Mobile Health

Lecture 3
Photoplethysmography (PPG) and Mobile Health

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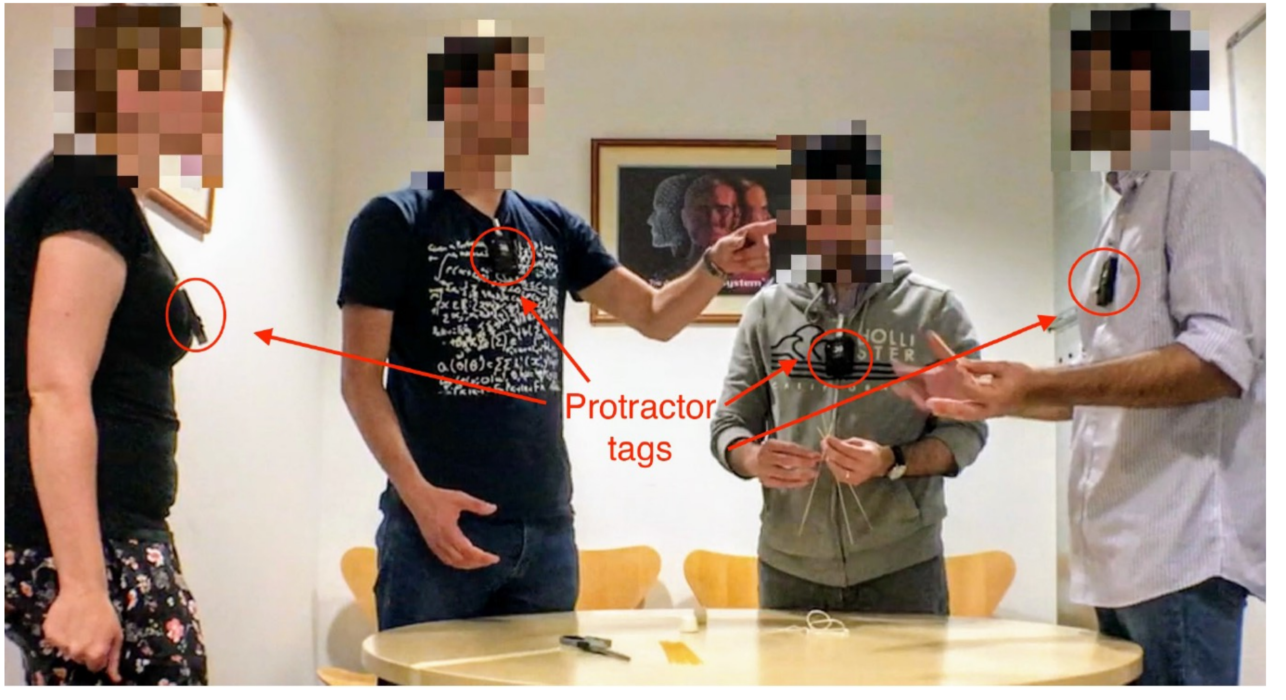
Light Sensing

- Wearable devices are being equipped with light sensors.
  - These sensors are used to mainly detect heart rate features.
- Other applications of light sensors exist
  - Detection of face to face contacts.

Interaction Monitoring:
Angle of Interaction with light sensing



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Measuring Interaction Proxemics with Wearable Light Tags. A. Montanari, Z.Tian, E. Francu, B. Lucas, B. Jones, X. Zhou, C. Mascolo. In Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT). Volume 2, Issue 1. Presented at Ubicomp 2018. Singapore. October 2018.

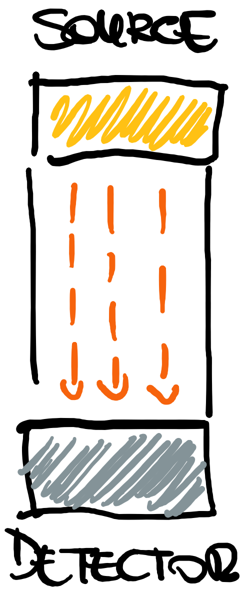
Essence of Photoplethysmography (PPG)

- It consists of a light emitting diode (LED) and a photodetector (PD).

- PPG signal measures the reflected (back-scattered) of the transmitted light through the region of tissues under examination. By looking at the intensity of the light at the PD, it is possible to detect variations in blood volume which occur with each heartbeat.

Classical PPG

- It measures the light through the tissue by placing the sensors on the opposite side.



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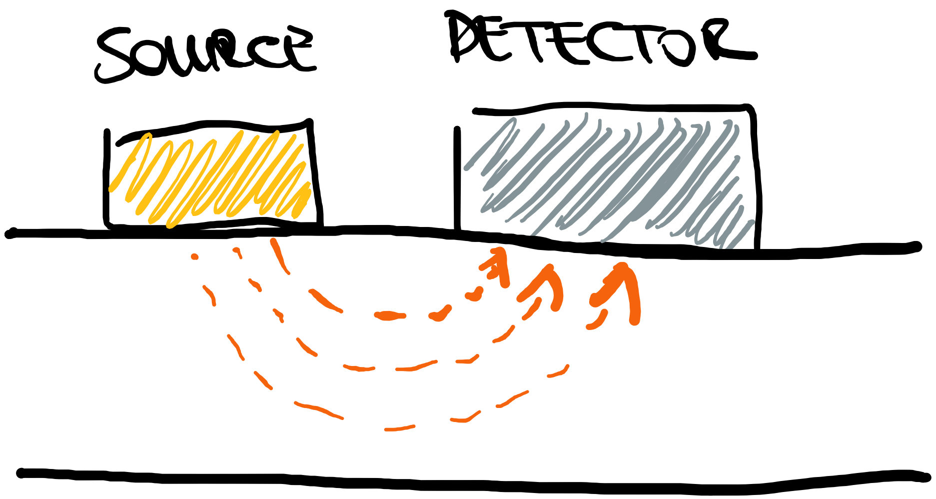
Reflective PPG

