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PERVASIVE SYSTEMS

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Beyond Listening:
The Evolution of Earables in Health and Wellbeing Monitoring

March 2024
Mobile and Wearable Health Seminar Series
University of Cambridge

Personal Introduction

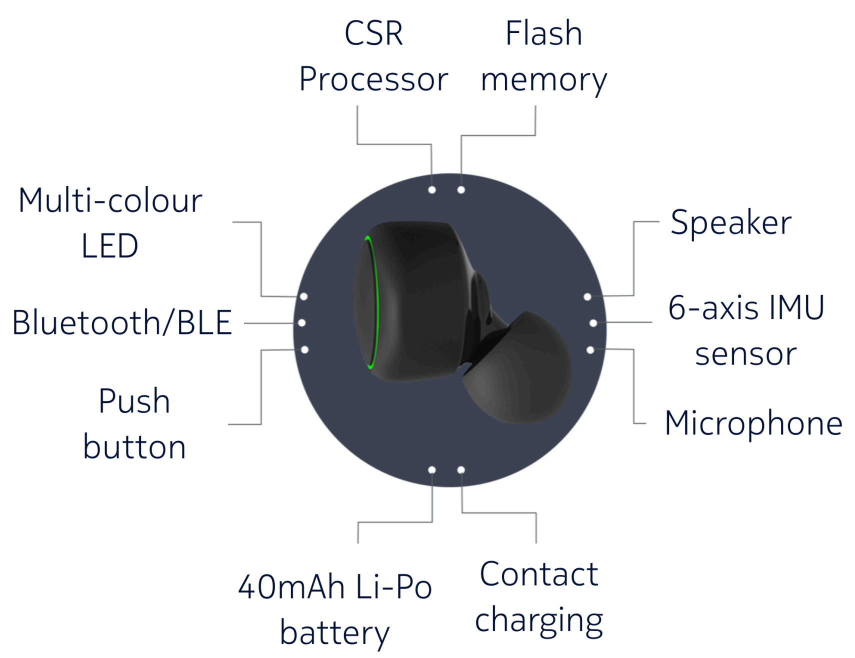
Principal Research Scientist and Tech Lead at Nokia Bell Labs

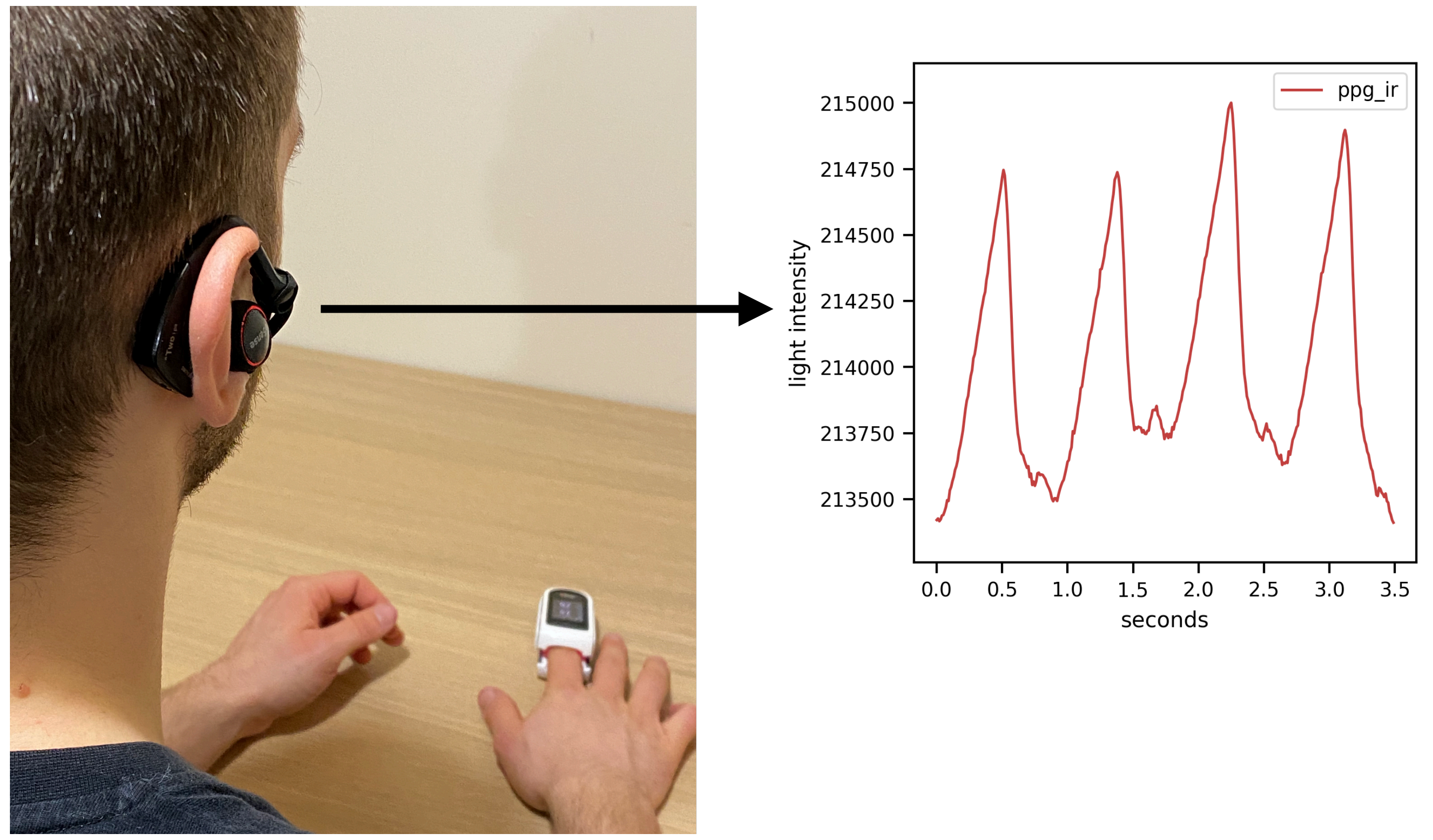
Earable computing

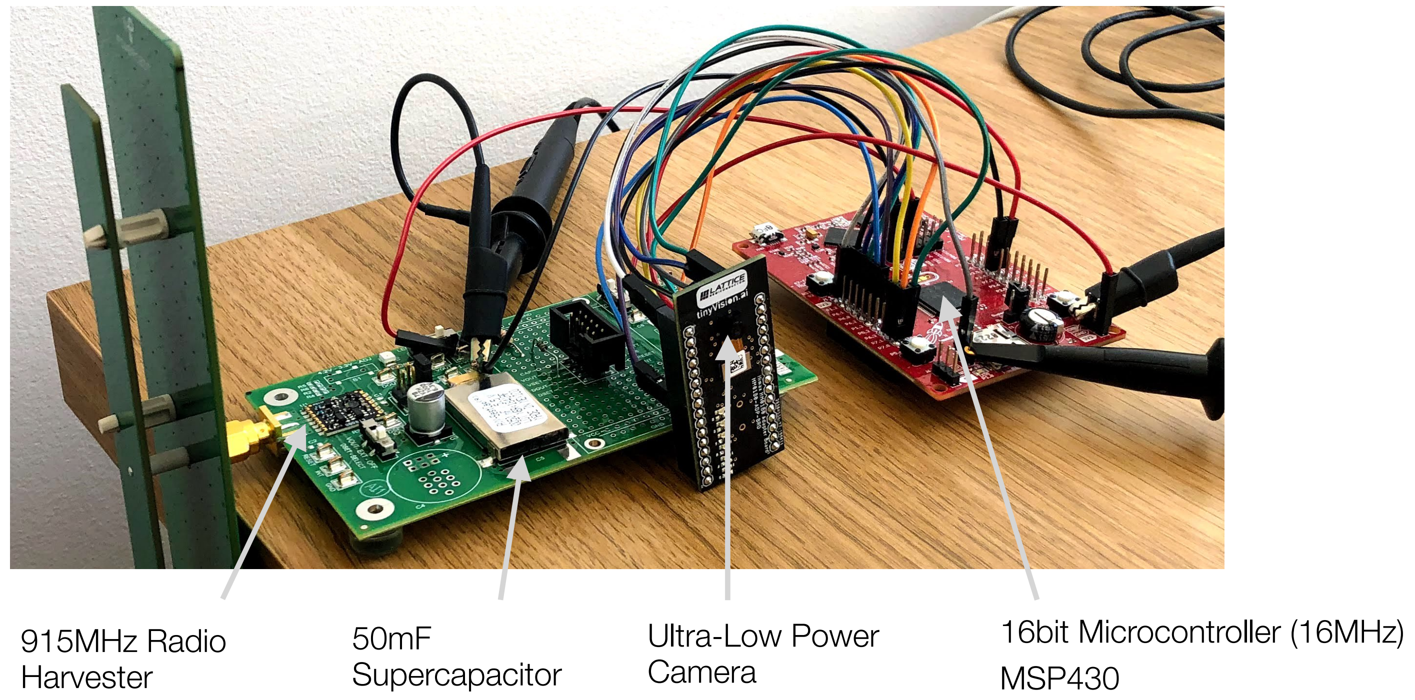
- Vital signs monitoring in the ear
- Activity and facial expressions recognition
- Platform development and community release (eSense)

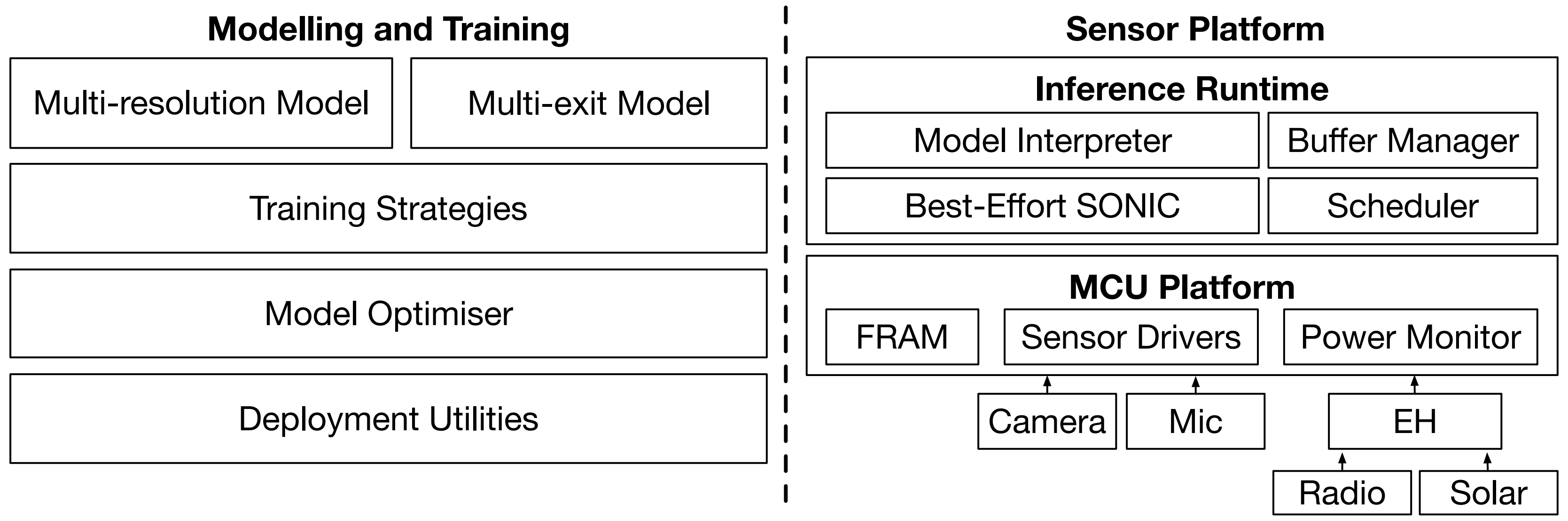
Intermittent computing and embedded machine learning

- Framework for energy-adaptive ML workloads on batteryless sensors









Agenda

- Earables as health and wellbeing devices
- PPG sensor for in-ear applications
- Placement of PPG in/around the ear
- Cuffless blood pressure estimation with earables
  - Dual PPG
  - Multi-modal PPG + Microphone
- Conclusion

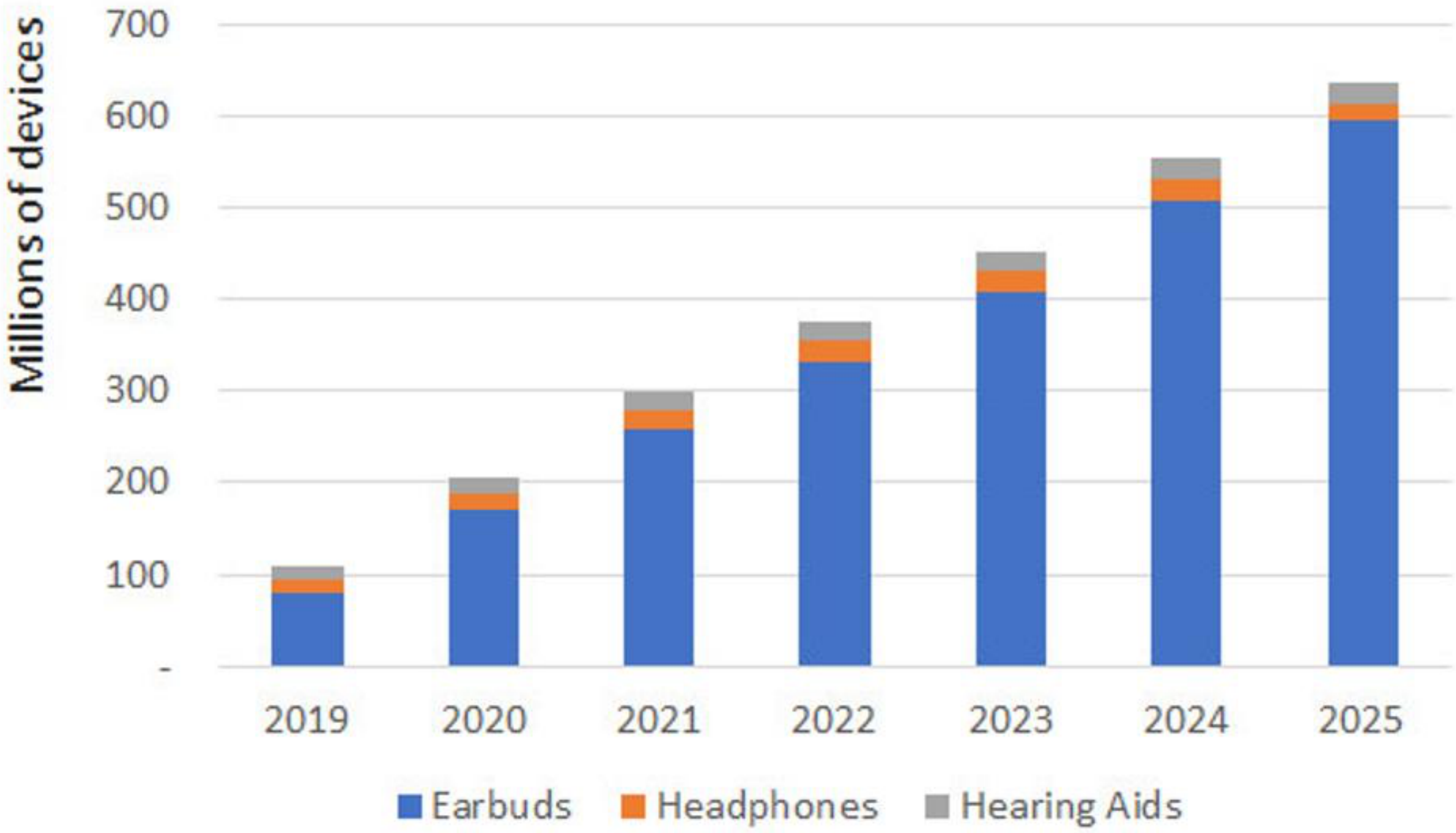
What is happening in the Earable Space ?

One of the fastest growing markets since the smartphone

Bragi started the trend in 2014 with a $3.4M Kickstarter campaign
Apple dominates since the introduction of AirPods in 2016

Continuous interest from industry and academia over the years

Estimated market to reach **$80Bn in 2025**, growing to **$120Bn by 2032**



Sources:
ABI Research — Wearable Report
WiForce — The Hearables Report 2020-2025
Market Research Future — Hearables Market Research Report

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Adoption is mainly driven by listening experience

Listening to different types of content is the main use case for True Wireless Earbuds

Companies are increasingly focusing on the **listening experience** with significant effort in this direction (e.g. 3D audio, noise cancelling, better call quality, …)

Sensory experience is still an under-utilised area in earables

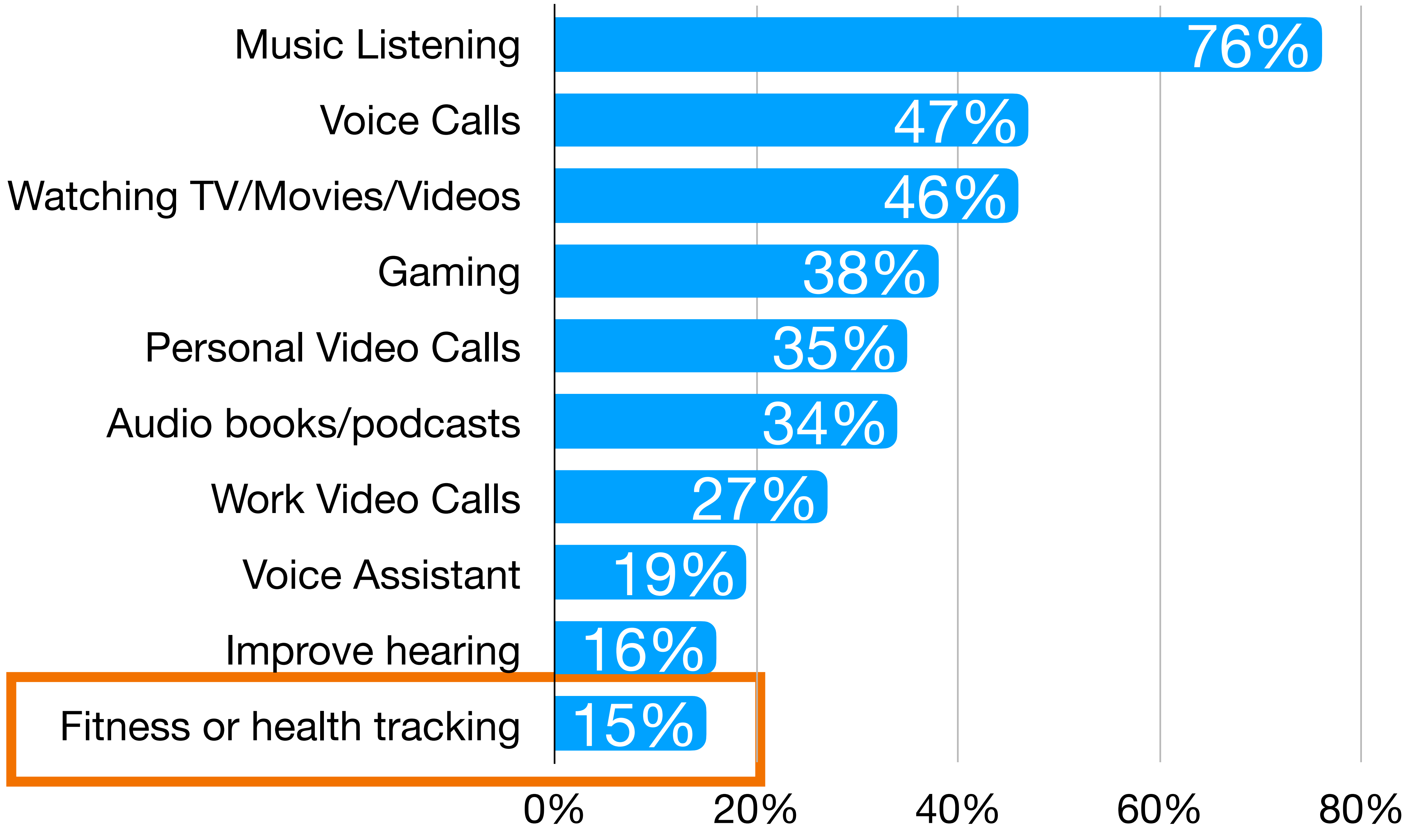
E.g. monitoring of physical, mental and social wellbeing but also health and vital signs monitoring

"More than half (54%) of consumers surveyed globally said they are likely or extremely likely to purchase wireless headphones or earbuds that offer additional features, such as voice assistance, **fitness biometrics**, or hearing assistance capabilities."

