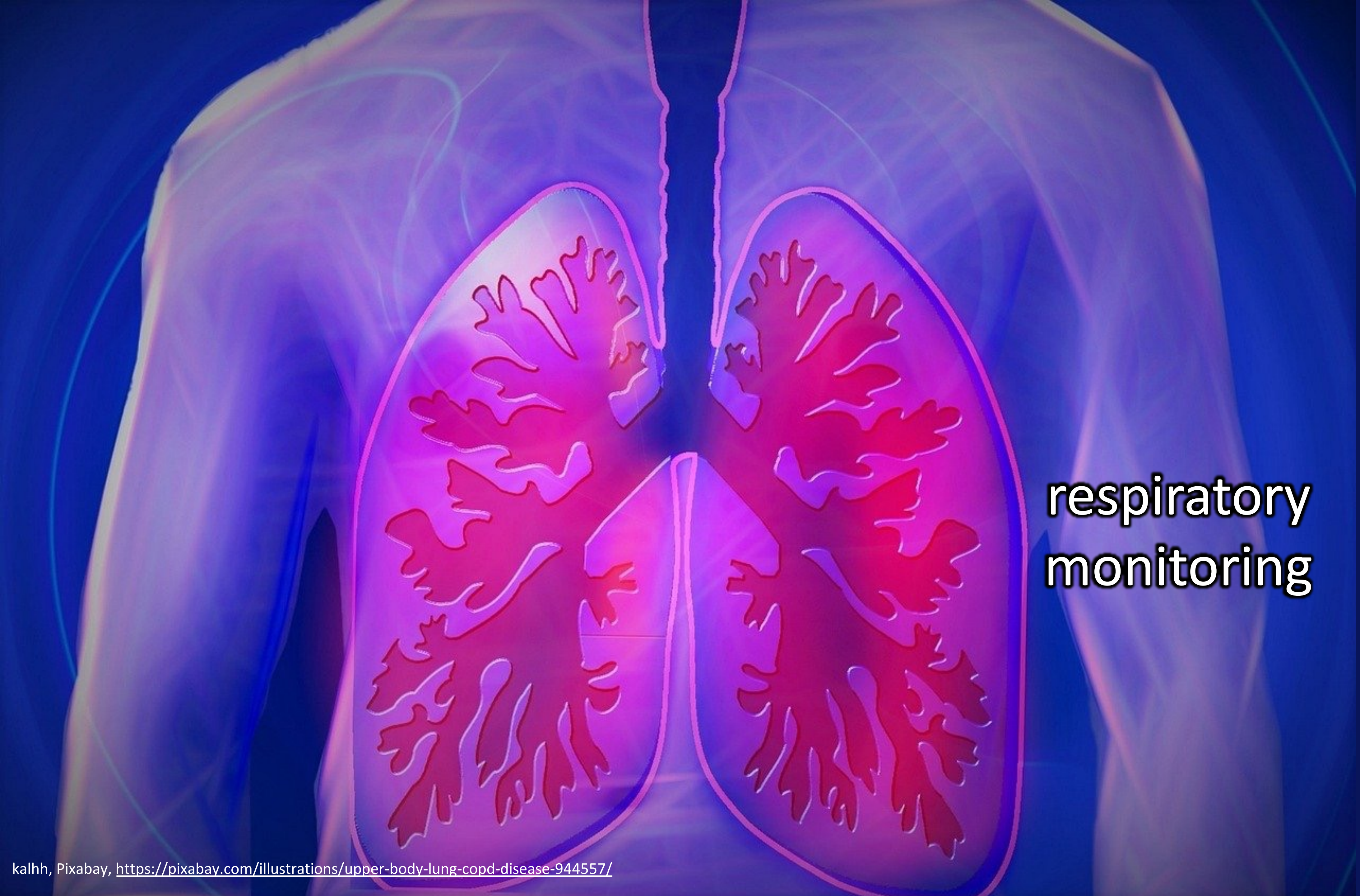
d/a found to be an independent predictor of cardiovascular mortality

Blood pressure and vascular ageing

For further information see:

Charlton P.H. *et al.*, **Assessing hemodynamics from the photoplethysmogram to gain insights into vascular age: a review from VascAgeNet**, *AJP: Heart Circ.*, 2022.
https://doi.org/10.1152/ajpheart.00392.2021

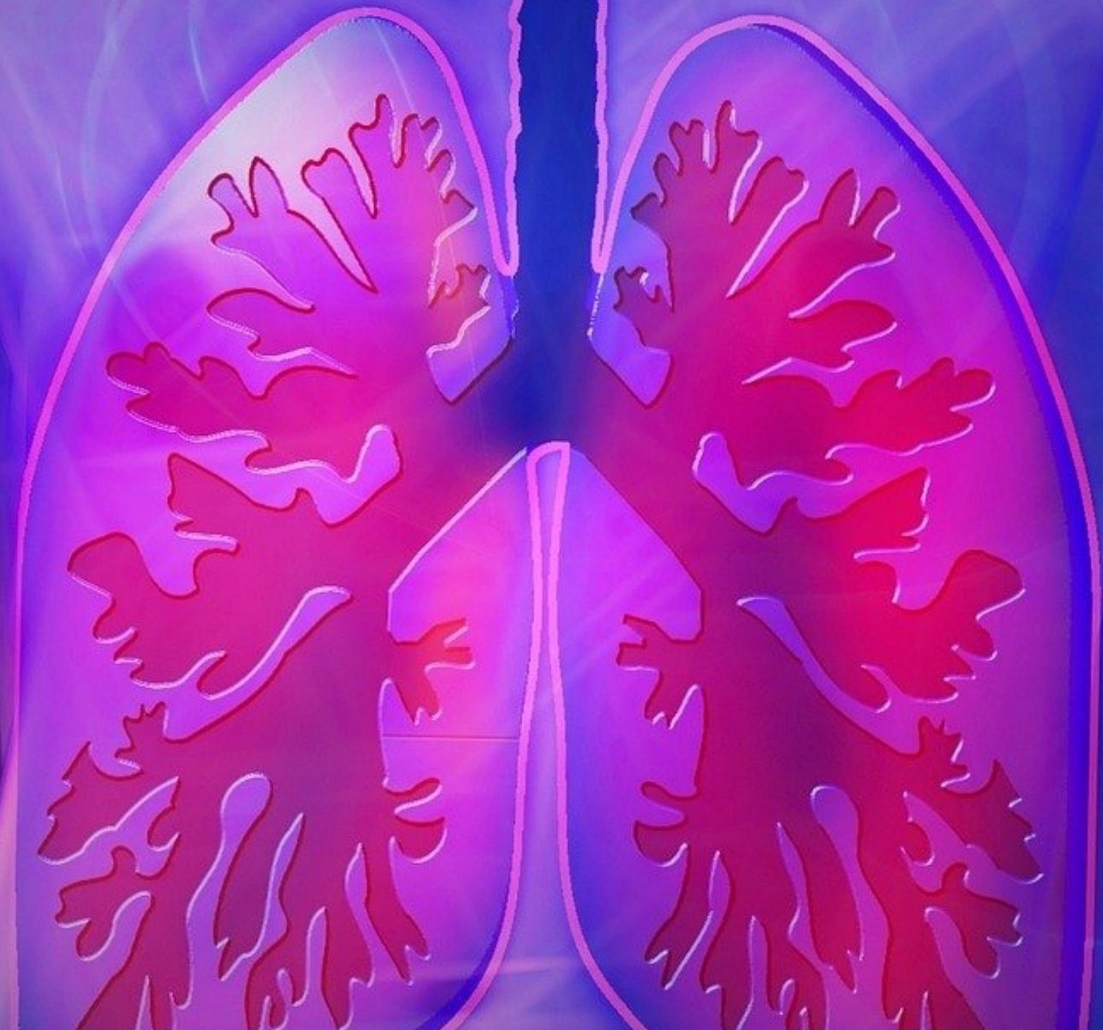




respiratory monitoring

kalhh, Pixabay, https://pixabay.com/illustrations/upper-body-lung-copd-disease-944557/

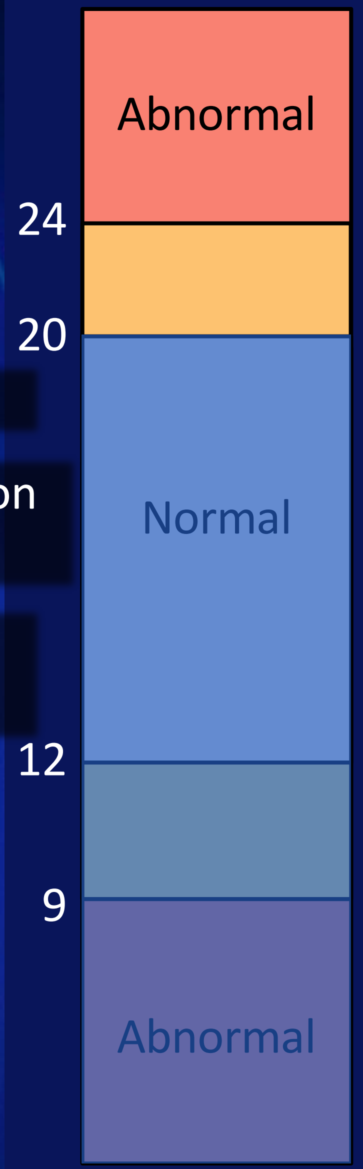
Respiratory rate (RR)
(breaths per minute)



