Stereo-BP: Non-Invasive Blood Pressure Sensing with Earables

Ananta Narayanan Balaji[†°] Andrea Ferlini[‡] Fahim Kawsar[‡] Alessandro Montanari[‡]
[†]National University of Singapore [‡]Nokia Bell Labs, Cambridge
[°]Work done while the author was interning at Nokia Bell Labs.

ABSTRACT

Frequent blood pressure monitoring with earables has been increasingly explored owing to its importance in diagnosing cardiac health. While previous solutions for blood pressure estimation in earables are uncomfortable and less accurate, the objective of this study is to achieve non-invasive, accurate and cuff-less blood pressure monitoring with PPG sensors integrated into earphones. To this end, we investigated photoplethysmograph (PPG) signals from the left and right ears and found that blood arrives earlier in the left ear due to the closer distance from the heart. Based on our findings, we propose **Stereo-BP** — an earable system leveraging the pulse time difference measured between PPG signals from our left and right ear-worn prototypes to estimate blood pressure. Our preliminary evaluation with 20 participants shows the feasibility of measuring systolic and diastolic blood pressure from the ears, with mean absolute errors of 3.97 mmHg and 3.83 mmHg, respectively, against ground truth blood pressure measurements from a clinical-grade cuff-based device. Our investigation shows the feasibility of Stereo-BP in providing frequent blood pressure estimation with future earables.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile devices**; • **Hardware** → **Sensor devices and platforms**; • **Applied computing** → **Consumer health**.

KEYWORDS

PPG, Earables, Blood pressure sensing.

ACM Reference Format:
Ananta Narayanan Balaji, Andrea Ferlini, Fahim Kawsar, Alessandro Montanari. 2023. Stereo-BP: Non-Invasive Blood Pressure Sensing with Earables. In *The 24th International Workshop on Mobile Computing Systems and Applications (HotMobile '23), February 22–23, 2023, Newport Beach, CA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3572864.3580341

1 INTRODUCTION

Blood pressure (BP) is a significant indicator of heart conditions such as stroke, heart failure, coronary artery disease and is one of the fundamental vital signs. Traditionally, BP measurements are done with an upper arm cuff-based BP monitor (i.e., sphygmomanometer). Owing to its discomfort and bulky form factor - which hinder frequent BP measurements, many techniques have been explored using wearables and mobile devices for user-friendly as well as automatic BP monitoring [8, 16, 20]. Common cuffless methods are based on pulse transit time (PTT) - which refers to the time necessary for the blood pressure wave to travel between two arterial sites [13, 27]. For instance, a PPG sensor placed on the wrist receives the blood pressure wave earlier than a PPG sensor placed on the finger of the same arm. This time delay between wrist and finger varies inversely with blood pressure. Hence, it has often been used to estimate blood pressure [27]. Previous works have used PTT between two PPG sensors placed at different locations such as wrist-finger, finger-toe [7, 13]. However, this has the drawback that two distinct, potentially unrelated, devices have to be placed on the body in contact with the skin, increasing the burden for the user.

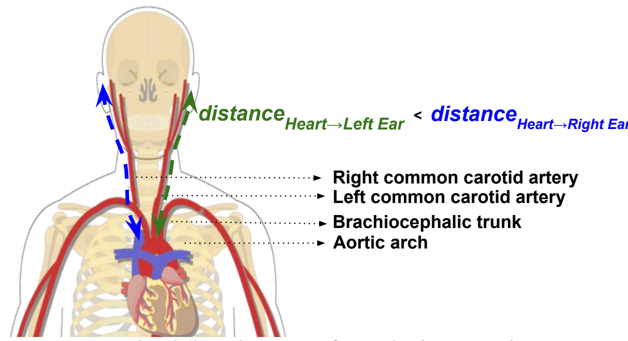

Fig. 1: Blood flow dynamics from the heart to the ears.

In this paper, we focus on a class of devices that already comes in pairs: earables [17, 22]. The ear represents a perfect location for sensing vital signs and heart-related biomarkers - owing to its complex vascular structure [14]. Several works approached BP estimation using sensors in or around the ear but still had to rely on additional signals from other devices on the body such as seismocardiogram (SCG) [34], ballistocardiogram (BCG) [18], bio-impedance [16] or electrocardiogram (ECG) [32], making these techniques cumbersome to wear and ultimately limiting usability. Few works have explored "earbuds-only" solutions to BP estimation. eBP [8] is an in-ear cuff-based system with inflatable balloons for measuring BP. However, ear-worn inflatable balloons are not user-friendly and cause pain over time. Truong et al. [29] explored the use of an in-ear microphone combined with a PPG sensor for estimating BP from a single ear-worn device. Yet, their approach requires a microphone very sensitive to low frequencies and advanced signal processing to boost the microphone's SNR.

