Using consumer wearables in healthcare and research

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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, 2018

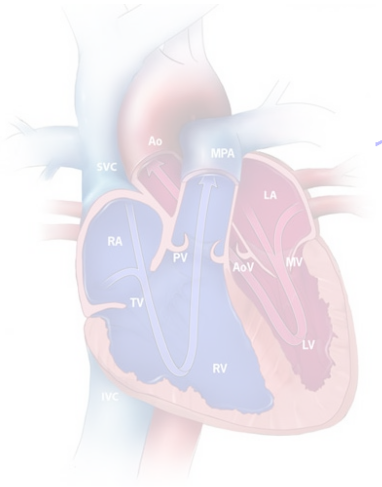
Photo by Luke Chesser on Unsplash

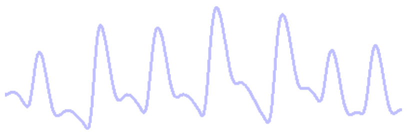

St. Thomas' Hospital

(artistic license – this heart rate is fictional)

Consumer Wearables

Challenges & Opportunities





Next Steps


WORLD MARATHON MAJORS
22km
Sue Ryder


Sue Ryder
WORLD
MARATHON
MAJORS
22km
Children's Trust
Sue Ryder

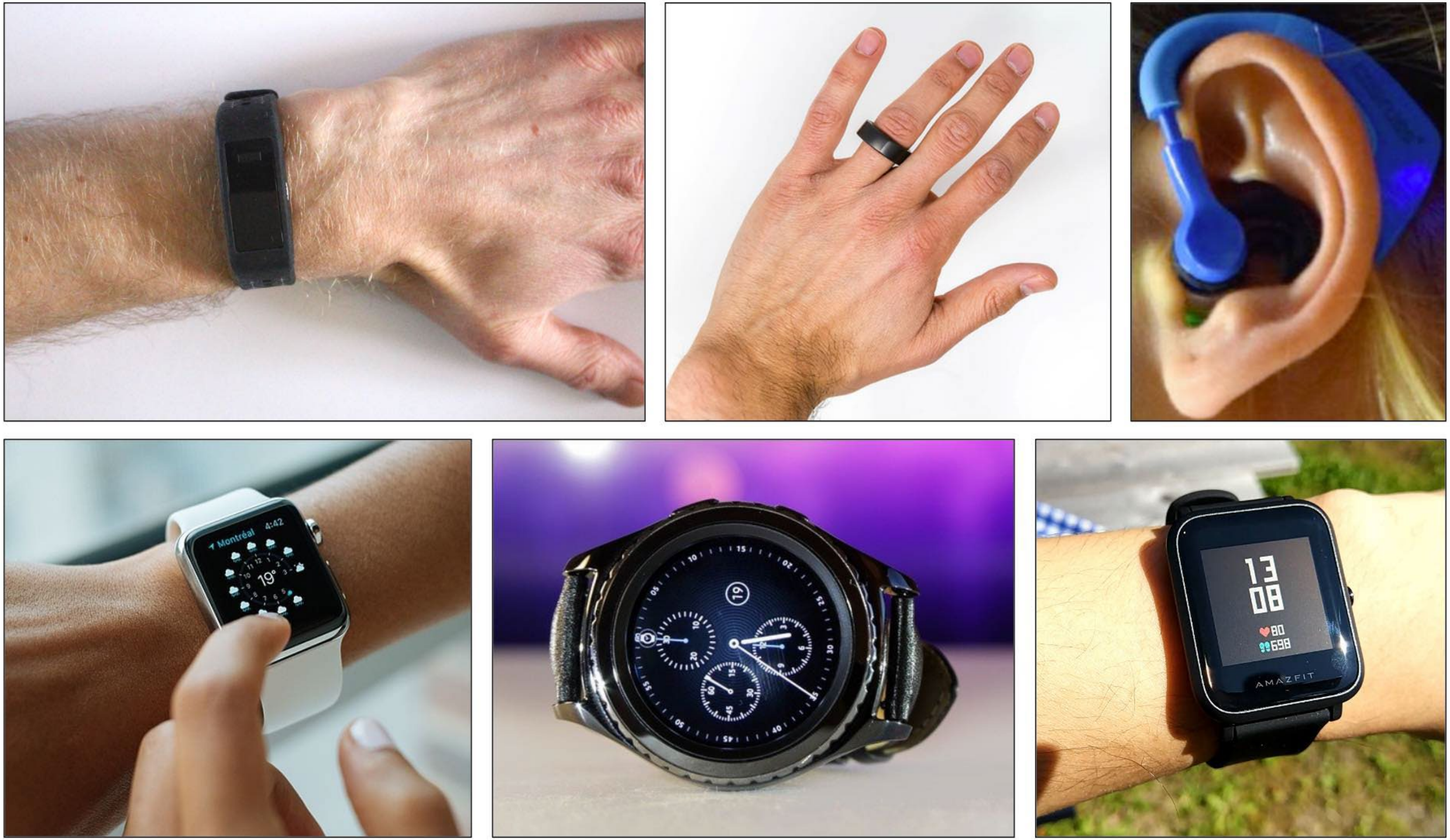

26287

WORLD MARATHON MAJORS
22km
money
23670
OFFICIAL ATTEMPT

WaterAid
OFFICIAL ATTEMPT

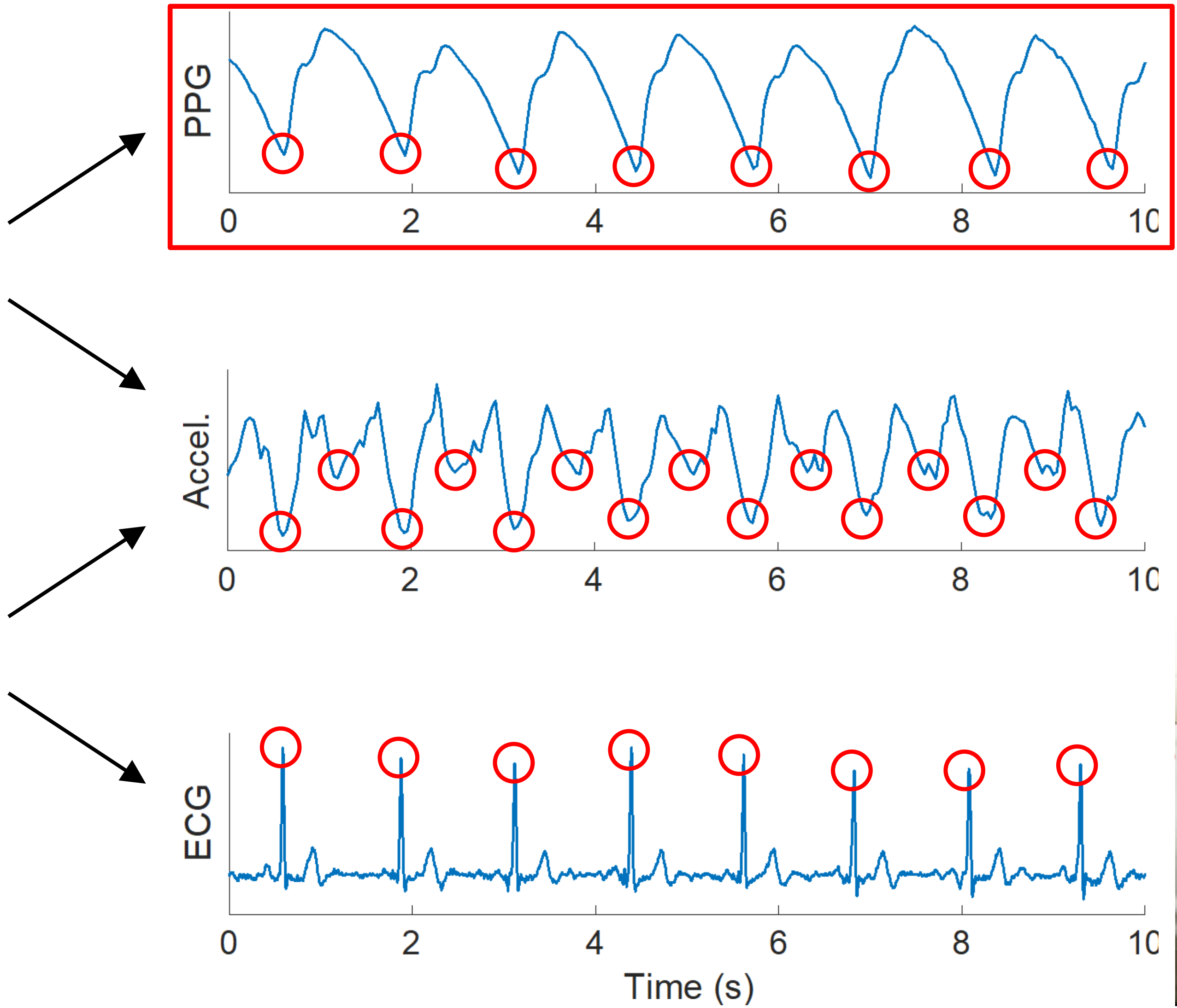

WORLD MARATHON MAJORS
22km
money
ATTEMPT

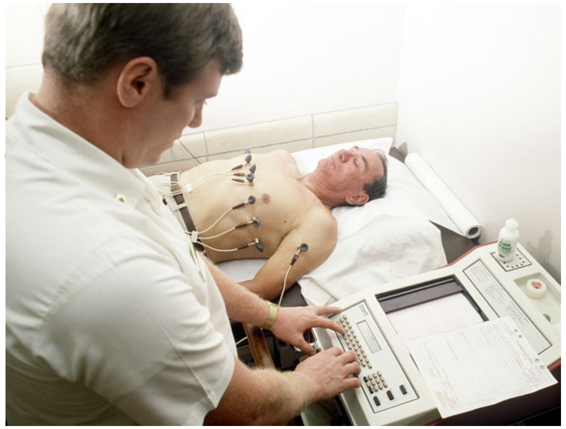

WaterAid
OFFICIAL ATTEMPT



Source: Charlton et al. Individual images: P. Charlton under CC BY 4.0; cropped from image by Marco Verch (CC BY 2.0); cropped image from Passler et al. under CC BY 4.0; cropped from image by GEEK KAZU (CC BY 2.0); cropped from image by Pixels (Pixabay License); cropped from image by Luke Chesser (CC0 1.0).

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

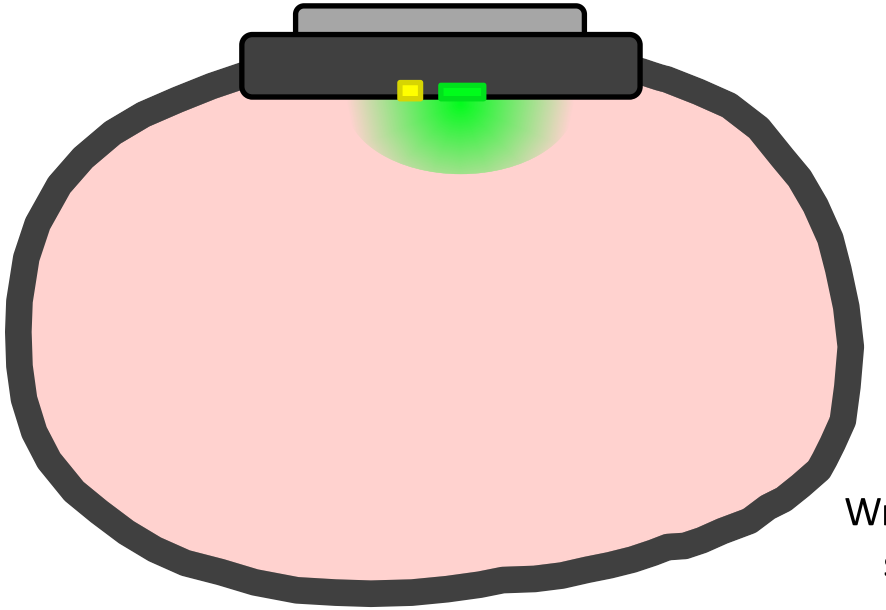




A **Smartwatch** which acquires electrocardiography (ECG) and accelerometry (Accel.) signals