- Measures the reflective light: sensors are on the same side of the tissue



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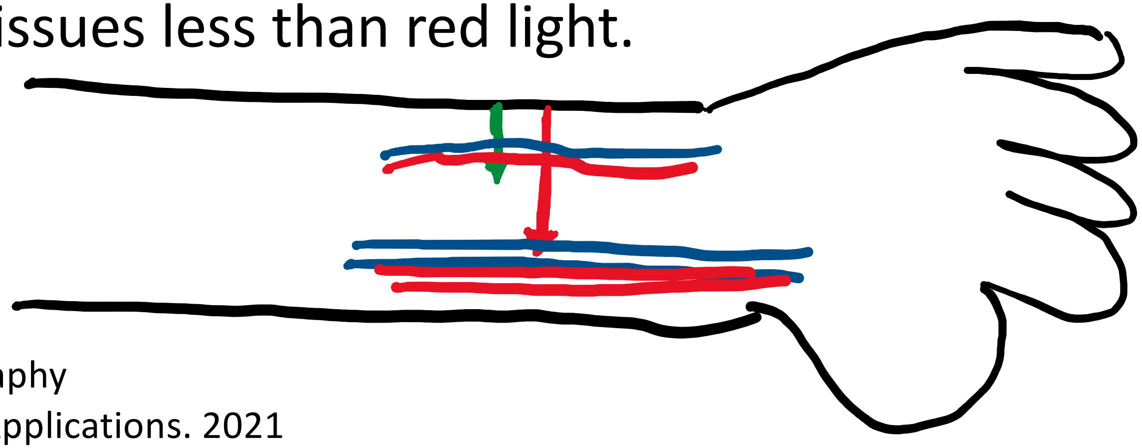
Light type

- The wavelength of the light used in PPG sensors typically ranges between 500nm (green colour) and 1100nm (infrared). Red and infrared (IR) lights are absorbed less by the water present in the human tissues compared to green light.
- Depending on the wavelength of the LED, the light is absorbed differently by the skin, achieving different depth in the tissue.
- Green light penetrates the tissues less than red light.



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More details: Photoplethysmography Technology, Signal Analysis and Applications. 2021

Wearable PPGs

Marozas and Charlton (2021) under CC BY 4.0.

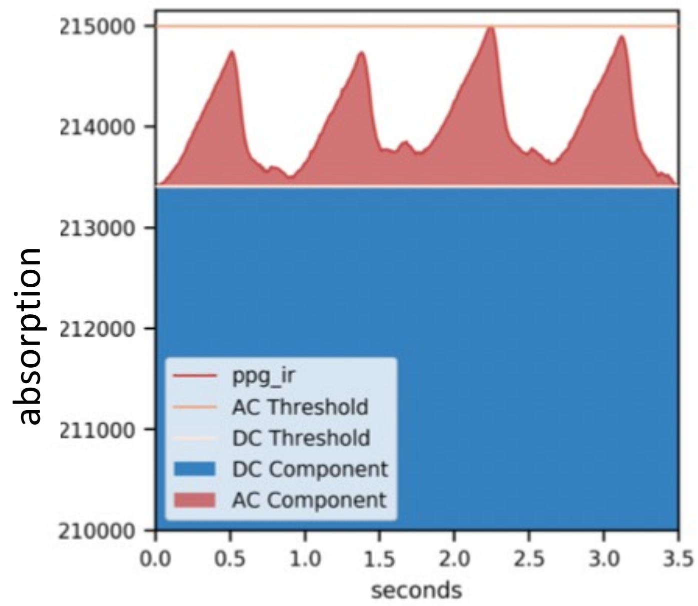
Cardiac Cycle

A cardiac cycle consists of two stages:

- Systole: blood pumped out of the heart rushes throughout the body, including all the peripheral tissue sites.
- Diastole: the heart muscle relaxes and allows the chambers to fill with blood.

Working of Heart Sensing with PPG

- Light absorption goes up when a systole pumps blood in the body and then goes down.
- Light absorption of oxygenated hemoglobin is different from that of reduced hemoglobin.
- Absorption has an oscillating (AC) component, due to volume change, normally from arterial blood, occurring between the emitter and the detector sensor.
- Non pulsatile component (DC) that results from light attenuated by skin, fingernails, tissue, bone, and static blood. The slow variation in the DC wave is also attributed to respiration, the sympathetic nervous system, blood pressure control, and thermoregulation.



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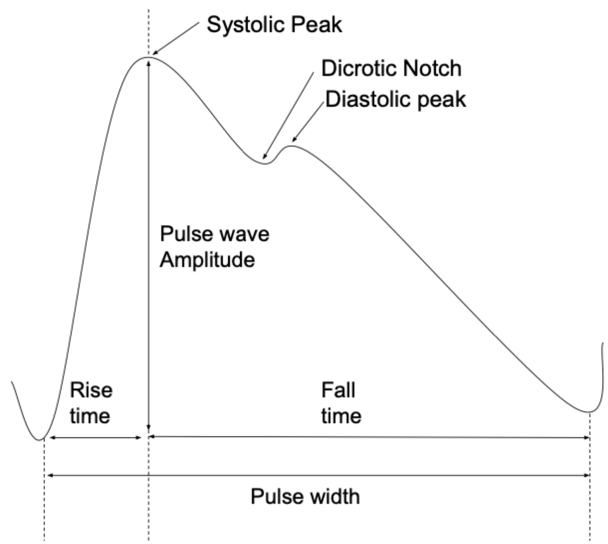
Measuring Heart Signal from PPG

- The signal has two phases:
- First Phase: the rising edge of the pulse or **anacrotic phase** primarily relates with systole.
- Systolic peak (less light)
- Second Phase: the falling edge of the pulse or **catacrotic phase** which is associated with diastole.
- The dicrotic notch: marker of the end of aortic systole and the beginning of diastole.