Leveraging the fact that earables are placed at predictable locations on the body, and building on the knowledge that the pulse transit time between two locations correlates with blood pressure, we introduce Pulse Time Difference (PTD), which is defined as the time difference between blood pulses at the left and right ear. Using PTD between the two ears, we explore the possibility of using PPG sensors in the left and right earbuds to estimate blood

HotMobile '23, February 22–23, 2023, Newport Beach, CA, USA

ACM ISBN 979-8-4007-0017-0/23/02…$15.00
https://doi.org/10.1145/3572864.3580341

pressure. Commonly the heart is located almost centrally beneath the chest/breast bone. However, it does protrude towards the left side (the left ventricle) since the heart's bottom left chamber pumps oxygenated blood throughout our body and needs to be stronger than the right ventricle which only pumps blood to the lungs [21]. Only in a few rare occurrences of *dextrocardia* [28], the heart remains slightly closer to the right side of the body than the left side. Given this observation, our work provides preliminary results to experimentally validate the following research questions: *(1) Does the blood pumped from the heart arrive earlier in the left ear than the right due to its vicinity to the heart? and, if so, (2) Can an earphone pair equipped with PPG sensors leverage the pulse time difference between the left and right ears to estimate blood pressure?*

The aortic arch is the segment of the aorta which distributes blood to the head and upper extremities (Figure 1). The right common carotid artery, supplying blood to the right ear, arises from the brachiocephalic trunk, whereas the left common carotid artery, supplying the left ear, branches out directly from the aortic arch. Previous studies [11] have validated that the mean ± SD length of the carotid artery from the aortic arch to the skull base was 22.2 ± 2.2cm for the right side and 20.8 ± 1.9cm for the left side. This supports our hypothesis that the blood reaches the left ear before the right ear given that the distance of the left common carotid artery from the heart to the left ear is shorter.

To experimentally validate this anatomical characteristic, we designed *Stereo-BP* — an ear-worn prototype (Fig. 3(b)) to collect perfectly synchronized left and right PPG signals at the ears. We also developed the associated signal processing pipeline to estimate blood pressure from the PTD between left and right ear PPG signals. We then conducted a user study with 20 participants involving a series of tasks for 25 minutes. During the study, PPG signals were continuously acquired from the Stereo-BP prototype and ground truth BP was measured at specific instances using a cuff-based monitor. Comparing the ground truth BP values with that estimated from the PTD, we show how an earable featuring PPG sensors in both ears could offer accurate BP estimates without the need for a cumbersome cuff.

2 STEREO-BP: SYSTEM DESIGN

2.1 Earable Prototype

We prototype Stereo-BP as a standalone ear-worn device to study the characteristics of PPG signals from the left and right ears. Fig. 3 shows a simplified view of the hardware components along with the device sitting on a desk and a participant wearing the device. The prototype contains two reflective PPG sensors MAXM86161[3] connected via I^2C to an ESP32 microcontroller. A micro SD card slot is available to record raw data locally. Both sensors are sampled at 350Hz. This is because the PTD between left and right ear is expected to be in the range 3-300ms and the usual 50-100Hz sampling frequency of PPG sensors would not provide enough resolution. For this work, we only use the green PPG wavelength (530nm) as it yields better SNR and motion resilience [19].

HW synchronization of left and right PPG signals. Since the PTD between the left and right ears is relatively small, there has to be perfect synchronization between the PPG signals acquired from the left and right ears. Synchronization ensures that the PTD

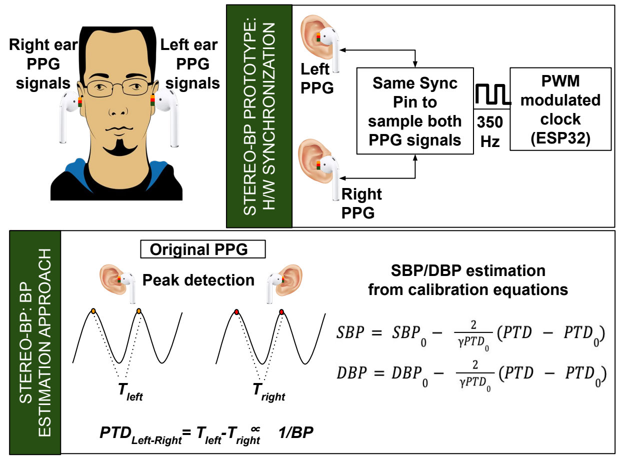

Fig. 2: Overview of the Stereo-BP's BP estimation approach.

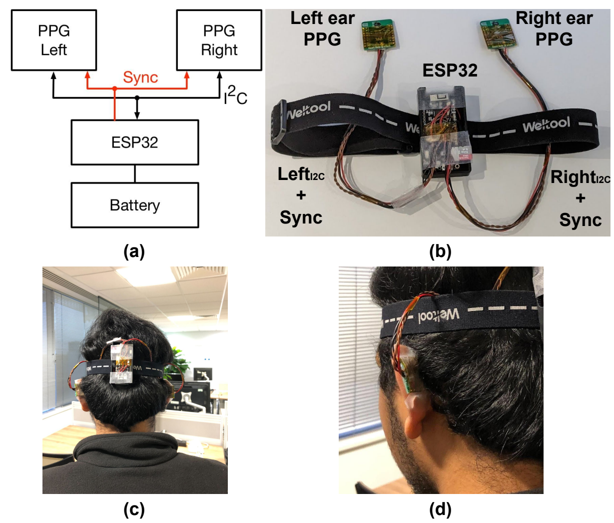

Fig. 3: (a) HW schematic. (b) Stereo-BP prototype. (c) User wearing Stereo-BP. (d) Zoomed-in PPG sensor placement on the ear helix.

is devoid of any delays from the asynchronous acquisition of left and right ear PPG signals. The MAXM86161 PPG sensor has a sync input pin which allows an external master device to acquire PPG signals only on the falling edge of the sync input. We set the ESP32 microcontroller as the master device and connected both the left and right PPG sensors to the same sync output GPIO pin in the ESP32 (Fig. 3(a)). This way, a PPG sample is acquired simultaneously from both PPG sensors when the ESP32's sync output toggles from logic HIGH to logic LOW. The sync pin in the microcontroller outputs a pulse width modulated (PWM) square wave signal at 350Hz, ensuring that samples are taken at the exact same time on the left and right ear PPG sensors.