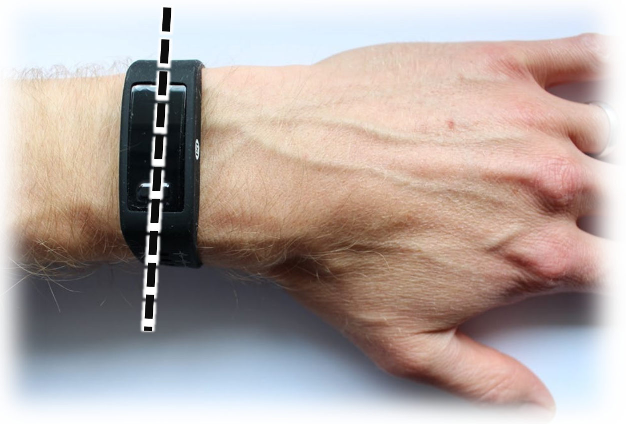
The Photoplethysmogram

Photoplethysmogram (PPG) Sensor

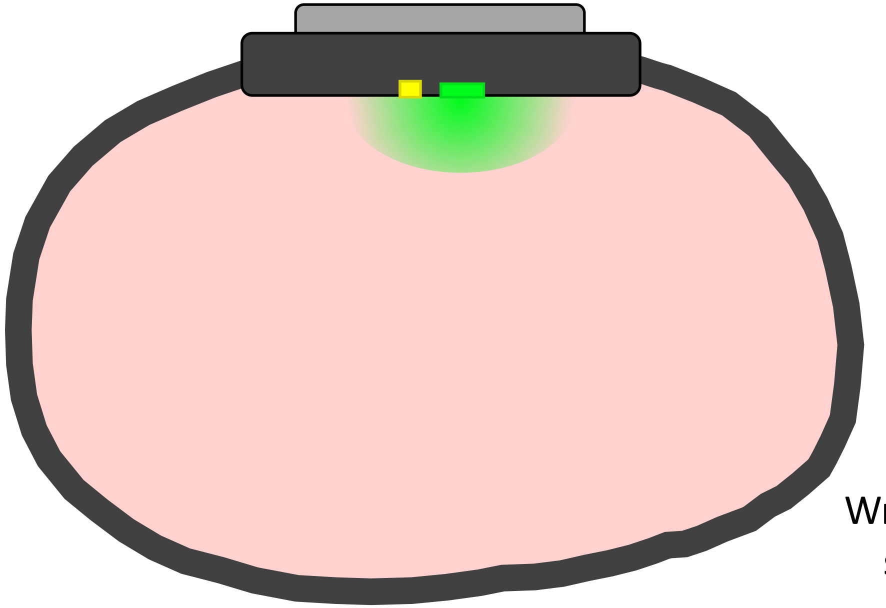


Wrist cross-section

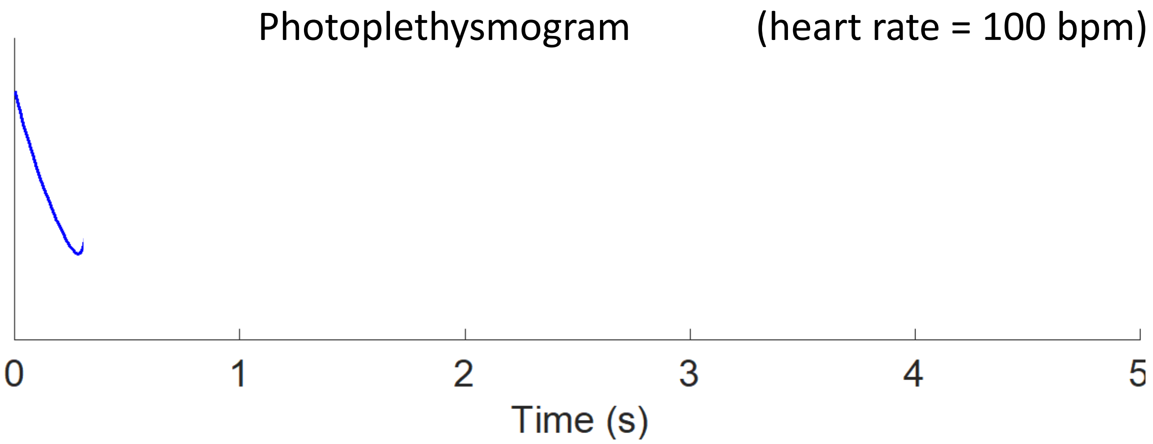
The Photoplethysmogram

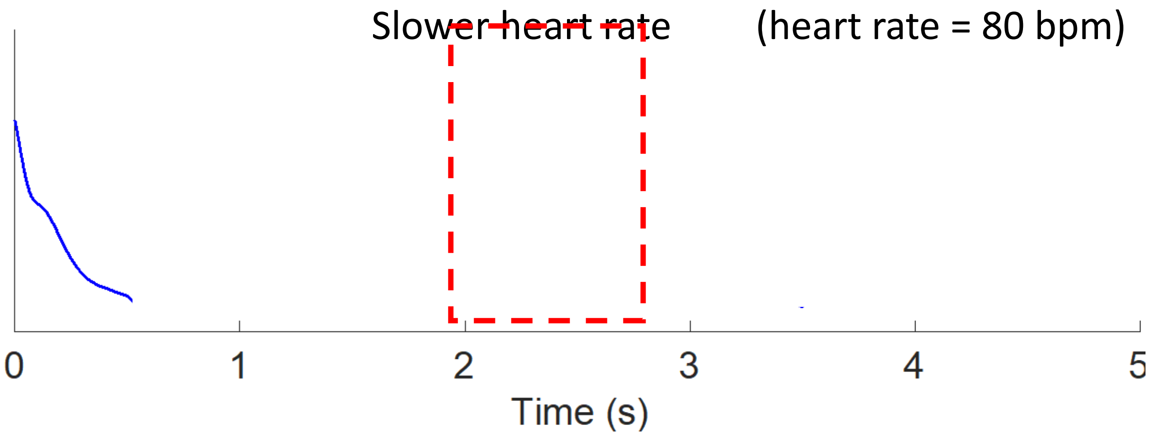


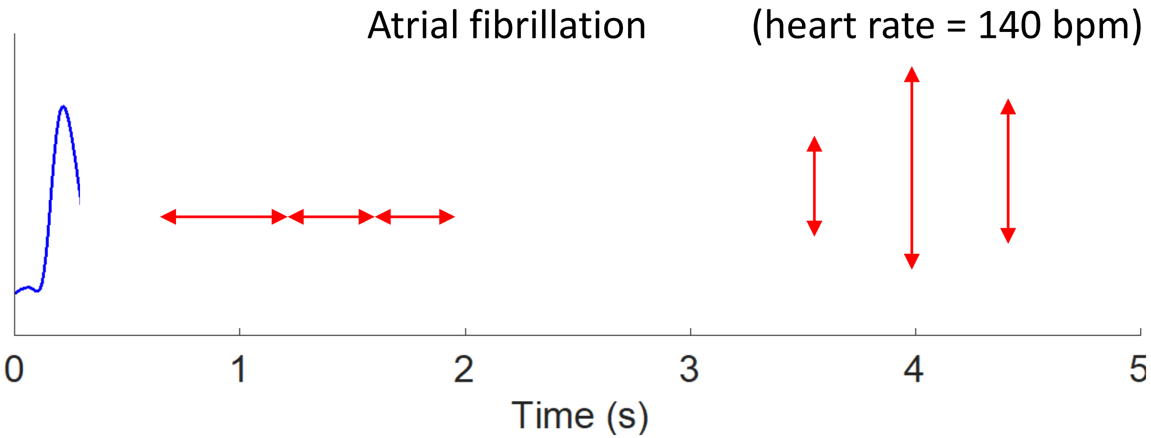
Photoplethysmogram (PPG) Sensor



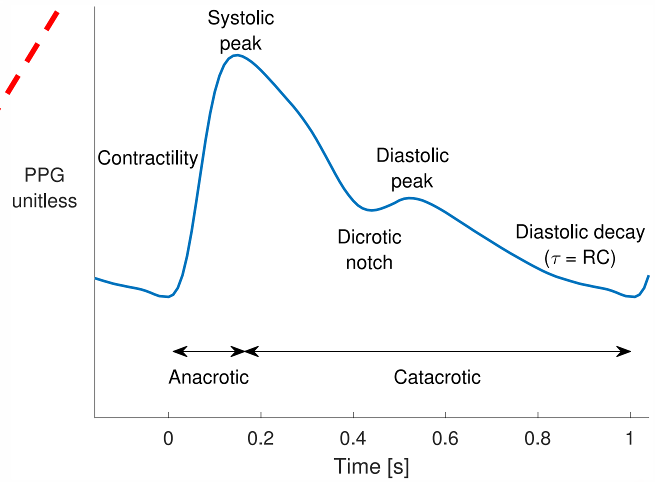
Wrist cross-section

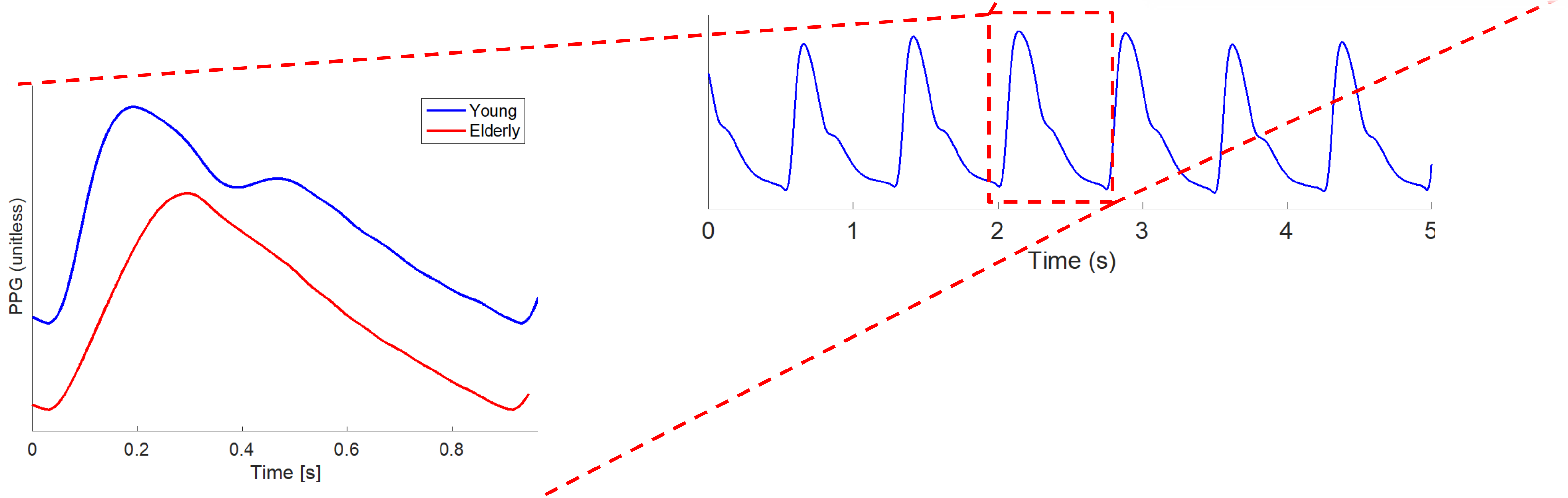




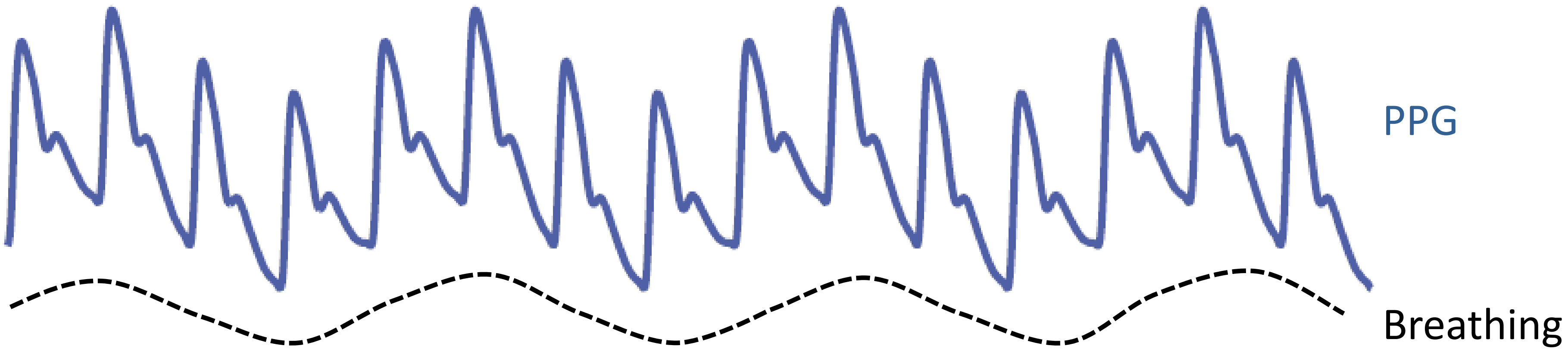


The Photoplethysmogram

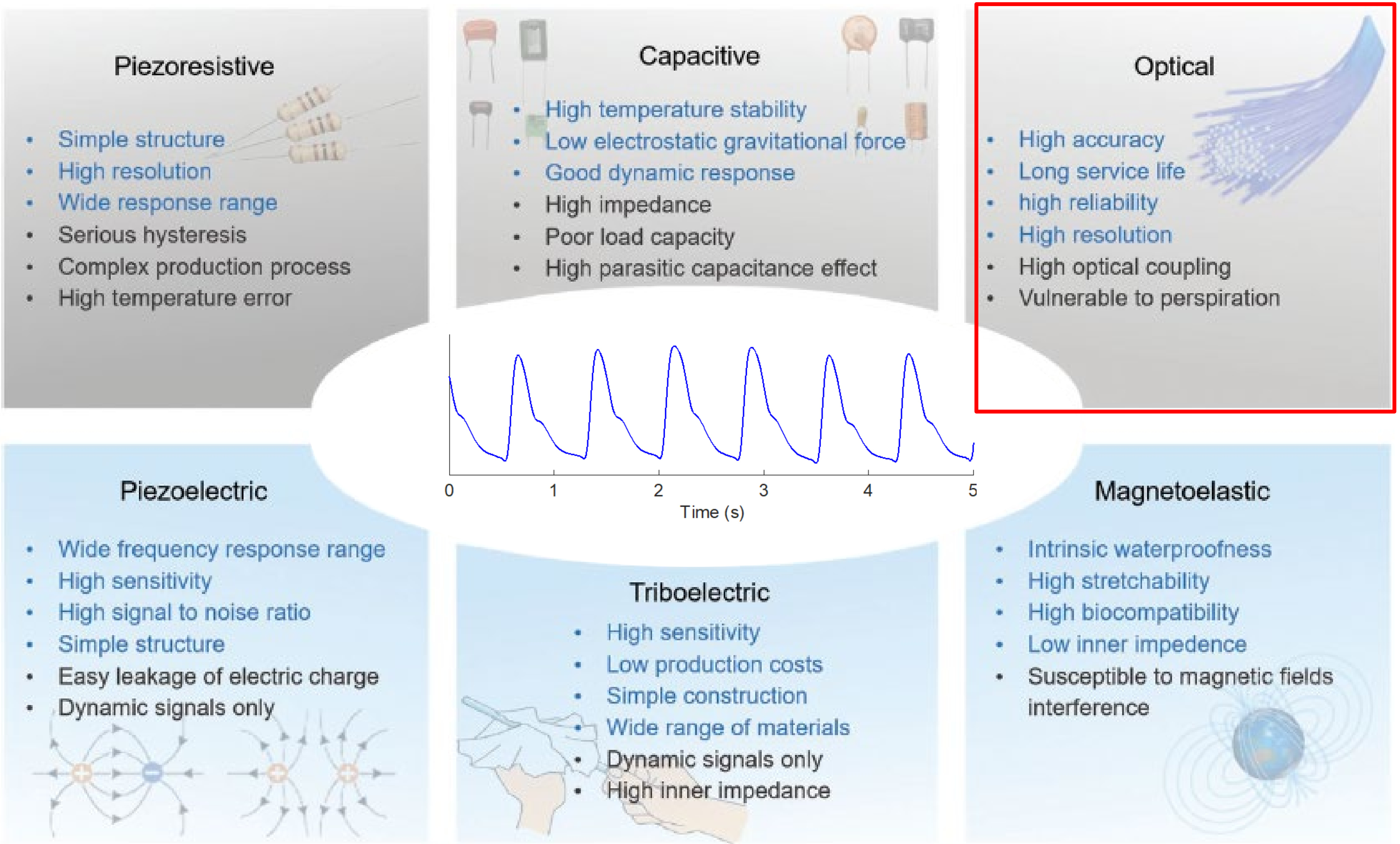




The Photoplethysmogram



Alternative pulse wave sensing approaches



Advantages:

- Not limited to arteries
- Oxygen saturation
- (non-contact)

Disadvantages:

- Power hungry
- Noisy

Meng K *et al.*, Wearable Pressure Sensors for Pulse Wave Monitoring, Advanced Materials, 2022. https://doi.org/10.1002/adma.202109357 (copyright)