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PPG Signal Cleaning

- Signal cleaning examples
  - Band pass filters
    - Eg to isolate the oscillating (AC) component [0.4-4Hz]
  - Cutting out unacceptable segments
    - Various techniques to define this
  - Skewness (S), Kurtosis (K) & Shannon Entropy measure if the signal have noise (on time domain as well as frequency domain).
    - Skewness measures signal symmetry while Kurtosis measures the sharpness of the distribution.

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Kurtosis

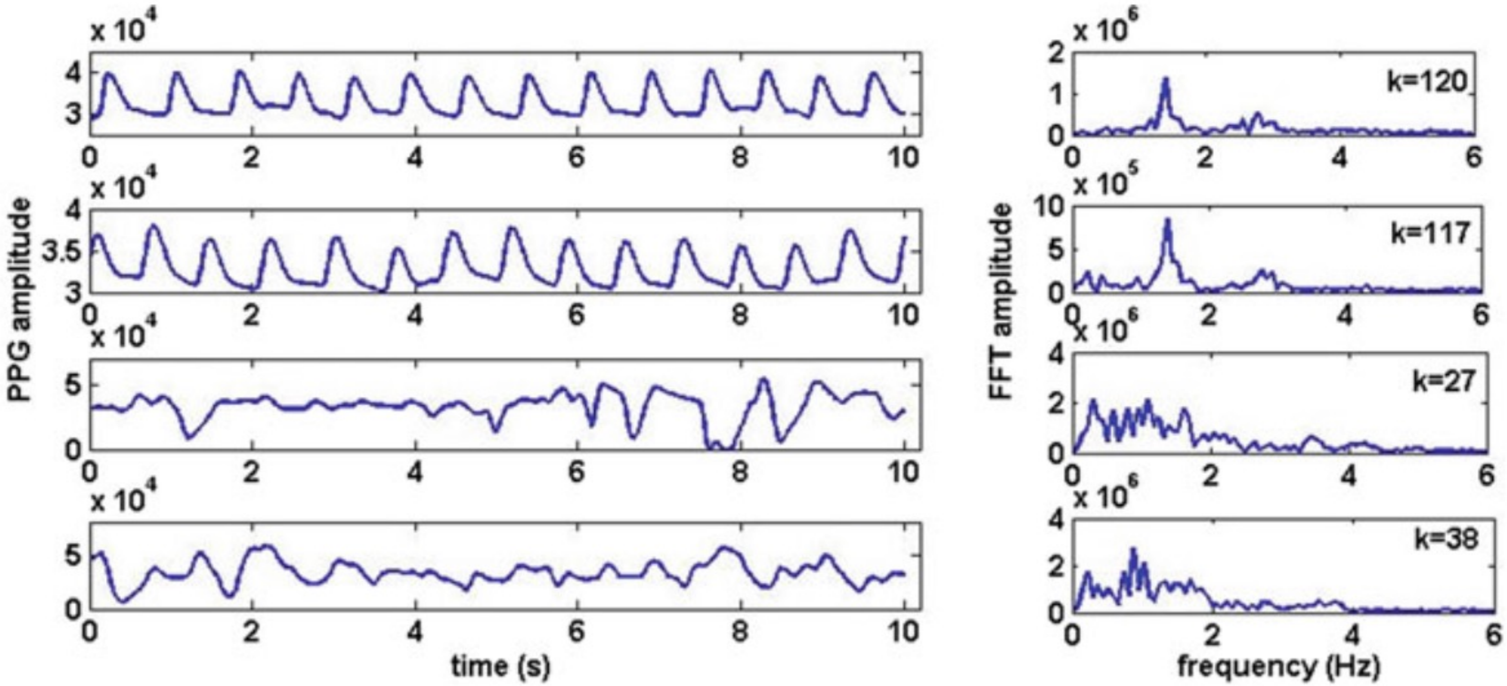

Figure from C. Orphanidou. Signal Quality Assessment in Physiological Monitoring. Springer 2018.

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Measuring Heart Rate with PPG

- Provided the signal is clean…
- Find the systolic peaks: count them into a time interval and extrapolate beats per minute.

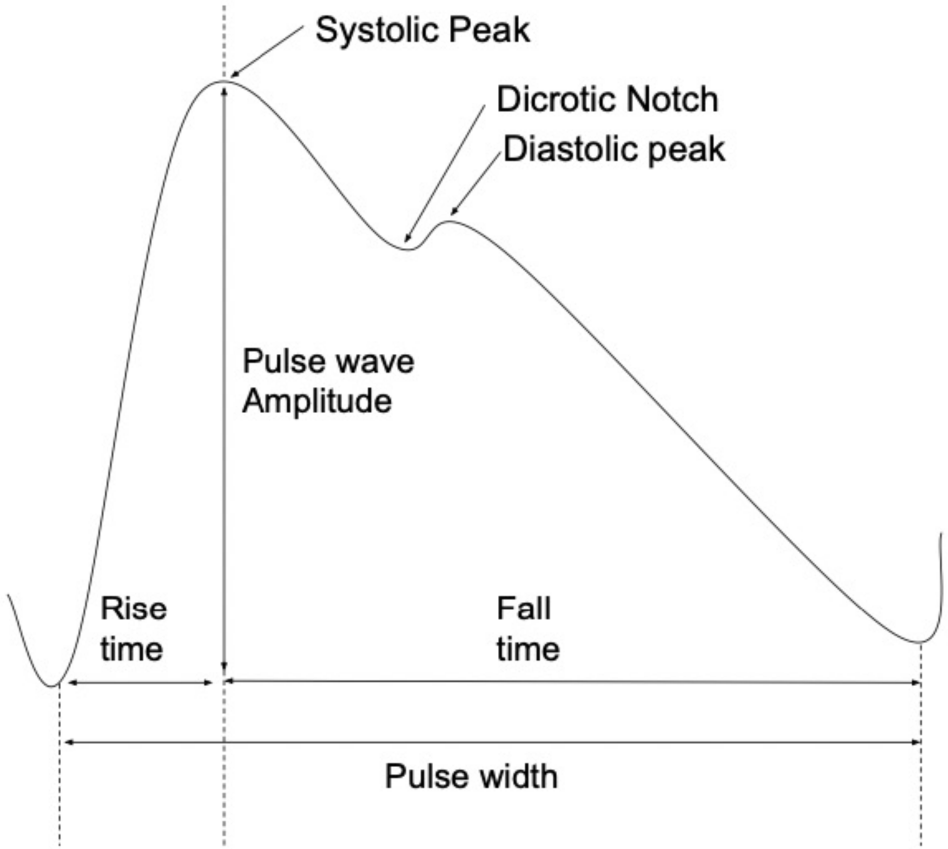
- What can influence the signal?
  - Breathing
  - Motion
  - Quality/fitting of the sensor