2.2 Blood Pressure Estimation Pipeline

The entire BP estimation pipeline runs on-device on the ESP32 and an overview is shown in Figure 2. The steps involved in the BP estimation pipeline are:

(1) **PPG signal acquisition:** The PPG signals are acquired from both left and right ears continuously. We use a software buffer to

store 30s of raw PPG signals (from both ears). Once the buffer is full, the PPG data in the buffer is used for BP estimation.

(2) **Filtering:** The green PPG signals from both earbuds are filtered with a band-pass filter with cut-off frequencies of 0.4Hz and 4Hz to remove any motion artifacts while preserving the heart pulses.

(3) **Peak detection:** The peaks of each PPG wave correspond to the systolic peaks. We locate the systolic peaks as the local maxima (peaks) between local minima (valleys). Once systolic peaks are located, the time at which they occur in the left and right ear PPG signals is stored (see bottom section of Figure 2).

(4) **Pulse Time Difference measurement:** The pulse time difference (PTD) between left and right ears is calculated as - $PTD_{Left\ ear \rightarrow Right\ ear} = t_{Left} - t_{Right}$, where t_{Left} and t_{Right} denote the time at which the PPG signal peaks occur in the left and right ear, respectively. This difference captures the propagation speed of the pulse wave through the left and right common carotid artery which depend on elastic properties of the arteries [13, 27].

(5) **Blood pressure estimation:** Previous works have shown how variations in blood pressure affect pulse wave velocity (PWV)[27], and we know that PWV is inversely proportional to the time taken by the pulse wave to travel a certain distance:

$$PWV \propto \frac{1}{PTD} \tag{1}$$

where PTD is as defined above. The Moens-Korteweg's formula expresses PWV using vessel dimensions, blood density and arterial wall elasticity [31] as follows:

$$PWV = \sqrt{\frac{E \cdot h}{r\rho}} \tag{2}$$

where E is the elastic modulus, ρ is the blood density, h and r are the wall thickness and radius of the blood vessel respectively. While Hughes et al. [15] empirically deduced that the elastic modulus of the arterial walls (E) increases exponentially with blood pressure:

$$E = E_0 e^{\gamma P} \tag{3}$$

where E_0 and γ are constants which depend on the measurement site and population [15, 30]. This means that when there is a change in BP, the elastic modulus E is significantly higher than the vessel wall thickness and radius (h and r) in Eq. 2, and hence, pulse wave velocity also increases with an increase in BP. From these observations, Chen et al. [9] substituted Eq. 1 and 3 into Eq. 2 and expressed estimated BP, i.e. P_e, as:

$$P_e = P_b - \frac{2}{\gamma T_b} \Delta T \tag{4}$$

where P_b is the base blood pressure level, ΔT is the change in pulse wave propagation time, T_b is the pulse wave propagation time corresponding to the pressure level P_b and γ is a coefficient ranging from 0.016 to 0.018 [15]. Chen et al. validated this equation for systolic blood pressure. Re-writing Eq. 4 as a function of the pulse time difference (PTD) measured between the left and right ears, we obtain:

$$SBP = SBP_0 - \frac{2}{\gamma PTD_0}(PTD - PTD_0) \tag{5}$$

Similarly, other works have shown the validity of the same model for diastolic blood pressure (DBP) [12]. Thus, we can derive DBP as:

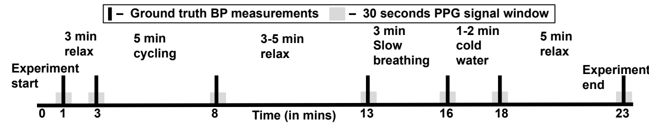

Fig. 4: Timeline of our user study protocol.

$$DBP = DBP_0 - \frac{2}{\gamma PTD_0}(PTD - PTD_0) \tag{6}$$

where SBP_0, DBP_0 and PTD_0 represent the baseline systolic and diastolic blood pressure and baseline pulse time difference of an individual. To estimate blood pressure from the ears, we derive the parameters SBP_0, DBP_0 and PTD_0 by calibrating the PTD values against ground truth BP values from a cuff-based BP monitor for each user using a least squares fit. To derive the coefficient γ, we first obtain the elastic modulus (E) for each population group (based on age) from [30] and then compute γ using Eq. 3 and the baseline blood pressures. In doing so, the BP models are tailored to the specific user and require explicit calibration before they could be used to estimate BP. We leave the investigation of how such calibration could be eliminated from our approach to future work. After calibration, the model parameters (SBP_0, DBP_0, PTD_0 and γ) are programmed into the stereo-BP prototype. During the operation of Stereo-BP, we measure the PTD between each consecutive PPG peak and average all the obtained PTD values over a time window of 30s. The average PTD is then used in the models in Eq. 5 and 6 to obtain the SBP and DBP values, respectively. Notice that our calibration relies on the fact that mechanical characteristics of blood and blood vessels change slowly over time (e.g., over several years). This allows us to estimate blood pressure with a single calibration procedure. However, if the mechanical characteristics change significantly (e.g., due to the use of medications or after a long period of time since the initial calibration), a new calibration has to be performed to capture the new blood vessels properties. We further discuss this limitation of our work in § 4.