Elevated RR

associated with:

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

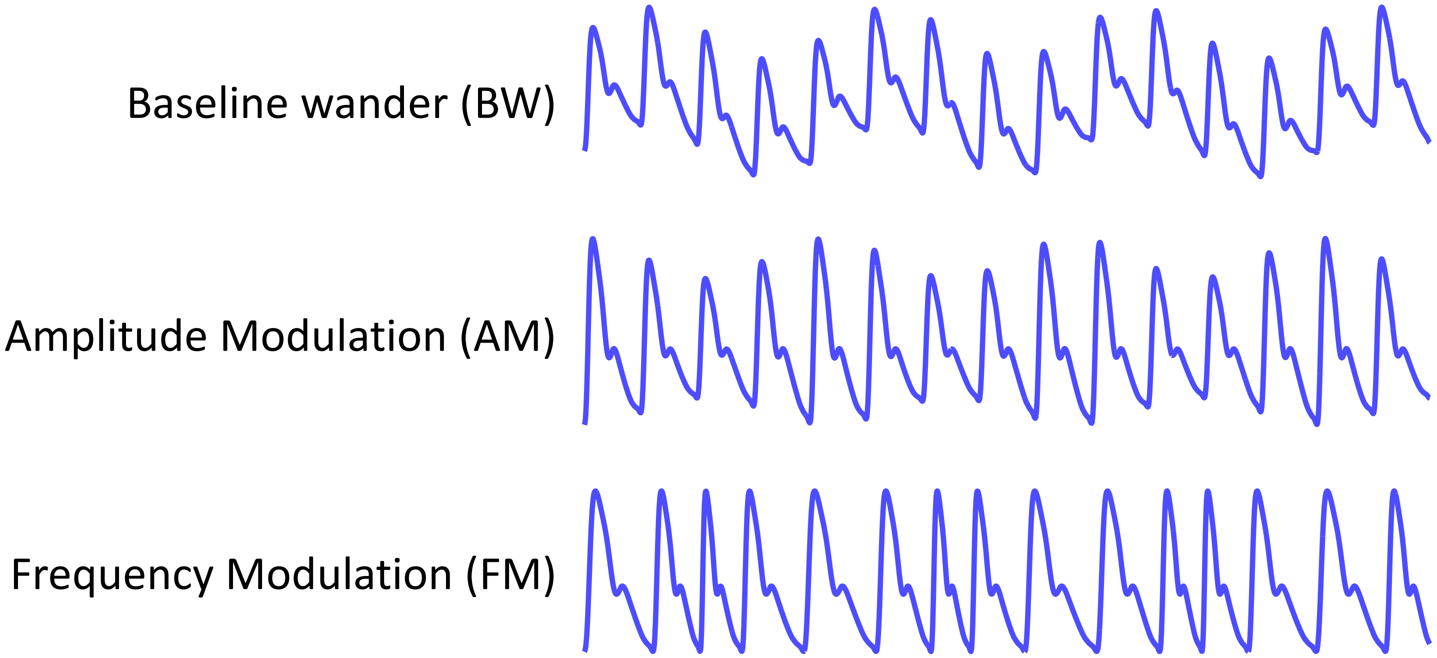


kalhh, Pixabay, https://pixabay.com/illustrations/upper-body-lung-copd-disease-944557/ Royal College of Physicians, 'National Early Warning Score (NEWS) 2: Standardising the assessment of acute-illness severity in the NHS', 2017

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

Estimating respiratory rate

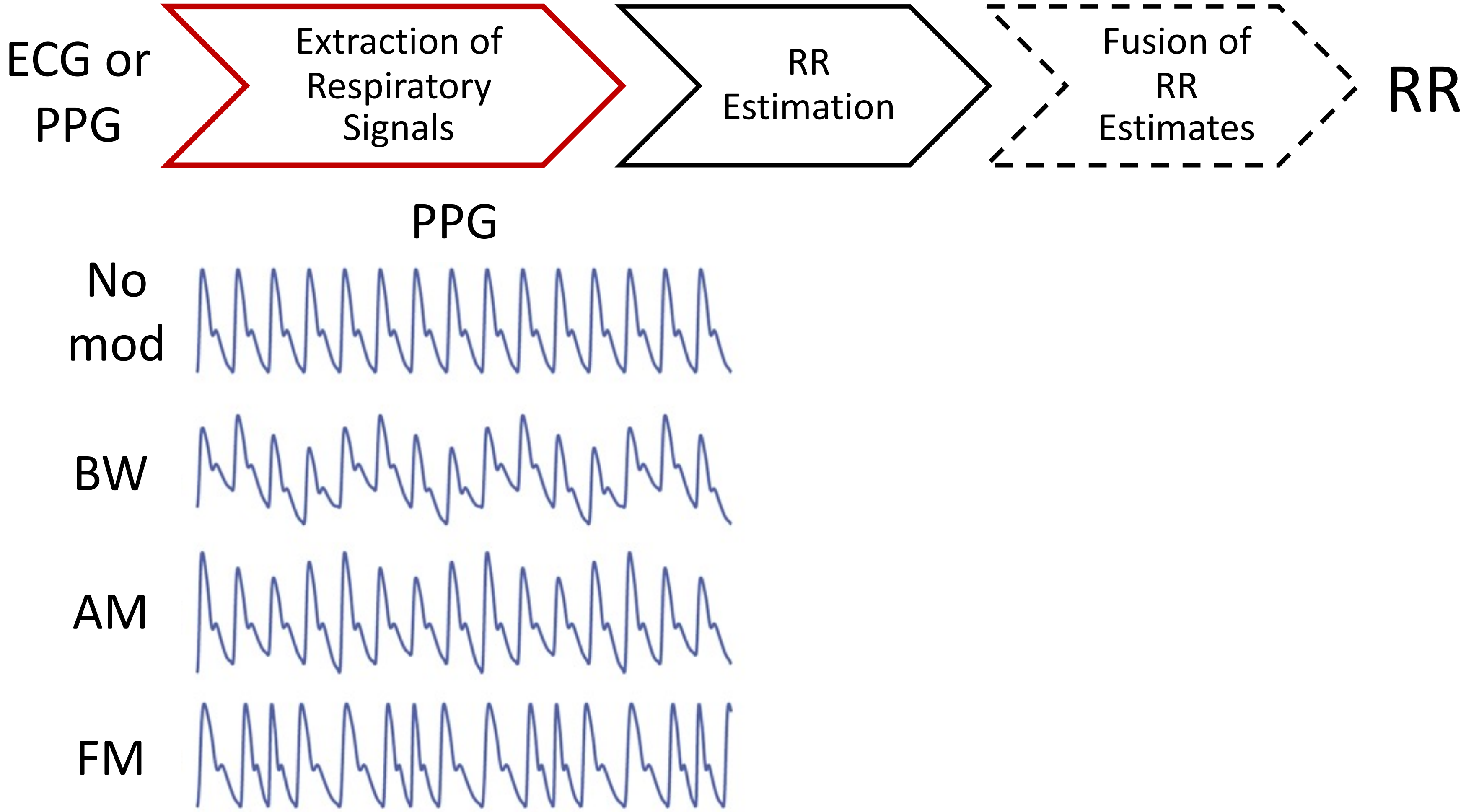
Influence of breathing:



Charlton PH *et al.*, An assessment of algorithms to estimate respiratory rate from the electrocardiogram and photoplethysmogram, Phys. Meas., 2016.
https://doi.org/10.1088/0967-3334/37/4/610 (CC BY 3.0)

Estimating respiratory rate

Respiratory rate is estimated by analysing the respiratory modulations in the PPG:



Estimating respiratory rate

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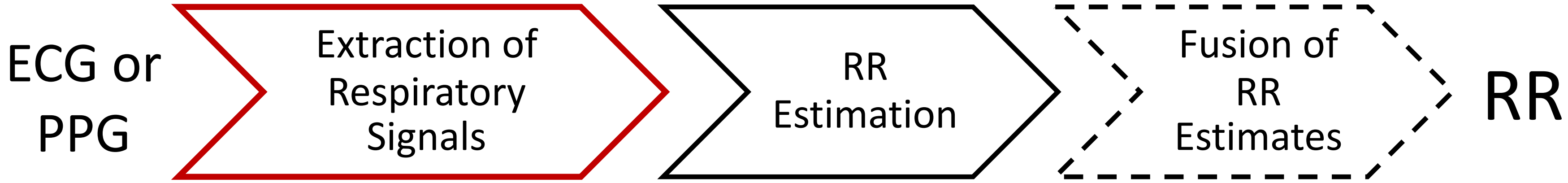