Alternative pulse wave sensing approaches

Alternative sensing technologies

Potential alternatives to photoplethysmography:

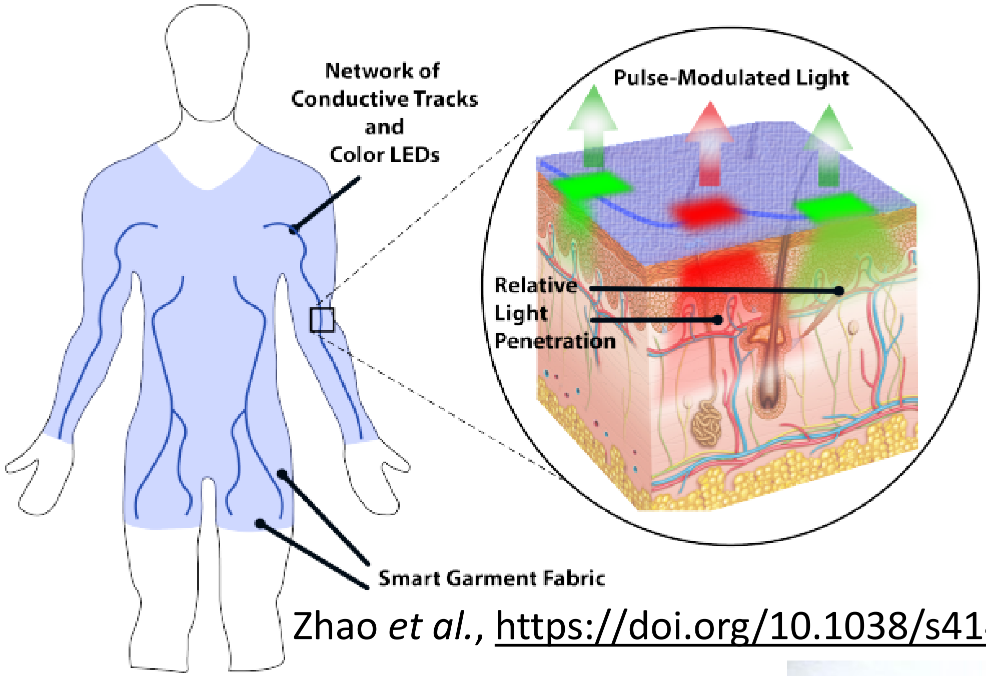
- *Triboelectric sensing
- *Piezoresistive sensing
- *Piezoelectric sensing
- *Capacitive sensing
- *Magnetoelastic sensing
- Magnetic induction plethysmography
- Doppler ultrasound and acoustic sensing
- Impedance plethysmography
- Speckle plethysmography

* See: Meng K *et al.*, https://doi.org/10.1002/adma.202109357

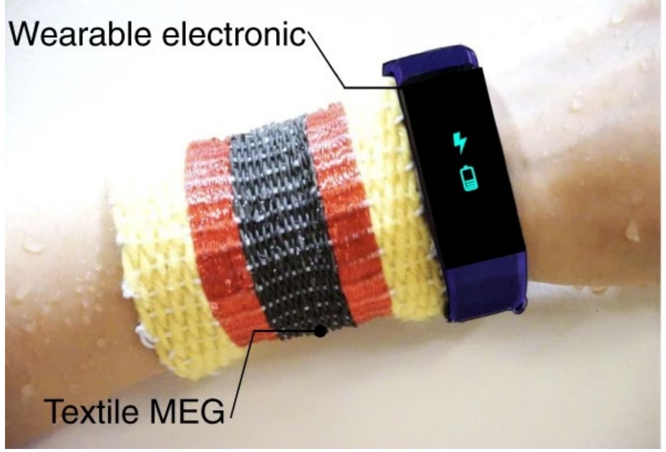
Alternative pulse wave sensing approaches

Alternative form factors

- E-textiles



Zhao *et al.*, https://doi.org/10.1038/s41467-021-27066-1 (CC BY 4.0)

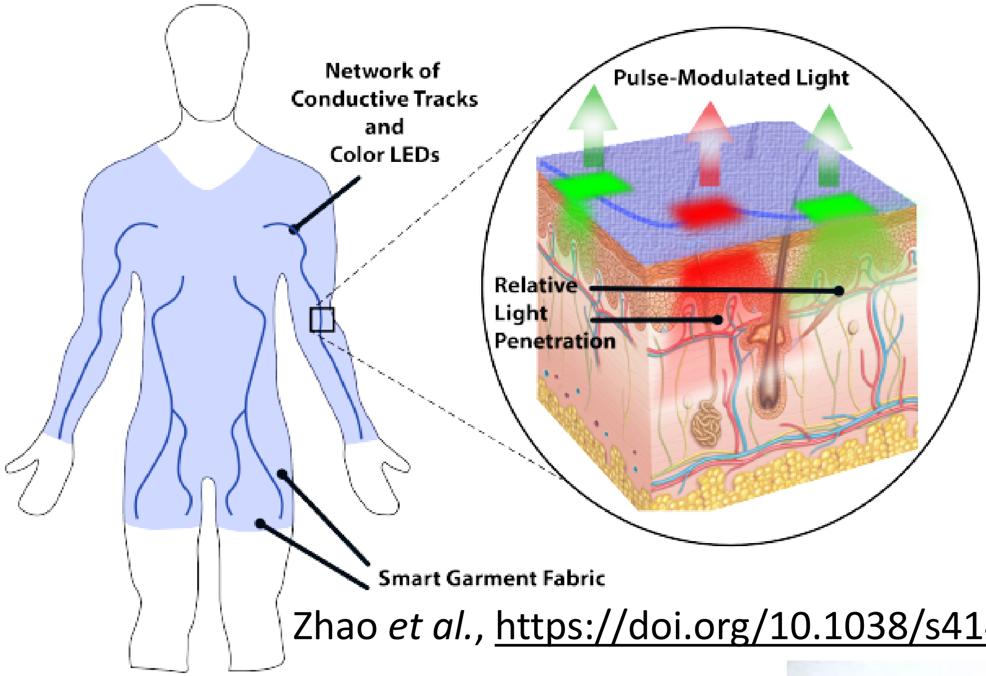


Iakovlev D *et al.*, https://doi.org/10.3390/bios8020033 (CC BY 4.0)