3 EVALUATION

3.1 Data Collection Procedure

Study Population. We recruited 20 participants (7 females, avg. age = 31.5, std = 13.4) for our data collection. All the participants were healthy and had no history of cardiovascular diseases. They were individually briefed about the study and gave written, informed consent to take part in it (a compensation of $10 was offered). The study received IRB approval from our institution.

Study Protocol. The participants were asked to wear Stereo-BP on the head, as per Fig. 3(c). The device is secured behind the head with a rubber band while the PPG sensors are attached behind each ear helix. The PPG sensors need to be aligned on the same horizontal axis to avoid PTD time delays arising from the misalignment of the left and right ear sensors. The investigator manually positioned the sensors on the participants making sure they were aligned on the same horizontal axis. Ground truth BP was measured using the Omron M7 Intelli IT [2], a cuff-based BP monitor worn on the left arm. Since continuous BP measurements require invasive techniques like arterial catheterization, we opted for an accurate

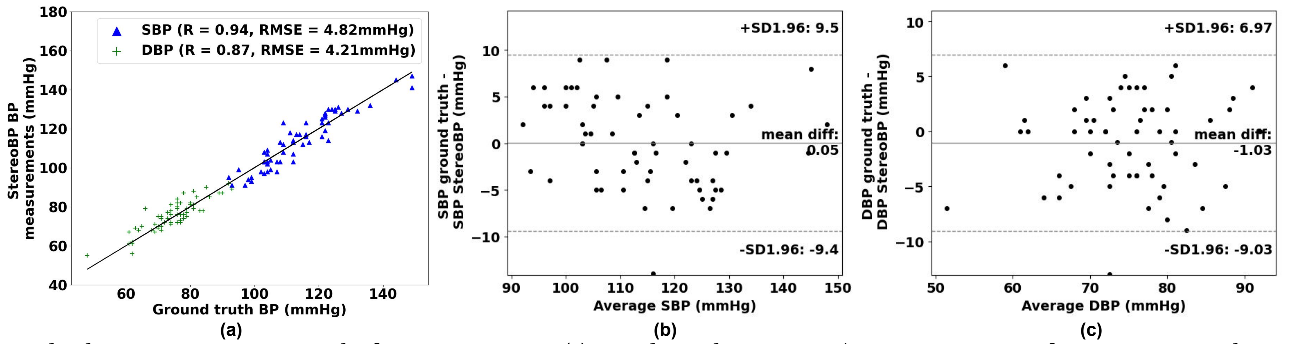

Fig. 5: Blood pressure estimation results for 20 participants. (a) Correlation between SBP/DBP measurements from Stereo-BP and ground truth blood pressure device. (b) Bland-Altman plots comparing SBP measurements from Stereo-BP and from the ground truth device. (c) Bland-Altman plots comparing DBP measurements from Stereo-BP and from the ground truth device.

yet conventional monitoring device that relies on a cuff for BP measurement.

For the entire duration of the experiment, the participants remained seated, with their feet and back supported. To induce changes in the participants' BP, we asked them to perform three activities: light physical exercise on a stationary bicycle, slow/deep breathing, and immersing their hand in cold water (cold pressor test). During physical exercise, blood pressure gradually increases and hits a plateau. Blood pressure reverts back to resting values gradually after the exercise [26]. Slow and deep breathing activates the parasympathetic nervous system and dilates blood vessels, reducing the overall blood pressure [24]. Submerging the hand in cold water instantly increases the BP levels which then gradually decrease owing to our heat regulation mechanism [23]. Ground truth BP measurements were taken at specific instances before and after each activity as described in Fig. 4. This resulted in a total of 7 ground truth blood pressure measurements per participant. The ground truth device took approximately 50 seconds to complete the measurement and the black lines in Fig. 4 report the approximate middle point for each measurement. The gray area around the ground-truth measurement reports the time window used to average the PTD values. This way, we compute the average PTD over a time window of 30s for each ground truth measurement.

For each participant, we collected synchronized PPG signals from left and right ears for the duration of the study and 7 ground truth blood pressure measurements along with their associated timestamps obtained from a cuff-based BP monitor. We also collected demographic information about the participants (age, gender) and other physiological characteristics (height, weight, body mass index, upper body measurements between the chest and left/right ears). Specifically, the following upper body measurements were collected: chest circumference (cm), chest-to-head length (cm), chest-to-left ear length (cm), chest-to-right ear length (cm), left-to-right ear length (cm), upper-body length (cm). The dataset will be made publicly available on https://www.esense.io/.

Longitudinal user study. Despite the preliminary nature of this work, we wanted to verify if our approach could yield accurate BP estimation even after several days from the calibration procedure. Hence, 9 out of the 20 participants (3 female, avg. age = 26.5 years and std = 4.6 years) were invited for two follow-up sessions. Each follow-up session was conducted after at least 7 days after the previous one. During each session, the participants repeated the same set of activities explained in Section 3.1 and ground truth data were collected at the same intervals.

Earable BP estimation approach	Number of participants	SBP error (mmHg)	DBP error (mmHg)
eBP [8]	35	1.8 ± 7.2	3.1 ± 7.9
Truong et al. [29]	10	4.07 ± 3.07	5.61 ± 4.09
Stereo-BP	**20**	**3.97 ± 3.09**	**3.83 ± 2.95**

Table 1: Mean absolute errors (MAE ± SD) of the Stereo-BP estimation compared against other approaches implemented on earables.