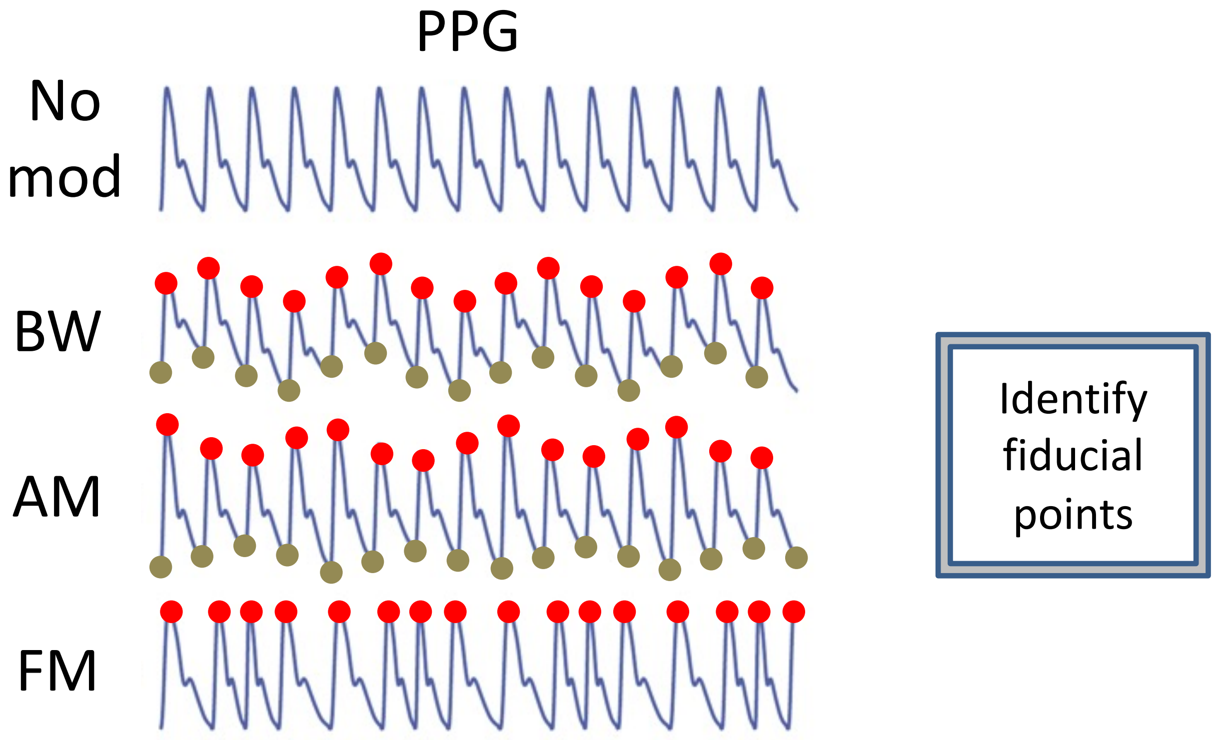

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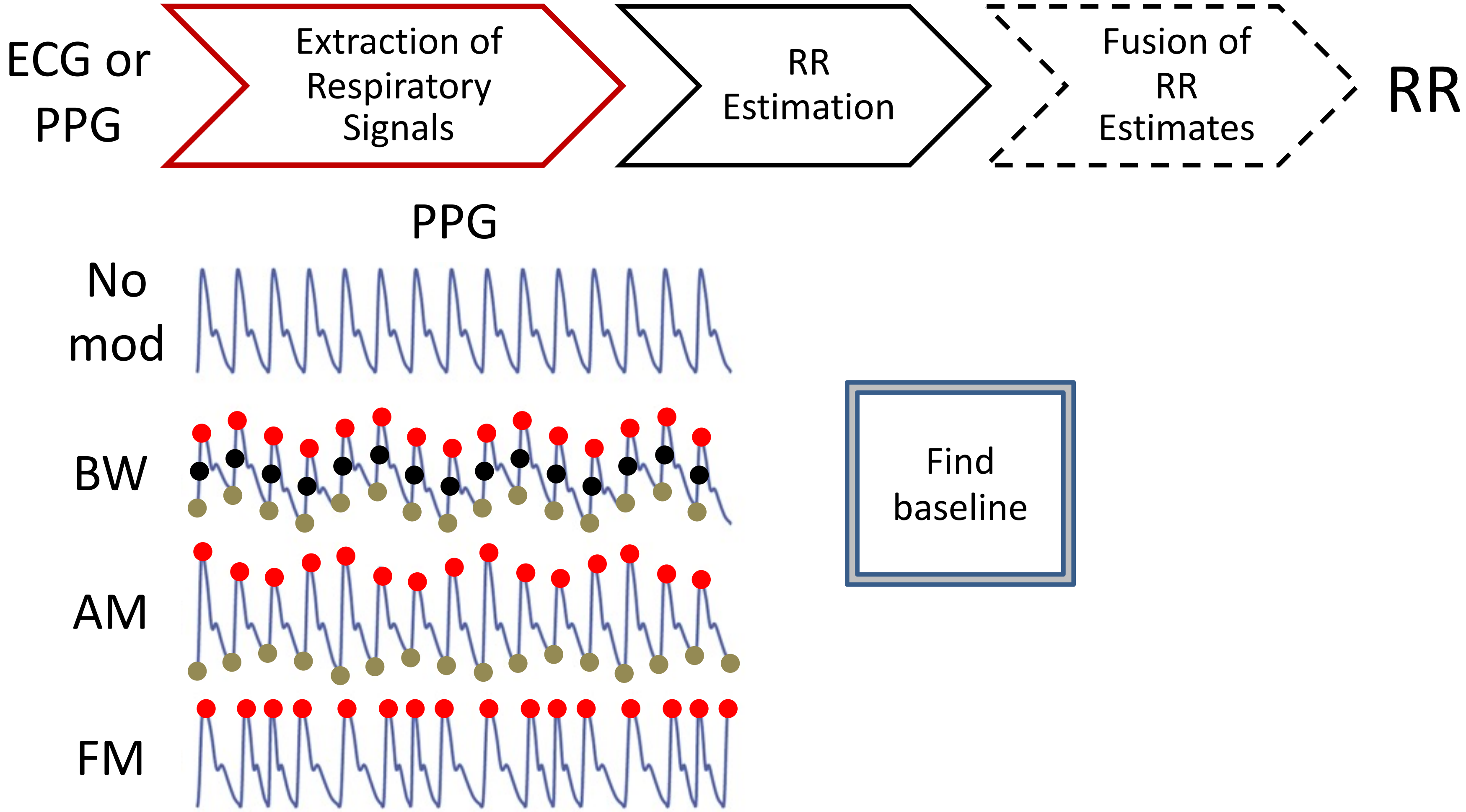

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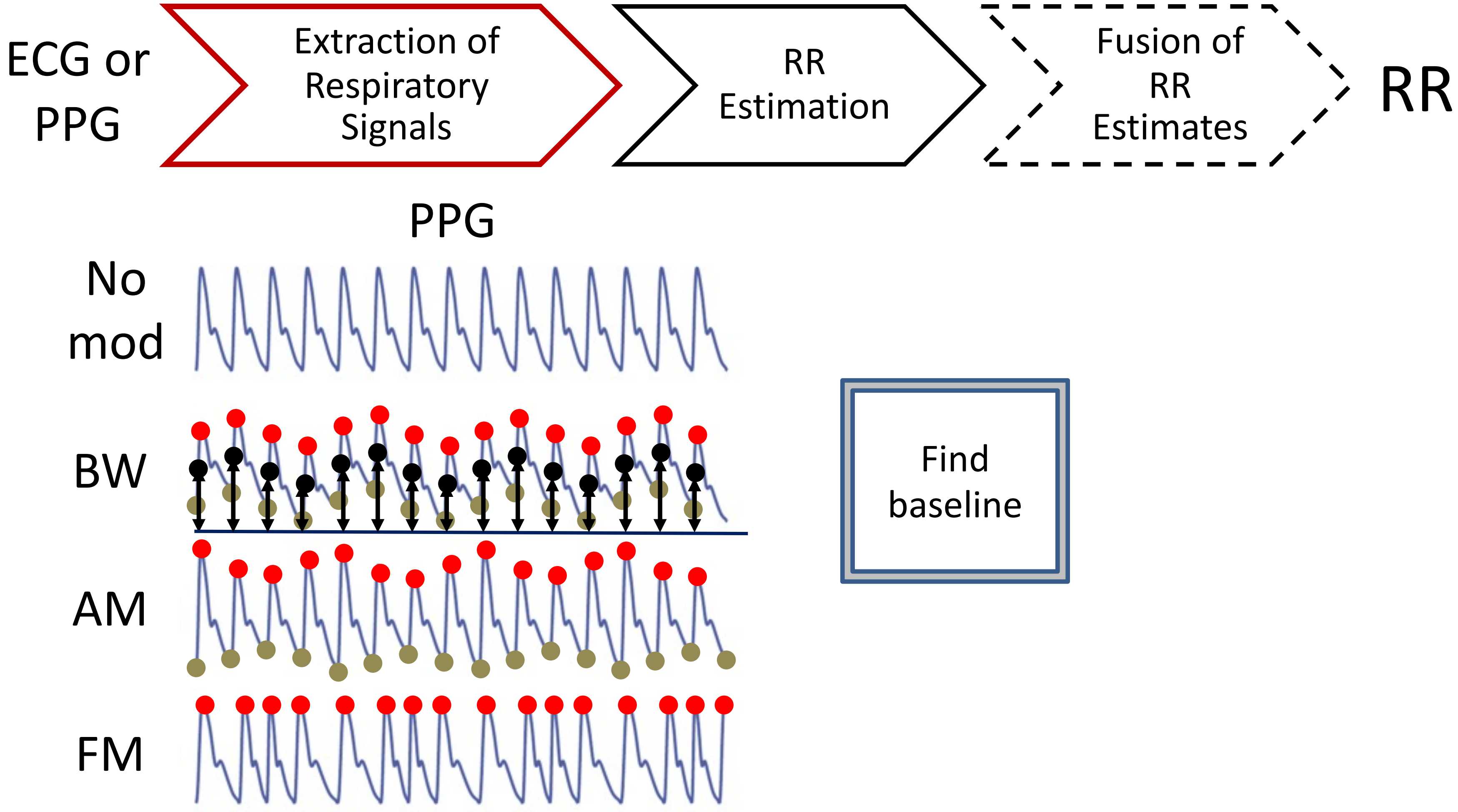