"There is growing demand for enhanced sensor capabilities and fitness & health tracking, which have risen year-on-year."

"The State of Sound Report 2022" — Qualcomm

Which of the following do you use your current true wireless earbuds for?



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Time and date
Calls and messages
Music streaming

2009
Samsung S9110 Watch Phone

Activity and sleep tracking
Blood Oxygen level
Heart rate
ECG
Environmental sound monitoring
Handwashing monitoring
Apps

2020
Apple Watch Series 6

Music playback
Calls

2015
Onkyo W800BT

Active Noise Cancelling
Transparency mode
Spatial audio
Adaptive EQ

2019
Apple AirPods Pro

The future of earables
will be **sensory-rich**
and **health-oriented**

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The Importance of Cardiovascular Health

- **Cardiovascular diseases** (CVD) are the **top cause of death globally**, causing an estimated **17.9 million deaths in 2019**
- **High blood pressure** and hypertension affect more than **1 billion people worldwide**
- Only about **42% of adults** with hypertension are **aware of their condition**
- **Frequent monitoring and early detection** are crucial for reducing CVD risks and improving medication outcomes

Source:
World Health Organization

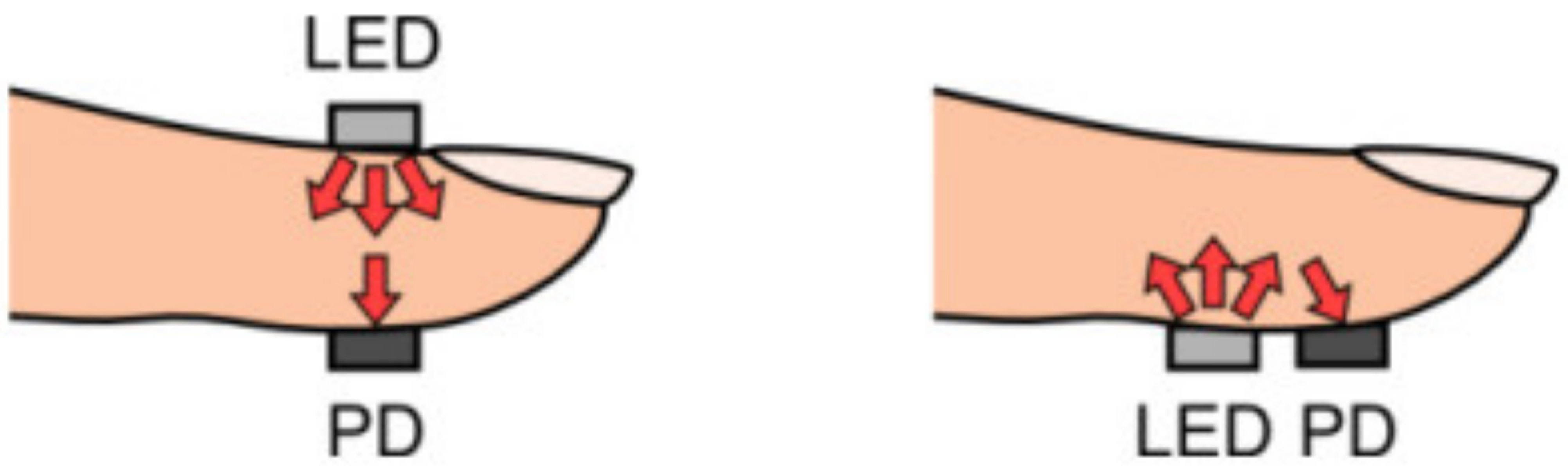
Earables Are Well Positioned For Frequent Monitoring

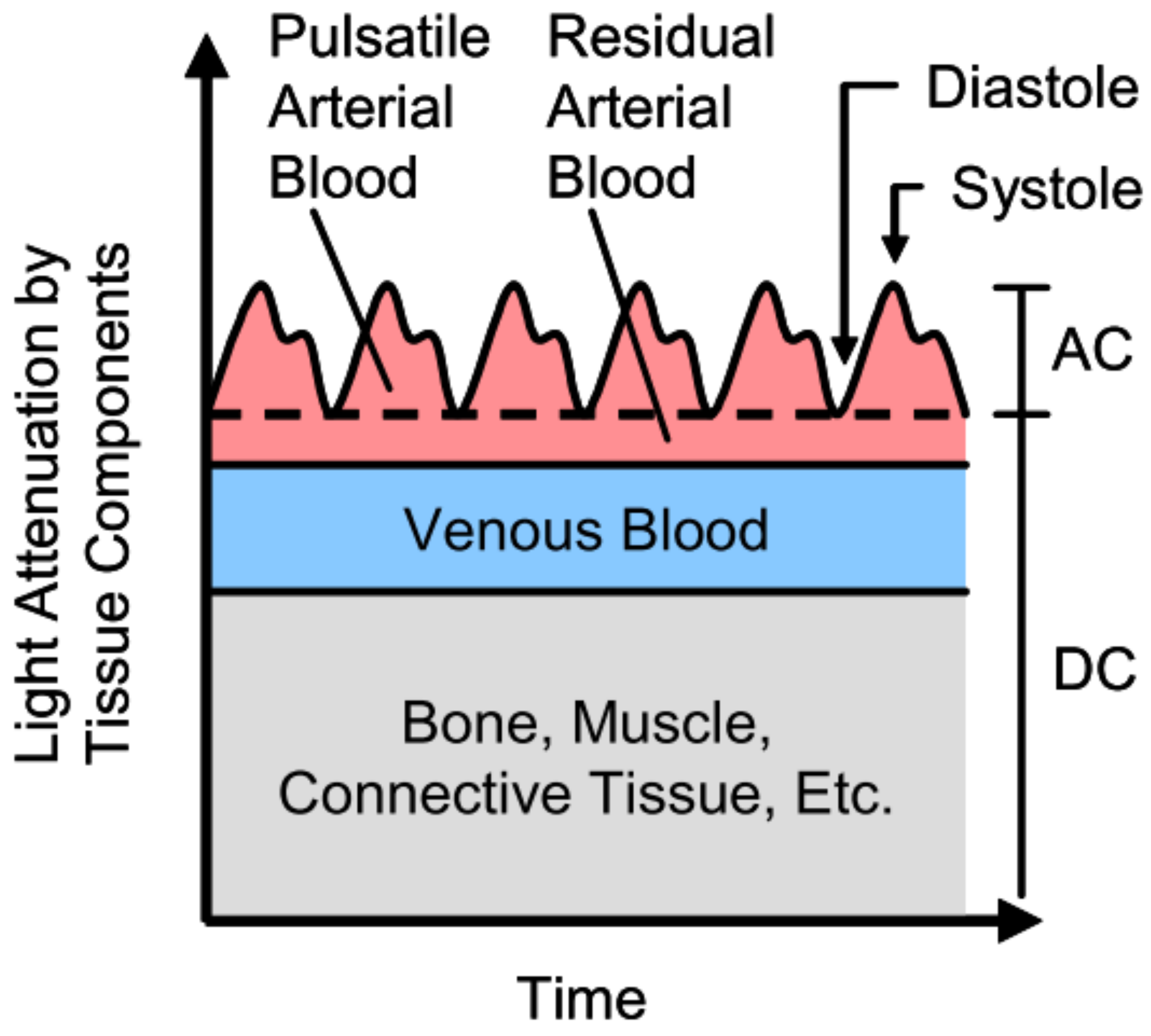
- Established purpose & socially accepted
- Unique placement for robust sensing
  - Dense vascular structure
  - Head is less susceptible to motion artefacts
- Intimate and privacy preserving interaction

Photoplethysmogram

PPG: a cheaper alternative to ECG

- There are essentially two ways of measuring blood volume changes from PPG:
  - **Light Transmission** (used when collecting PPG data from finger-tips and earlobes).
  - **Light Reflectance** (it is the approach used by smartwatches and off-the-shelves wearables).
- Light is more absorbed by blood than by tissues. Hence, small volume changes correspond to changes in the intensity of light (voltage of the signal).





PPG signals alone can be used to derive a number of vital signs

Heart Rate [**HR**], Blood Oxygen Saturation [**SpO2**], and Respiration Rate [**RR**]

+ Temperature

+ Blood Pressure

5 Key Vital Signs of Human Body

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WHY IN-EAR PPG?

Technical Reasons

Why in-ear PPG?

- PPG is **straightforward to implement** (LEDs + photodiodes) and mechanically easy to integrate in an earable form
- PPG's output signal is **easy to interpret**

Biological Reasons

Why in-ear PPG?

- The **ears** are supplied by **several blood vessels**, branches of major arteries (external carotid artery)
- The human **head is less susceptible to motion artifacts** thanks to the natural vibration damping of the musculoskeletal system

Usability Reasons

Why in-ear PPG?

- Earables have to be:
  - **Lightweight**
  - **Ergonomically comfortable**
  - **Non-invasive**
- PPG, thanks to its **mechanical simplicity**, is the most suited sensor to seamlessly integrate into a sensory earable

Where is the optimal positioning of an in-ear PPG sensor?

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To what extend is in-ear PPG **robust** to **motion** artifacts?

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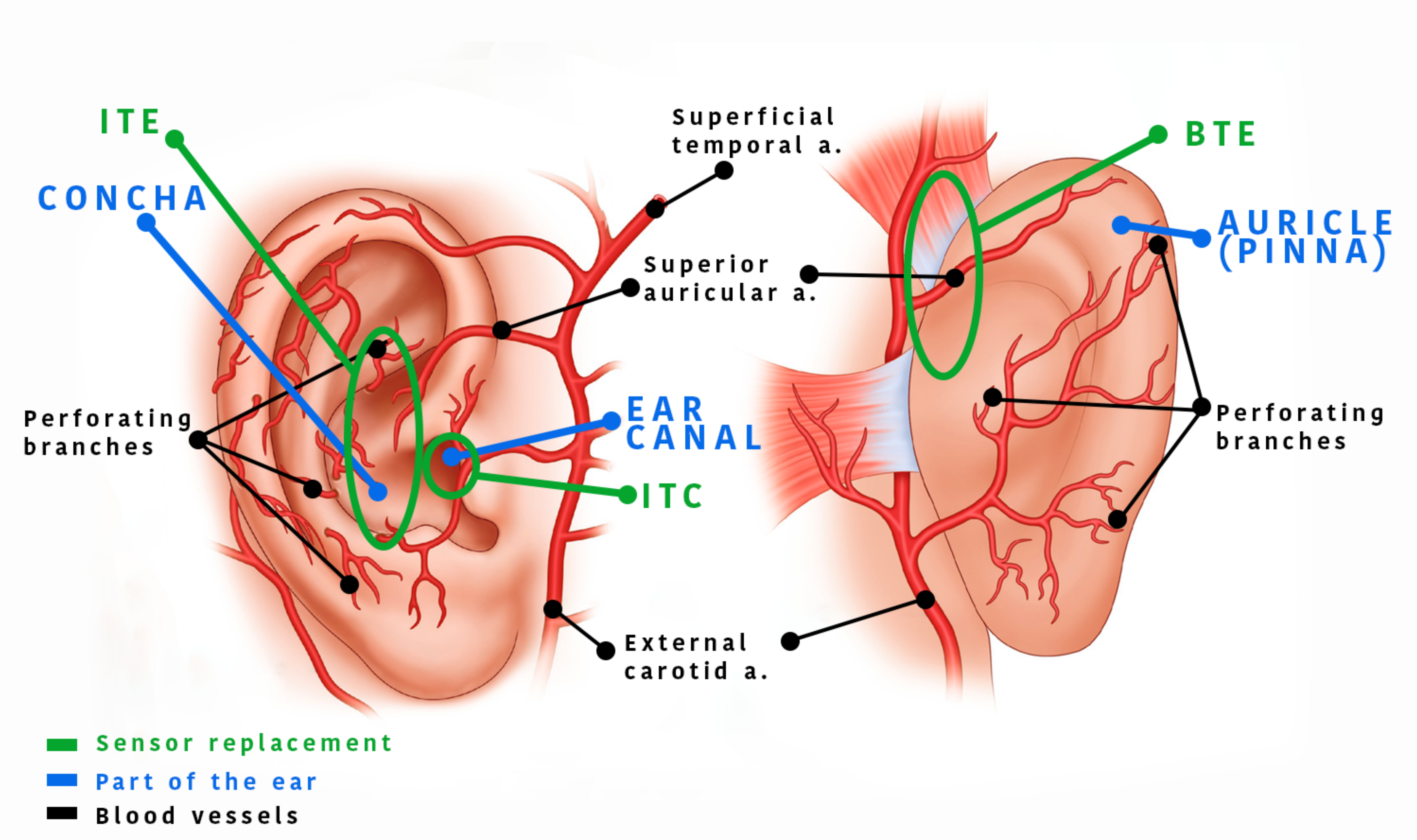
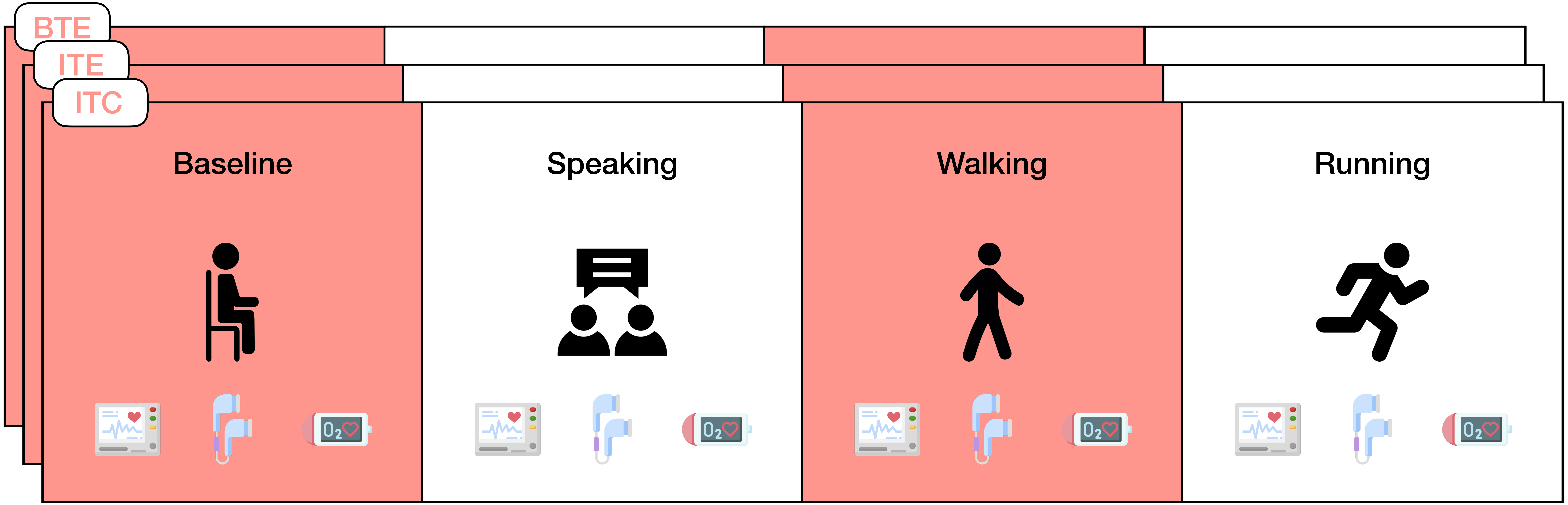
Ear Anatomy



BTE - Behind the Ear | **ITE** - In the Ear | **ITC** - In the Canal

Study Protocol



- 12 healthy participants, 2 females, 24-40 years of age, mean 30.4
- Red and IR PPG collected in 3 different locations (BTE, ITE, ITC)
- Compare the extracted vitals with those calculated from medical grade ground truth devices
- Roughly 1 hour of data per participant

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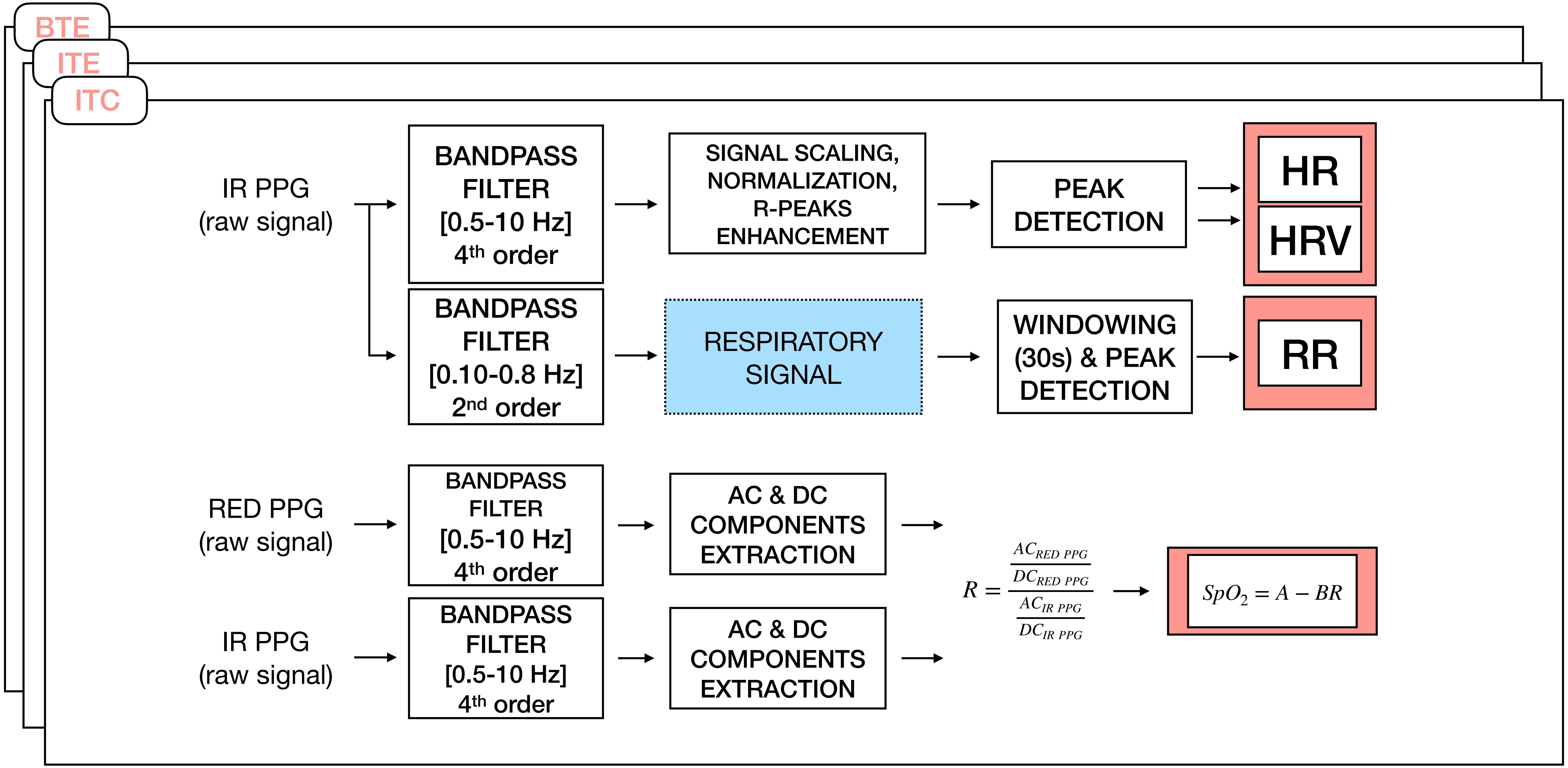
Study Protocol

Vital Sign Extraction



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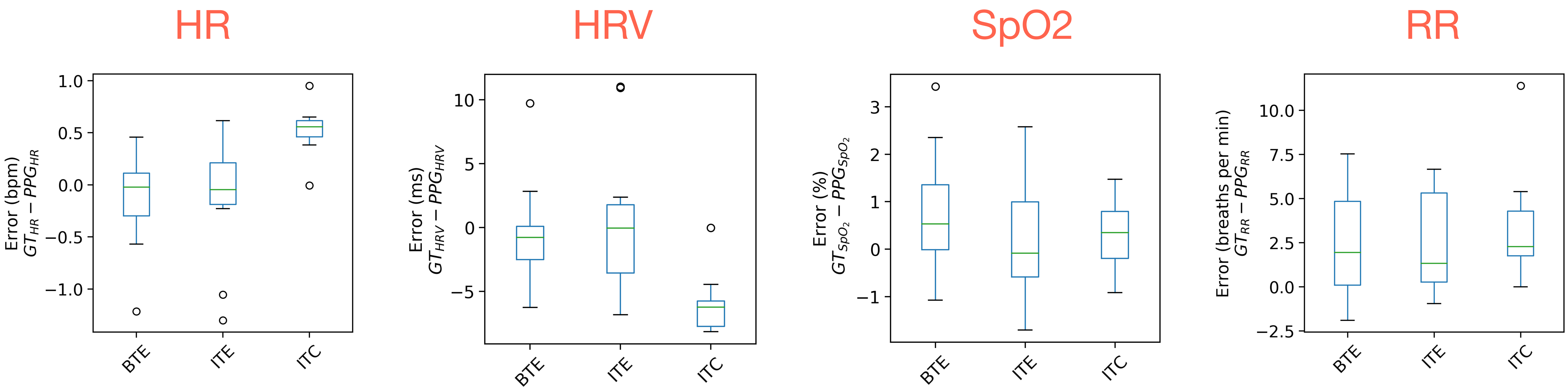
Inaccuracy at Rest

Where is the optimal positioning of an in-ear PPG sensor?