Blood Pressure Models Calibration. As described in §2.2 our BP estimation models need to be calibrated to find the values of the parameters SBP_0 , DBP_0 and PTD_0. As mentioned above, in the first instance we aim at finding these calibration parameters for each user individually. Therefore, for each user, we use the PTD values and the corresponding ground truth BP measurements at the ***first four instances*** (out of the seven we collected) to solve Equation (5) and Equation (6) and estimate the calibration parameters. The remaining 3 instances for each participant were used to evaluate our approach and calculate the error from the ground truth. For the longitudinal user study performed with 9 participants, the same calibration parameters estimated in the first session (i.e. week 1) were used for the other two sessions (week 2 and week 3) and all 7 measurements for both sessions are used to estimate the Stereo-BP errors against ground truth.

3.2 Results

In this section, we first report the performance of Stereo-BP in measuring the pulse time difference (PTD) between the left and right ears using PPG signals, and then its BP estimation accuracy. With this evaluation, we aim at providing an initial step towards answering the two research questions in §1.

PTD Between Left and Right Ears. We validate our hypothesis that blood arrives earlier at the left ear by looking at the first 3 minutes of data collected with Stereo-BP, when the participants were in a relaxed state. We found that the PTD between left and right ears is *always negative*, validating our hypothesis. We observe an average PTD value of -41.3ms with a standard deviation of 27.4ms on the PPG data obtained from 20 participants.

Blood Pressure Estimation. Figure 5(a) reports the correlation between the ground truth blood pressure and the blood pressure estimated by Stereo-BP for all the users. The plot indicates that the

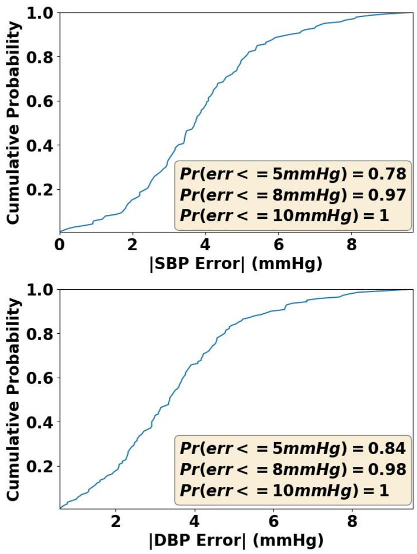

Fig. 6: CDF of the absolute error between the estimated BP from Stereo-BP and the ground truth BP measurements.

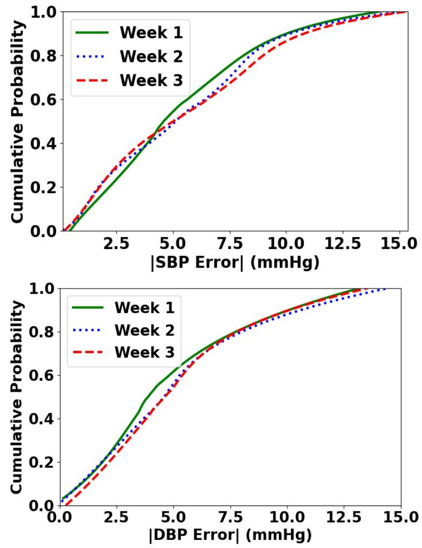

Fig. 7: CDF of the absolute errors from Stereo-BP for the 9 participants who took part in the longitudinal study over 3 weeks.

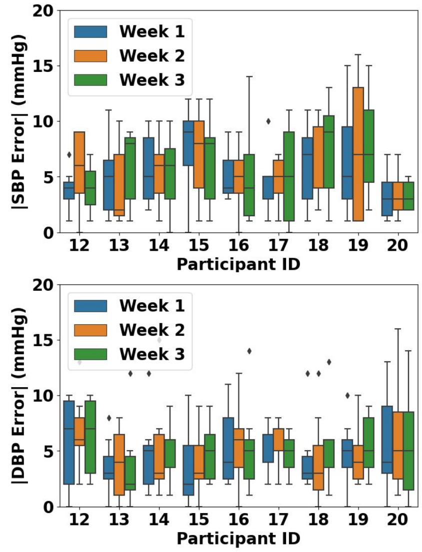

Fig. 8: Boxplots of the absolute error between the estimated SBP/DBP from Stereo-BP and the ground truth BP.

Stereo-BP measurements agree very well with the ground truth BP. The estimated SBP and DBP values from Stereo-BP show a high correlation coefficient of R=0.94 and R=0.87, respectively. Assuming a non-normal distribution for the ground truth measurements and Stereo-BP, we verify the similarity between them with the TOST equivalence procedure using the Wilcoxon Rank-Sum Test. We find the similarity is significant (p-value < 0.05) within [-4, 6] equivalence bounds.

The Bland-Altman plots in Figure 5(b) and Figure 5(c) show the agreement between Stereo-BP and the ground truth BP measurements for SBP and DBP. The mean error is close to zero with only a few data points outside the confidence intervals (±1.96 of the standard deviation of the error). The mean absolute errors (MAE ± SD) are 3.97 ± 3.09 mmHg and 3.83 ± 2.95 mmHg for SBP and DBP, respectively. Figure 6 plots the cumulative distribution function (CDF) of the absolute SBP and DBP errors in Stereo-BP. Stereo-BP achieves SBP/DBP errors lower than ±5, ±8, and ±10mmHg with a probability of 0.78/0.84, 0.97/0.98 and 1.0/1.0, demonstrating the good accuracy of our approach.