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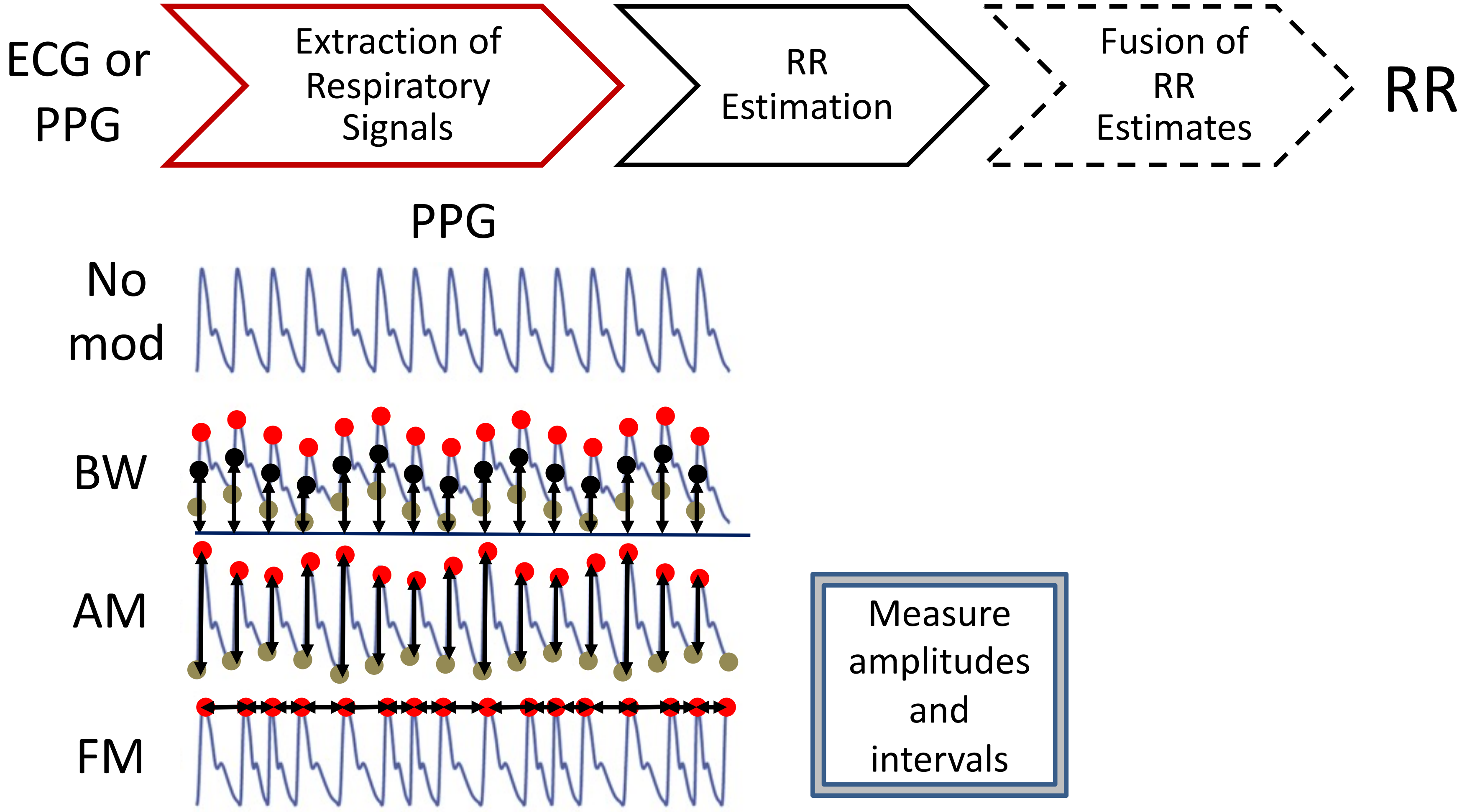

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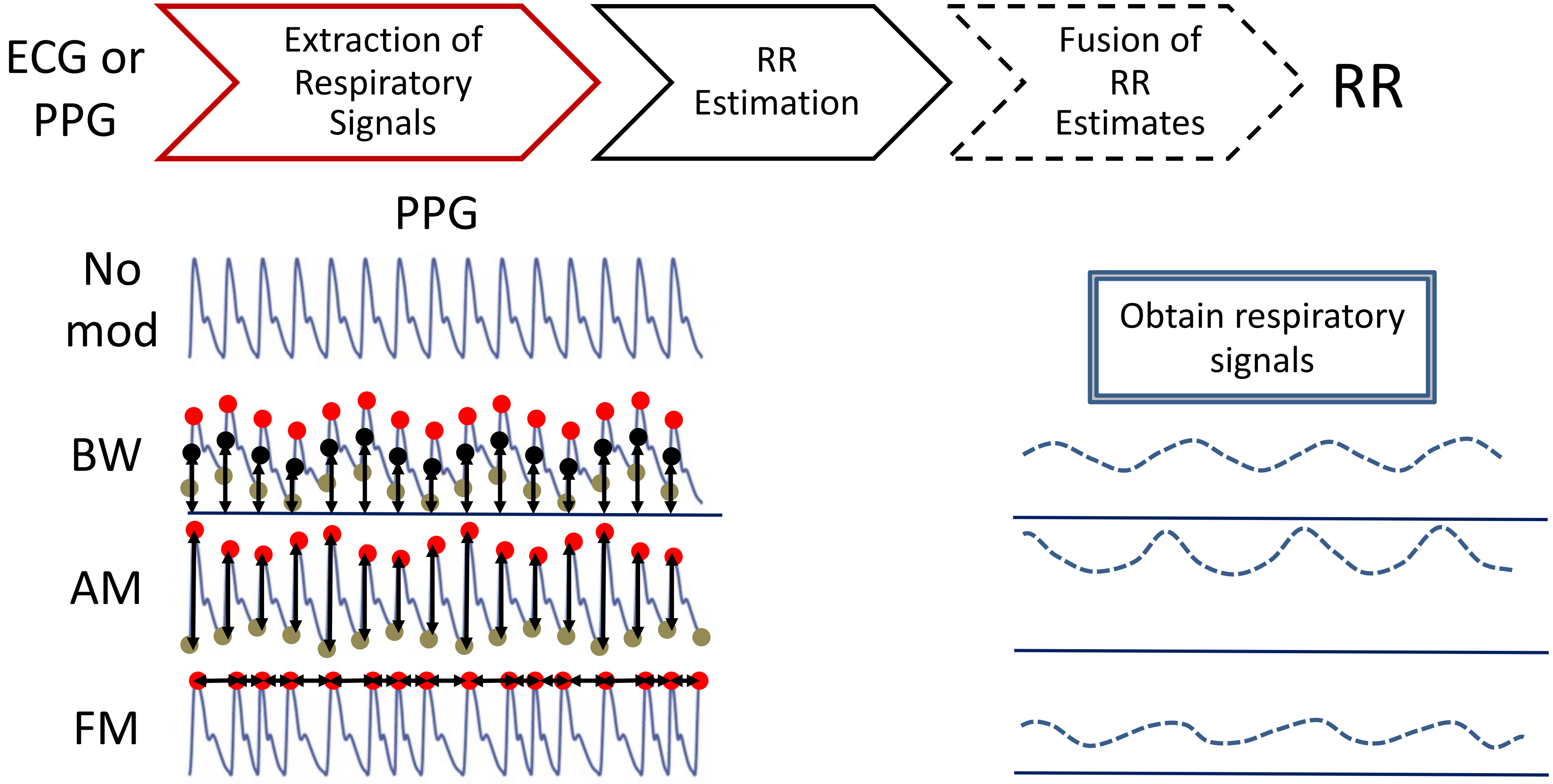