Interbeat-intervals (IBIs)

- The **interval between consecutive heartbeats** is used for applications such as arrhythmia identification and pulse rate variability.
- IBIs are extracted by measuring the time delay between occurrences of a particular fiducial point on consecutive pulse waves.
    - Fiduciary points could be the pulse onset, the systolic and diastolic peaks, and the dicrotic notch.
- Intervals between pulse onset seem to work well.

More details in Chapter 4 of Photoplethysmography Technology, Signal Analysis and Applications. 2021. Elsevier.

PPG: Time Domain Features



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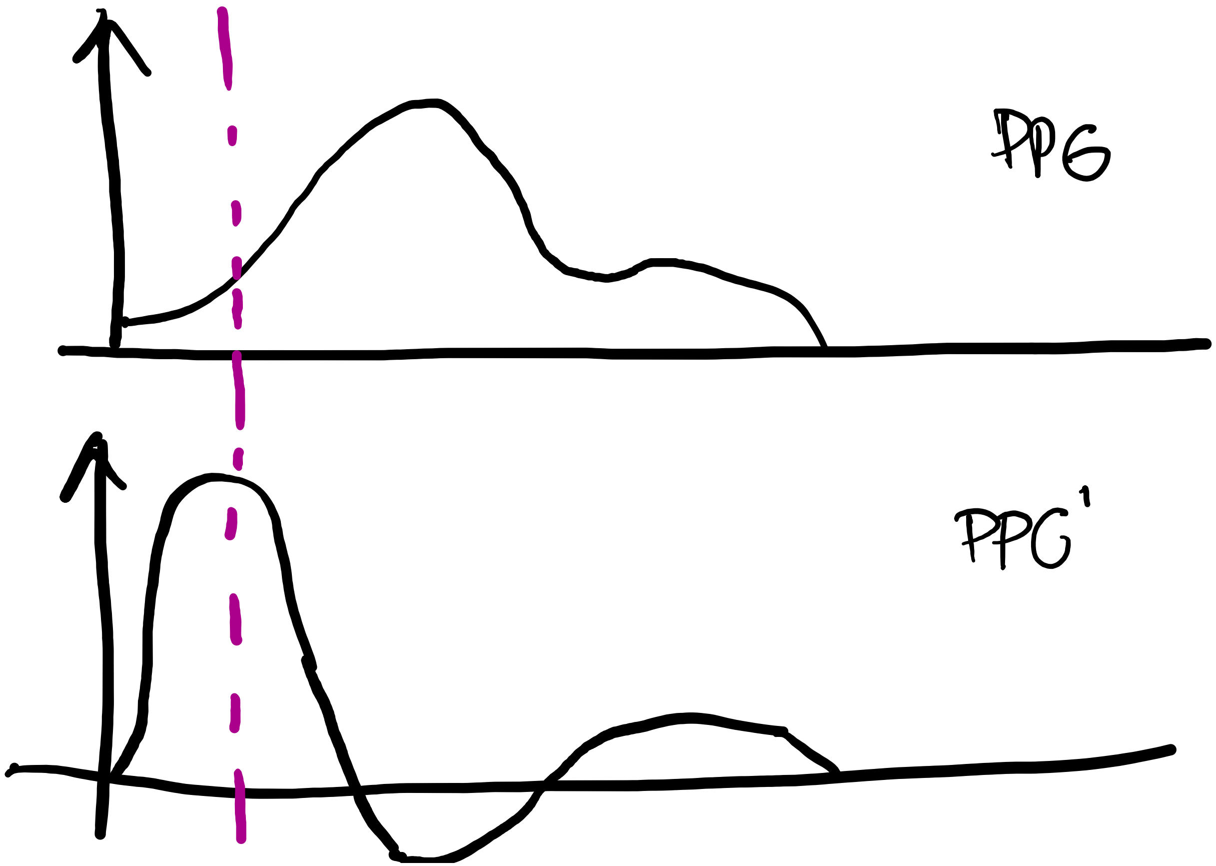
First Derivative of PPG



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Calculation of Pulse Onset

- On the PPG wave
  - Find the point corresponding to the max of the first derivative.
  - Draw tangent
  - Draw tangent on min point
  - Point 5 is the pulse onset