Table 1 summarizes the MAE ± SD errors of Stereo-BP against an in-ear cuff-based approach [8] and in-ear multimodal approach combining PPG and microphone sensors [29]. Although the MAE of eBP is slightly lower compared to Stereo-BP, the SD of errors is much higher than the ones achieved by Stereo-BP which also benefits from being a non-invasive approach without a cuff inflating inside the ear canal. Stereo-BP also achieves better accuracy compared to [29]. The high level of agreement we observe between Stereo-BP and the ground truth is expected because the BP estimation models are calibrated using the data of a specific user, hence they can very well capture the relationship between PTD and BP.

Longitudinal Blood Pressure Estimation. To assess the long-term validity of Stero-BP, we asked 9 out of the original 20 participants to take part in a follow-up user study (Section 3.1). During the follow-up sessions in weeks 2 and 3, the blood pressure values were estimated using the calibration parameters of week 1. Figure 7 reports the CDF curves of Stereo-BP's absolute SBP/DBP errors against reference BP during weeks 1, 2 and 3. Since the different CDFs are almost identical, it is evident that the calibration of the BP estimation models is reliable also across a few weeks.

Week	SBP error (mmHg)	DBP error (mmHg)
Week 1	5.29 ± 3.41	4.79 ± 3.45
Week 2	5.46 ± 3.71	5.15 ± 3.68
Week 3	5.59 ± 3.92	5.17 ± 3.37

Table 2: MAE ± SD of Stereo-BP blood pressure estimation during a 3 week longitudinal study with 9 participants.

The PTD of weeks 1 and 3 also remained highly correlated with $\rho = 0.94$. Assuming a non-normal distribution of the PTD values of weeks 1 and 3, the TOST equivalence procedure using the Wilcoxon Rank-Sum Test reports significant similarity (p-value < 0.05) within [-5, 5] equivalence bounds.

Figure 8 shows the box plots of Stereo-BP's weekly absolute SBP/DBP errors against the ground truth BP for each participant. The errors remained quite similar for each week indicating the reliability of our calibration approach. Table 2 summarises the weekly BP mean absolute error ± SD across the 9 participants. Although our study is limited to 3 weeks with just 9 participants, we plan to conduct a long-term user study to collect data on a monthly basis from more participants to further explore the long-term feasibility and robustness of our BP estimation approach.

4 DISCUSSION

Frequent blood pressure monitoring is essential to diagnose and prevent heart-related diseases. This has motivated the research community to explore less invasive methods for BP monitoring [8, 32]. In this work, we explored how to leverage earables to unobtrusively monitor blood pressure from the ears. Our preliminary results show that Stereo-BP can estimate SBP and DBP with mean absolute errors of 3.97 ± 3.09 mmHg and 3.83 ± 2.95 mmHg, respectively, against ground truth measurements taken with a clinical grade cuff-based BP monitor.

Stereo-BP requires a simple signal processing pipeline to measure the pulse time difference between the left and right ears and estimate BP. With the aid of a Monsoon Power Monitor [1] we measured the power consumption of our prototype when powered with a nominal voltage of 3.7V and running at the lowest ESP32 frequency of 80MHz. We found that Stereo-BP consumes 82.5mW on average (22.3mA current draw) when the two PPG sensors are sampled at 350Hz. This figure increases to 101.8mW (27.5mA current draw) when logging the raw PPG data to the micro SD. In terms of latency, once 30s of PPG data is sampled, Stereo-BP takes only 43ms for BP estimation, this includes the peak detection in both left and right PPG signals and the evaluation of the two linear models described in § 2.2. Given the low latency and power consumption, Stereo-BP exhibits high potential to be integrated into future earables for non-invasive, continuous BP estimation.

Practicality of Stereo-BP on Modern Earables: Earables are gradually integrating all the sensors necessary for cuff-less BP estimation, thus becoming a more and more promising platform. It is now common to see earbuds featuring PPG sensors (e.g., Amazfit Powerbuds [4] and Powerbuds Pro [5]). Additionally, the dual nature of earbuds (left and right) offers an interesting venue to explore BP monitoring using a multi-site approach, as shown in this paper. We acknowledge most people might not wear earables for an extended period of time (except hearing aids), hence the fine-grained temporal coverage might be an issue. Yet, Stereo-BP can still provide an accurate picture of the user's longitudinal BP trends by taking a few periodic measurements every day.

In our preliminary exploration of BP estimation with earables, we used skin-compatible tape to secure two PPG sensors behind each ear helix. This resulted in stable PPG signals which were also less prone to motion artifacts. While this approach helped us to focus on the prototype and the signal processing pipeline, we appreciate it is not practical for consumer devices. In the future, we plan to try different mechanical designs to better integrate PPG sensors into earable devices while ensuring comfort. Regardless of the mechanical design, our BP estimation pipeline can be easily ported into other devices, as it does not require expensive computational resources and it is simple to implement.

The presence of wires connecting the left and right sensors in our prototype is another factor that hinders the usability of the current device. Hence, we plan to explore how to implement Stereo-BP on true wireless stereo (TWS) earbuds. TWS earbuds are arguably the most comfortable earables.However, the lack of wires connecting the two buds makes it harder to ensure a tight time synchronization between the left and right earbuds, paramount for accurate PTD measurements. Additionally, coordination on which earbud performs the BP estimation is also necessary to balance battery consumption. These are all challenges that can be explored in future works.