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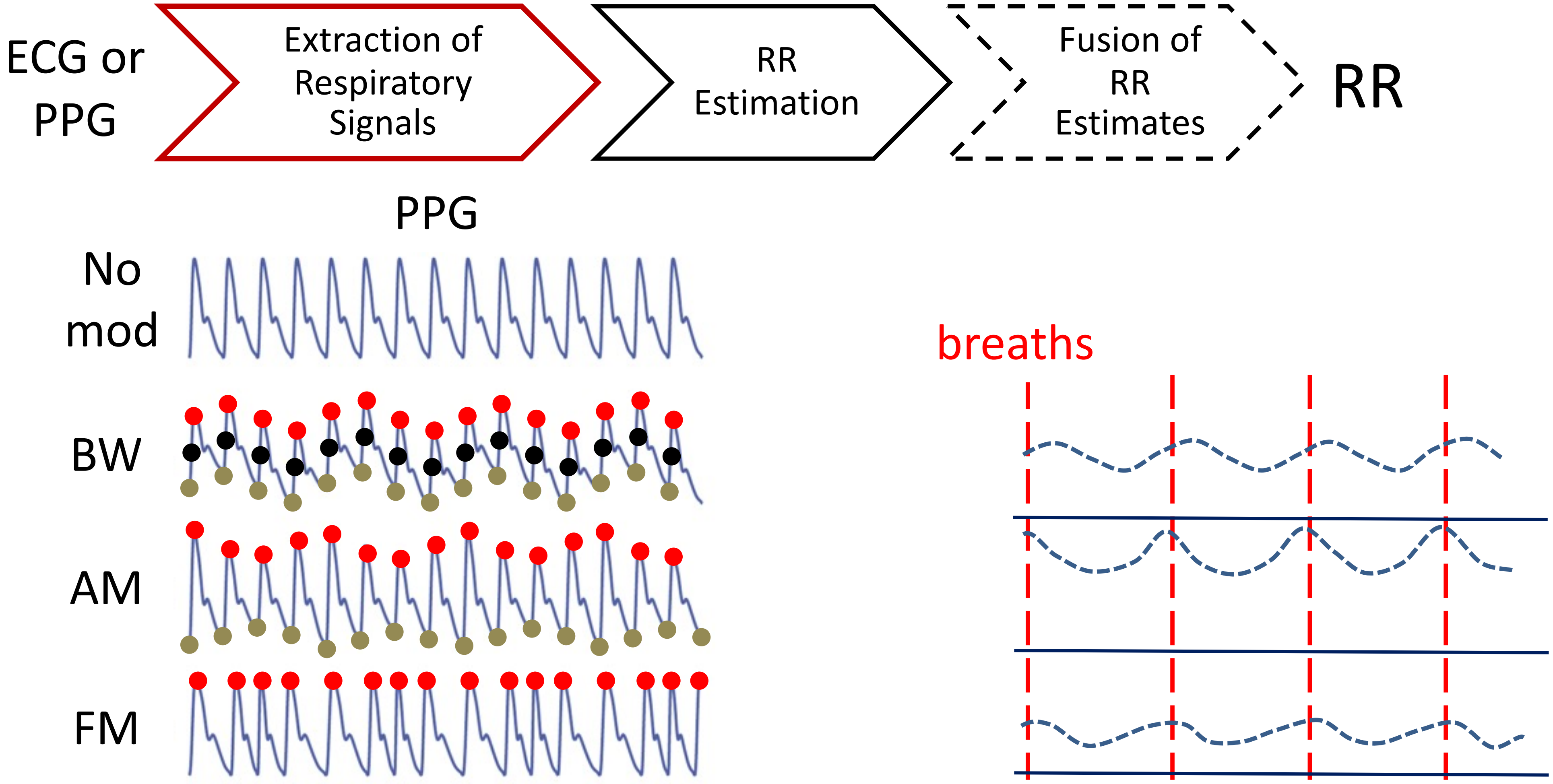

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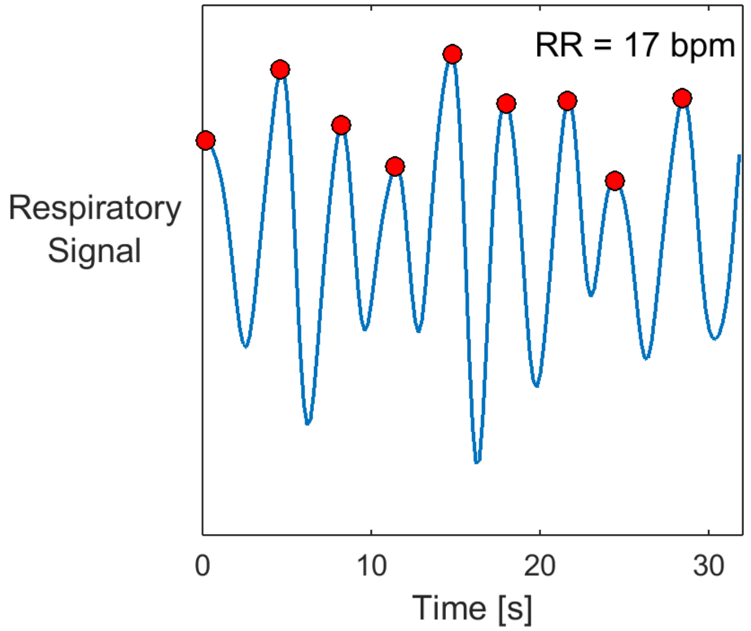

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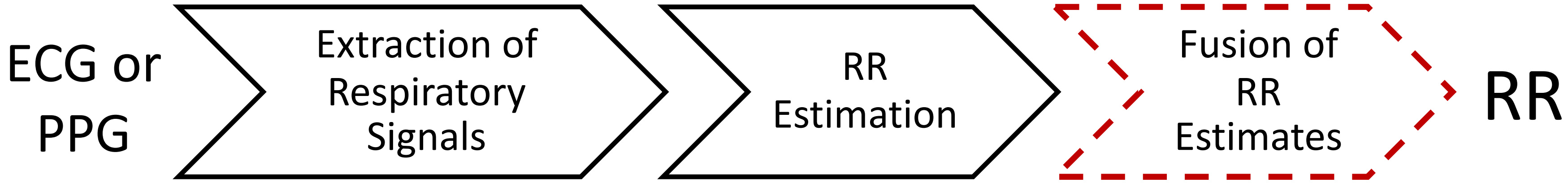
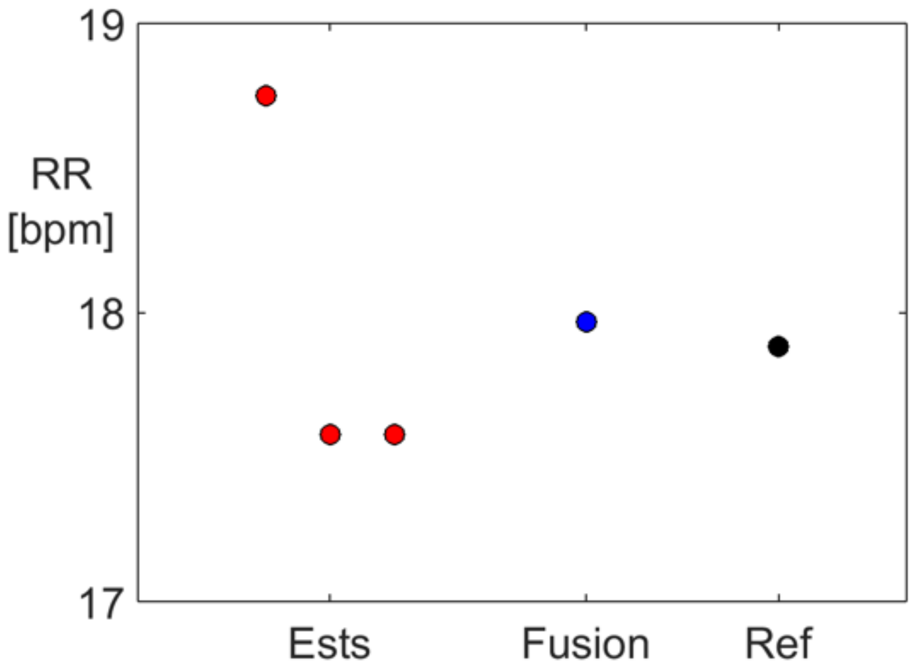
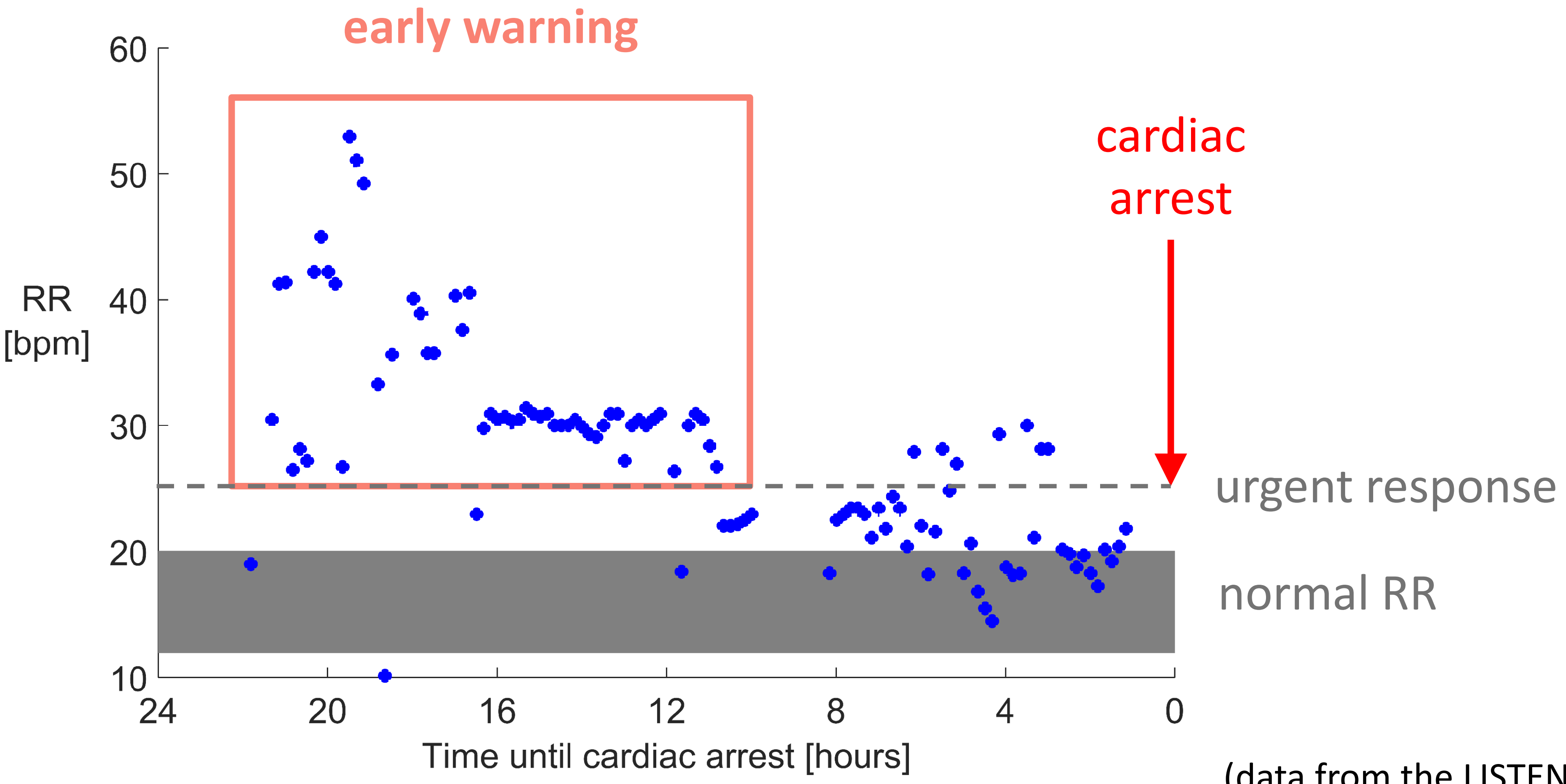