Alternative pulse wave sensing approaches

Alternative form factors

- E-textiles
- Miniaturize inorganic sensors



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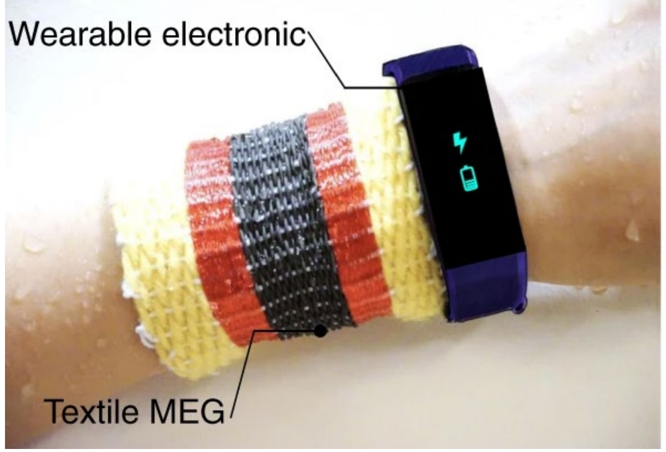
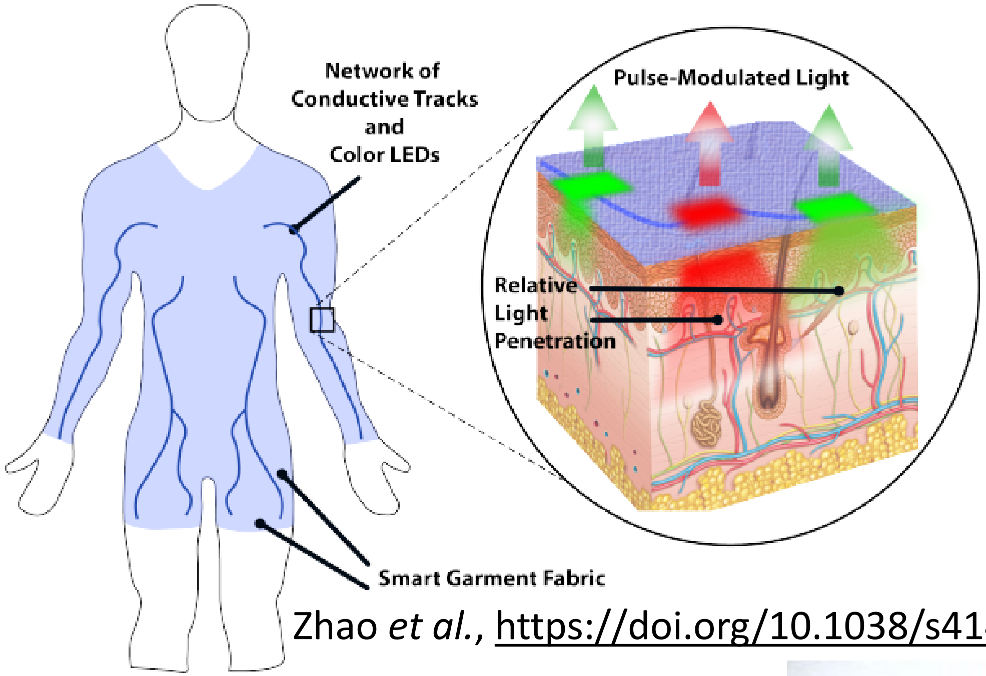


Iakovlev D *et al.*, https://doi.org/10.3390/bios8020033 (CC BY 4.0)

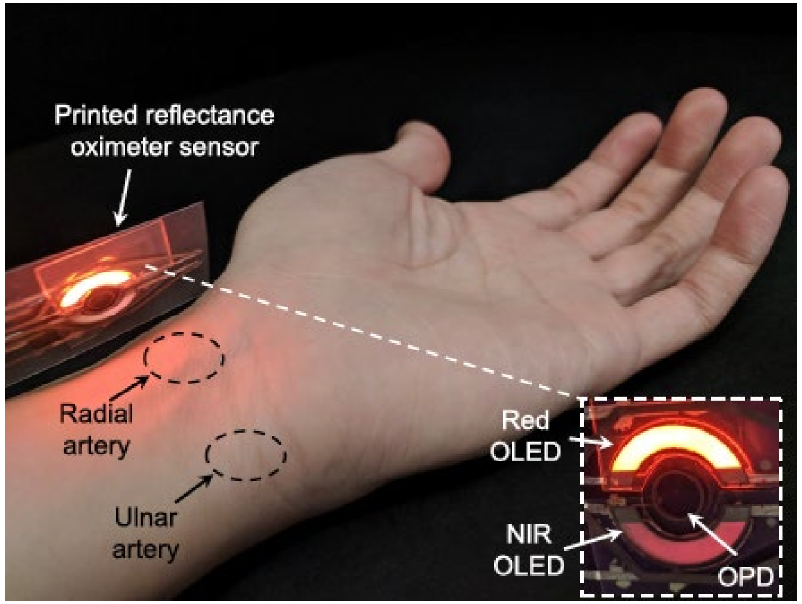
Alternative pulse wave sensing approaches

Alternative form factors

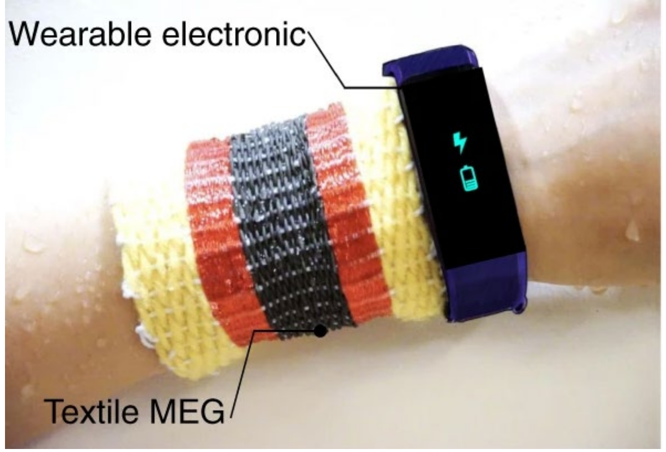
- E-textiles
- Miniaturize inorganic sensors
- Organic, flexible sensors



Zhao *et al.*, https://doi.org/10.1038/s41467-021-27066-1 (CC BY 4.0)



Khan Y *et al.*, https://doi.org/10.1109/ACCESS.2019.2939798 (CC BY 4.0)



Iakovlev D *et al.*, https://doi.org/10.3390/bios8020033 (CC BY 4.0)

Potential Applications

- 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

Further Reading

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:

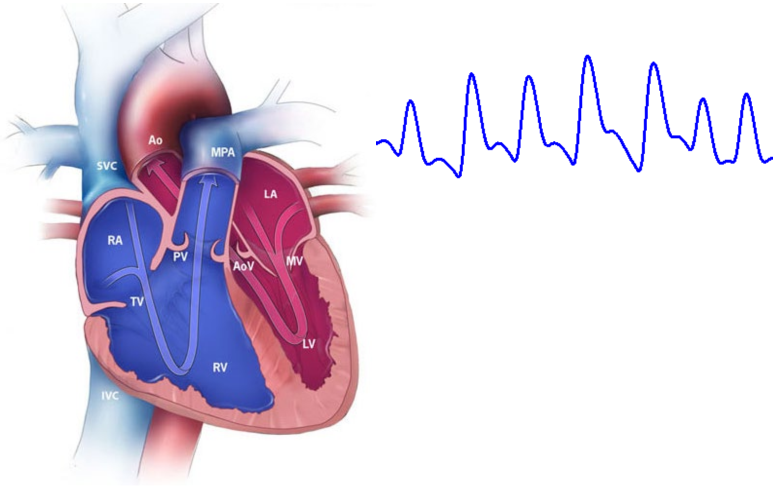
Charlton P.H. *et al.*, **Wearable Photoplethysmography for Cardiovascular Monitoring**, Proc. *IEEE*, 2022, https://doi.org/10.1109/JPROC.2022.3149785

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

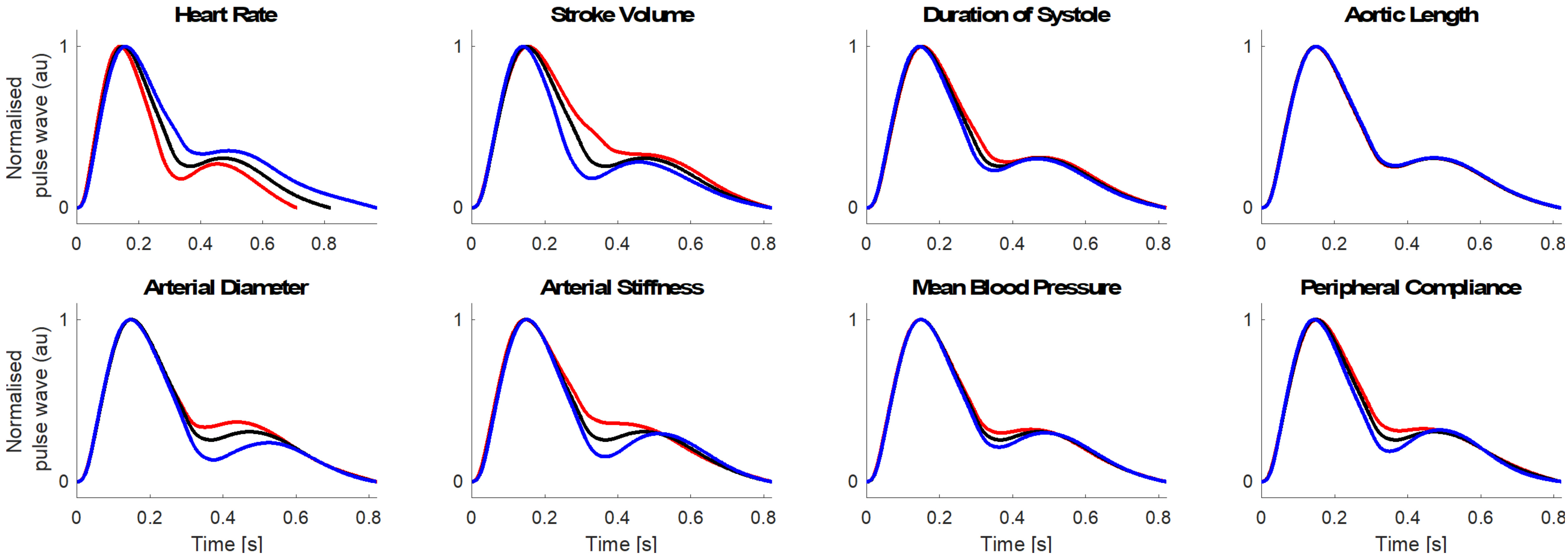
Consumer Wearables

Challenges & Opportunities



Next Steps

The photoplethysmogram contains a wealth of cardiovascular information

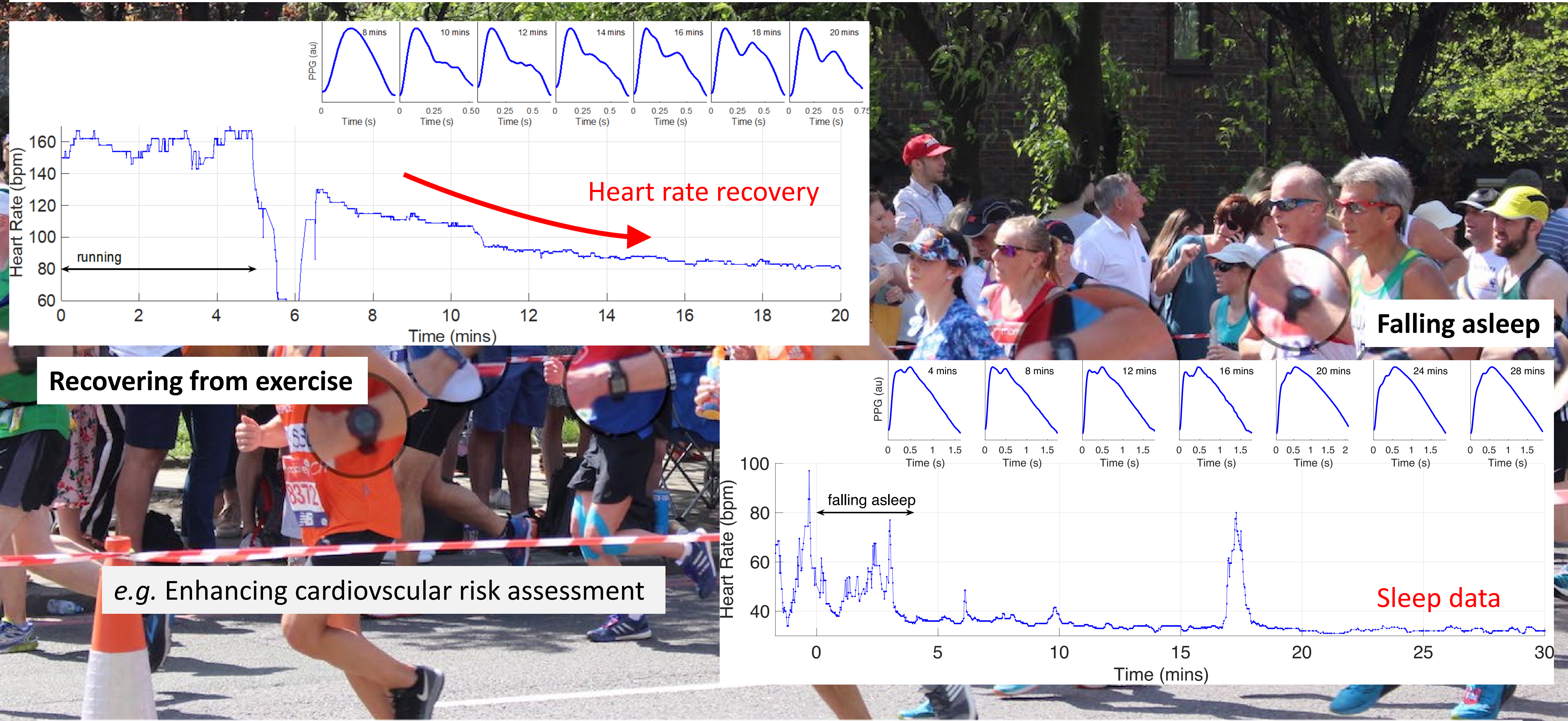


Black – mean value for 25 year old; **Red** – 1 standard deviation above mean; **Blue** – 1 standard deviation below mean