User Study Sample: Given the preliminary nature of this work, our data collection campaign included a limited number of participants and was done under controlled settings. As a result, the BP values distribution across our population was limited, since all subjects were healthy and without heart-related conditions. We employed the same activities adopted in the literature to alter the participants' BP. However, the lack of health conditions in our population and the limited age range did not result in very low or very high BP values. Additionally, the pulse time difference we use to estimate blood pressure might be affected by a series of cardiovascular conditions, like cardiac arrhythmia [10] or dextrocardia, or medications, such as blood thinners. The impact of these factors on Stereo-BP accuracy has not been studied in our current user trial. We acknowledge these as limitations of the current work. In the future, we plan to run a more thorough investigation on users experiencing various heart-related ailments and explore the system's performance under daily life conditions (e.g., during body motion).

Population-scale Calibration: The linear models we employ to estimate BP from PTD represent a baseline approach that fits well with the limited number of participants we have at the current development stage. Similar models have been used in the literature when the number of participants is limited [25], however, several other models have also been proposed [6]. A more sophisticated approach encompassing various parameters (age, weight, height etc.) or machine learning models can be applied. However, these approaches require a larger amount of data to work properly. We plan to evaluate them in future work.

Population-scale calibration helps reduce the need for individual calibration by categorizing users into groups based on health and anatomical features such as height, age, BMI, cardiac health, etc. Earlier studies [33] have proposed that users can be grouped based on the relationship between systolic blood pressure and pulse transit time, and then models built for each group, rather than for each user, can be used to predict blood pressure accurately for all users within a group. From our user trial, we found that PTD increases as the height and BMI of the user increases - suggesting that users can potentially be categorized into groups based on height and BMI. While these are preliminary observations, future large-scale user studies involving many participants have the potential to reveal useful features that could be used to categorize users, and thereby help in the creation of group-based models for BP estimation.

Despite these limitations and improvement points, we believe our work offers an empirical evaluation of cuff-less BP monitoring from the ears using off-the-shelf components.

5 CONCLUSION

We proposed Stereo-BP - an earable prototype that enables the collection of synchronised PPG signals from the left and right ears. Through a user study with 20 healthy participants we empirically demonstrated that heart pulse waves reach the left ear before the right ear due to the proximity to the heart. We then showed how this time difference (i.e., pulse time difference) can be used to estimate systolic and diastolic blood pressure with mean absolute errors of 3.97 mmHg and 3.83 mmHg, respectively. With its low power consumption and promising accuracy, Stereo-BP represents a preliminary step towards non-invasive BP monitoring with earables. In the future, we plan to deploy the Stereo-BP pipeline into TWS earbuds integrated with in-ear PPG sensors and investigate the performance of the system via large-scale user studies on users with cardiovascular conditions.

REFERENCES

[1] 2016. High Voltage Power Monitor. https://www.msoon.com/online-store/High-Voltage-Power-Monitor-p90002590

[2] 2019. M7 Intelli Blood pressure monitor. https://tinyurl.com/M7Intelli

[3] 2019. MAXM86161 specifications. https://tinyurl.com/MAXM86161

[4] 2021. Amazfit PowerBuds: In-ear bluetooth headset that can detect heart rate. https://www.amazfit.com/en/powerbuds

[5] 2021. Amazfit PowerBuds Pro - Amazfit en. https://www.amazfit.com/en/powerbuds-pro

[6] Daniel Barvik, Martin Cerny, Marek Penhaker, and Norbert Noury. 2021. Noninvasive Continuous Blood Pressure Estimation from Pulse Transit Time: A review of the calibration models. *IEEE Reviews in Biomedical Engineering* (2021).

[7] Robert C Block, Mohammad Yavarimanesh, Keerthana Natarajan, Andrew Carek, Azin Mousavi, Anand Chandrasekhar, Chang-Sei Kim, Junxi Zhu, Giovanni Schifitto, Lalit K Mestha, et al. 2020. Conventional pulse transit times as markers of blood pressure changes in humans. *Scientific Reports* 10, 1 (2020), 1–9.

[8] Nam Bui et al. 2019. eBP: A Wearable System For Frequent and Comfortable Blood Pressure Monitoring From User's Ear. In *The 25th Annual International Conference on Mobile Computing and Networking* (Los Cabos, Mexico) *(MobiCom '19)*. Association for Computing Machinery, New York, NY, USA, Article 53.

[9] Wenxi Chen, Toshiyo Kobayashi, Seiichi Ichikawa, Yasuo Takeuchi, and Tatsuo Togawa. 2000. Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. *Medical and Biological Engineering and Computing* 38, 5 (2000), 569–574.

[10] Yang Chen, Shoulin Huang, Tong Wang, and Ting Ma. 2020. Validation of Pulse Transit Time Based Blood Pressure Estimation on Atrial Fibrillation Patients. In *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, 2679–2682.

[11] Farooq Choudhry, John Grantham, Ansaar Rai, and Jeffery Hogg. 2015. Vascular geometry of the extracranial carotid arteries: An analysis of length, diameter, and tortuosity. *Journal of neurointerventional surgery* 8 (04 2015).

[12] Xiaorong Ding, Bryan P Yan, Yuan-Ting Zhang, Jing Liu, Ni Zhao, and Hon Ki Tsang. 2017. Pulse transit time based continuous cuffless blood pressure estimation: A new extension and a comprehensive evaluation. *Scientific reports* 7, 1 (2017), 1–11.