Reliable HR, HRV, and SpO2, with ITC showing the least error variability

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Take Aways

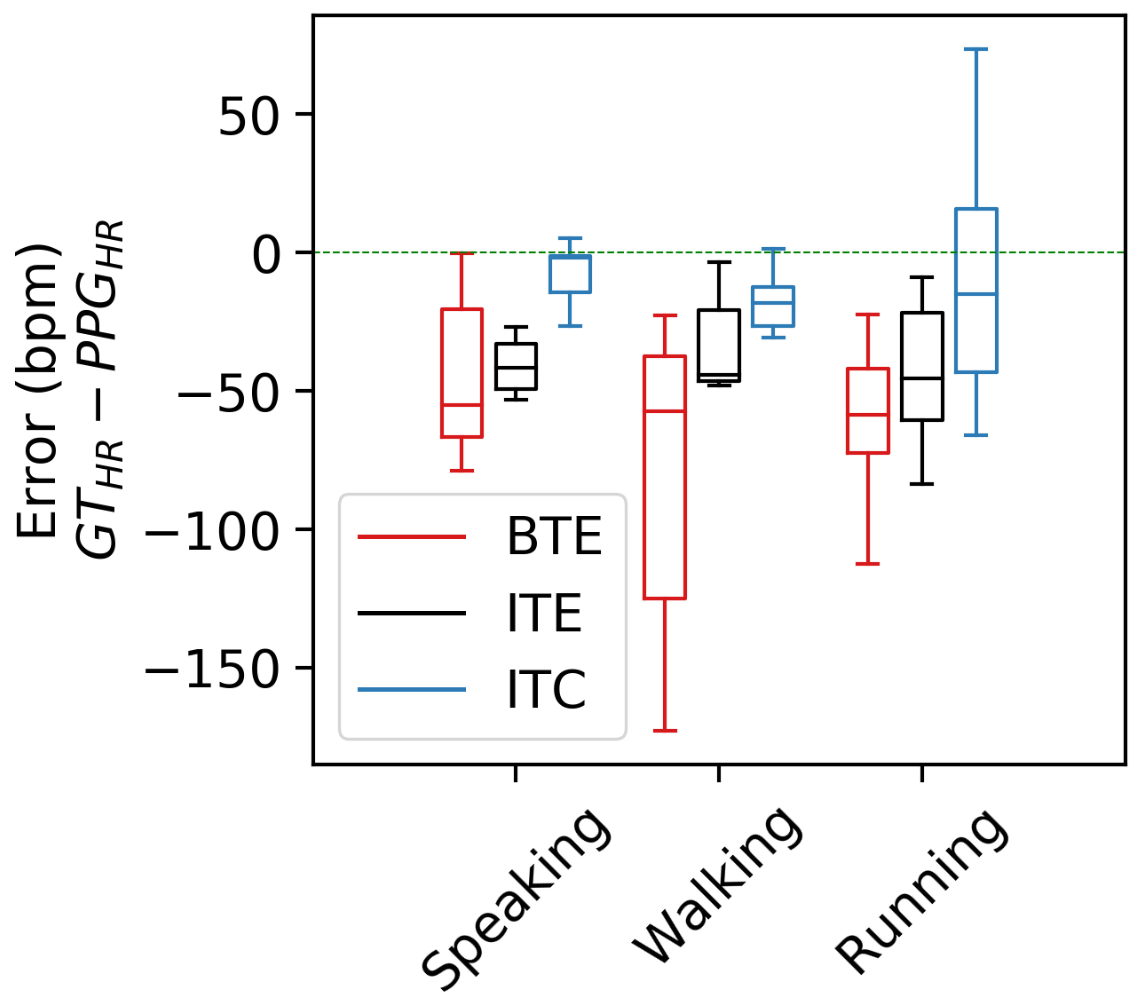
Where is the optimal positioning of an in-ear PPG sensor?

- Among the 3 placements, **ITC** consistently reports the **least variability** due to better **skin-sensor adhesion** and improved **ambient-light shielding** due to the natural darkness of the ear canal
- **RR** has a **larger error margin**, with a tendency of PPG in underestimating it. This could be improved by leveraging extra information from multi-modalities (e.g. microphones & IMU)

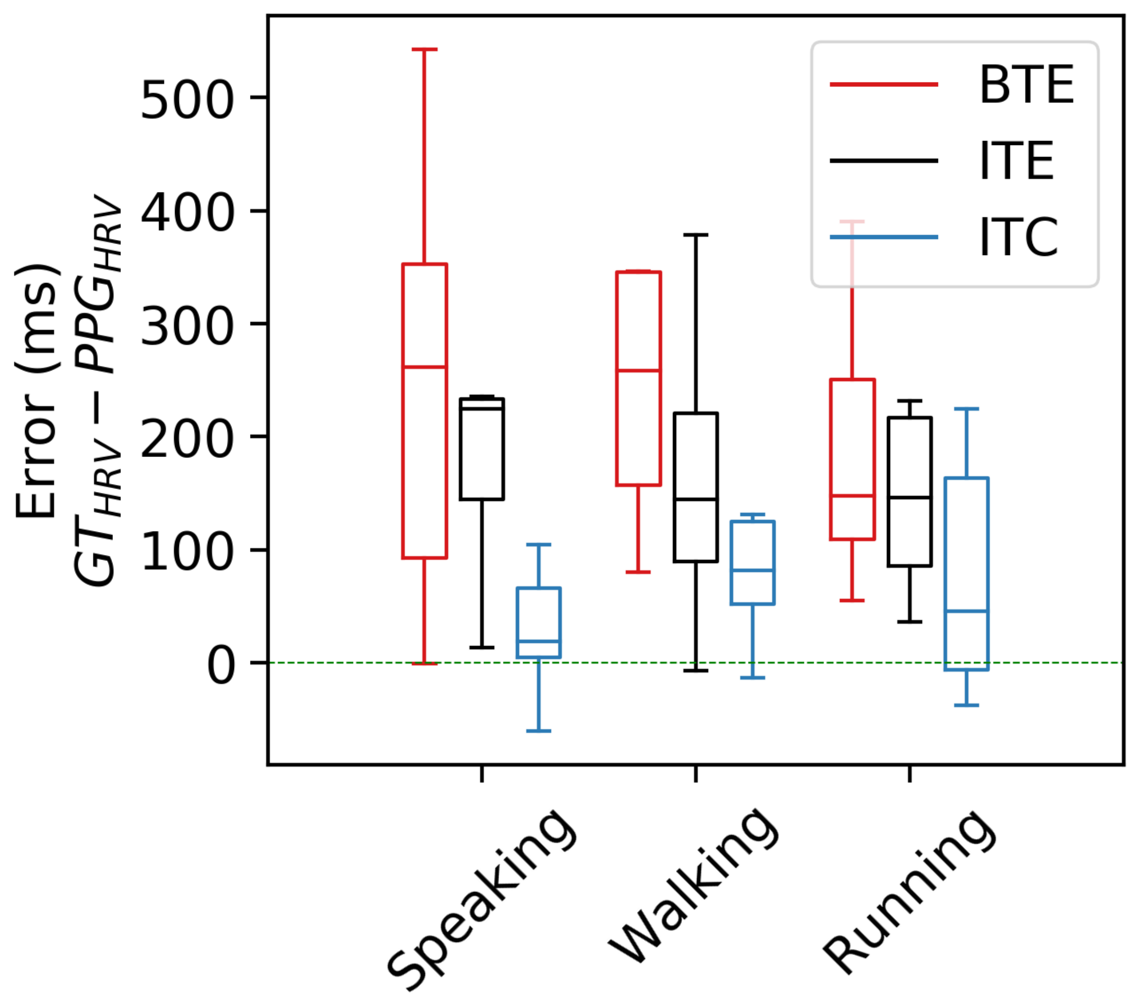
Inaccuracy with Motion

To what extend is in-ear PPG robust to motion artifacts?

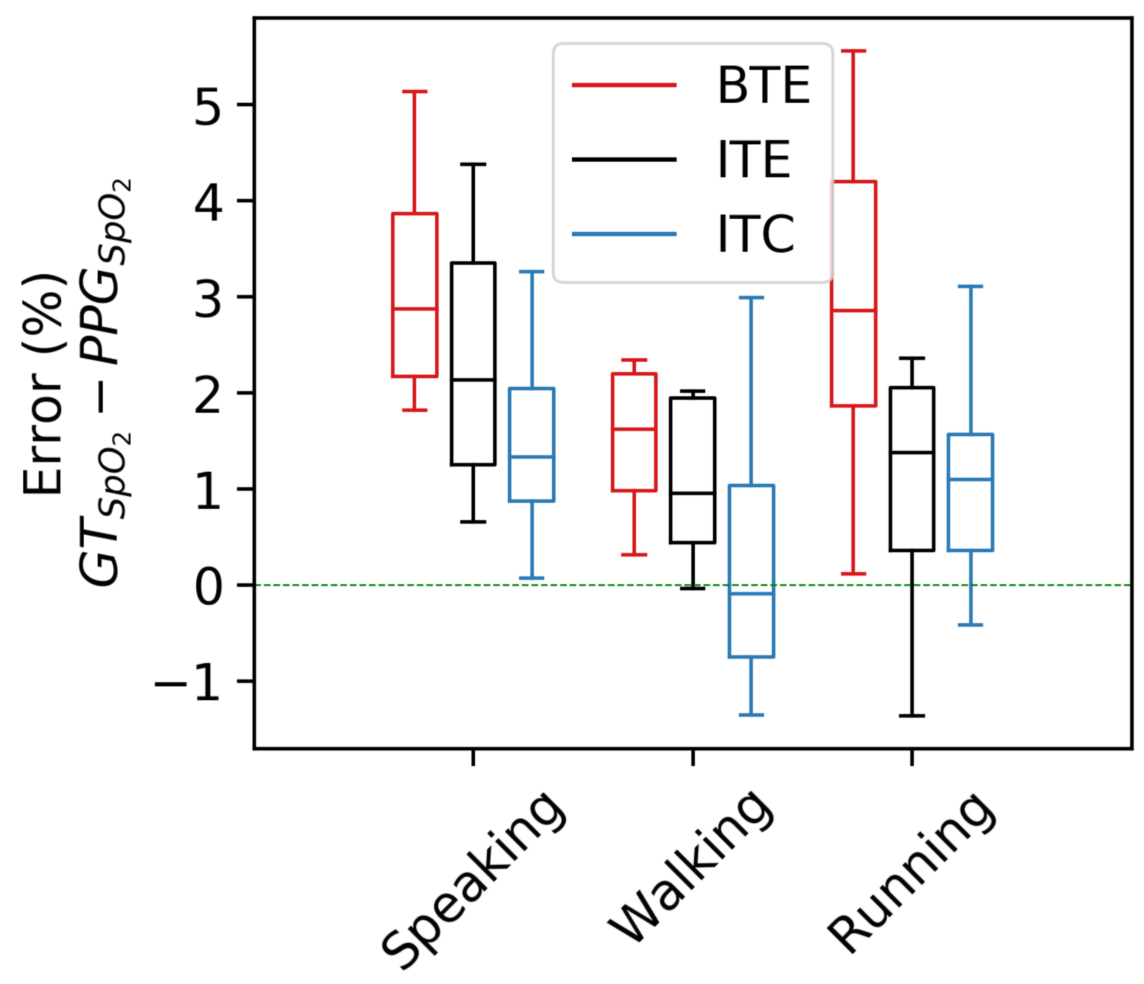
HR



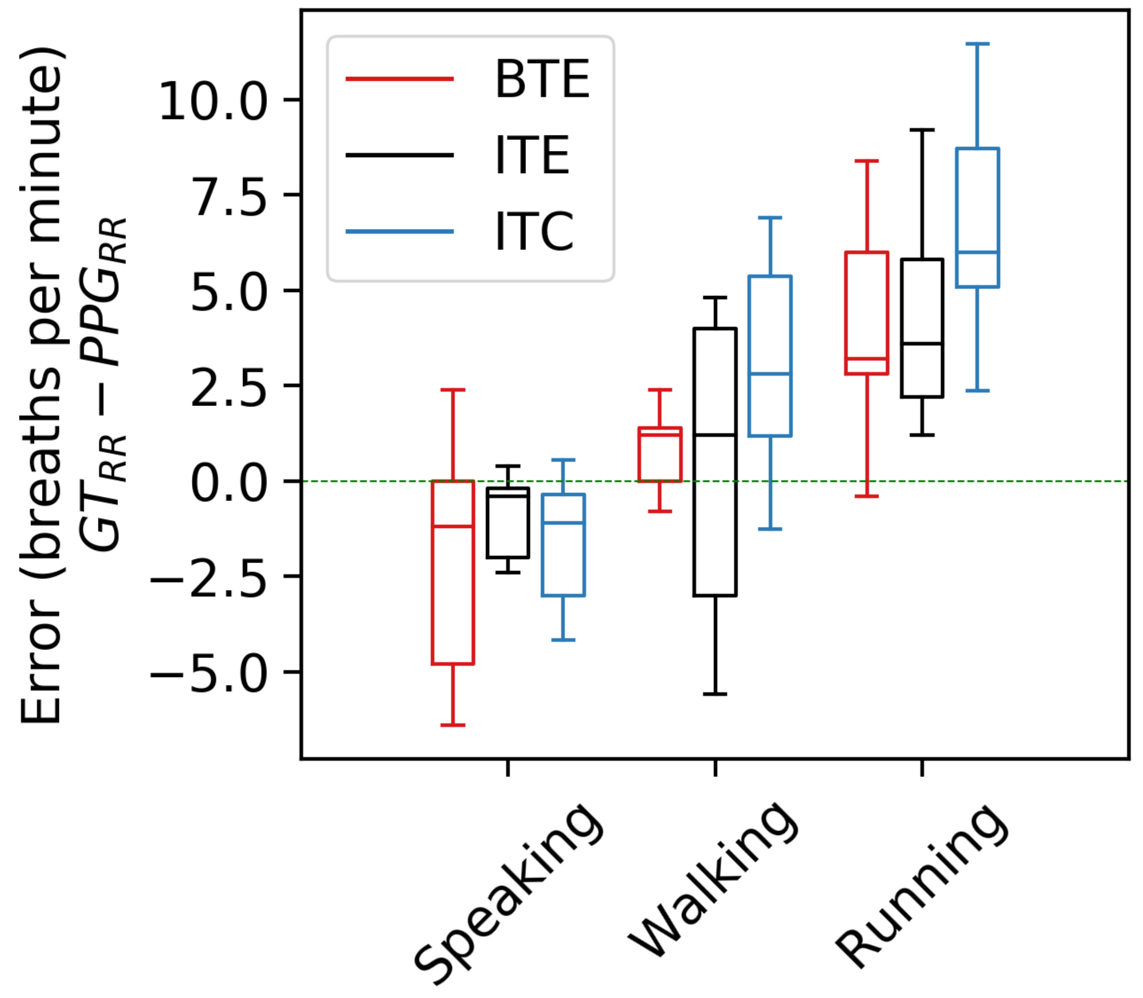
HRV



SpO2



RR



In-ear PPG at the ITC location suffer less from motion artifacts.

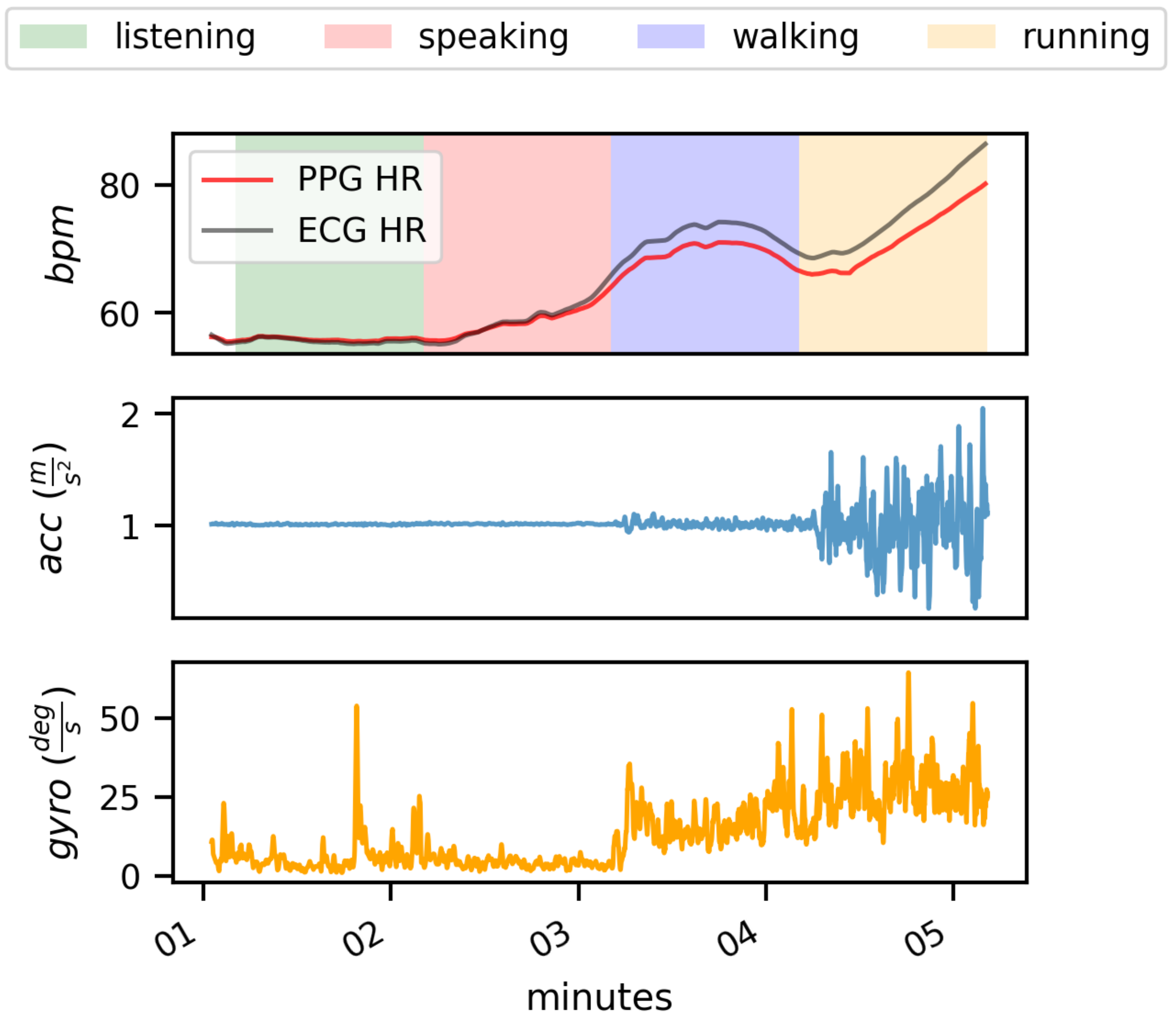
Take Aways

To what extend is in-ear PPG robust to motion artifacts?