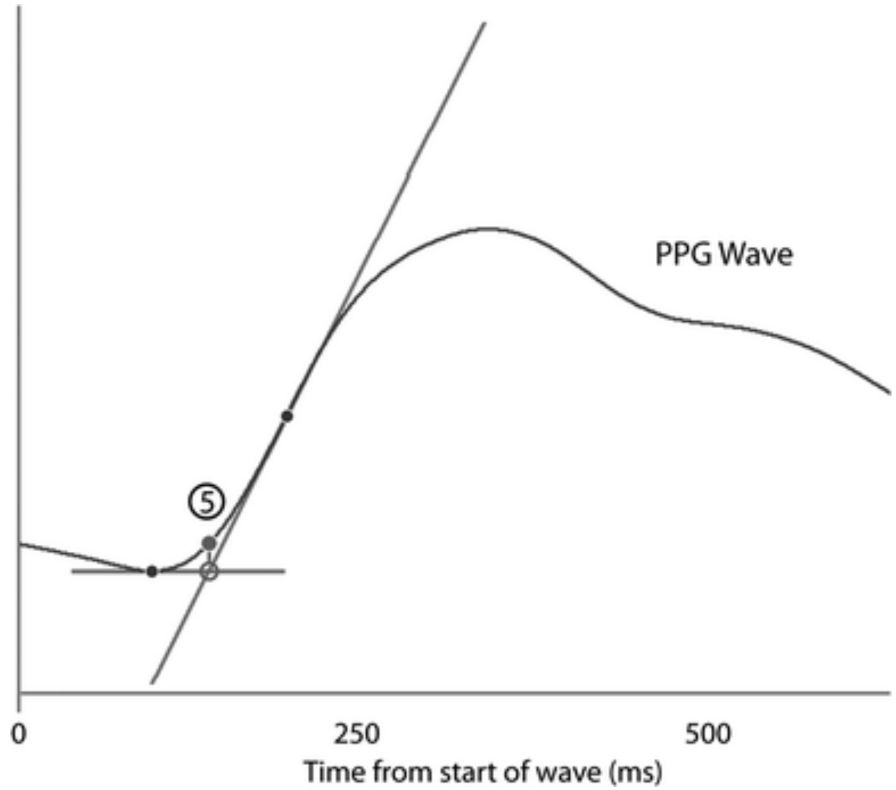

Figure from Hemon MC, Phillips JP. Comparison of foot finding methods for deriving instantaneous pulse rates from photoplethysmographic signals. J Clin Monit Comput. 2016 Apr;30(2):157-68.

Arterial Fibrillation (AF) Detection

- Common form of arrythmia causing high risk of stroke.
- Features such as IBIs and pulse amplitude are used to classify samples AF or non-AF (time series of features).
- Calculate summary of statistics of these time series of features (mean, SD, entropy).
- Classification can be applied

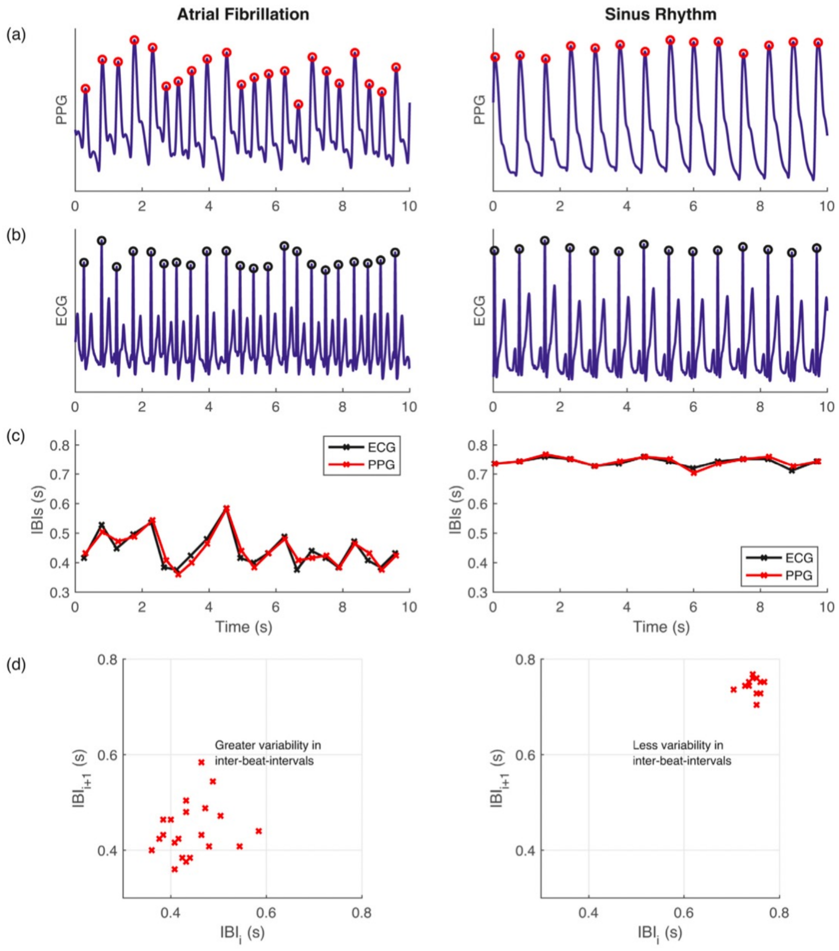

Image by P Charlton: Capitalising on Smart Wearables to Improve Health Monitoring. Presentation 2018

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Smartwatch PPG for AF

- PPG used over 1 minute. Classified as *regular or irregular* on the basis of the variation in the IBI **while at rest**.
- the IBIs are plotted on a Poincare plot and degree of dispersion is used to determine irregularity.
- If 5/6 consecutive tachograms within a 48-hour period are classified as irregular, the user is notified of an irregular pulse.
- 419,297 participants.
- The positive predictive value of an individual tachogram was 0.71 (wrt ECG).
- The positive predictive value of an irregular pulse notification was 0.84.

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The NEW ENGLAND JOURNAL of MEDICINE

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*

Heart Rate Variability and IBI

- Heart Rate Variability (HRV) is an important measure of heart health.
  - When we are stressed our HRV is lower.
  - However too high HRV is also very unhealthy.

- HRV measures the change in IBI over time.