Assessing clinical utility

ECG-derived RRs every 10 mins on hospital ward



(data from the LISTEN study)

Identifying Obstructive Sleep Apnea

Key publications:

- Behar *et al.*, Feasibility of single channel oximetry for mass screening of obstructive sleep apnea, *EClinicalMedicine*, 2019
- Behar *et al.*, Single-channel oximetry monitor versus in-lab polysomnography oximetry analysis: Does it make a difference?, *Physiological Measurement*, 2020

Infectious Disease Surveillance

Fitness trackers of the future …

COVID-19

Heart rate

Sleep

Activity

Influenza-like illness

Resting heart rate

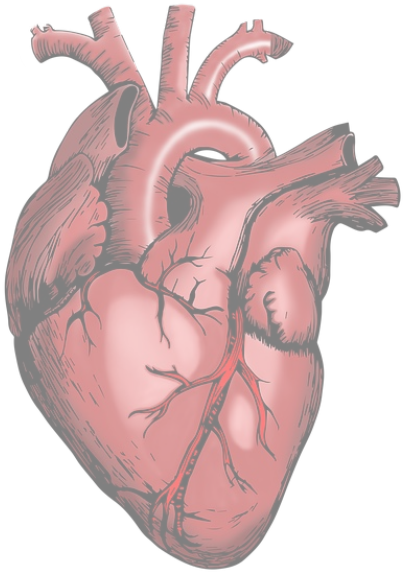
Sleep duration

Radin *et al*. Harnessing wearable device data to improve state-level real-time surveillance of influenza-like illness in the USA: a population-based study. *Lancet Digit. Heal.* 2020

Quer *et al.*, Wearable sensor data and self-reported symptoms for COVID-19 detection. *Nat Med*, 2020

Gadaleta *et al.* Passive detection of COVID-19 with wearable sensors and explainable machine learning algorithms. *npj Digit Med,* 2021

Applications



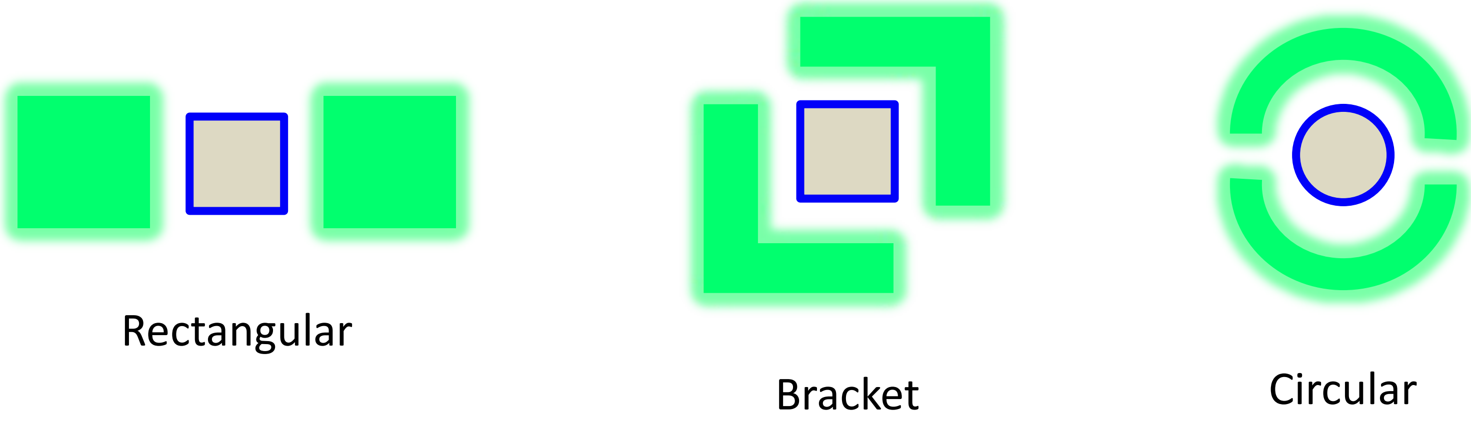
Research and Development

Challenges

Optimising sensor design

What is the optimal sensor design for obtaining photoplethysmography signals?

- Sensor geometry

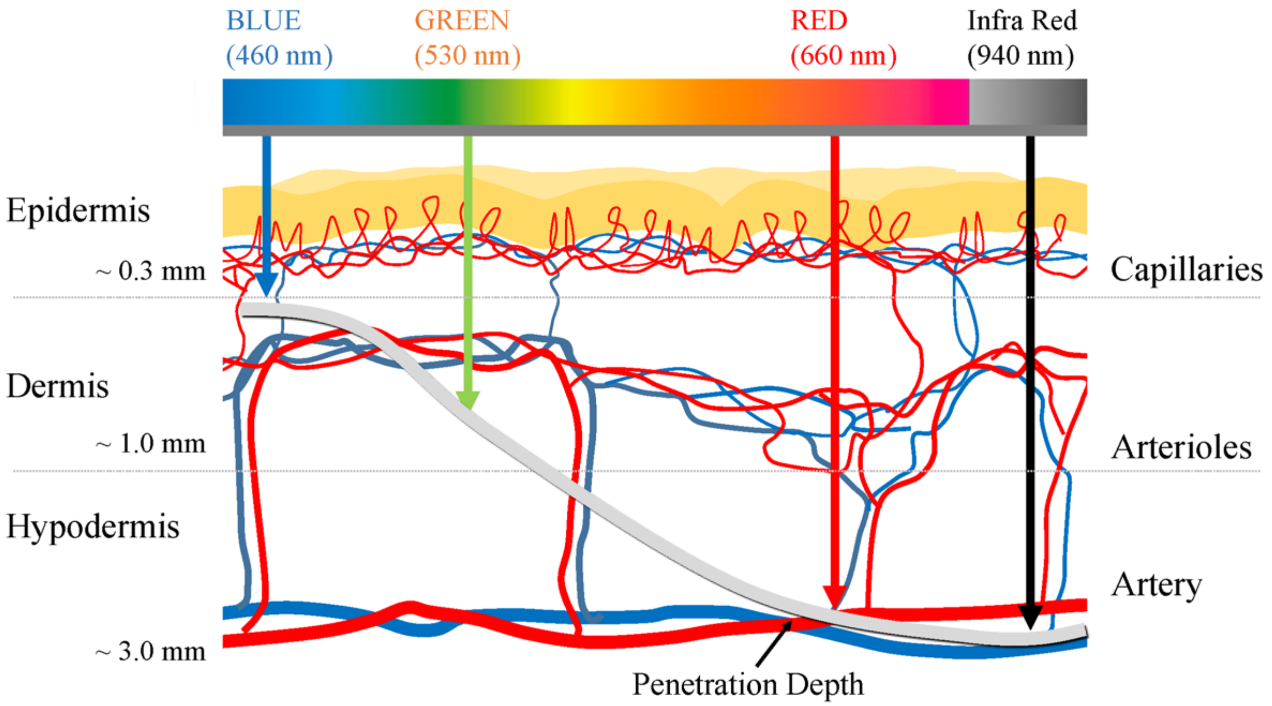


Affects the amplitude of the signal:
See Khan et al. (2019): DOI: 10.1109/ACCESS.2019.2939798 (CC BY 4.0)
(from which the images were adapted)

Optimising sensor design

What is the optimal sensor design for obtaining photoplethysmography signals?