- Despite better fit, **ITC** still suffer from **motion artifacts**: the error grows proportionally with the intensity of the artifacts (15% for speaking, up to 30% when the user runs)

- Interestingly the **SpO2** estimate is not worsening with the artifacts intensity but rather remains **constant**

- PPG-extracted vital signs follow a **similar pattern to that of ground truth**



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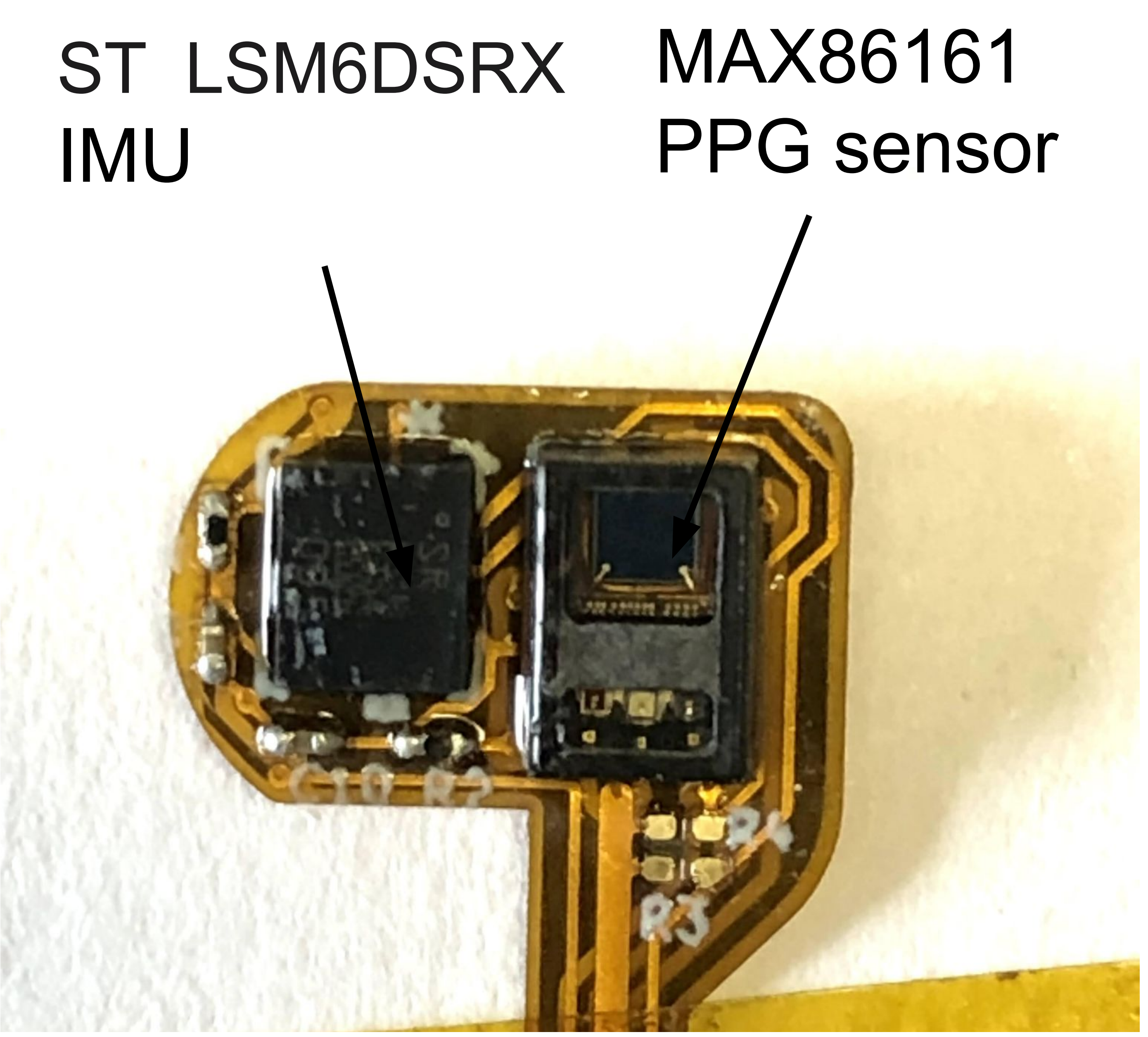
Outlook

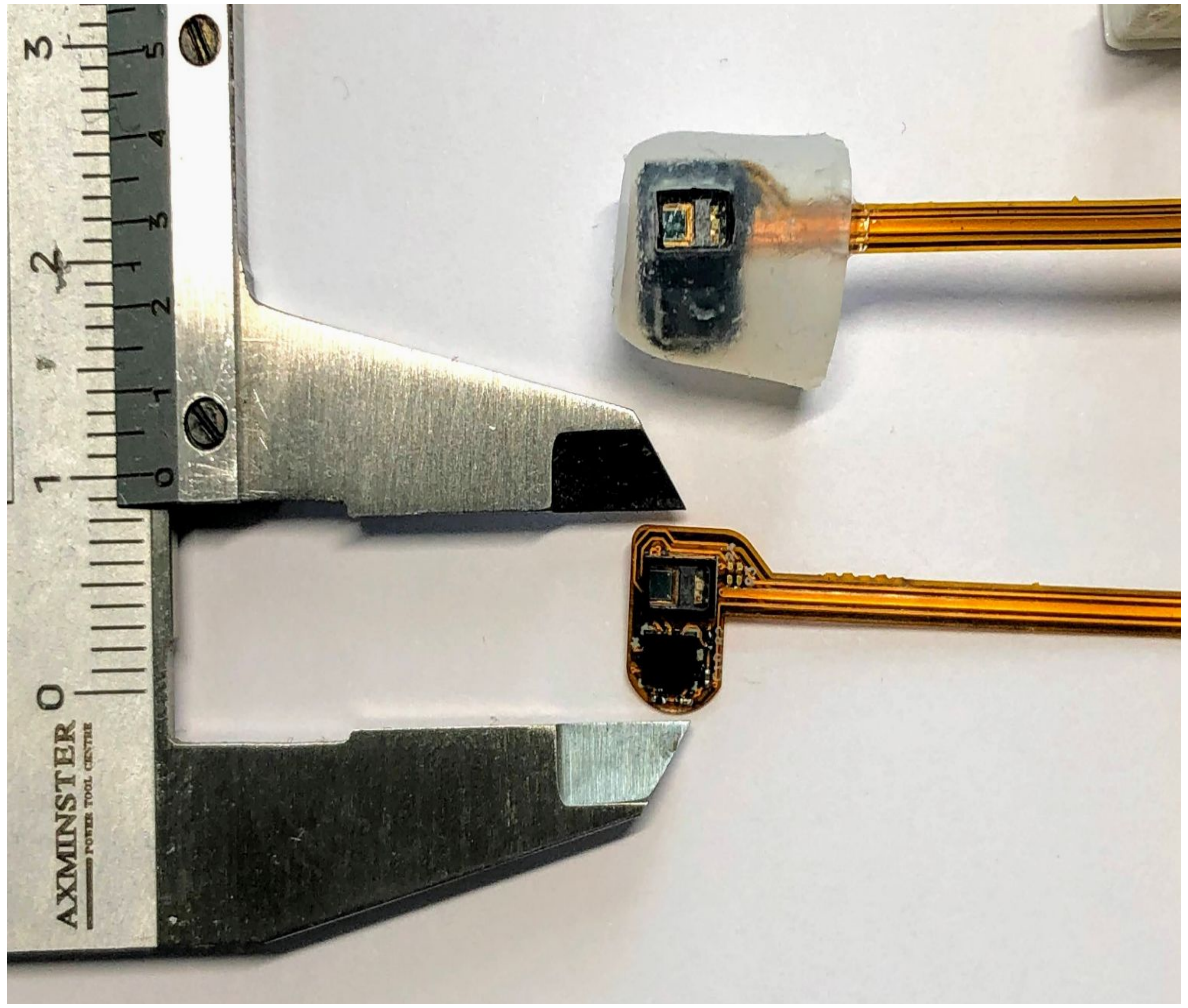
Form Factor & Ear-Tip Design

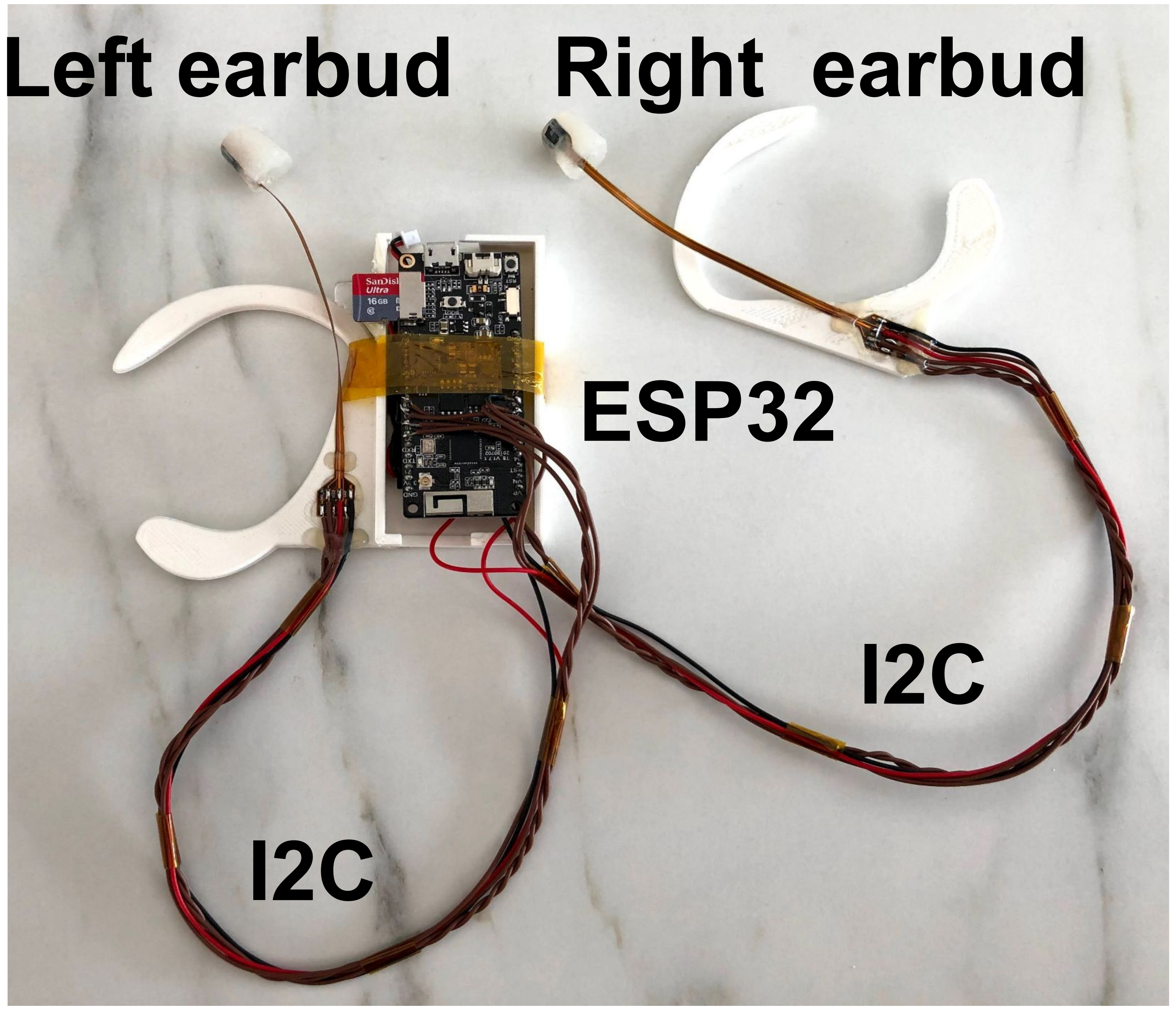
- **PPG** is a remarkably useful sensor for vital signs monitoring
- **ITC PPG** liberates us from a specific **earable-form design** given ear-tips are default features for most earables
- Challenges in designing an ear-tip with integrated PPG include:
  - Ensuring a **tight seal** for accurate data collection
  - Providing a **stable fit** to reduce motion artifacts and accommodate various users
  - Maintaining **comfort** for extended wear
- The variety in ear sizes and shapes makes creating a **universal ear-tip** a significant challenge for engineers and designers
- **ITE PPG** offers a promising solution with a balance between integration ease and signal quality

Outlook

Form Factor & Ear-Tip Design







Can we estimate blood pressure with in-ear PPG?

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What is blood pressure?

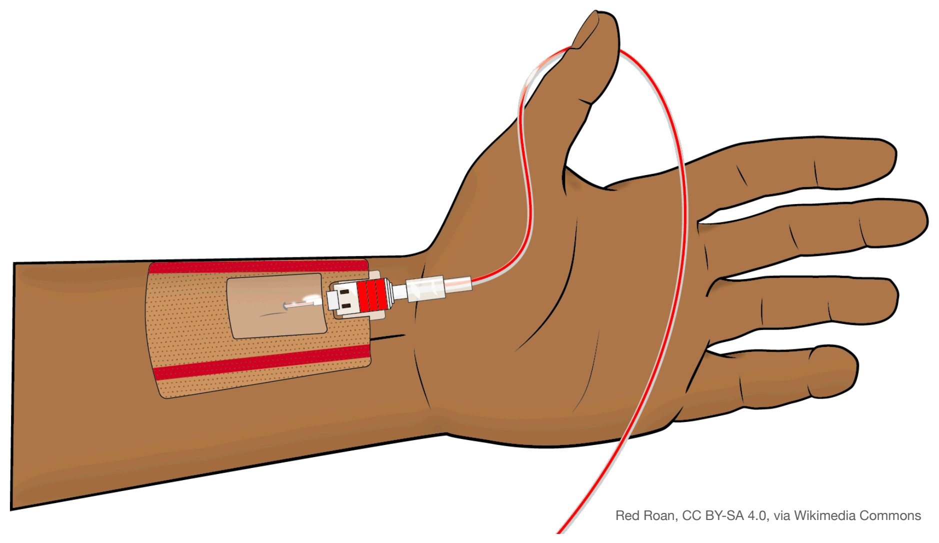
- BP is the pressure of circulating blood against the walls of blood vessels
- **Systolic Blood Pressure** (SBP) is the peak pressure during the heart's contraction phase or systole
- **Diastolic Blood Pressure** (DBP) is the lowest pressure when the heart is relaxed or in the diastole phase
- Typically recorded in millimeters of mercury (mmHg)

BLOOD PRESSURE CATEGORY	SYSTOLIC mm Hg (upper number)	and/or	DIASTOLIC mm Hg (lower number)
NORMAL	LESS THAN 120	and	LESS THAN 80
ELEVATED	120 – 129	and	LESS THAN 80
HIGH BLOOD PRESSURE (HYPERTENSION) STAGE 1	130 – 139	or	80 – 89
HIGH BLOOD PRESSURE (HYPERTENSION) STAGE 2	140 OR HIGHER	or	90 OR HIGHER
HYPERTENSIVE CRISIS (consult your doctor immediately)	HIGHER THAN 180	and/or	HIGHER THAN 120

Traditional BP Measurement Methods

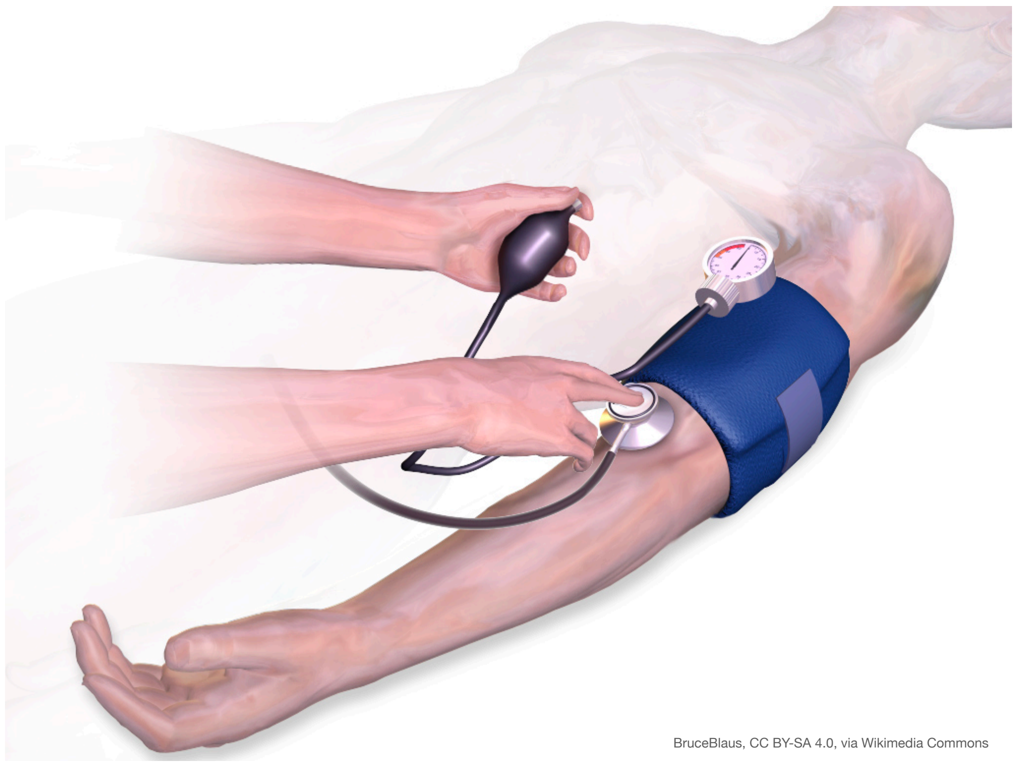
ARTERIAL CATHETERISATION

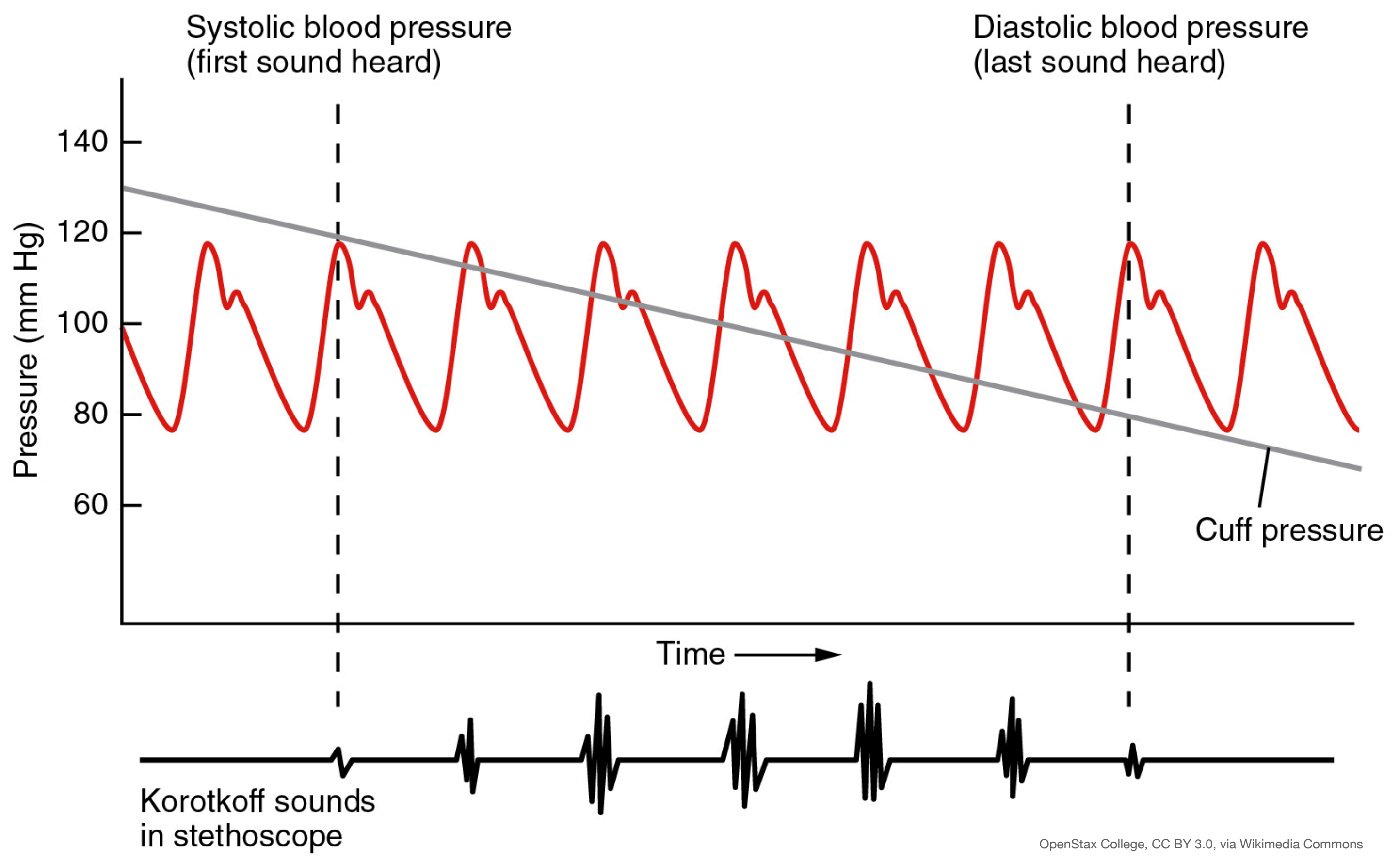
Hollow tube inserted into an artery to monitor blood pressure in real-time