HRV Time and Frequency Domain Features

Parameter	Unit	Description
SDNN	ms	Standard deviation of NN intervals
SDRR	ms	Standard deviation of RR intervals
SDANN	ms	Standard deviation of the average NN intervals for each 5 min segment of a 24 h HRV recording
SDNN index (SDNNI)	ms	Mean of the standard deviations of all the NN intervals for each 5 min segment of a 24 h HRV recording
pNN50	%	Percentage of successive RR intervals that differ by more than 50 ms
HR Max − HR Min	bpm	Average difference between the highest and lowest heart rates during each respiratory cycle
RMSSD	ms	Root mean square of successive RR interval differences
HRV triangular index		Integral of the density of the RR interval histogram divided by its height
TINN	ms	Baseline width of the RR interval histogram

Parameter	Unit	Description
ULF power	ms^2	Absolute power of the ultra-low-frequency band (≤0.003 Hz)
VLF power	ms^2	Absolute power of the very-low-frequency band (0.0033–0.04 Hz)
LF peak	Hz	Peak frequency of the low-frequency band (0.04–0.15 Hz)
LF power	ms^2	Absolute power of the low-frequency band (0.04–0.15 Hz)
LF power	nu	Relative power of the low-frequency band (0.04–0.15 Hz) in normal units
LF power	%	Relative power of the low-frequency band (0.04–0.15 Hz)
HF peak	Hz	Peak frequency of the high-frequency band (0.15–0.4 Hz)
HF power	ms^2	Absolute power of the high-frequency band (0.15–0.4 Hz)
HF power	nu	Relative power of the high-frequency band (0.15–0.4 Hz) in normal units
HF power	%	Relative power of the high-frequency band (0.15–0.4 Hz)
LF/HF	%	Ratio of LF-to-HF power

From Shaffer F, Ginsberg JP. An Overview of Heart Rate Variability Metrics and Norms. Front Public Health. 2017 Sep 28;5:258. doi: 10.3389/fpubh.2017.00258. PMID: 29034226; PMCID: PMC5624990.

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Respiration Rate and PPG

- Respiratory rate (RR), the number of breaths taken in a minute, is used for diagnosis and prognosis in a range of clinical settings.

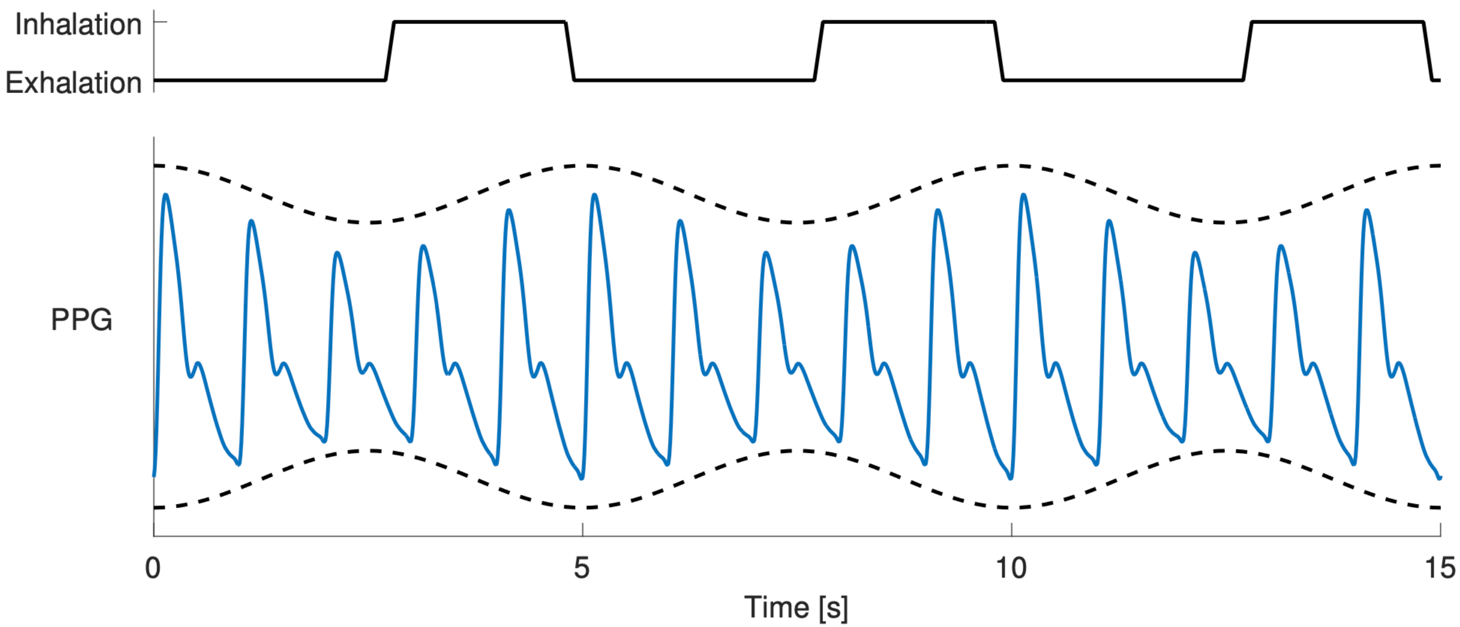

Figure from P. Charlton. Continuous Respiratory Rate Monitoring to Detect Clinical Deteriorations using Wearable Sensors. PhD Thesis. 2017.

RR Modulation

- **Baseline wander**: Changes in tissue blood volume caused by inhalation.
- **Amplitude modulation**: Stroke volume is reduced during inhalation.
- **Frequency modulation**: heart rate increases during inspiration and decrease during exhalation.