- Wavelength of light



Affects the penetration depth:
See Han et al. (2019): DOI: [10.3390/s19245441]() (CC BY 4.0), *from which the image was sourced*

Optimising sensor design

What is the optimal sensor design for obtaining photoplethysmography signals?

- Sensor attachment:
  - contact pressure
  - vulnerability to motion artifact
- Simultaneous signals:
  - Accelerometry for motion detection and cancellation
  - Electrocardiography for pulse arrival time
- Alternative pulse wave sensing technologies

Algorithm development

What are the optimal algorithms for estimating physiological parameters?

- Understanding prior work - many algorithms proposed:
  - >100 for estimating respiratory rate from PPG or ECG
  - >39 different pulse wave features used to assess vascular ageing from the PPG
- Interpreting prior work:
  - Performance differs greatly between algorithms
  - Performance differs on different datasets
- Leaderboards: (e.g. paperswithcode.com)
  - Open-source algorithms
  - Well-labelled public datasets
- Incorporating uncertainty assessment

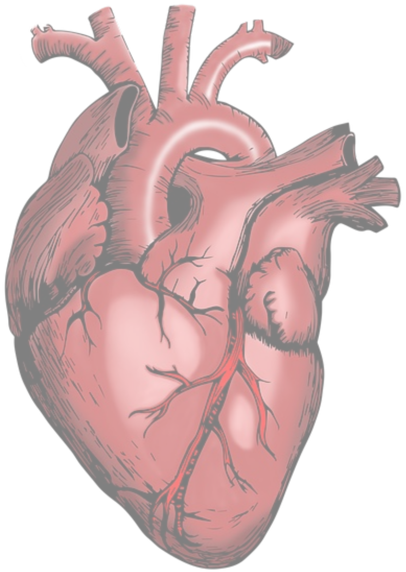
Integration into clinical pathways

How should wearable data be integrated into clinical decision making?

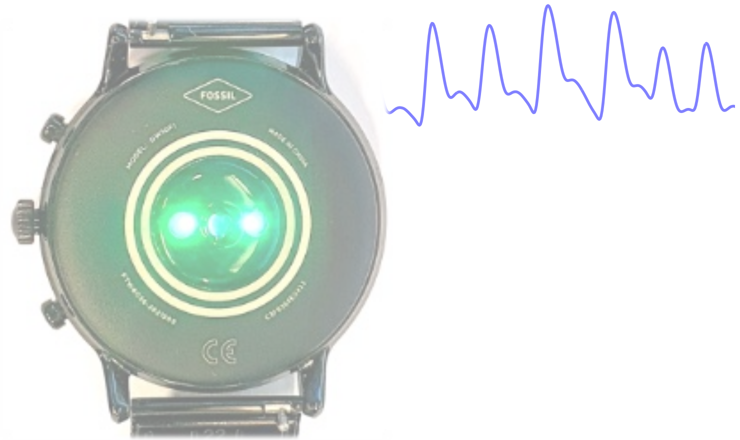
- Screening programmes
- Patient-led measurements to prompt clinical assessment
- Supplementary clinical use in specific settings
- Self-directed health monitoring
- Population-level surveillance

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

Applications



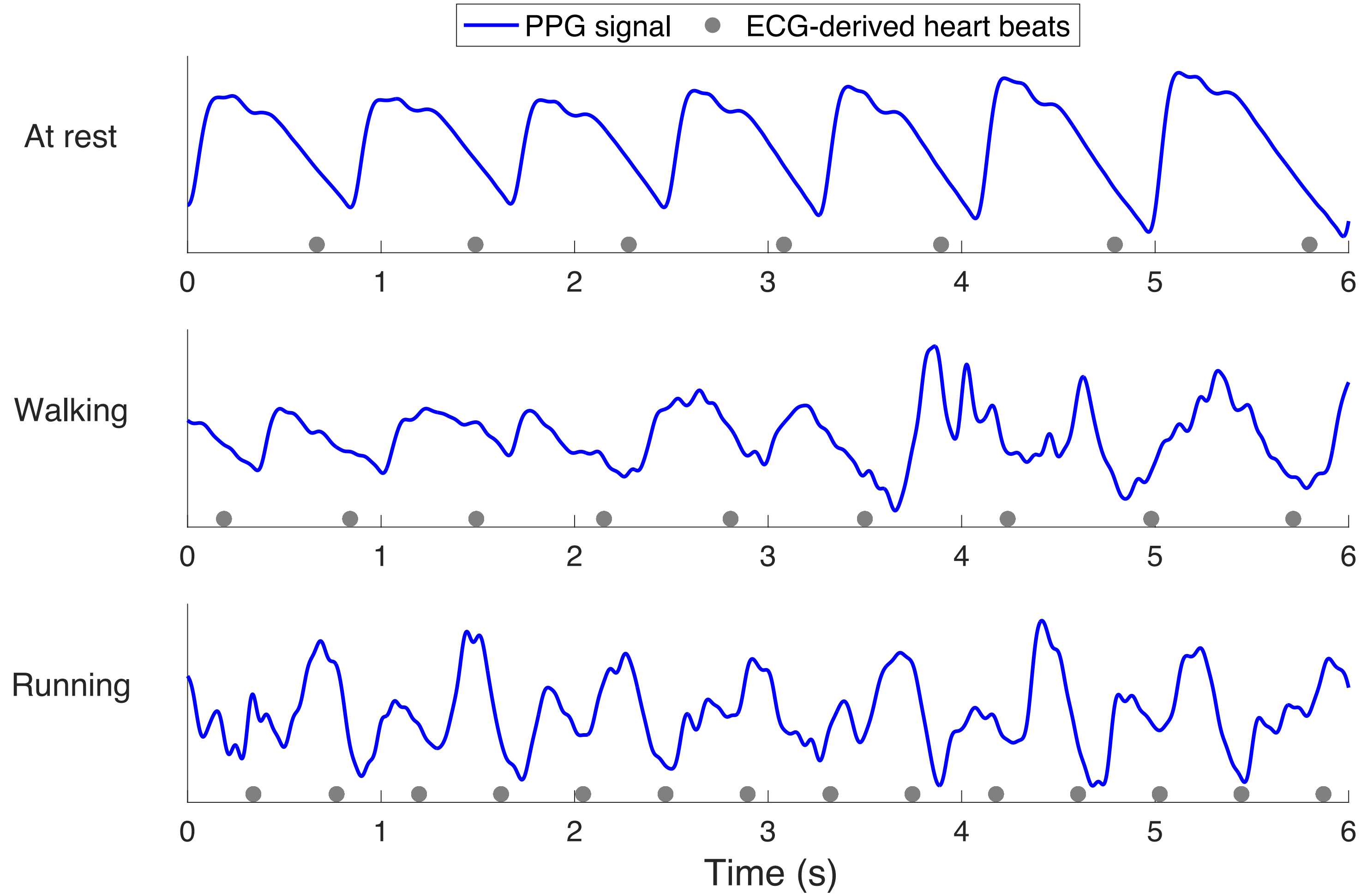
Research and Development



Challenges

Optimising sensor design

Motion artifact:



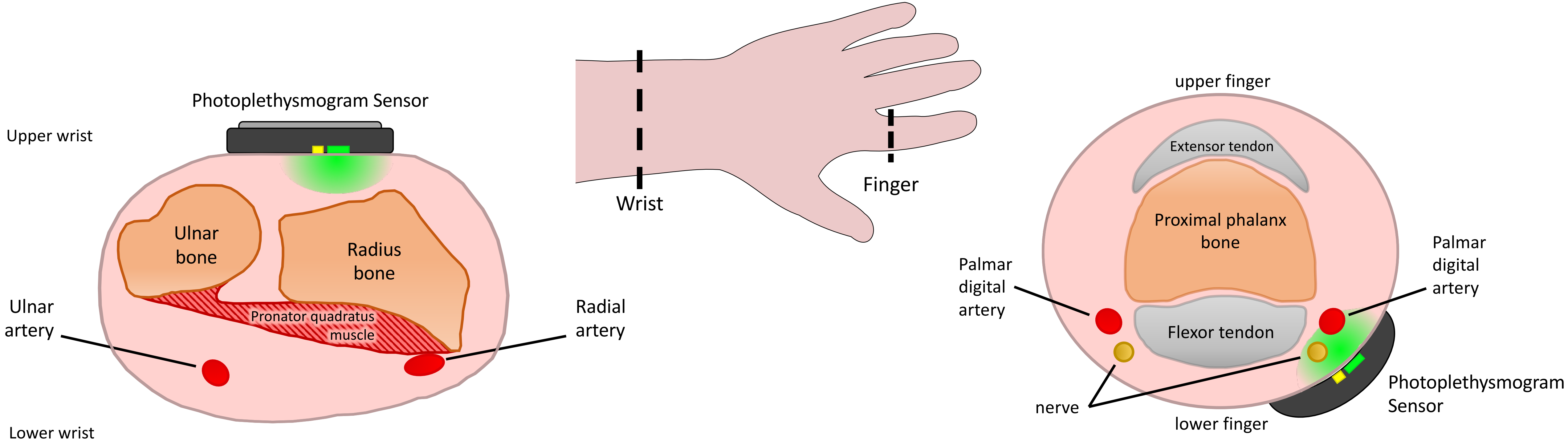
Potential strategies:

- Exclude artifactual data
- Motion artifact cancellation

Optimising sensor design

Unobtrusiveness vs. utility:

- Measurement site



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

Optimising sensor design

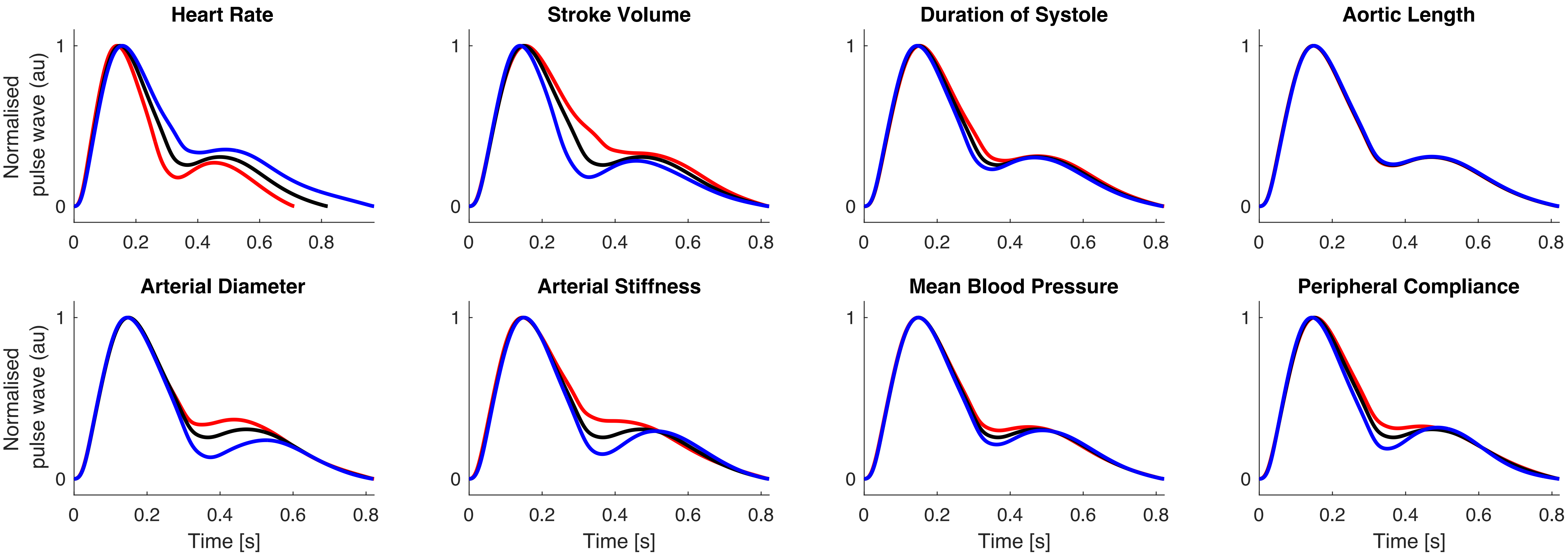
Unobtrusiveness vs. utility:

- Measurement site
- Pulse arrival time

Algorithm development

What are the physiological origins of the PPG signal?

Black – mean value for 25 year old
Red – 1 standard deviation above mean
Blue – 1 standard deviation below mean



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

Algorithm development

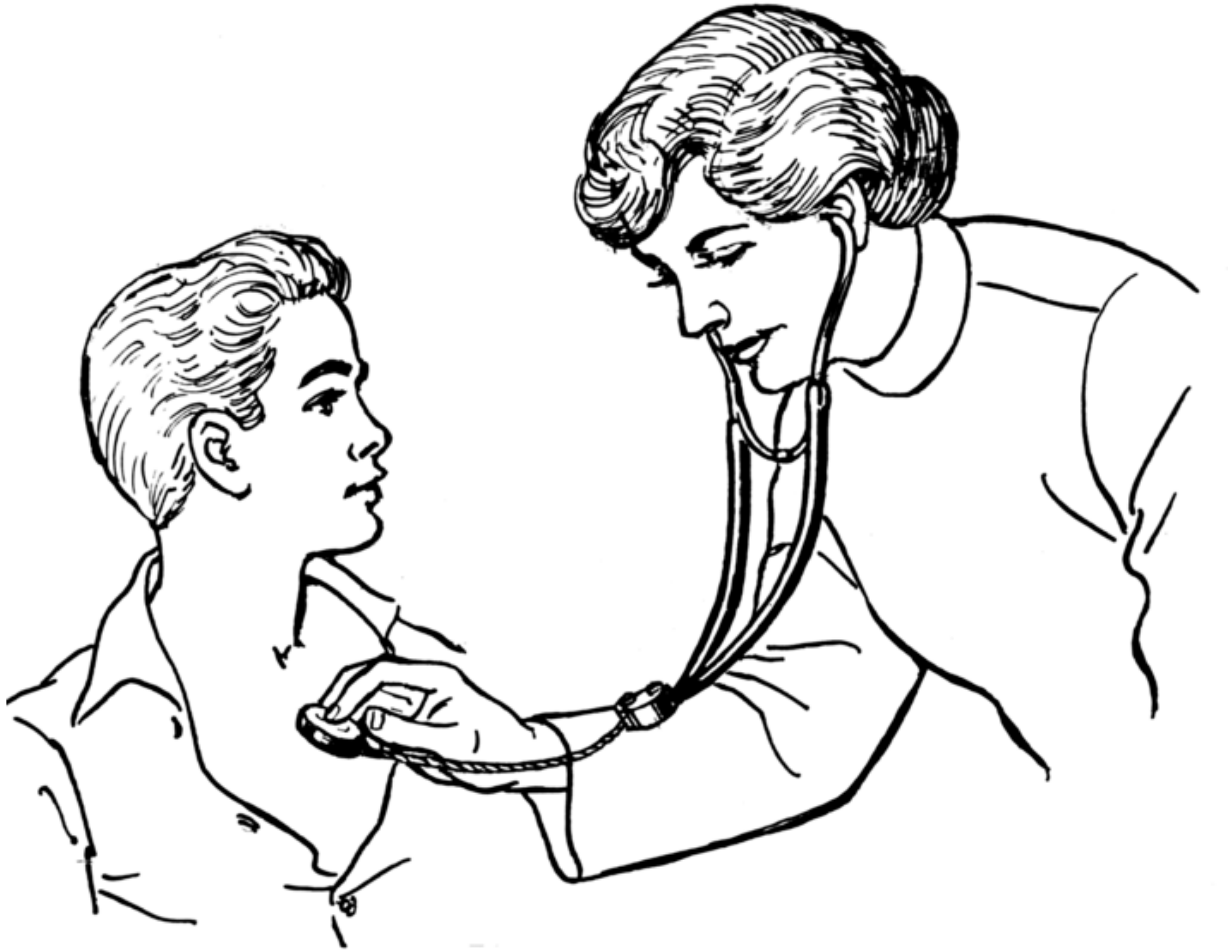
How should algorithms be developed, trained, and validated?

- Simulated data and controlled experiments can be used to develop initial algorithms
- Further development and training should be performed with real-world data
- Validation should be performed using robust, agreed protocols (see Mukkamala 2021, Hypertension)
- Performance monitoring could be performed using device data

Transformative initiatives:

- Access to raw sensor data (PPG signals)
- Linking device data with participant outcomes via opt-in studies

Integration into clinical pathways



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

With grateful thanks to:

- The British Heart Foundation
- The many colleagues and patients who have contributed to our research.

Wearable photoplethysmography devices have many potential applications, including cardiovascular and respiratory monitoring.

Key steps required to make these a reality include optimising sensor design, algorithm development, and integration into clinical pathways.

Despite the challenges, when used clinically, photoplethysmography devices should be like a climbing rope:

- highly reliable
- validated
- for specific purposes

Further reading:

Charlton P.H. *et al.*, **Wearable photoplethysmography for cardiovascular monitoring**, *Proceedings of the IEEE*, 2022, https://doi.org/10.1109/JPROC.2022.3149785 (CC BY 4.0)

Charlton PH and Marozas V, **Wearable photoplethysmography devices**, in Photoplethysmography, Elsevier, 2022. http://peterhcharlton.github.io/publication/wearable_ppg_chapter/

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 (CC BY 3.0)

Charlton P.H. *et al.*, **Establishing best practices in photoplethysmography signal acquisition and processing**, *Physiological Measurement*, 2022, https://doi.org/10.1088/1361-6579/ac6cc4 (CC BY 4.0)

Charlton P.H. *et al.*, **Assessing hemodynamics from the photoplethysmogram to gain insights into vascular age: a review from VascAgeNet**, *AJP Heart Circ*, 2022, https://doi.org/10.1152/ajpheart.00392.2021 (CC BY 4.0)

Wearable photoplethysmography devices for health monitoring

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