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

Many people use wearables …

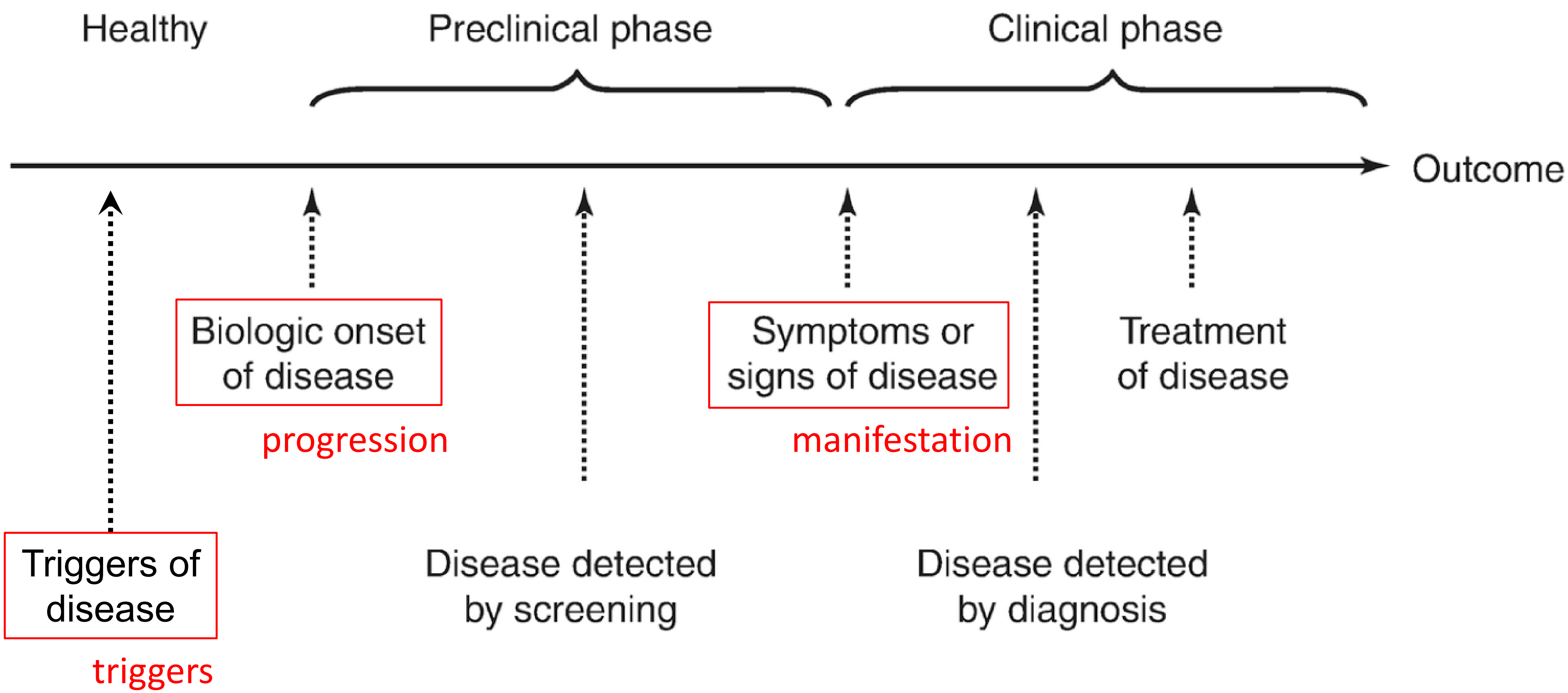
Many people use wearables … in daily life



e.g. Enhancing cardiovscular risk assessment

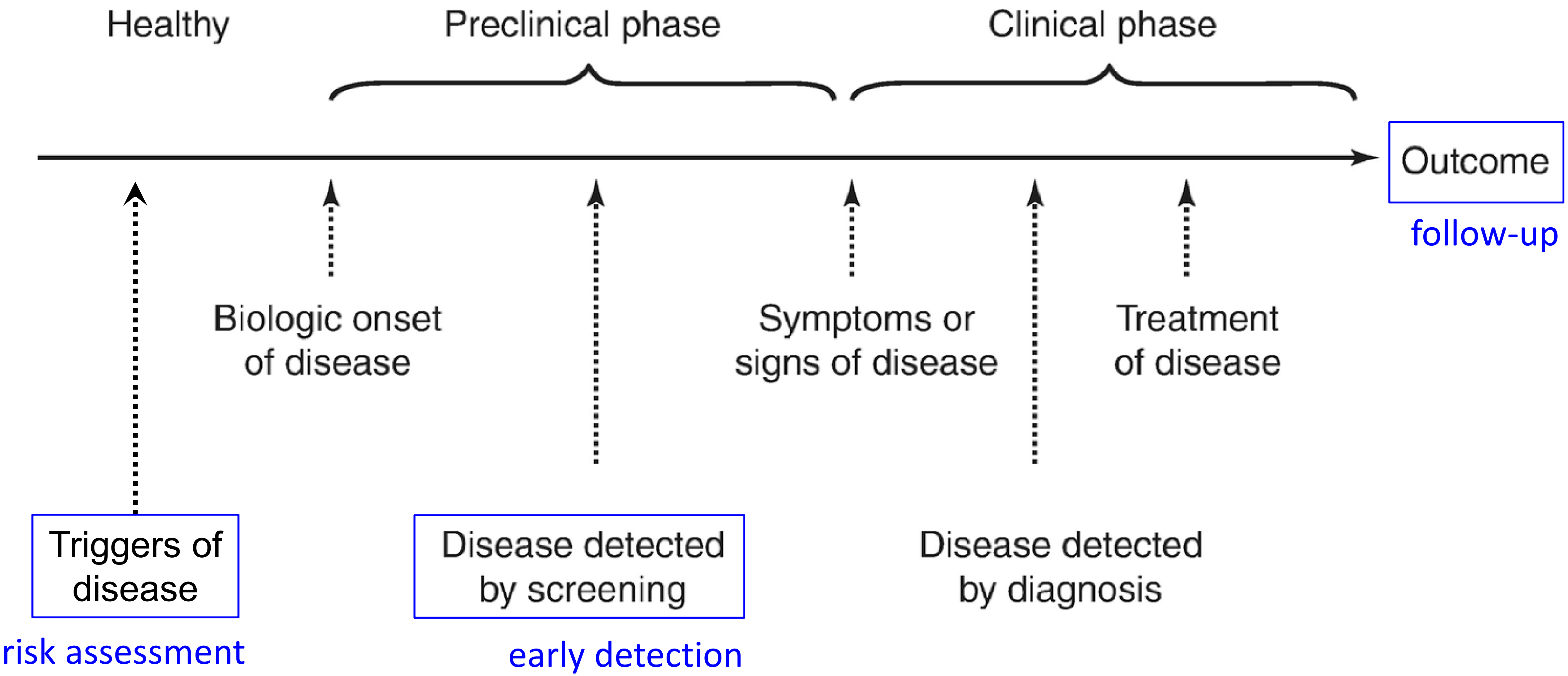
Source: Charlton et al., Acquiring wearable photoplethysmography data in daily life: the PPG Diary Study, https://doi.org/10.3390/ecsa-7-08233 (CC BY 4.0)

Opportunities afforded by wearables in research:



Adapted from: Balayla J, Prevalence threshold (φe) and the geometry of screening curves, PLoS ONE, https://doi.org/10.1371/journal.pone.0240215 (CC BY 4.0)

Opportunities afforded by wearables in healthcare:



Adapted from: Balayla J, Prevalence threshold (φe) and the geometry of screening curves, PLoS ONE, https://doi.org/10.1371/journal.pone.0240215

Opportunities afforded by wearables in healthcare:

Healthy

Pr

Inequality in access to consumer wearables

- Apple Watch series 9 currently £399

Biologic onset of disease

Responding to patient-reported wearable data

Di

risk assessment

SAFER wearables study

Assessing performance and acceptability of wearables for detecting atrial fibrillation

Reply slip:

SAFER wearables study

UNIVERSITY OF CAMBRIDGE
Department of Public Health and Primary Care

Reply Slip

Please complete and return this form only if you do NOT wish to join the SAFER Wearables Study

Title: The SAFER Wearables Study: A study of the acceptability and performance of wearables for atrial fibrillation screening in older adults.

Chief Investigator: Dr Peter Charlton, University of Cambridge

IRAS Project ID: 283812 {**Invite ID:** XXXX}

If you are willing, please indicate why you do not wish to take part:
(tick as many as apply)

☐ I don't want to take part in another research study
☐ I don't want to wear the devices
☐ I don't have time

☐ Other reasons:

____

____

Questionnaire:

3. If you removed any device before the end, then why?

☐ I didn't remove them before the end

☐ I removed the chest-patch because:

____

____

☐ I removed the wristband because:

____

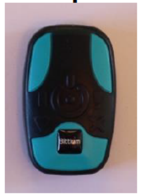
____

☐ I removed the watch because:

____

____

Chest-patch



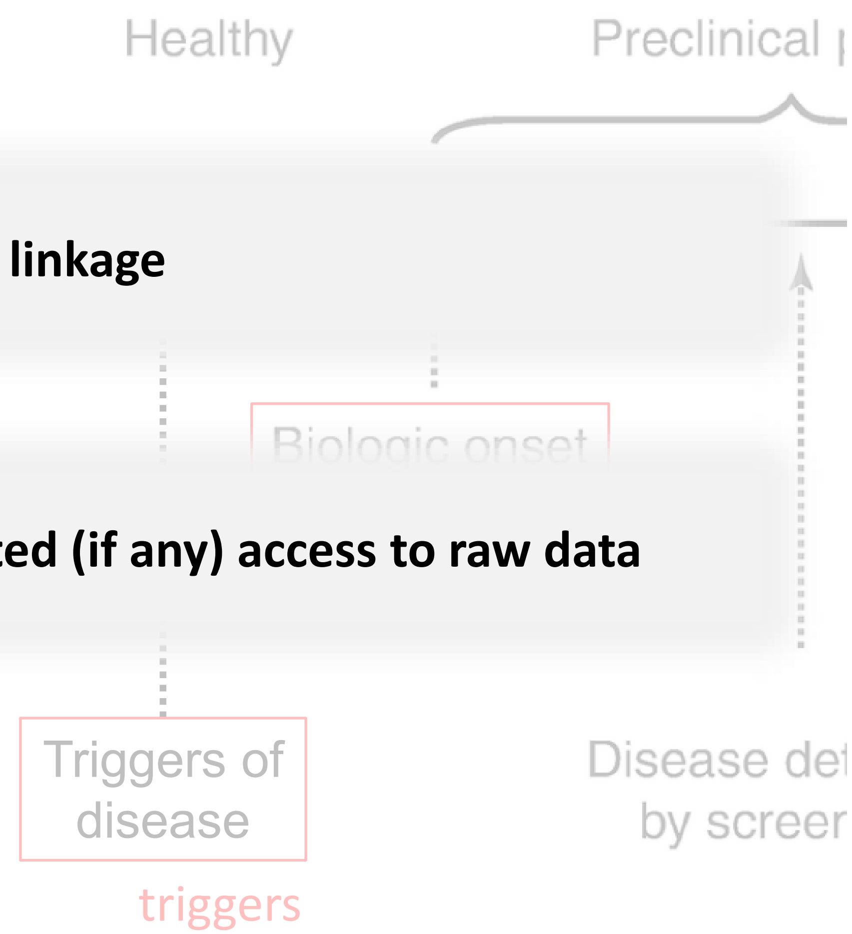
Wristband

Watch

Adapted from: Balayla J, Prevalence threshold (φe) and the geometry of screening curves, PLoS ONE, https://doi.org/10.1371/journal.pone.0240215 (CC BY 4.0)