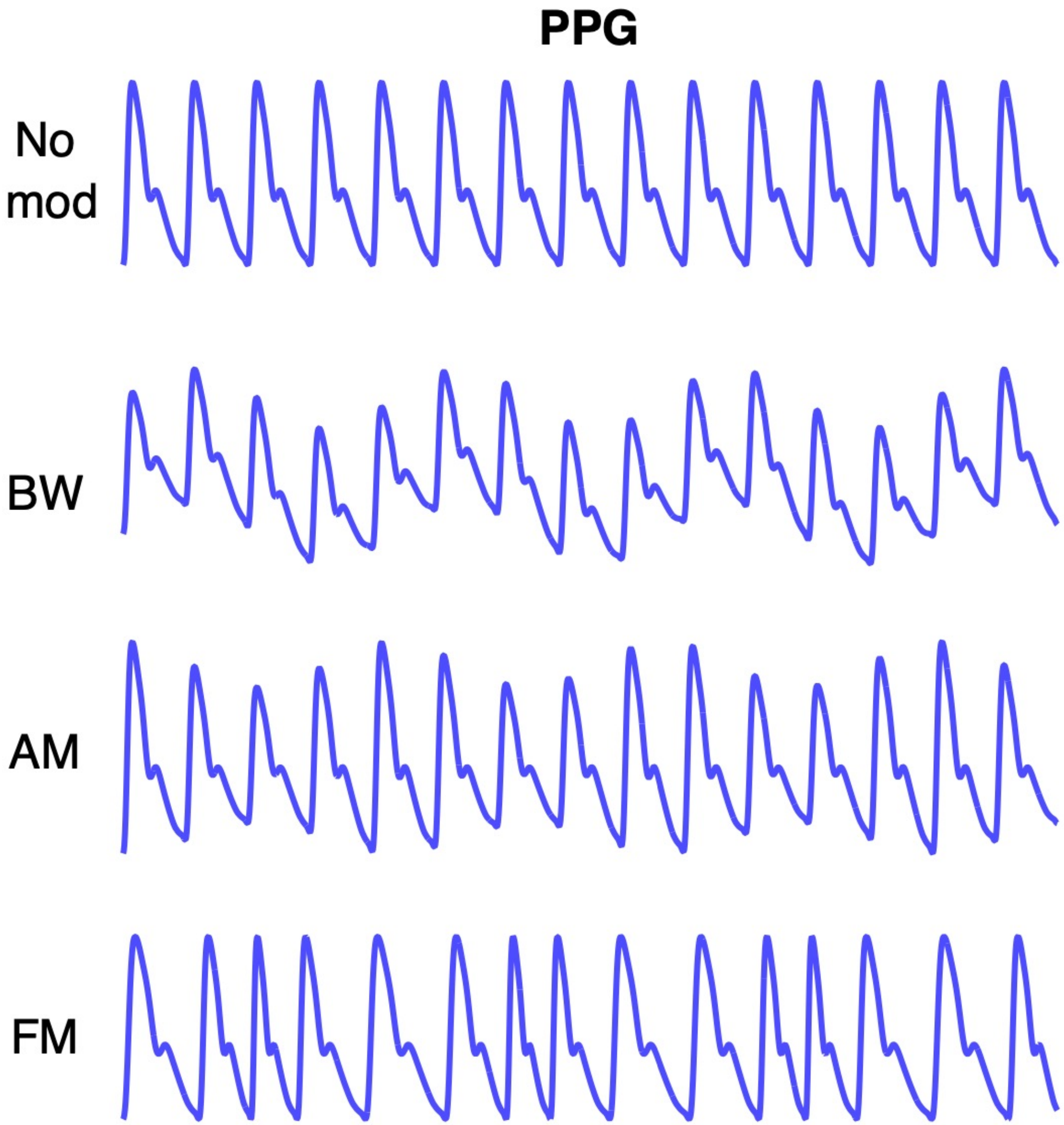

Figure from P. Charlton. Continuous Respiratory Rate Monitoring to Detect Clinical Deteriorations using Wearable Sensors. PhD Thesis. 2017.

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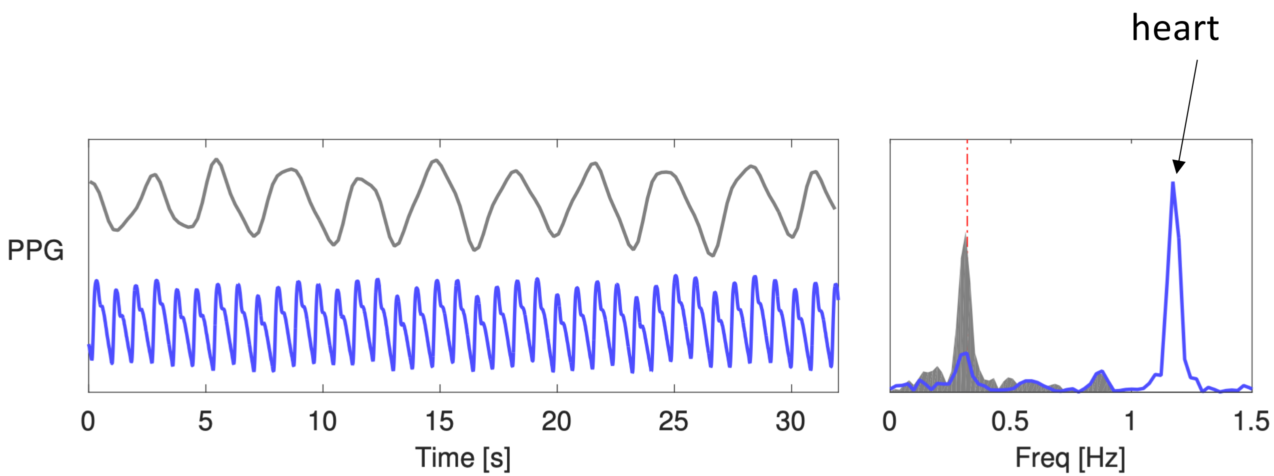
Respiration Rate Extraction

- Filter bands applied to keep frequencies at plausible Respiration Rate (RR) e.g., low pass filter at 35Hz to eliminate VHFs. Filters specific to the range eg filters the max peak of the heart in the figure and then obtain RR as the frequency of the max power.