AUSCULTATORY METHOD

A cuff compresses and releases an artery in a controlled way. Sounds of blood through the narrowed artery are heard with a stethoscope. SBP and DBP are measured using a manometer attached to the cuff.





OSCILLOMETRIC METHOD

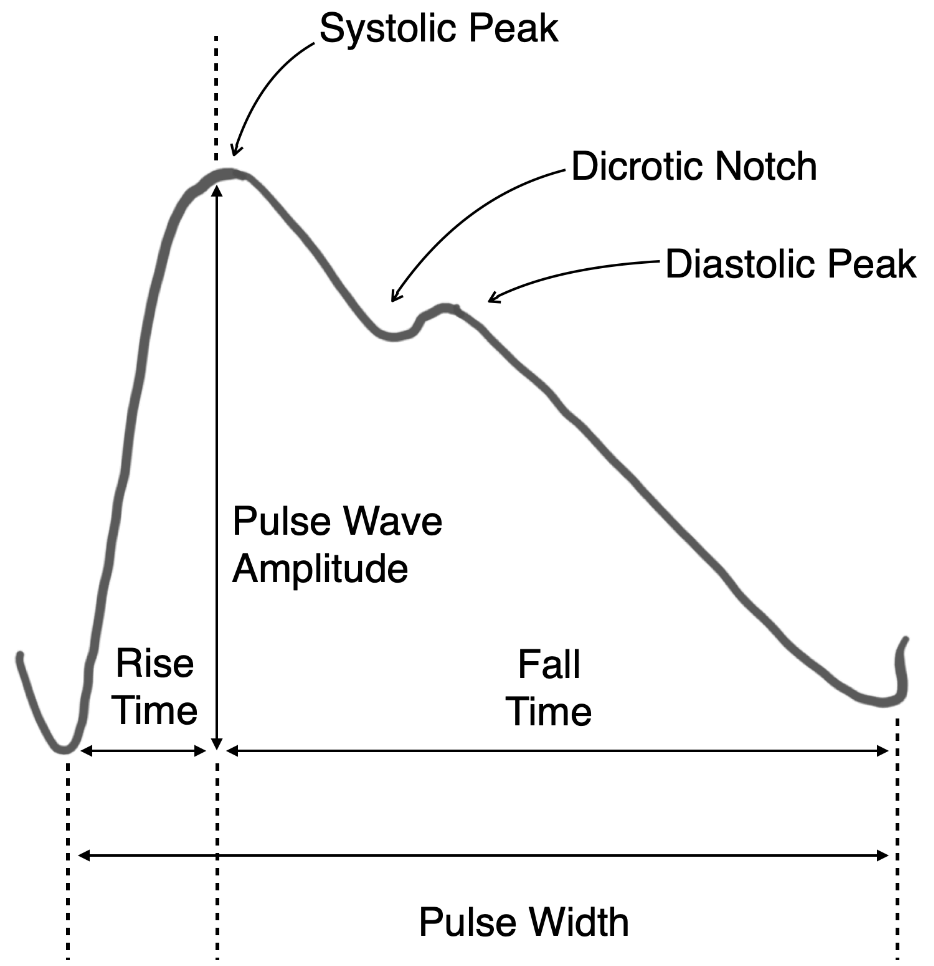
Similar to the Auscultatory method but involves the observation of oscillations in the cuff pressure as it is first inflated and then slowly deflated. Some devices do not completely occlude the artery, they measure the Mean Arterial Pressure and the estimate SBP and DBP.

Blood Pressure Monitoring with PPG Sensors (Cuffless)

PULSE MORPHOLOGY

Features of the PPG wave are used to estimate blood pressure, often employing learning approaches.

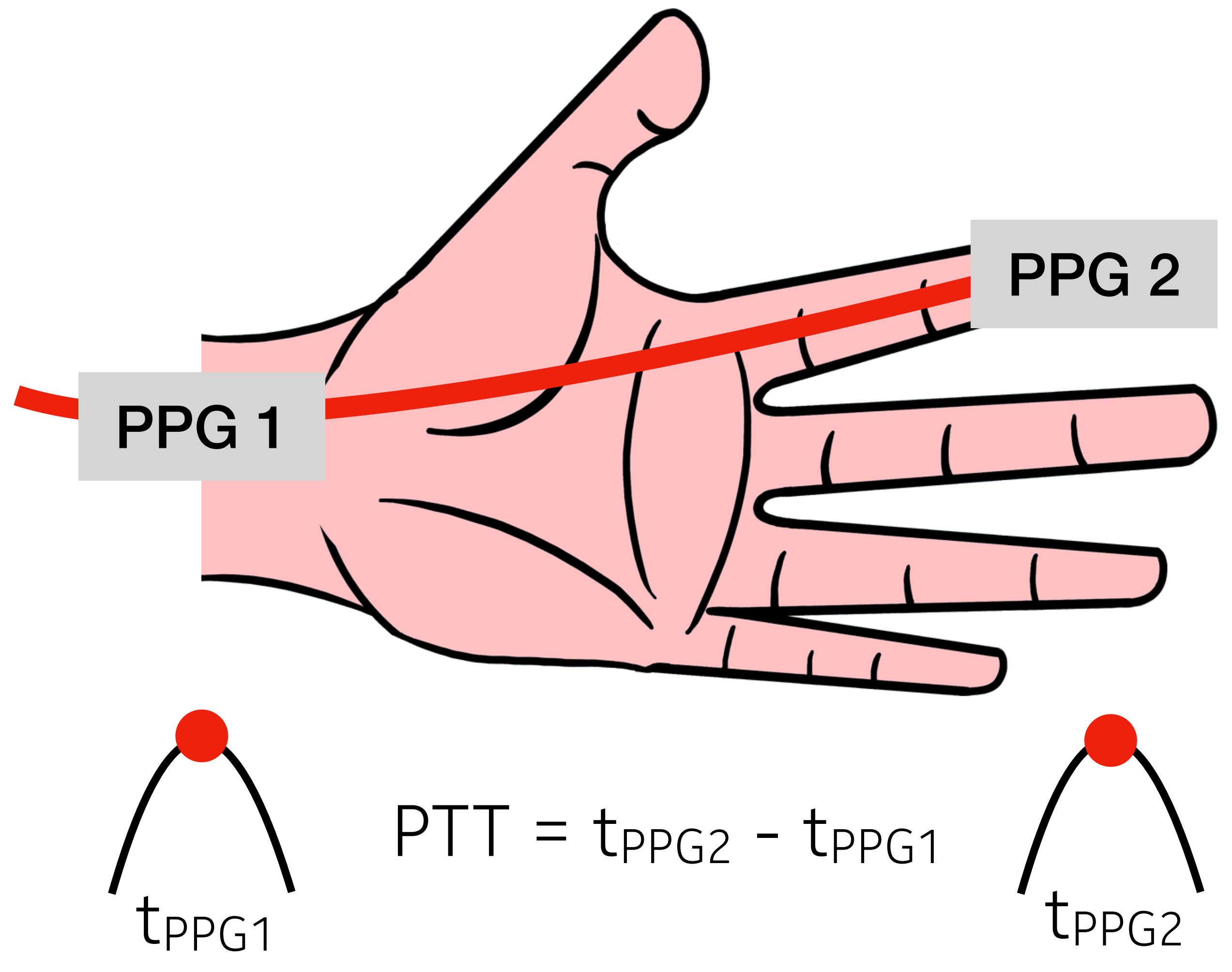
Several factors can affect the pulse morphology. Most importantly: sensor configuration, sensor placement, pressure on the skin.



PULSE TRANSIT TIME

Time necessary for the blood pressure wave to travel between two arterial sites (e.g., wrist and finger of the same arm). This time interval varies inversely with blood pressure.

Calibration between blood pressure and PTT is done using a clinical grade blood pressure monitor.



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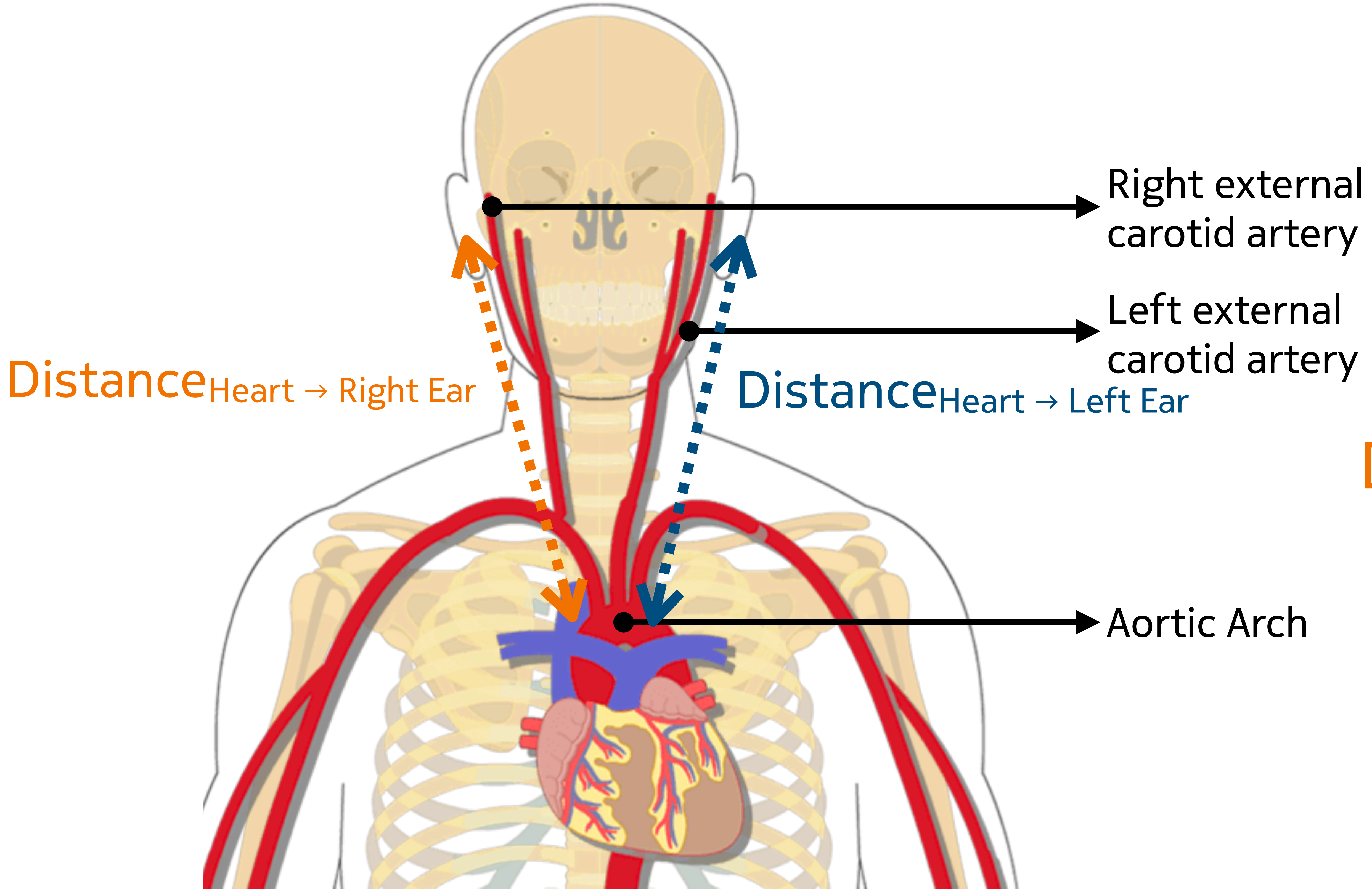
Head and Upper Body Anatomy



$\text{Distance}_{\text{Heart} \rightarrow \text{Right Ear}} > \text{Distance}_{\text{Heart} \rightarrow \text{Left Ear}}$

(22.2 ± 2.2cm) (20.8 ± 1.9cm)

The heart protrudes towards the left side of our body

Farooq Choudhry, John Grantham, Ansaar Rai, and Jeffery Hogg. "Vascular geometry of the extracranial carotid arteries: An analysis of length, diameter, and tortuosity". Journal of Neurointerventional Surgery 8 (04 2015).

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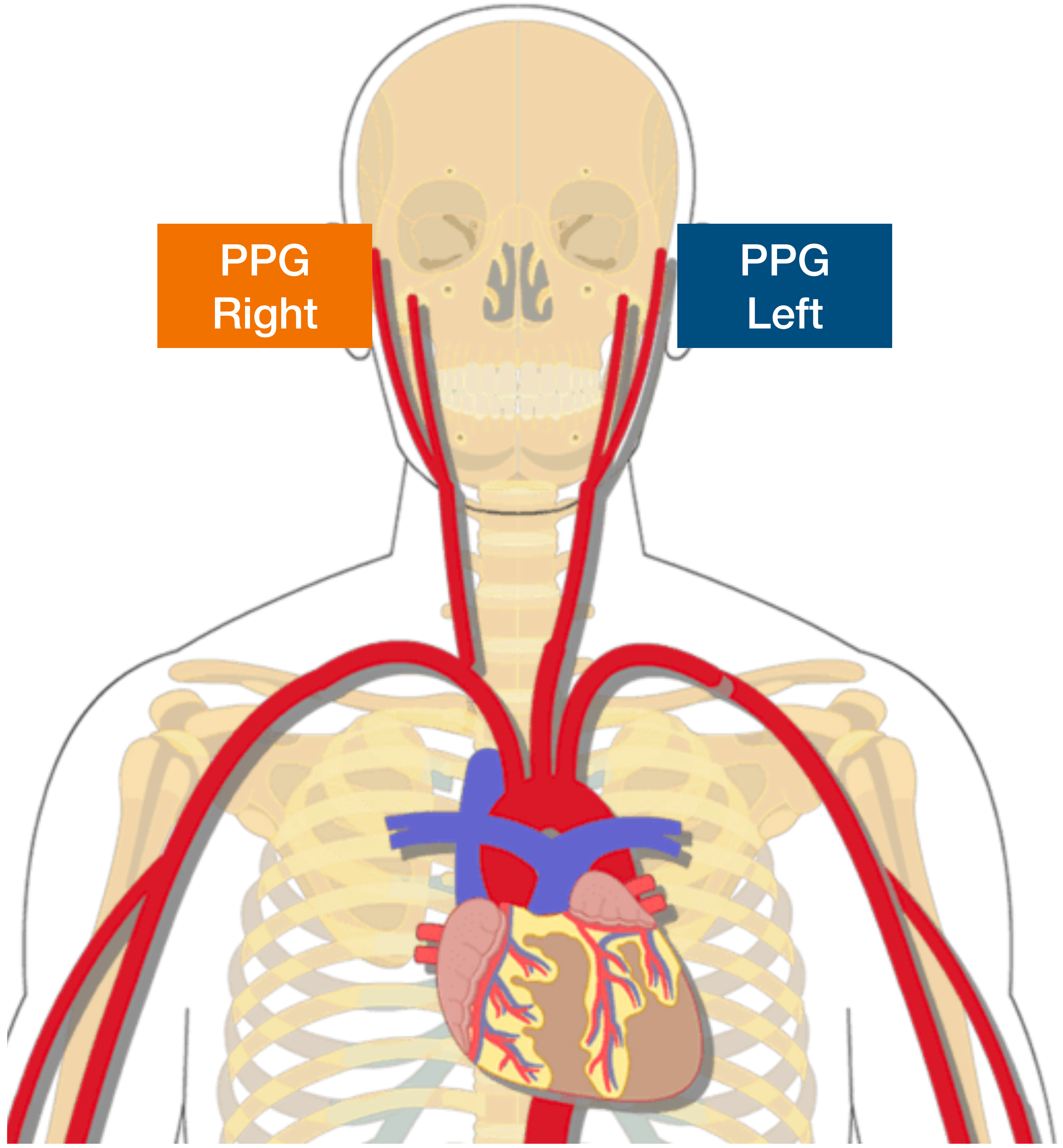
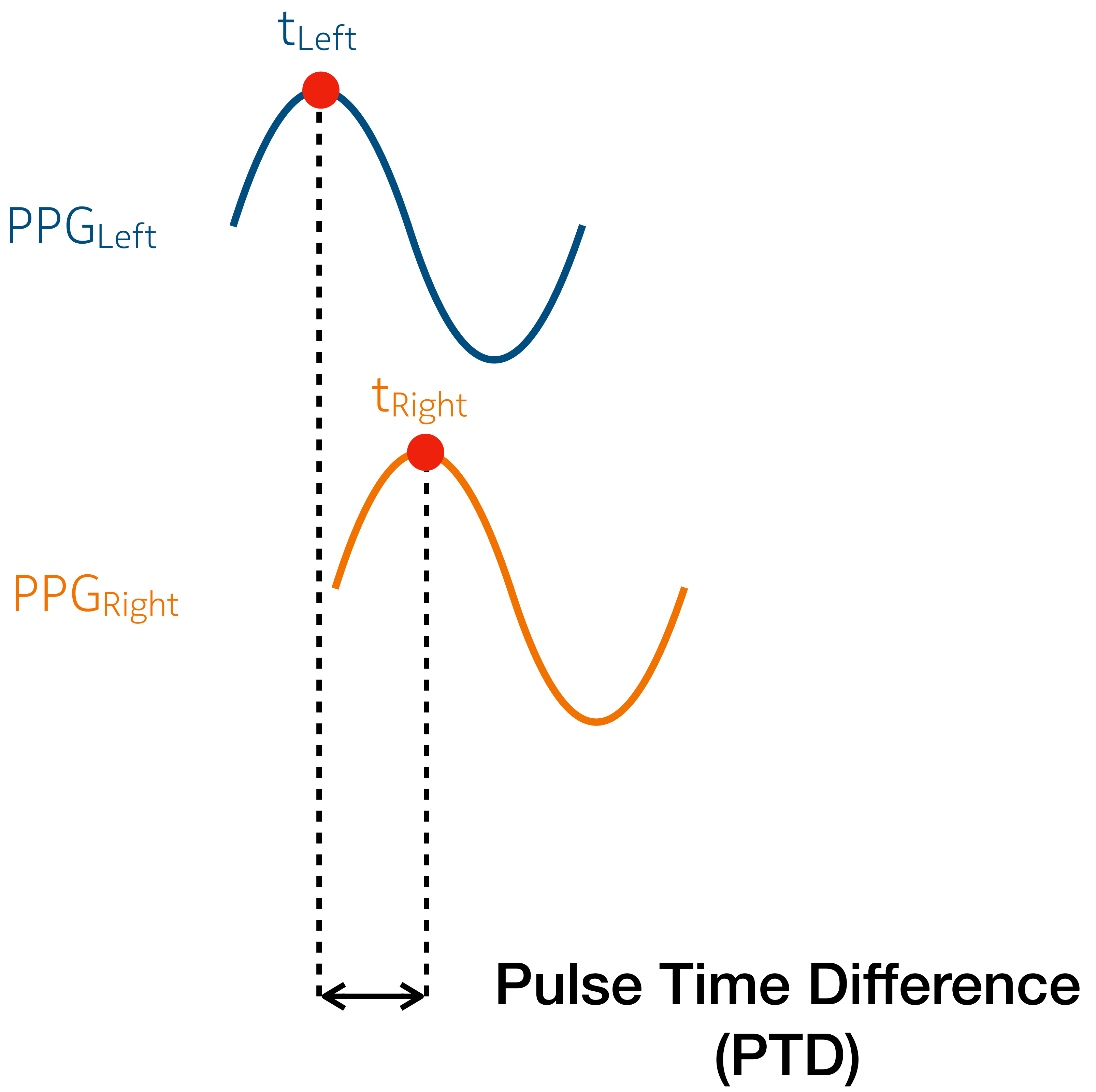
Pulse Time Difference Between The Ears





$$PTD = t_{Right} - t_{Left}$$

Can we measure PTD with in-ear PPG?