[13] Mohamed Elgendi, Richard Fletcher, Yongbo Liang, Newton Howard, Nigel H Lovell, Derek Abbott, Kenneth Lim, and Rabab Ward. 2019. The use of photoplethysmography for assessing hypertension. *NPJ digital medicine* 2, 1 (2019).

[14] Andrea Ferlini, Alessandro Montanari, Chulhong Min, Hongwei Li, Ugo Sassi, and Fahim Kawsar. 2021. In-Ear PPG for Vital Signs. *IEEE Pervasive Computing* (2021).

[15] DJ Hughes, Charles F Babbs, LA Geddes, and JD Bourland. 1979. Measurements of Young's modulus of elasticity of the canine aorta with ultrasound. *Ultrasonic imaging* 1, 4 (1979), 356–367.

[16] Bassem Ibrahim and Roozbeh Jafari. 2019. Cuffless blood pressure monitoring from an array of wrist bio-impedance sensors using subject-specific regression models: Proof of concept. *IEEE transactions on biomedical circuits and systems* 13, 6 (2019), 1723–1735.

[17] Fahim Kawsar, Chulhong Min, Akhil Mathur, and Alessandro Montanari. 2018. Earables for personal-scale behavior analytics. *IEEE Pervasive Computing* 17, 3 (2018), 83–89.

[18] Chang-Sei Kim, Andrew M Carek, Ramakrishna Mukkamala, Omer T Inan, and Jin-Oh Hahn. 2015. Ballistocardiogram as proximal timing reference for pulse transit time measurement: Potential for cuffless blood pressure monitoring. *IEEE Transactions on Biomedical Engineering* 62, 11 (2015), 2657–2664.

[19] SeungMin Lee, HyunSoon Shin, and ChanYoung Hahm. 2016. Effective PPG sensor placement for reflected red and green light, and infrared wristband-type photoplethysmography. In *2016 18th International Conference on Advanced Communication Technology (ICACT)*.

[20] Kenta Matsumura, Peter Rolfe, Sogo Toda, and Takehiro Yamakoshi. 2018. Cuffless blood pressure estimation using only a smartphone. *Scientific reports* 8, 1 (2018).

[21] Steve Meek and Francis Morris. 2002. Introduction. I—Leads, rate, rhythm, and cardiac axis. *BMJ* 324, 7334 (2002), 415–418.

[22] Chulhong Min, Alessandro Montanari, Akhil Mathur, Seungchul Lee, and Fahim Kawsar. 2018. Cross-modal approach for conversational well-being monitoring with multi-sensory earables. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. 706–709.

[23] S Mishra, M Manjareeka, and J Mishra. 2012. Blood pressure response to cold water immersion test. *International Journal of Biology, Pharmacy and Allied Sciences* 10 (2012), 1483–1491.

[24] Hisao Mori, Hareaki Yamamoto, Masaomi Kuwashima, Saburo Saito, Hiroshi Ukai, Kouichi Hirao, Mikio Yamauchi, and Satoshi Umemura. 2005. How does deep breathing affect office blood pressure and pulse rate? *Hypertension research* 28, 6 (2005), 499–504.

[25] R. A. Payne, C. N. Symeonides, D. J. Webb, and S. R. J. Maxwell. 2006. Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure. *Journal of Applied Physiology* 100, 1 (2006), 136–141.

[26] Ahmad Sabbahi, Ross Arena, Leonard A. Kaminsky, Jonathan Myers, and Shane A. Phillips. 2018. Peak Blood Pressure Responses During Maximum Cardiopulmonary Exercise Testing. *Hypertension* 71, 2 (2018), 229–236.

[27] Josep Solà and Ricard Delgado. 2019. *The Handbook of Cuffless Blood Pressure Monitoring A Practical Guide for Clinicians, Researchers, and Engineers.*

[28] Sanjanaa Srikant, Darshit Dave, and Dhara Dave. 2021. Isolated Dextrocardia with Situs Solitus–Dextroversion in a Ugandan Baby: A Case Report. *International Medical Case Reports Journal* 14 (2021), 797.

[29] Hoang Truong, Alessandro Montanari, and Fahim Kawsar. 2022. Non-Invasive Blood Pressure Monitoring with Multi-Modal In-Ear Sensing. In *ICASSP 2022 - 2022 IEEE International Conference on Acoustics, Speech and Signal Processing*.

[30] Tokuhisa Uejima et al. 2020. Age-specific reference values for carotid arterial stiffness estimated by ultrasonic wall tracking. *Journal of Human Hypertension* 34, 3 (2020), 214–222.

[31] Charalambos Vlachopoulos, Michael O'Rourke, and Wilmer W Nichols. 2011. *McDonald's blood flow in arteries: theoretical, experimental and clinical principles.* CRC press.

[32] Eric S Winokur, David Da He, and Charles G Sodini. 2012. A wearable vital signs monitor at the ear for continuous heart rate and pulse transit time measurements. In *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2724–2727.

[33] Syunsuke Yamanaka, Koji Morikawa, Hiroshi Morita, Ji Young Huh, and Osamu Yamamura. 2021. Calibration-Free Cuffless Blood Pressure Estimation Based on a Population With a Diverse Range of Age and Blood Pressure. *Frontiers in Medical Technology* 3 (2021). https://doi.org/10.3389/fmedt.2021.695356

[34] Chenxi Yang and Negar Tavassolian. 2016. Pulse transit time measurement using seismocardiogram and in-ear acoustic sensor. (2016), 188–191.