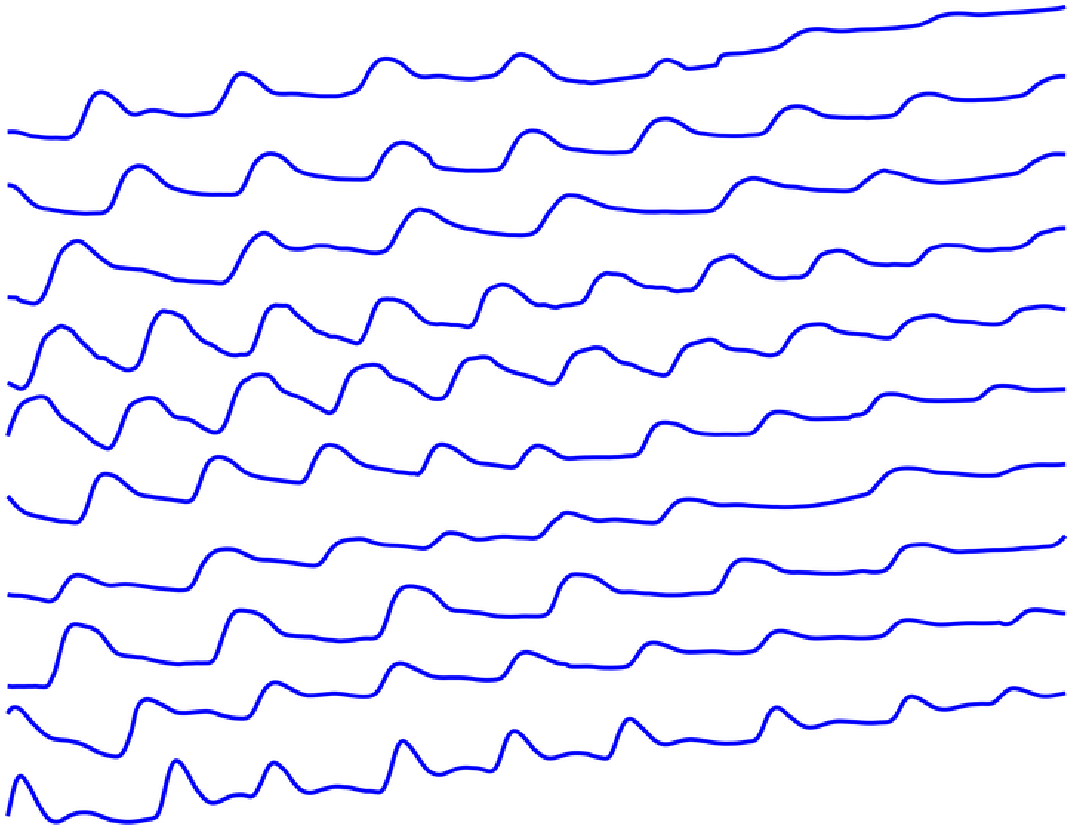
Using wearables in research:

SAFER
wearables study



Data linkage

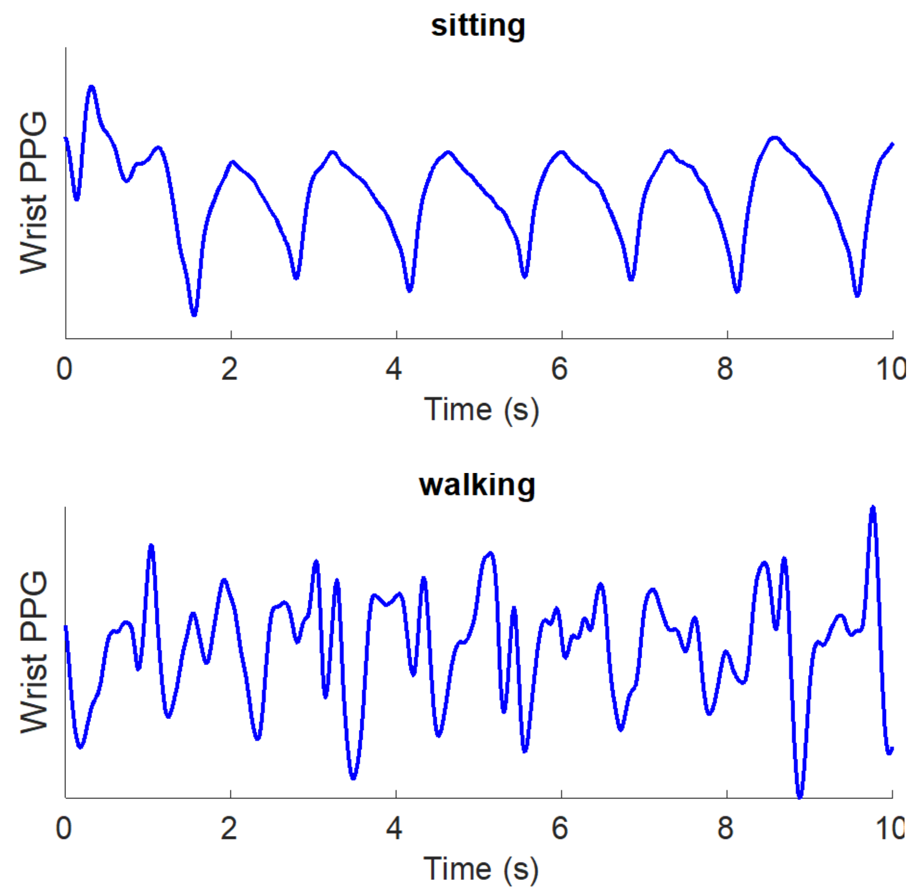
Limited (if any) access to raw data



Adapted from: Balayla J, Prevalence threshold (φe) and the geometry of screening curves, PLoS ONE, https://doi.org/10.1371/journal.pone.0240215 (CC BY 4.0)

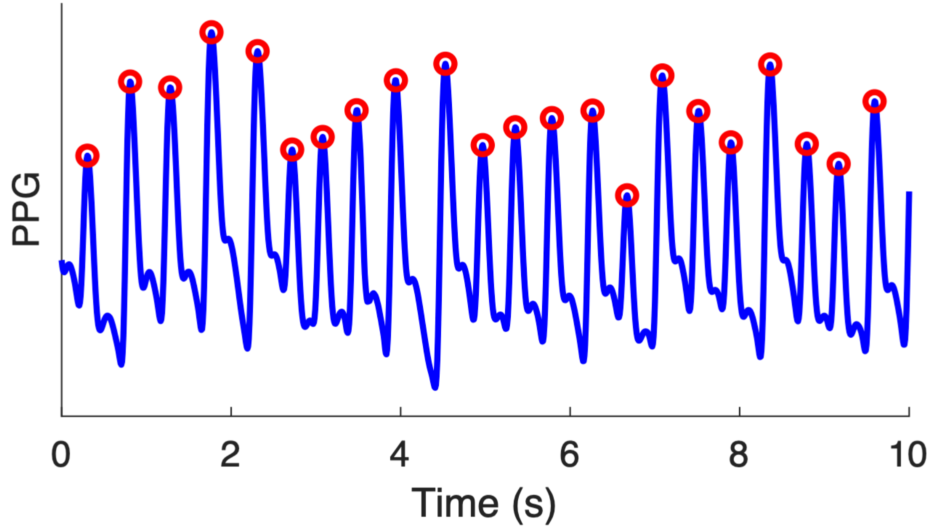
Many people use wearables … in daily life

Motion artifact



Our Contributions:

- Established threshold levels of activity below which inter-beat intervals can be accurately measured from the photoplethysmogram.
- Compared beat detection algorithms to identify the best performing algorithm for use in daily life.



P. H. Charlton, "Accelerometry-Guided Inter-Beat-Interval Assessment from Wrist Photoplethysmography," https://doi.org/10.5281/zenodo.8403222

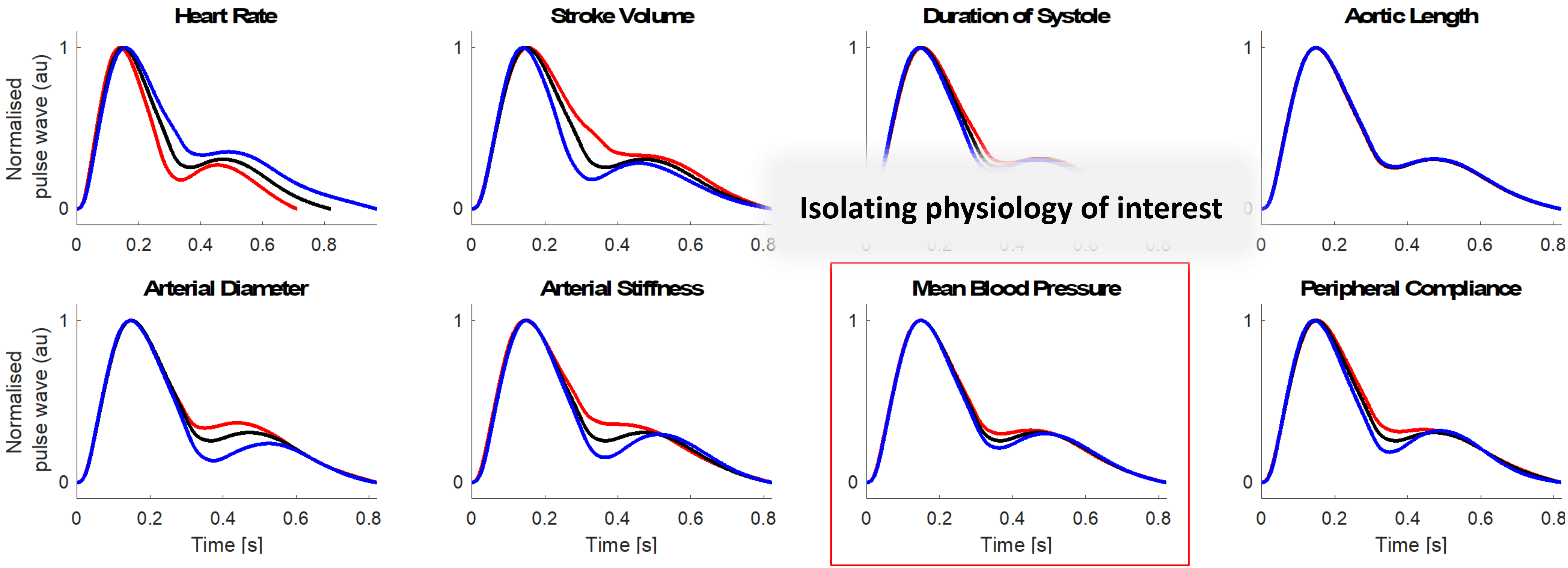
Many people use wearables

Performance across different subjects

Our Contribution:

Al-Halawani R. *et al.*, **A review of the effect of skin pigmentation on pulse oximeter accuracy**, *Phys Meas.*, 2023, https://doi.org/10.1088/1361-6579/acd51a

Cardiovascular determinants of the photoplethysmogram



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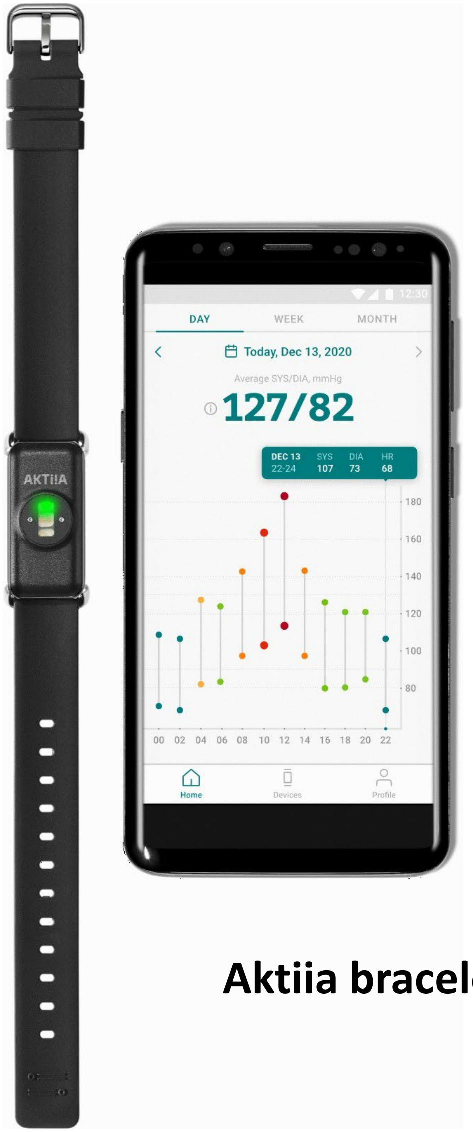
Red – 1 standard deviation above mean
Blue – 1 standard deviation below mean