Blood Pressure

- Blood pressure (BP) is widely measured to assess cardiovascular health. Abnormal BP incites several diseases that can lead to complications for vital organs such as the heart and brain.

- PPG placed in two location and measuring the time it takes for the pulse wave to travel from one to the other.
- BP inversely proportional to pulse wave travel time.
- Peak time shift used to measure the travel time of the pulse wave.

Arterial Stiffness (AS)

- Arteries tend to stiffen as we age. Consequently, transmission of the pulse (and its return) tends to get faster.
- AS is measured similarly to BP by using pulse wave timing.

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More details in Photoplethysmography. Technology, Signal Analysis and Applications. P. A Kyriacou and J. Allen. Elsevier, 2022.

Oxygen Saturation (SpO2)

- Oxygenated hemoglobin absorbs less red light emitted whereas deoxygenated hemoglobin absorbs less infrared light. Thus, the ratio between red and infrared light intensities measured by the PPG sensor can be used to estimate peripheral oxygen saturation (SpO2).

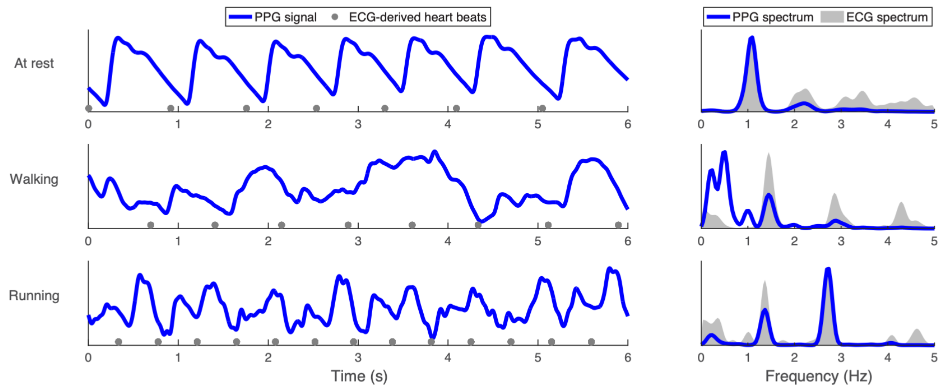
$$R = \frac{R_{red}}{R_{infrared}} = \frac{AC_{red}/DC_{red}}{AC_{infarared}/DC_{infrared}}$$

Control for …

- MOTION
- Demographics (age/height/weight)
- Location of sensing

Motion

- Avoid to sample when accelerometer detects activity.
- Correlate accelerometer data to filter out motion artifacts.
- Use estimates over time.
- Performance of wrist-worn devices for HR monitoring found summary mean absolute errors of 2.15 bpm (95% confidence interval 1.84–2.46) during rest, compared to 7.70 bpm (6.32–9.07) during treadmill activities.



Charlton, P.H., 2021. Realising the potential of wearables. IPEM Scope 31 (1), 50–53.

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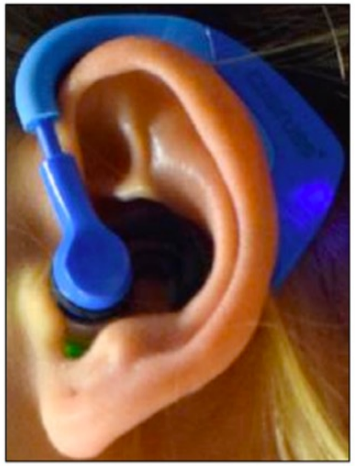
Wearable Devices: PPG

- Sampling:
  - Wearable devices typically sample the PPG at between 50 and 100 Hz.
  - Studies have shown that HR can be estimated from PPG signals sampled at 9 Hz, pulse rate variability (PRV, equivalent to HRV) at 25 Hz, respiratory rate at 16–18 Hz. Generally PPG features can be accurately measured at sampling frequencies of at least 60 Hz.
- Battery: only sample when low activity detected.

More details in Chapter 12, Photoplethysmography Technology, Signal Analysis and Applications. 2021

The new frontier…



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NON-INVASIVE BLOOD PRESSURE MONITORING WITH MULTI-MODAL IN-EAR SENSING

Hoang Truong, Alessandro Montanari, Fahim Kawsar

Nokia Bell Labs, Cambridge (UK)

ABSTRACT

Continuous blood pressure monitoring is the key to mitigate significant risks for stroke, heart failure and coronary artery disease. Current gold-standard blood pressure devices cause discomfort and interfere with users' activities. This paper explores an earable system, which continuously monitors users' blood pressure from the ear. We propose a measurement technique based on the vascular transit time which utilises the time difference between the S1 heart sound and the PPG upstroke in one pulse cycle. We develop a multi-modal sensing hardware and processing pipeline and we evaluate it with 10 participants showing average errors in line with the range recommended by the Association for the Advancement of Medical Instrumentation: 4.07 mmHg for systolic and 5.61 mmHg for diastolic blood pressure.

behind the head [11, 12]. These approaches however, increase system complexity and limit usability.

We overcome the aforementioned issues by exploiting the different propagation times of sound and blood through the human body and estimate blood pressure from a single device in the ear. The ear is a remarkable location to measure not only blood pressure but also a plethora of other vital signs (e.g., heart rate and blood oxygen saturation). The recent popularity of ear-worn devices (i.e, earables) and earbuds with in-ear microphones or PPG sensor integration makes them a perfect avenue for unobtrusive BP monitoring [13, 14].

The key to our approach is embedding an in-ear microphone and a PPG sensor in the same earable device. This multi-modal approach can measure the vascular transit time (VTT). VTT is the delay between the moment the heart starts pumping blood (denoted by the first heart sound, S1) and the upstroke of the corresponding PPG

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47th IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2022), May 2022

Questions