Can we leverage PTD between left and right ears to estimate BP?

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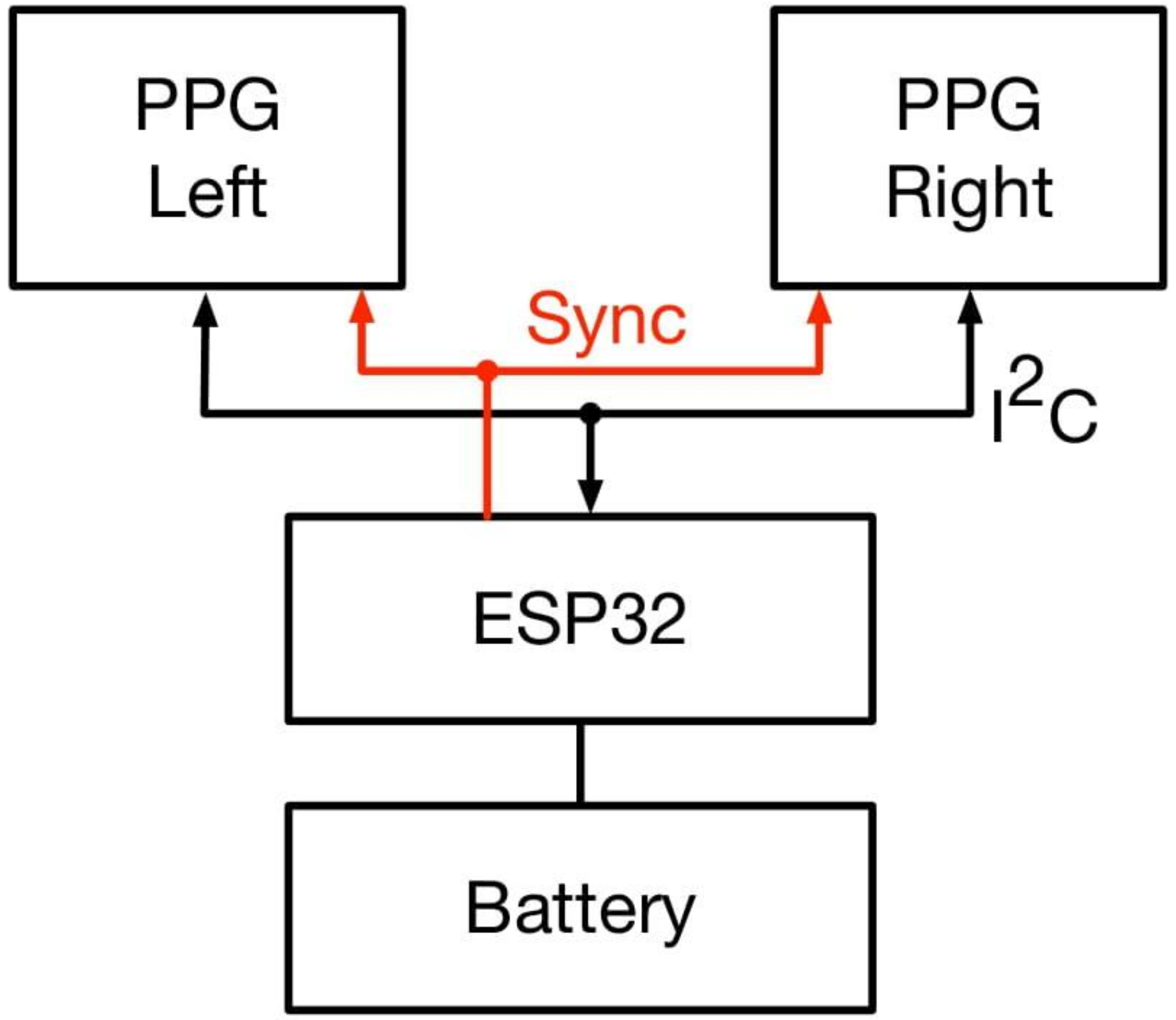
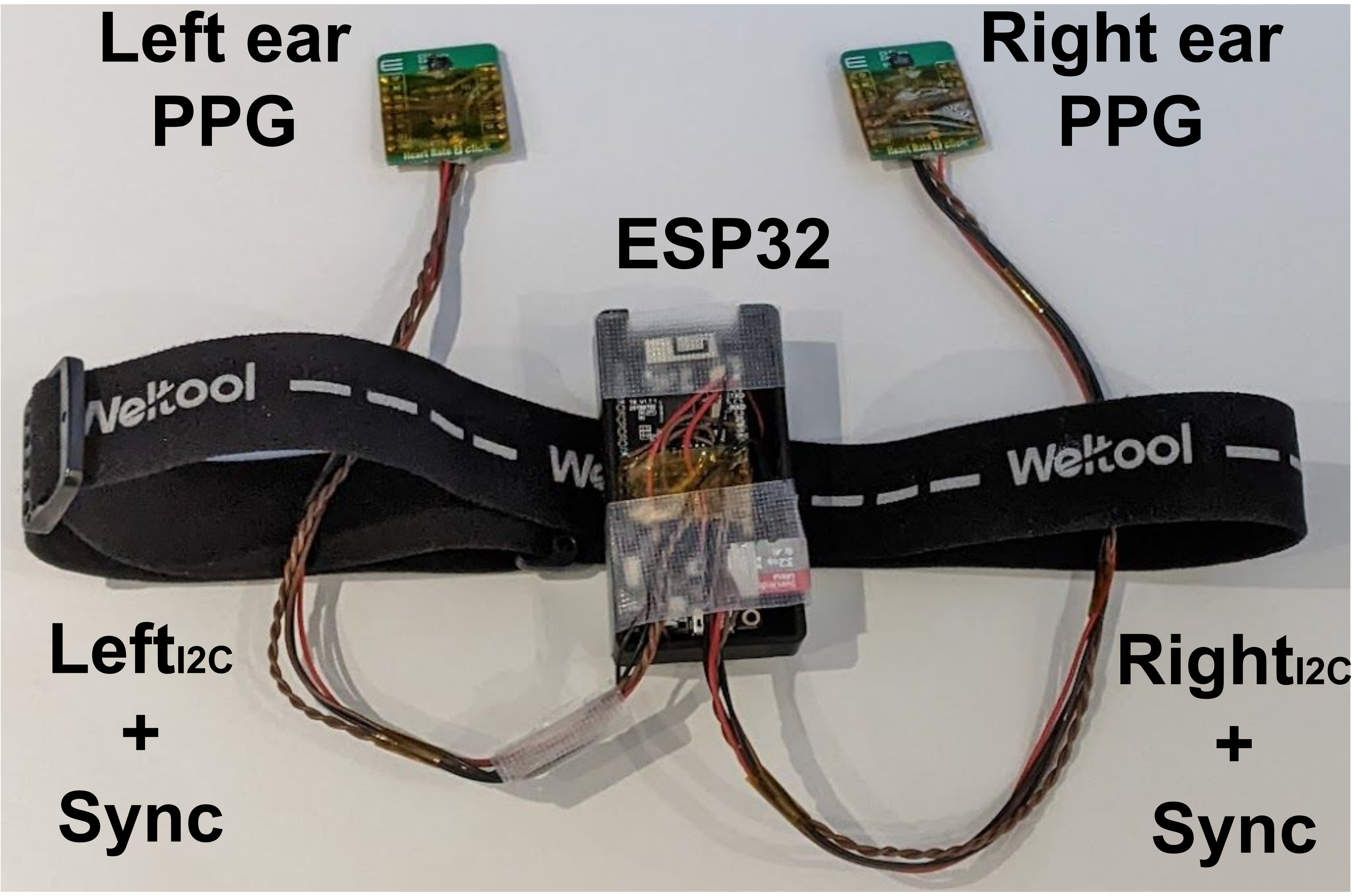
Stereo-BP: Exploiting Pulse Time Difference Between The Ears

Hardware Prototype

Given the expected PTD is in the order of few milliseconds the design of the system was crucial:

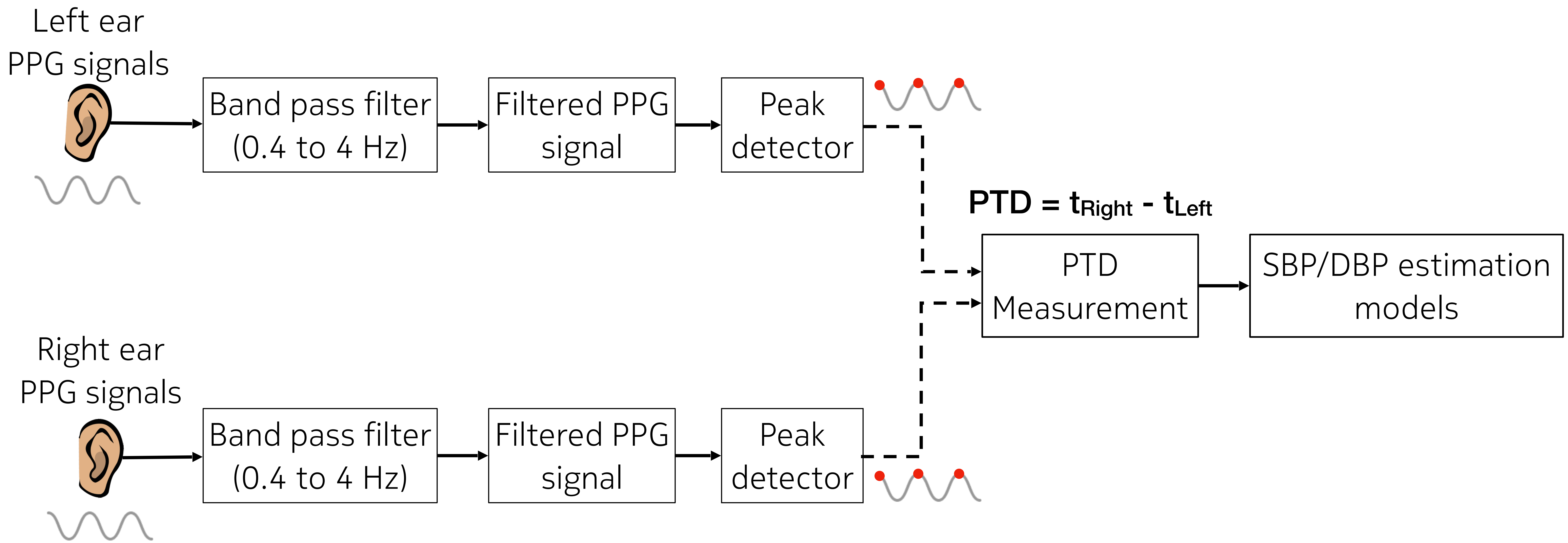
- High frequency sampling rate to increase signal resolution
- Synchronisation of left and right sensors to ensure accurate PTD measurement





Stereo-BP: Exploiting Pulse Time Difference Between The Ears

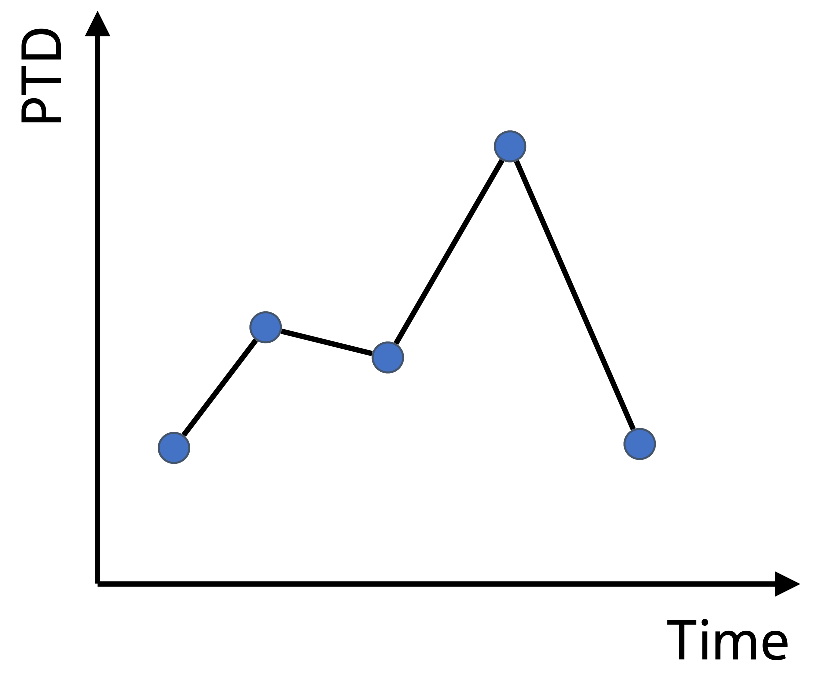
Blood Pressure Estimation Pipeline



Stereo-BP: Exploiting Pulse Time Difference Between The Ears

BP Estimation Models

THE NEED FOR ESTIMATION MODELS



PTD shows relative changes in blood pressure

To convert the PTD times into values in mmHg we need to model the relationship PTD/BP and calibrate the models

BLOOD PRESSURE ESTIMATION MODELS

We derive SBP and DBP models from related works and anatomical characteristics:

$$SBP = SBP_0 - \frac{2}{\gamma PTD_0}(PTD - PTD_0)$$

$$DBP = DBP_0 - \frac{2}{\gamma PTD_0}(PTD - PTD_0)$$

- SBP_0 and DBP_0 are the baseline systolic and diastolic blood pressure
- PTD_0 is the baseline pulse time difference
- γ is a constant which depends on age

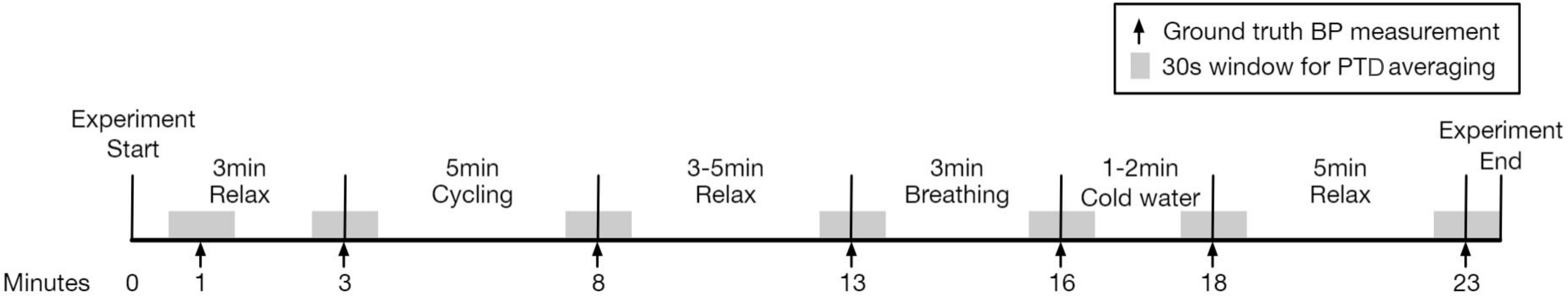
SBP_0,DBP_0 and PTD_0 are derived via least square fit of pairs:

[PTD, GT BP]

Where *GT BP* is taken with a cuff-based BP monitor

Stereo-BP: Exploiting Pulse Time Difference Between The Ears

Preliminary User Study



- 20 healthy participants, 7 females, mean age 31.5
- Synced PPG data from left and right ears
- Timestamped ground truth BP measurements taken with Omron BP monitor
- Physical exercise on a stationary bicycle, slow/deep breathing, and immersing hand in cold water to induce BP changes
- Personalised model calibration is done with 4 pairs of (PTD, Ground truth BP) points, remaining used for testing