Case Study: Detecting hypertension



Aktiia bracelet

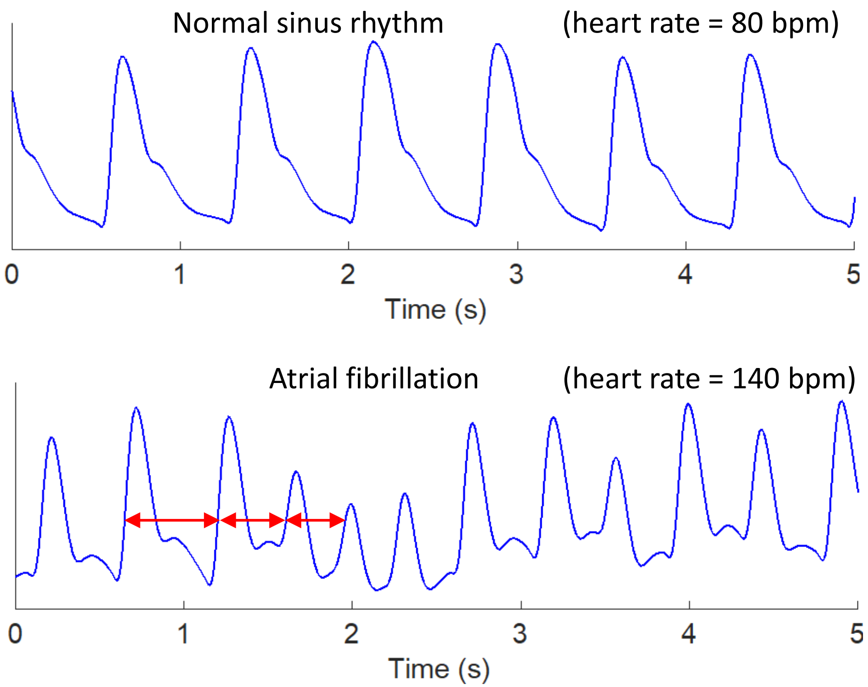
- Much research on estimating blood pressure from the photoplethysmogram
- Mixed performance
- Estimating absolute blood pressure vs. detecting potentially elevated blood pressure

Case Study: Detecting 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

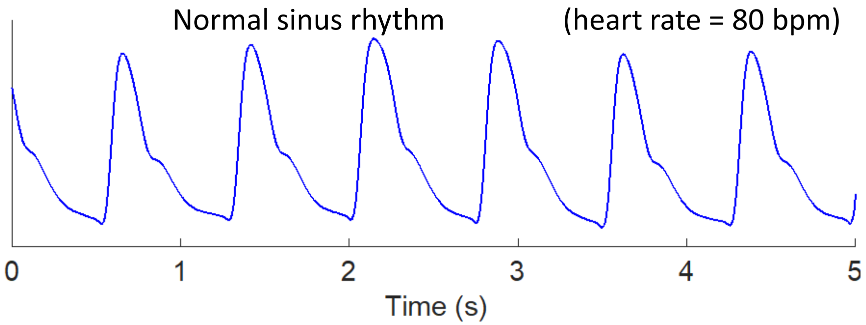
Case Study: Atrial fibrillation detection

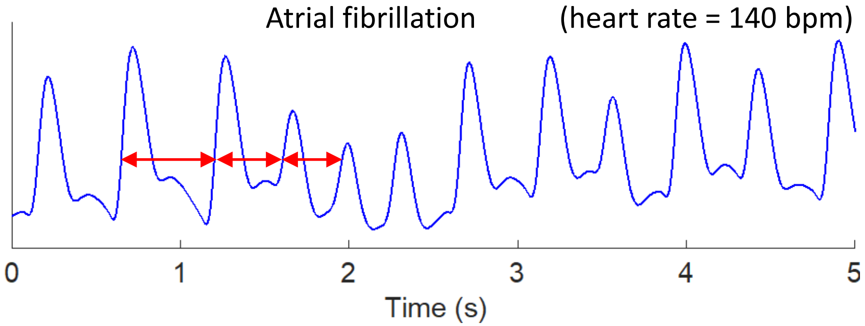


Irregular beat-to-beat intervals

Case Study: Atrial fibrillation detection

Perez M.V. *et al.* Large-scale assessment of a smartwatch to identify atrial fibrillation. *N. Engl. J. Med.* **2019**, *381*, 1909–1917, doi:10.1056/NEJMoa1901183





Irregular beat-to-beat intervals

0.5% alert rate

84% positive predictive value

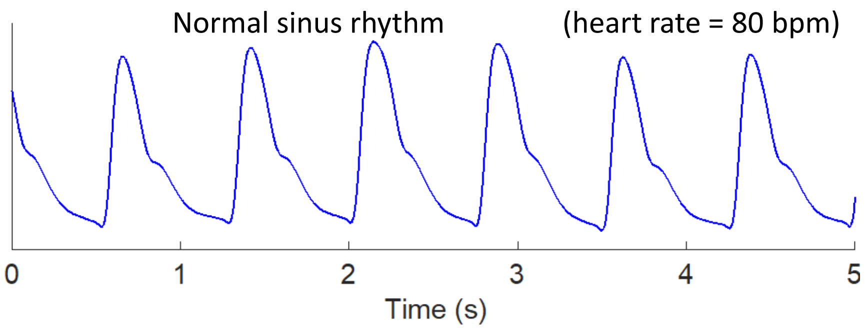
117 days monitoring per individual

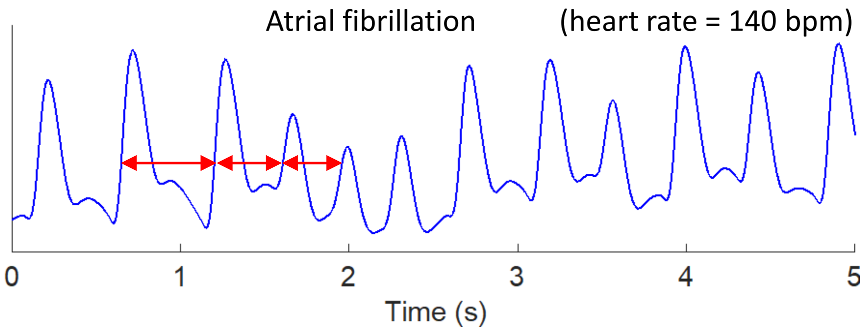
Case Study: Atrial fibrillation detection

Lubitz S. *et al.* Detection of Atrial Fibrillation in a Large Population using Wearable Devices: The Fitbit Heart Study. *Circulation.* **2022**, doi: 10.1161/CIR.0000000000001041

0.2% **alert rate**

98% **positive predictive value**





Irregular beat-to-beat intervals

Case Study: Atrial fibrillation detection

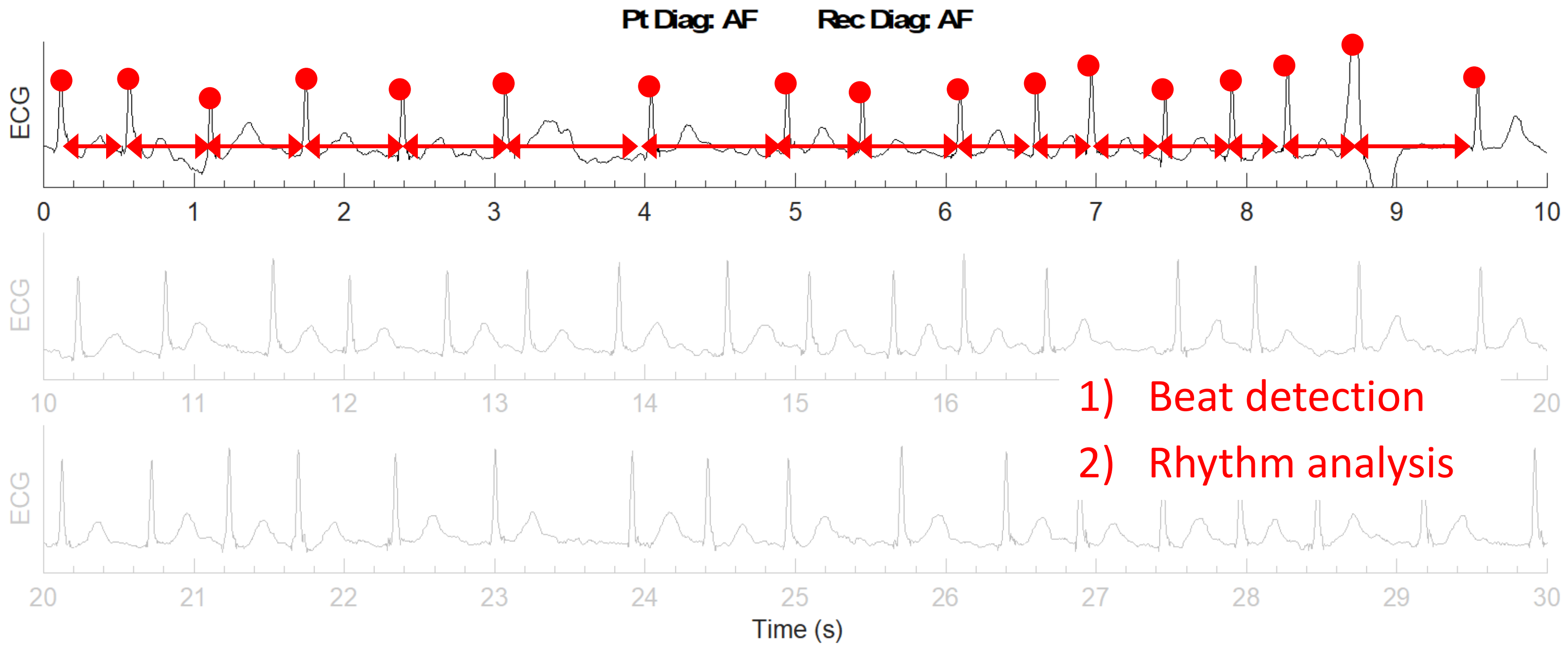
Our Contributions:

- Using photoplethysmography to detect inter-beat intervals

Case Study: Atrial fibrillation detection

Our Contributions:

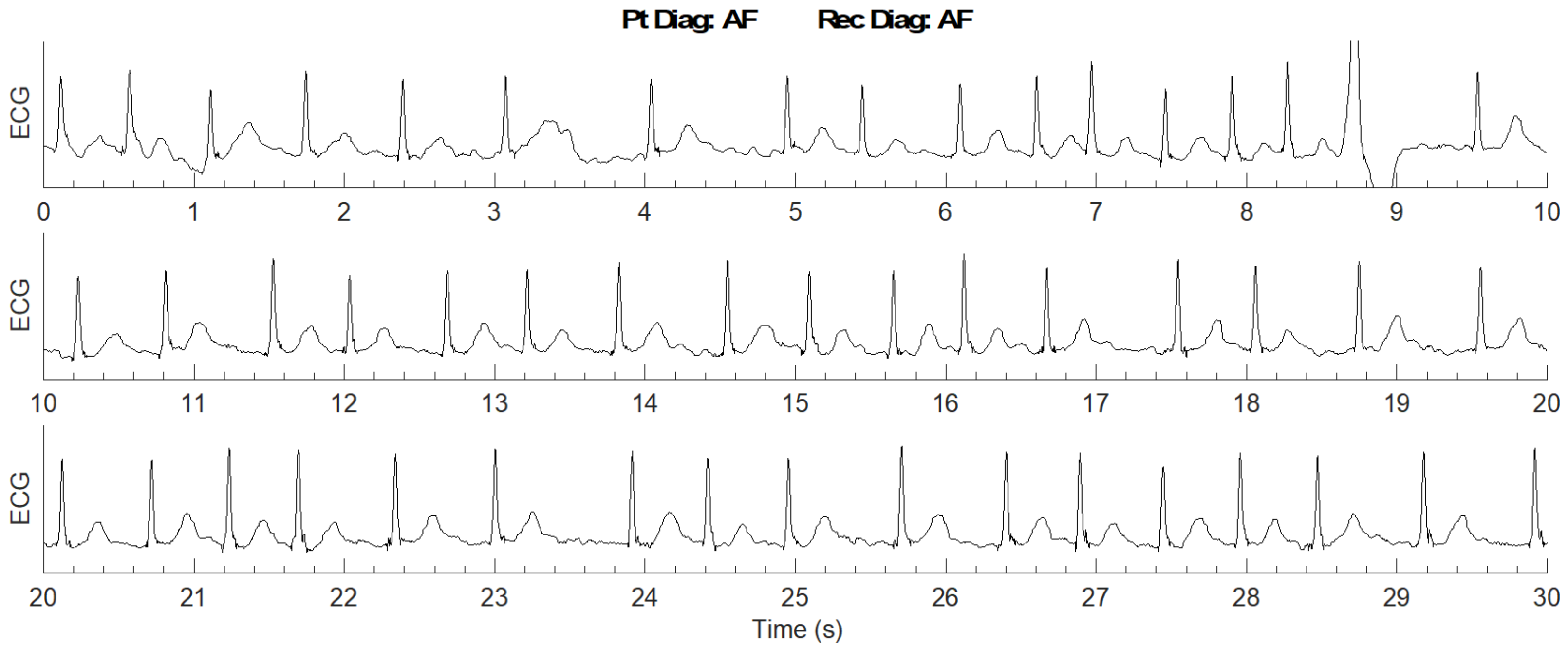
- Using photoplethysmography to detect inter-beat intervals
- Identifying AF reliably from inter-beat intervals



