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

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Personal Introduction

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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
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.”
2009
Samsung S9110 Watch Phone
Time and date
Calls and messages
Music streaming

2015
Onkyo W800BT
Music playback
Calls

2019
Apple AirPods Pro
Active Noise Cancelling
Transparency mode
Spatial audio
Adaptive EQ

2020
Apple Watch Series 6
Activity and sleep tracking
Blood Oxygen level
Heart rate
ECG
Environmental sound monitoring
Handwashing monitoring
Apps

The future of earables will be sensory-rich and health-oriented
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
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
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?
To what extend is in-ear PPG robust to motion artifacts?
Ear Anatomy

BTE - Behind the Ear | ITE - In the Ear | ITC - In the Canal
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
Study Protocol
Vital Sign Extraction

IR PPG (raw signal) → BANDPASS FILTER [0.5-10 Hz] 4th order → SIGNAL SCALING, NORMALIZATION, R-PEAKS ENHANCEMENT → PEAK DETECTION → HR, HRV

RED PPG (raw signal) → BANDPASS FILTER [0.5-10 Hz] 4th order → AC & DC COMPONENTS EXTRACTION → RR

IR PPG (raw signal) → BANDPASS FILTER [0.10-0.8 Hz] 2nd order → RESPIRATORY SIGNAL → WINDOWING (30s) & PEAK DETECTION → RR

SpO2 = A − BR

AC & DC COMPONENTS EXTRACTION
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
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?

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**.
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

ST LSM6DSRX IMU
MAX86161 PPG sensor
Can we estimate **blood pressure** with in-ear PPG?
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).

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

\[
PTT = t_{PPG2} - t_{PPG1}
\]
Head and Upper Body Anatomy

The heart protrudes towards the left side of our body

Distance_{Heart \rightarrow Right Ear} → Distance_{Heart \rightarrow Left Ear}

Distance_{Heart \rightarrow Right Ear} = (22.2 \pm 2.2 \text{cm})

Distance_{Heart \rightarrow Left Ear} = (20.8 \pm 1.9 \text{cm})

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?
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

PTD = t_{Right} - t_{Left}

SBP/DBP estimation models
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
- \(\gamma\) 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
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
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 assess 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

![Cumulative Probability Graphs for SBP and DBP](image)
Stereo-BP: Exploiting Pulse Time Difference Between The Ears

Take Aways

- Heart is closer to the left ear than the right ear
- $\text{PTD}_{\text{Left} \rightarrow \text{Right}}$ 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?
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

Pumping

‘LUB’

S1

‘DUB’

S2

Filling

Atrioventricular valves closing

Start of systolic contraction

Semilunar valves closing

End of systolic contraction
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

In-ear PPG

DC Removal \rightarrow Gaussian Smoothing \rightarrow Systolic peak detection

DC Removal \rightarrow LPF at 4Hz \rightarrow S1 marker detection \rightarrow S2 marker detection
BP Estimation Models

- VTT and ET show relative changes in blood pressure
- Calibration of parameters $\alpha$ and $\gamma$ 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
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
Results

**SBP**

**SBP MAE** = 2.50 ± 2.20 mmHg

**DBP**

**DBP MAE** = 2.42 ± 2.62 mmHg
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 can 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

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