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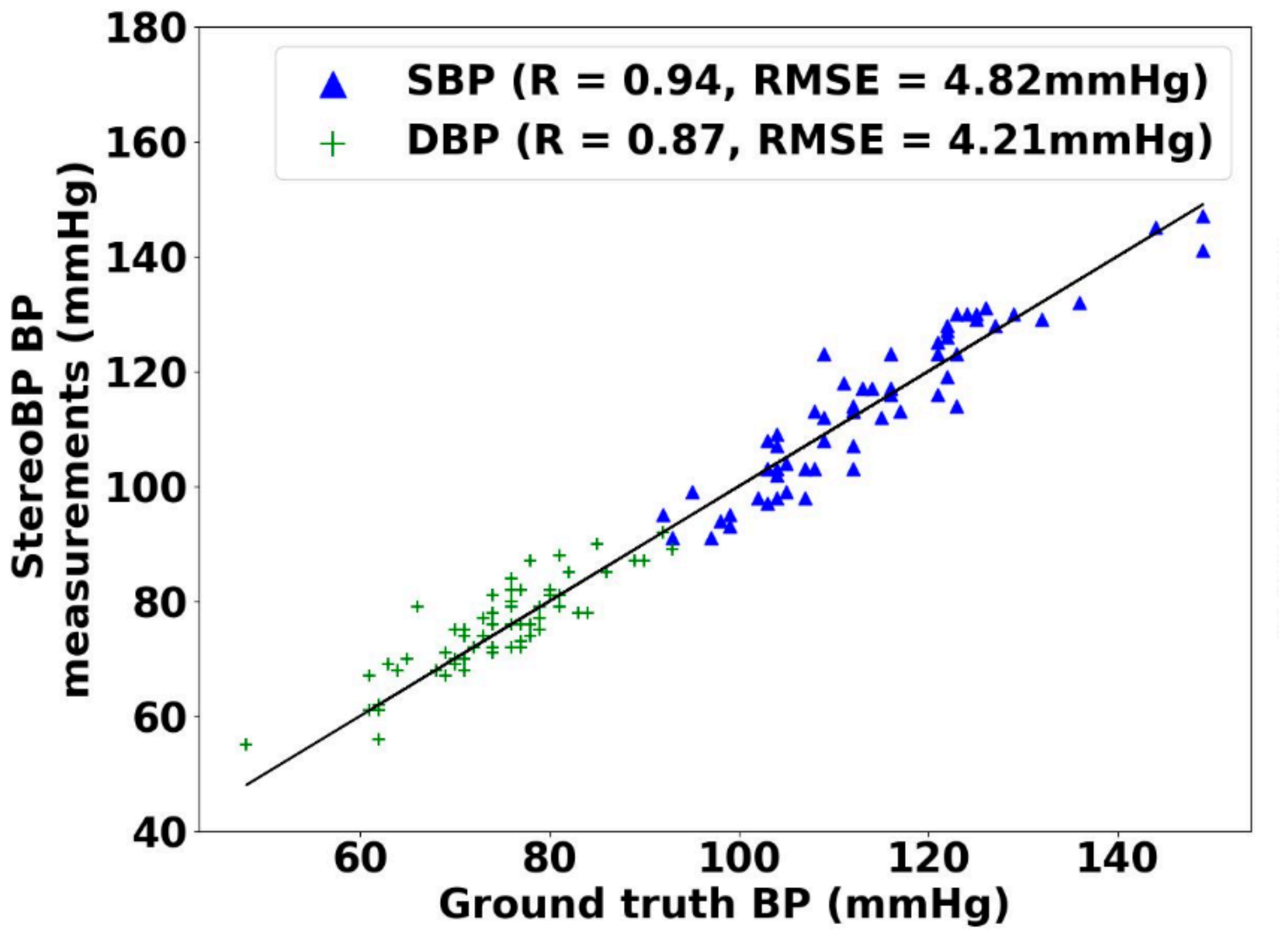
Stereo-BP: Exploiting Pulse Time Difference Between The Ears

Results

PTD BETWEEN LEFT AND RIGHT EARS

- Use the first 3 minutes of data (relaxed state)
- Blood **always arrives earlier** in the left ear than the right ear
- **Mean PTD 41.3ms ± 27.4ms**

BLOOD PRESSURE ESTIMATION



SBP MAE = 3.97 ± 3.09 mmHg

DBP MAE = 3.83 ± 2.95 mmHg

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Stereo-BP: Exploiting Pulse Time Difference Between The Ears

Longitudinal performance of Stereo-BP

9 Participants have been invited for 2 follow-up sessions to asses model calibration stability

Week 1 - User study

Perform calibration on Week 1

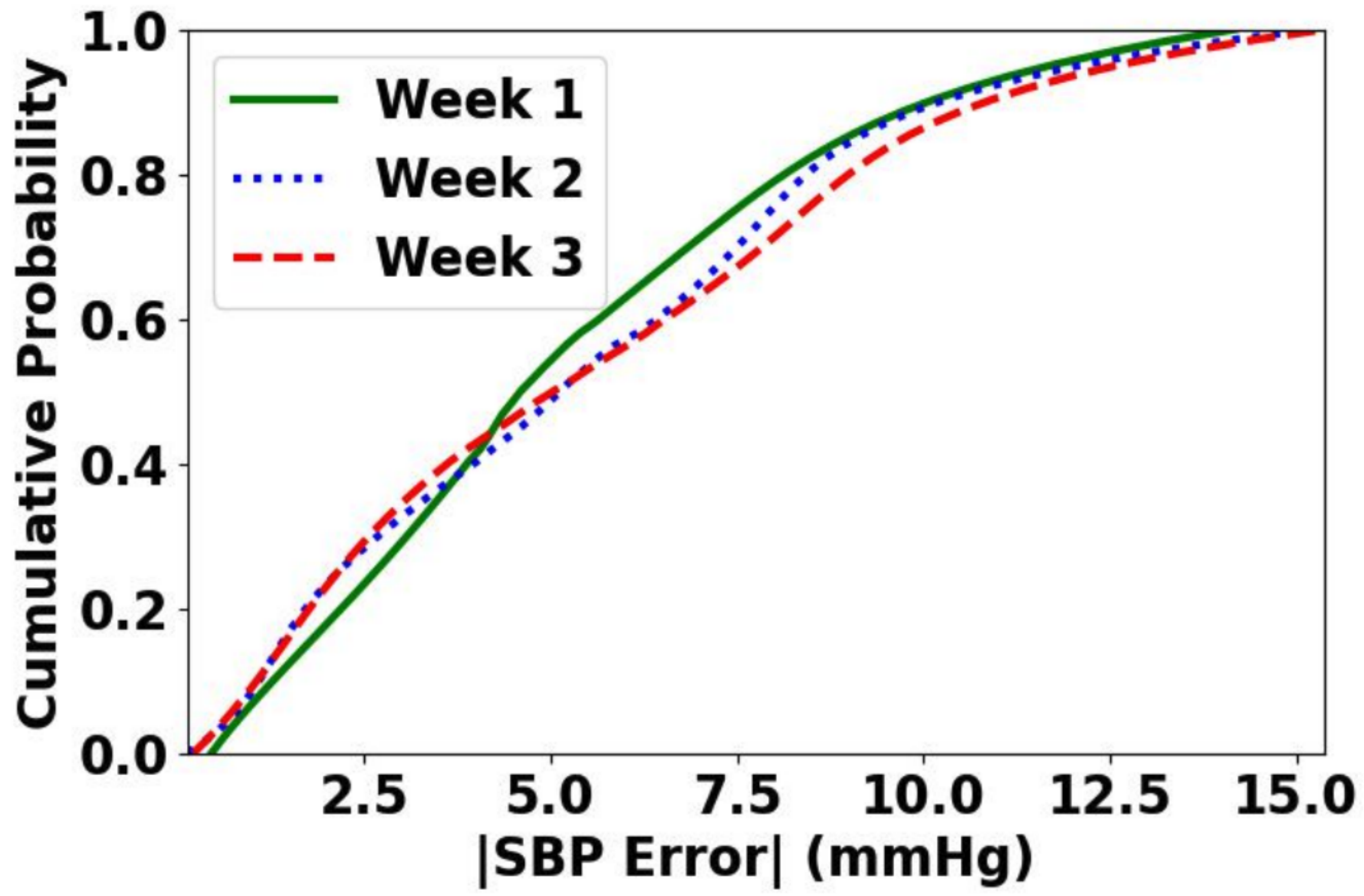
Week 2 - User study

Test Stereo-BP's performance with calibration made on Week 1

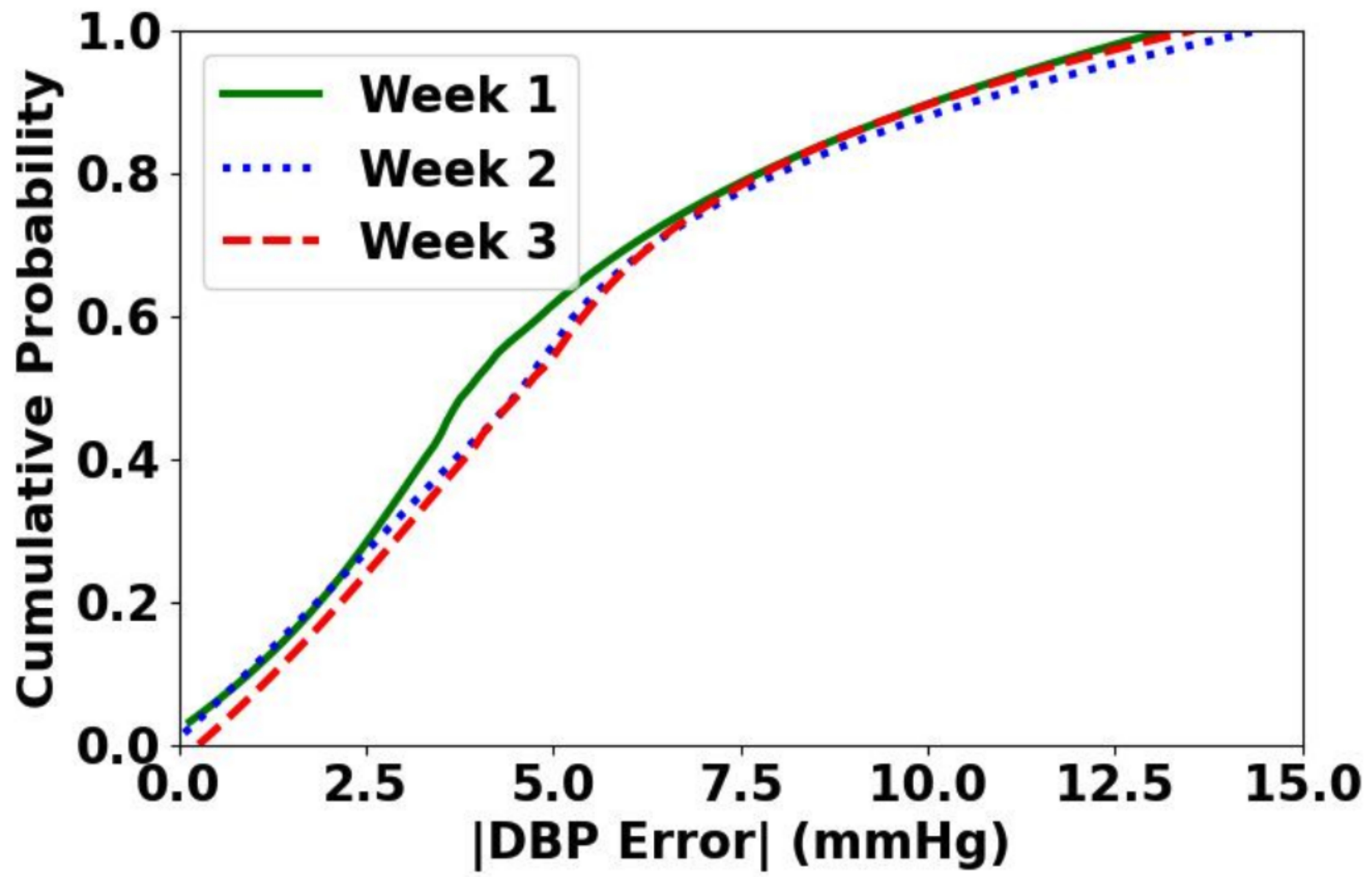
Week 3 - User study

Test Stereo-BP's performance with calibration made on Week 1

SBP



DBP



Stereo-BP: Exploiting Pulse Time Difference Between The Ears

Take Aways

- Heart is **closer to the left** ear than the right ear
- $PTD_{Left \rightarrow Right}$ ear varies inversely with blood pressure
- 'Stereo-BP' – Uses **synced PPG sensors** present in left and right earbuds to estimate blood pressure

Limitations

- Requires calibration
- Tight synchronisation between left and right earbuds
- Limited sample size

Can we use a **single earbud**?

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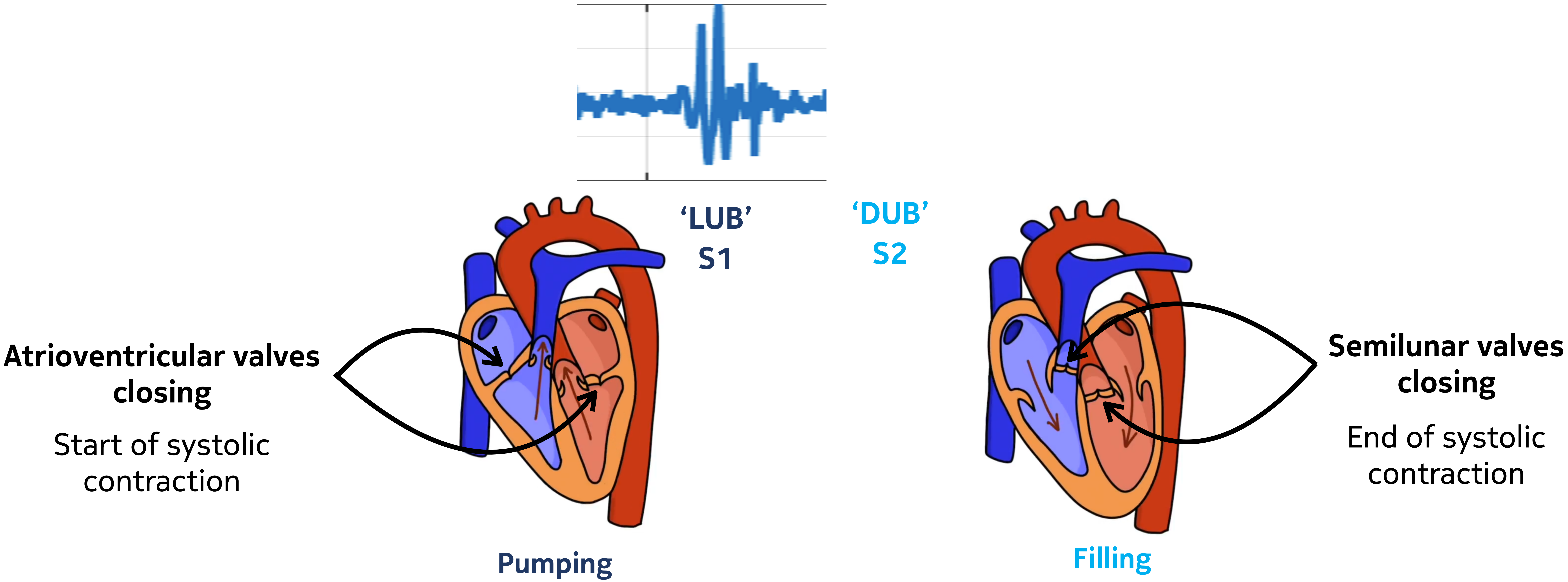
Heart Sounds

Blood travel time through the body is linked to BP (PTT and PTD methods)

A single in-ear PPG sensor cannot measure this time

A reference point is needed to determine the time interval



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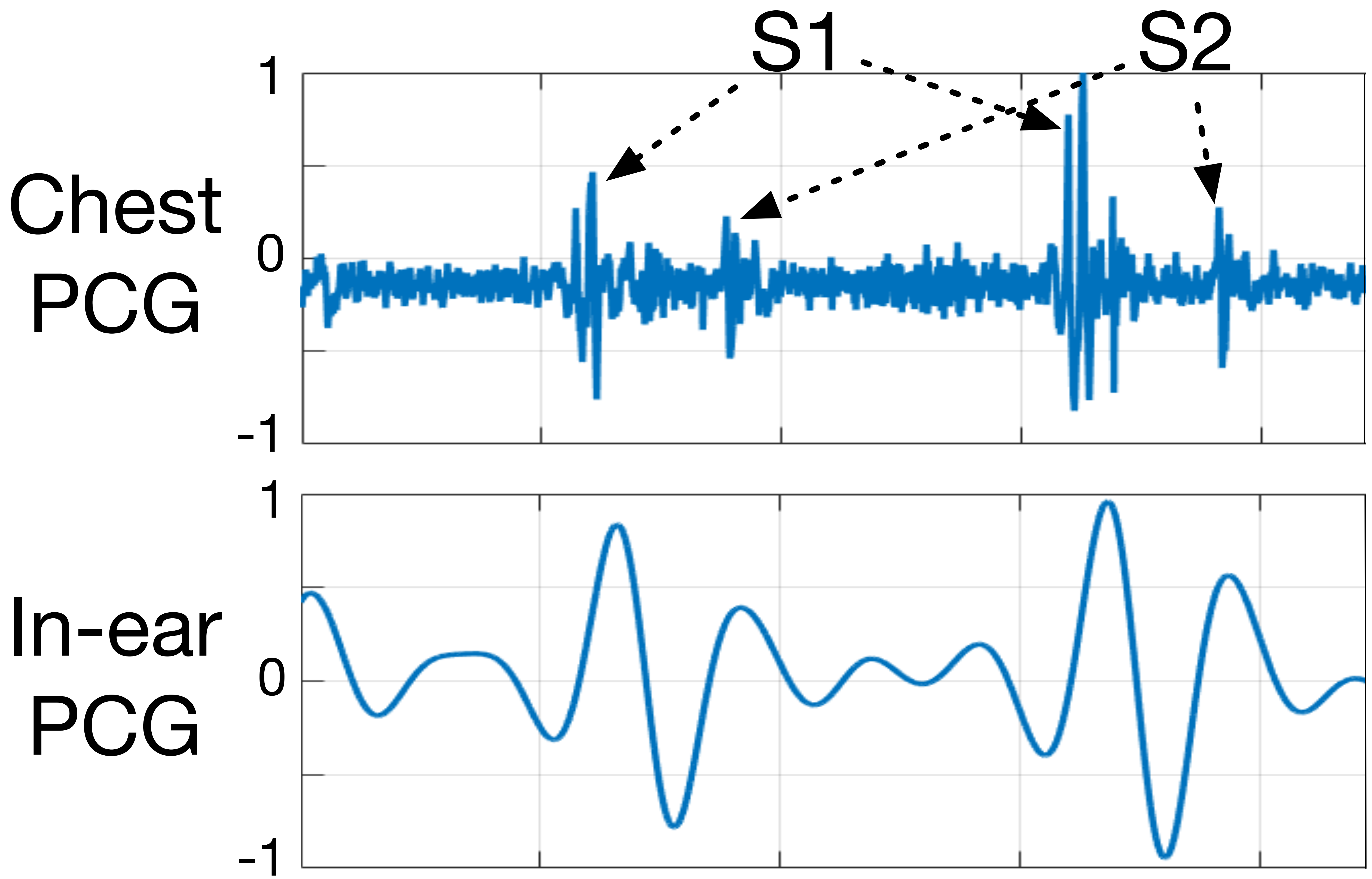
In-Ear Heart Sounds

Heart sounds can be detected from the ear if the ear canal is well sealed (occlusion effect)

Acoustic signal heavily attenuated and distorted as it travels through tissues and organs



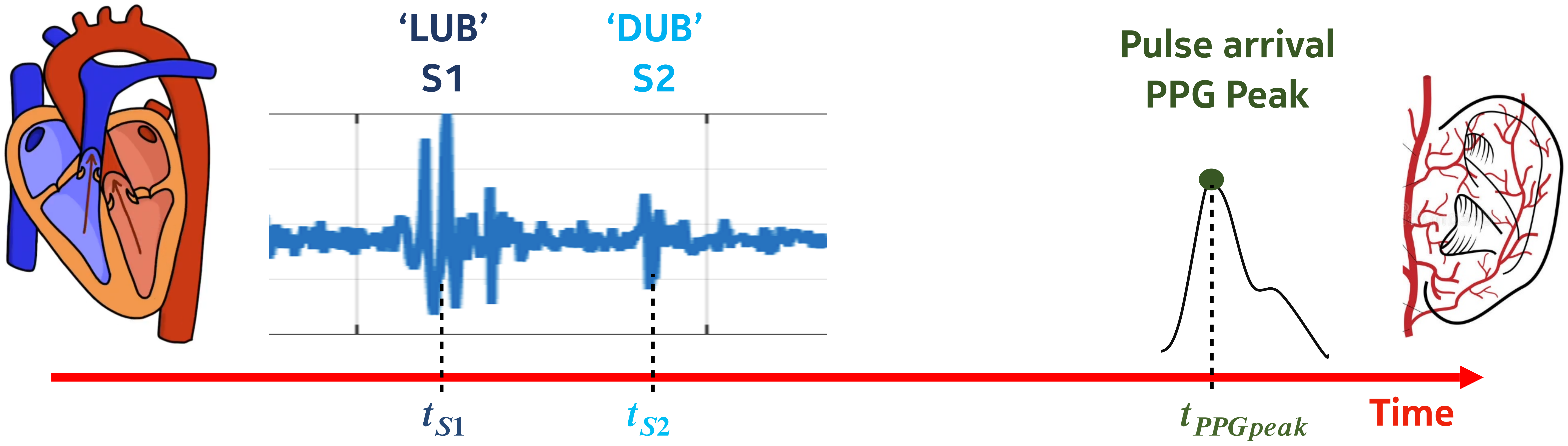
Our Approach

OBSERVATION

Sound travels much faster within the body compared to blood

Heart sounds' avg speed ~1500m/s

Blood's avg speed ~20-50cm/s



Vascular transit time:

$$VTT = t_{PPGpeak} - t_{S1}$$

Ejection time:

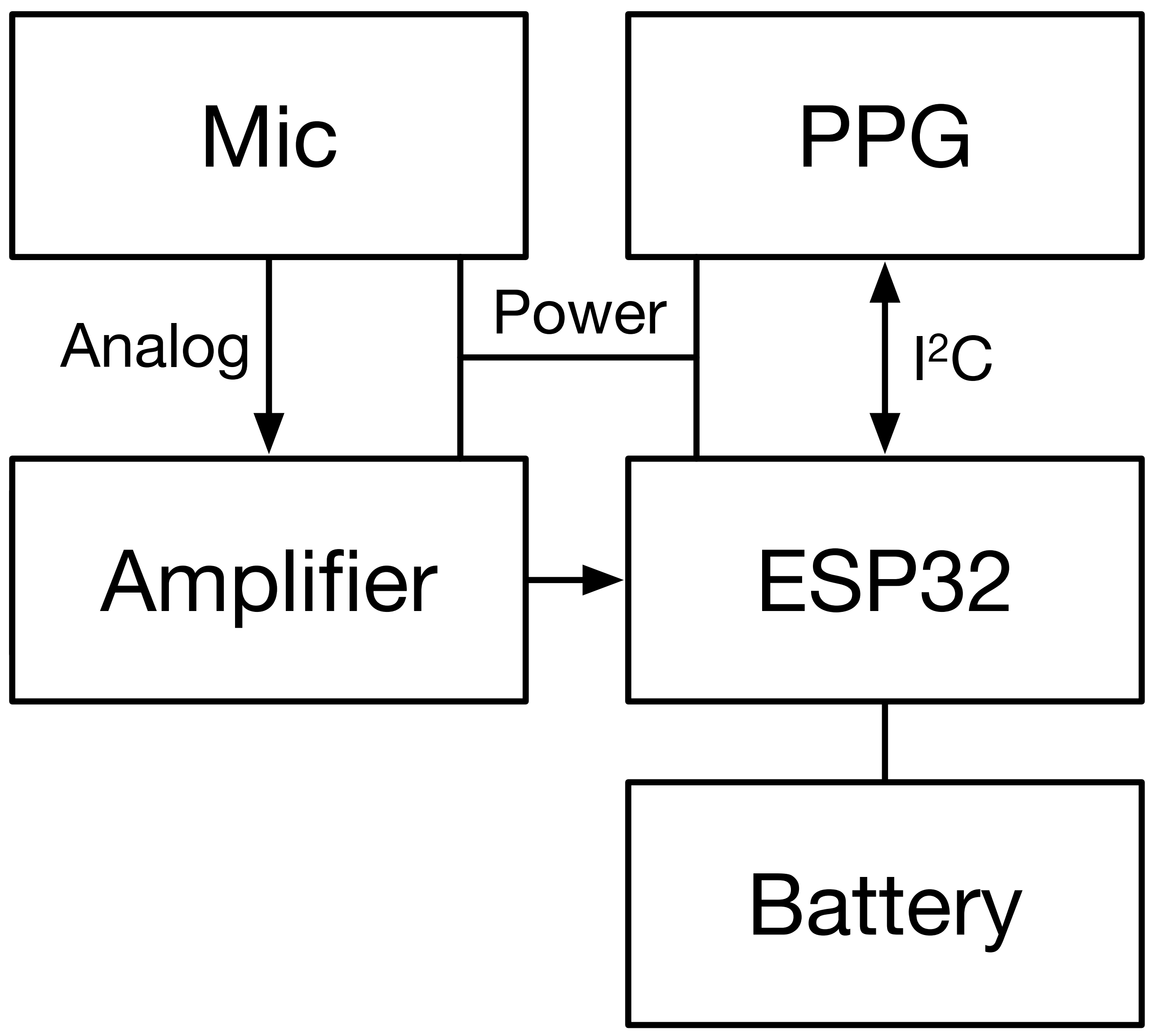
$$ET = t_{S2} - t_{S1}$$

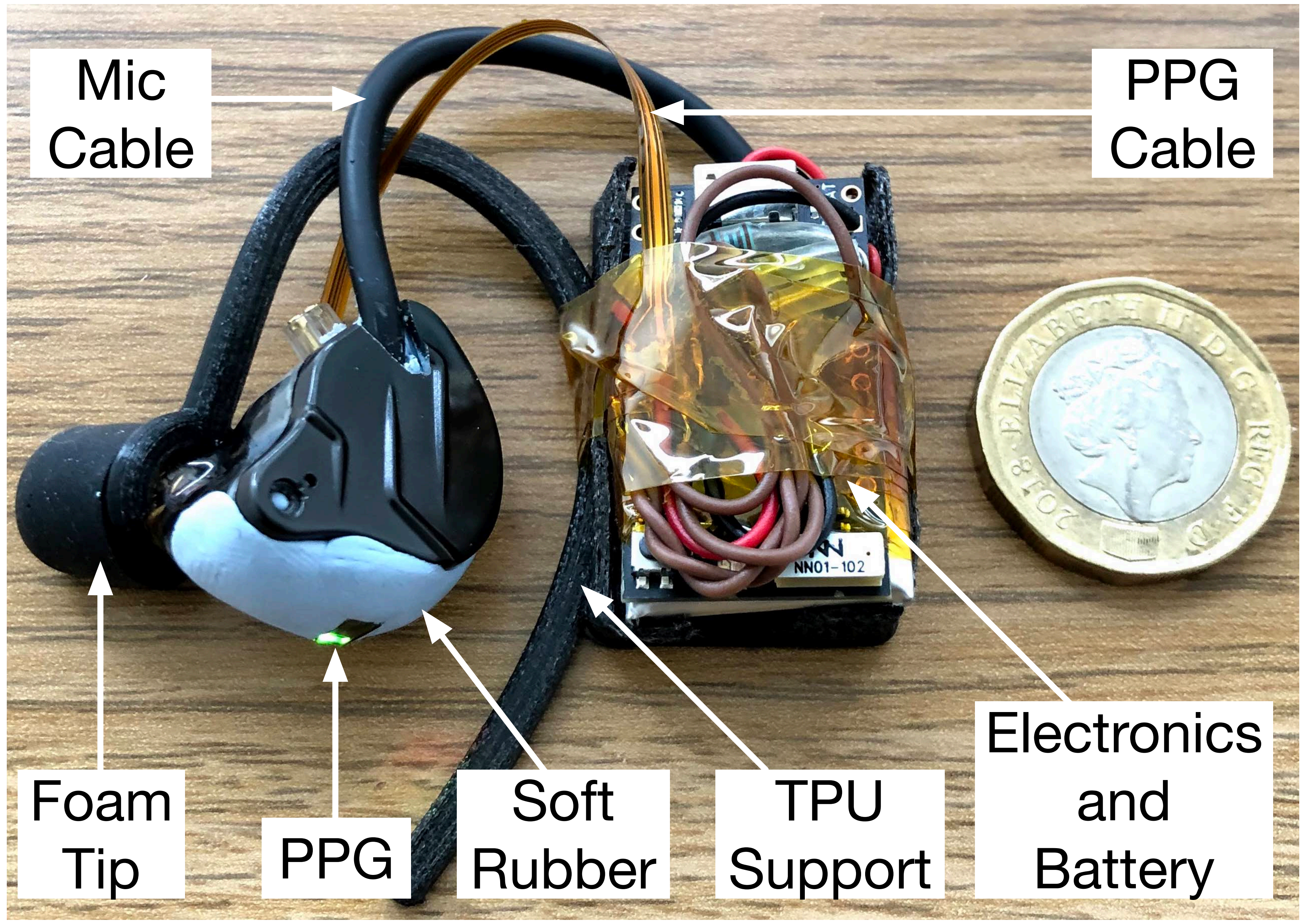
$$VTT \propto Systolic\_BP$$

$$ET \propto \frac{1}{Diastolic\_BP}$$

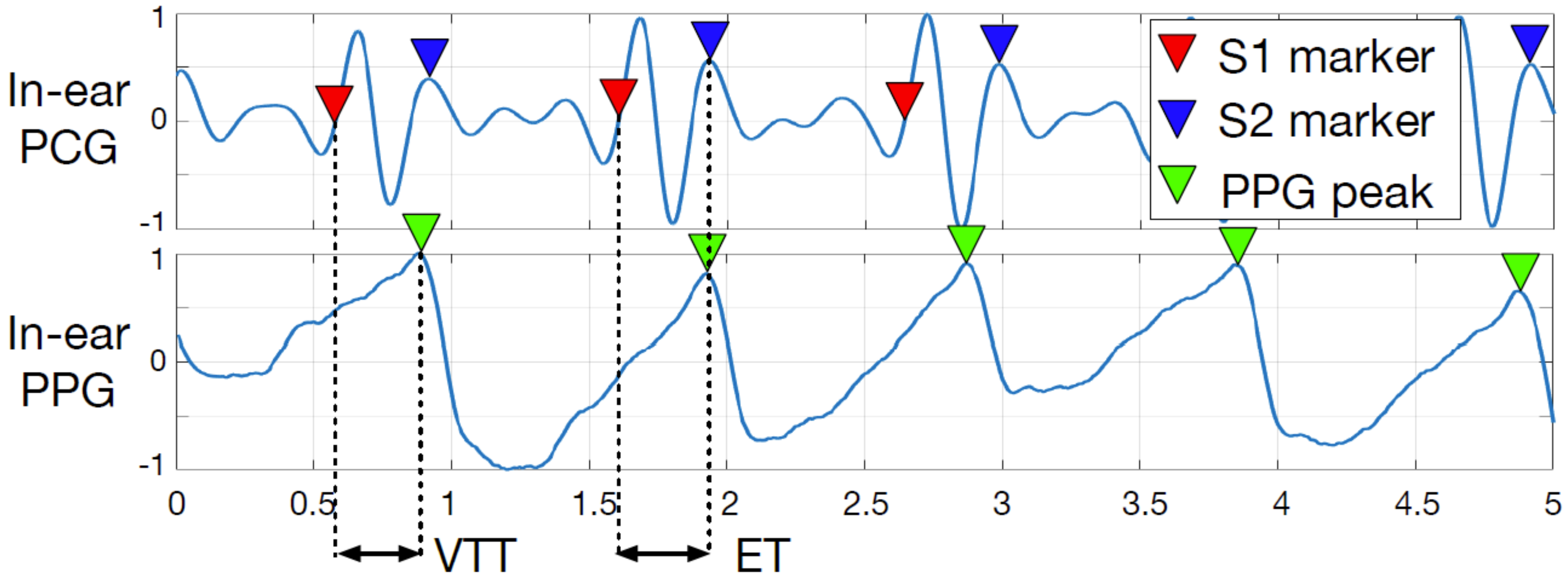
HW Prototype

- Analog microphone with extended low frequency response
- Foam ear tips for better ear canal sealing





Sensing Pipeline



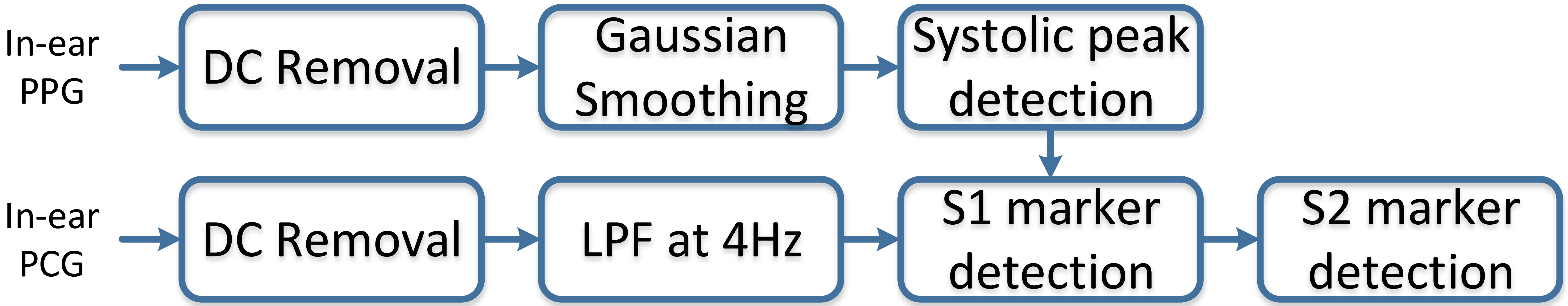
Vascular transit time:

$$VTT = t_{PPGpeak} - t_{S1}$$

Ejection time:

$$ET = t_{S2} - t_{S1}$$

- Forward-backward filter to preserve temporal features
- S1 and S2 identified searching backwards from PPG peak



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BP Estimation Models

- VTT and ET show relative changes in blood pressure
- Calibration of parameters α and γ with a cuff-based BP monitor

$$SBP = \alpha_1 VTT + \alpha_0$$

$$DBP = SBP - PP$$

$$PP = \gamma_1 \frac{ET}{VTT^2} + \gamma_2 \frac{1}{VTT^2} + \gamma_0$$ Pulse Pressure

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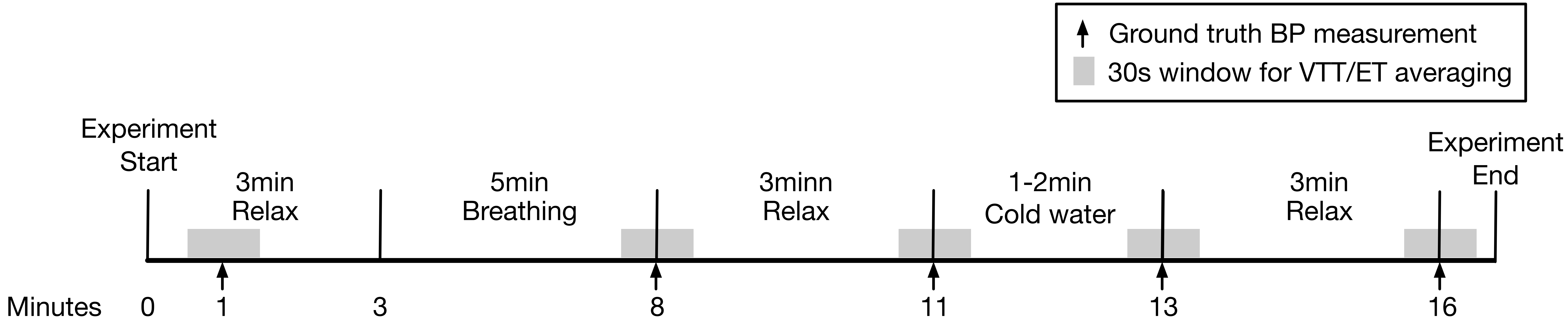
Preliminary User Study



- 10 healthy participants, 2 females, mean age 29,6
- Synced mic and PPG data from the left ear
- Timestamped ground truth BP measurements taken with Omron BP monitor
- Slow/deep breathing and immersing hand in cold water to induce BP changes

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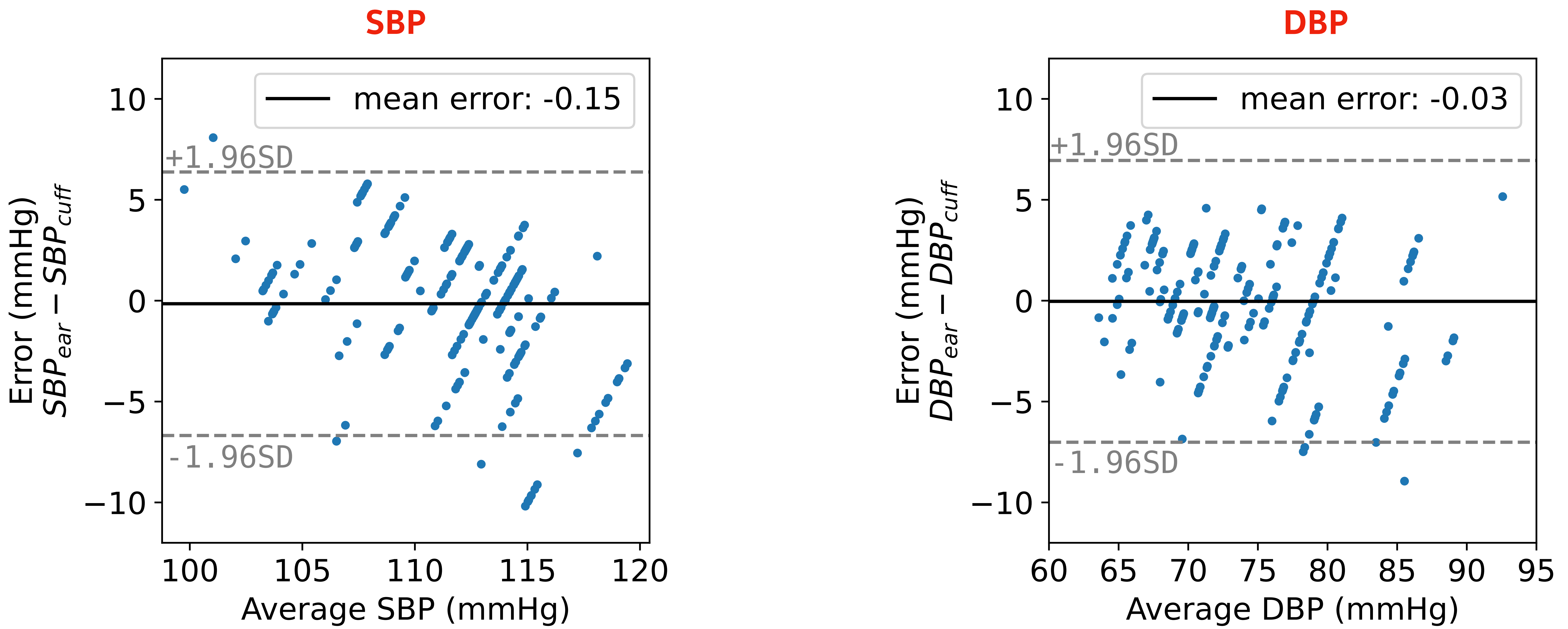
Results



SBP MAE = 2.50 ± 2.20 mmHg

DBP MAE = 2.42 ± 2.62 mmHg

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Take Aways

- Estimate BP from single ear-worn device
- Leverage **different propagation speed** of sound and blood
- Low-compute pipeline

Limitations

- Requires calibration
- Limited sample size
- Small data distribution

Conclusion

- **PPG** is a remarkably useful sensor for **in-ear** vital signs monitoring
- Other important vitals cam be monitored from the ear: **breathing rate** and **breathing volumes**
- **Hearing health**
- Many challenges to overcome:
  - Ear canal sealing quality monitoring
  - Reduce the need for calibration on BP estimation
  - Better processing pipelines to improve usability (ANC, music playing)
  - Clinical trials

References

- **In-Ear PPG for Vital Signs**, IEEE Pervasive Computing 2022
- **Non-Invasive Blood Pressure Monitoring with Multi-Modal In-Ear Sensing**, ICASSP 2022
- **Stereo-BP: Non-Invasive Blood Pressure Sensing with Earables**, HotMobile 2023
- **OptiBreathe: An Earable-based PPG System for Continuous Respiration Rate, Breathing Phase, and Tidal Volume Monitoring**, HotMobile 2024
- **EarSet: A Multi-Modal Dataset for Studying the Impact of Head and Facial Movements on In-Ear PPG Signals**, Nature Scientific Data 2023
- **Unobtrusive Air Leakage Estimation for Earables with In-ear Microphones**, IMWUT 2023

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PERVASIVE SYSTEMS

Thank you!

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