Case Study: Atrial fibrillation detection

Our Contributions:

- Using photoplethysmography to detect inter-beat intervals
- Identifying AF reliably from inter-beat intervals
- Diagnosis of AF from single-lead ECGs

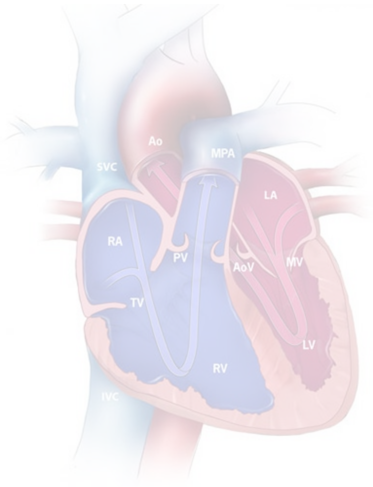


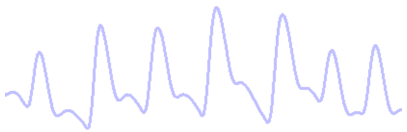
Case Study Summary

Case Study	Technology	Clinical Setting	Confirmation	Potential benefits
Detecting hypertension	Difficult to estimate blood pressure from photoplethysmography	established – detection of hypertension in daily life	Clear – subsequent cuff measurement	Ubiquitous Early detection In daily life
Detecting obstructive sleep apnea	Challenges in oxygen saturation assessment (reflectance, skin type)	new – opportunistic detection at home	Unclear	Ubiquitous Early detection
Atrial fibrillation (AF) detection	(relatively) Straight-foward implementation	(relatively) new – opportunistic screening for asymptomatic AF	Emerging – simultaneous ECG on wearable device	Ubiquitous Early detection Asymptomatic AF

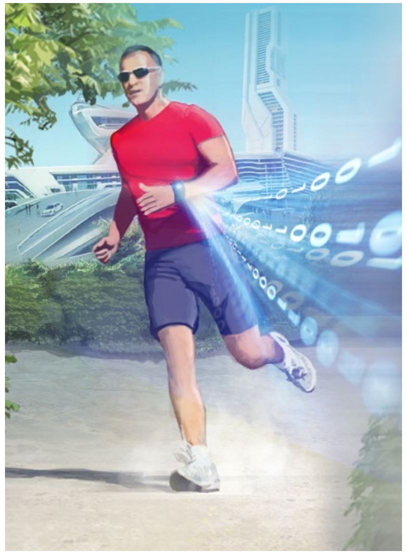
Consumer Wearables

Challenges & Opportunities





Next Steps



Selecting a clinical use case

Consider:

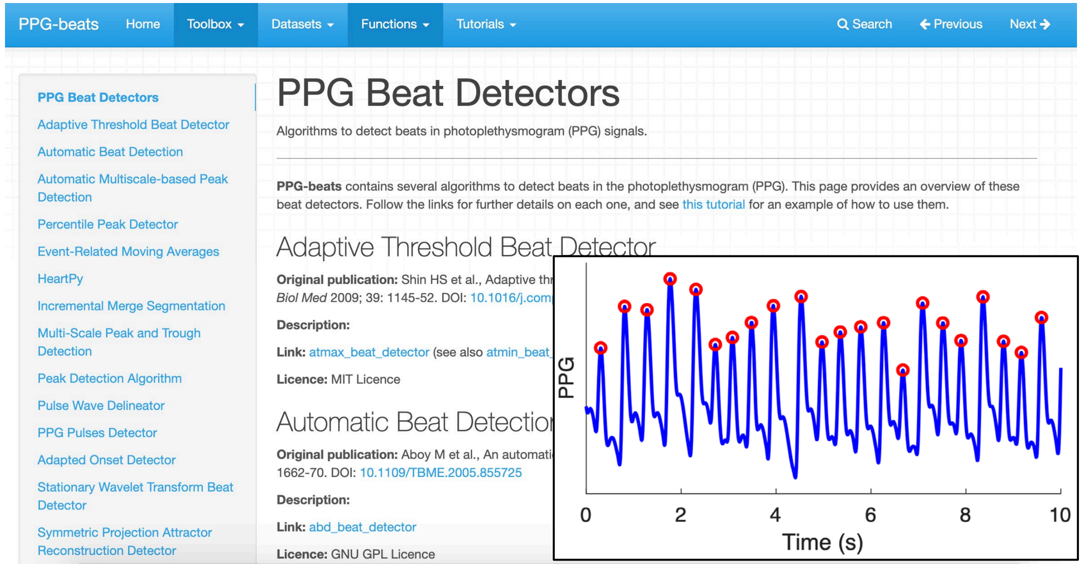
- Would a wearable add value to current practice? *e.g.*
  - Physiological assessment where it would not otherwise be performed
  - Frequent monitoring where measurements would otherwise be intermittent
- Would the results be actionable? *e.g.*
  - Prompt further assessment (relatively safe)
  - Diagnosis (and treatment) (higher risk)
- Could it be integrated into a clinical pathway?
- Is it cost-effective?
- Many use cases focus on "prevention of avoidable illness and its exacerbations" (NHS Long Term Plan)

Advancing the technology

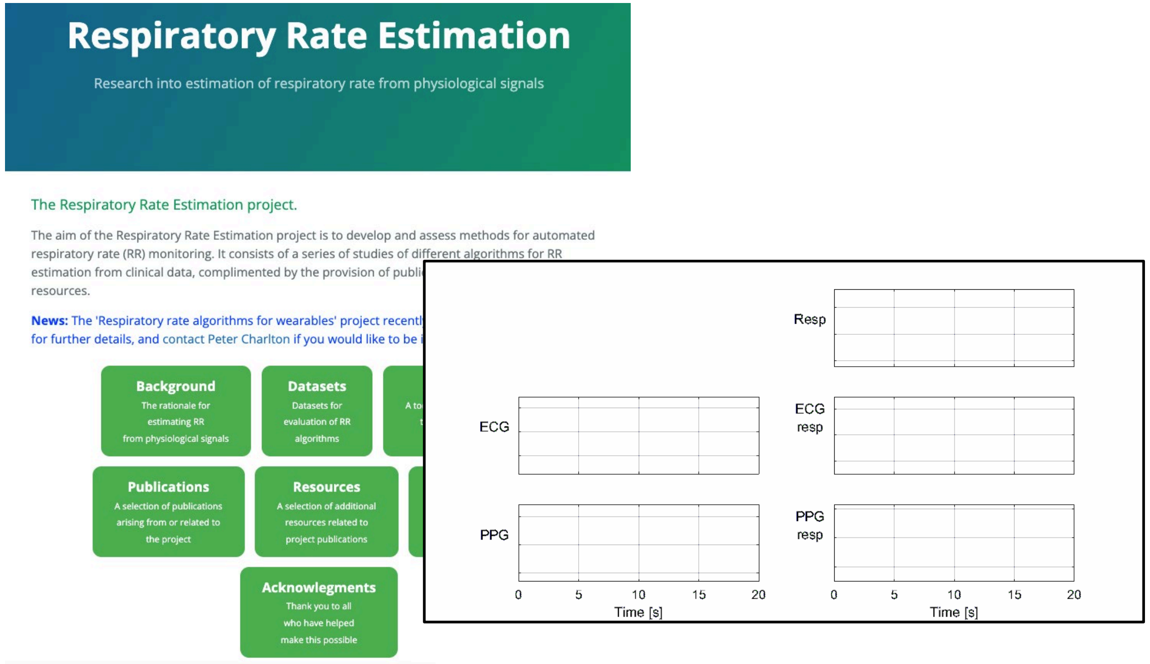
Several potential directions:

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

Open-source algorithms:



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



https://peterhcharlton.github.io/RRest

Validating devices

The INTERLIVE Network:

Goal: "To develop gold standard protocols for the validation of wearables in order to improve the accuracy and reliability of physical activity patterns assessment."

Validation protocols published for:

- Step counts
- Heart rate
- Energy expenditure
- Maximal oxygen consumption

See: https://www.interlive.org/

Cuffless blood pressure estimation:

- New IEEE standard being developed
- Requiring a new approach

See: Mukkamala et al., Hypertension, 2020

Understanding the needs of stakeholders

Photo by Tatiana Zanon on Unsplash

Identifying potential clinical pathways

- Screening
- Patient-led measurements to prompt clinical assessment *e.g.*
  - Bradycardia as sign of possible heart block: https://doi.org/10.1016/j.jaccas.2019.11.087
  - Smartwatch ECG capturing ventricular tachycardia: https://doi.org/10.1016%2Fj.hrcr.2020.08.003 ; https://doi.org/10.1016/j.cjco.2021.12.003
  - Incidental findings during follow-up of smartwatch-detected tachycardia: https://doi.org/10.1177/20542704211068651
- Identifying side-effects of treatments, *e.g.*
  - Bradycardia or arrhythmia after medication: https://doi.org/10.1177/23247096211069761
- Population-level surveillance
- Self-directed health monitoring

Large-scale studies

Heart rate variability with photoplethysmography in 8 million individuals: a cross-sectional study

Aravind Natarajan, Alexandros Pantelopoulos, Hulya Emir-Farinas, Pradeep Natarajan

https://doi.org/10.1016/S2589-7500(20)30246-6

ORIGINAL ARTICLE

Large-Scale Assessment of a Smartwatch to Identify Atrial Fibrillation

Marco V. Perez, M.D., Kenneth W. Mahaffey, M.D., Haley Hedlin, Ph.D., John S. Rumsfeld, M.D., Ph.D., Ariadna Garcia, M.S., Todd Ferris, M.D., Vidhya Balasubramanian, M.S., Andrea M. Russo, M.D., Amol Rajmane, M.D., Lauren Cheung, M.D., Grace Hung, M.S., Justin Lee, M.P.H., Peter Kowey, M.D., Nisha Talati, M.B.A., Divya Nag, Santosh E. Gummidipundi, M.S., Alexis Beatty, M.D., M.A.S., Mellanie True Hills, B.S., Sumbul Desai, M.D., Christopher B. Granger, M.D., Manisha Desai, Ph.D., and Mintu P. Turakhia, M.D., M.A.S., for the Apple Heart Study Investigators*

https://doi.org/10.1056/NEJMoa1901183

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King’s College London

EPSRC
British Heart Foundation

The 50 co-authors of ‘The 2023 wearable photoplethysmography roadmap’, who greatly helped shape my thinking on this topic.

Wearables can provide a wealth of physiological information unobtrusively.

Much work is required to understand how to extract physiological data reliably, and how to use it in healthcare and research.

Perhaps in the future, wearables could be as essential in maintaining health as a rope is for climbing safely.

Using consumer wearables in healthcare and research

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

Slides available at: https://doi.org/10.5281/zenodo.10517773