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# Ear and Finger PPG Wearables for Night and Day Beat-to-Beat Interval Detection

Serj Haddad, Assim Boukhayma, and Antonino Caizzone

*Abstract*— **In this work, we study the accuracy of ear and finger photoplethysmography (PPG) based inter-beat interval (IBI) detection and estimation compared to the R-to-R interval (RRI) values derived from the electrocardiography (ECG). Seven male subjects with a mean age of $34.29 \pm 5.28$ years are asked to wear simultaneously the Senbiosys earbud SBE2200 and the Senbiosys ring SBF2200 together with the Shimmer3 ECG development kit. The study includes 43 recordings with a total duration of 72.21 hours divided into 37.10 and 35.11 hours of sleep and wake recordings, respectively. The obtained results show that the earbud PPG enables a higher beat detection rate and a more accurate IBI estimation than the ring. They also show that the performance of the beat detection and estimation is significantly better for the sleep recordings compared to the wake recordings with an increase of $\sim 1.5\%$ in the detection rate and a decrease of $\sim 1$ ms and $\sim 4$ ms in the mean absolute error (MAE) and the root mean square error (RMSE), respectively. Moreover, we propose a novel fusion scheme that smartly combines the IBI values from both devices and achieves a superior performance with a beat detection rate of 99.22% and an IBI estimation with MAE and RMSE values of 7.42 ms and 13.45 ms, respectively.**

## I. Introduction

Photoplethysmography (PPG) is one of the most attractive technologies that provides a low cost and an unobtrusive alternative for continuous heart-rate (HR) and heart rate variability (HRV) monitoring. It is based on illuminating the skin with a light-emitting diode (LED) and measuring the intensity of either the transmitted or the reflected light to the photo-sensor. This optical solution detects the variations in the volume of the blood flow. Analyzing these volumetric changes helps detect the heart beats and thus estimate the inter-beat intervals (IBI). The estimated IBI values further enable pulse-rate variability analysis (PRV).

In the past decade, different wearable devices, such as smart watches, smart rings, earbuds, headphones, etc., included PPG sensors, which triggered a significant interest among researchers to study the efficiency of PPG-based continuous HR and HRV monitoring solutions. These studies proved that the PPG-based PRV analysis is adequately accurate compared to the ECG-based HRV analysis [1], [2], for healthy subjects or subjects with regular heartbeats and for subjects with arrhythmia, such as atrial fibrillation (AF) [3], or different types of ectopic heartbeats [4]. In this work however, our main objective is to compare the beat-to-beat detection and estimation accuracy between the ear PPG and the finger PPG. The comparison is performed on data collected during both day/wake and night/sleep hours. Moreover, we propose a fusion scheme that combines the IBI outputs of both signals to mitigate the impact of the motion artifacts and improve the overall performance.

The paper is organized as follows. In Section II, we briefly discuss the importance of having two reliable PPG signals collected from two body sites that are far apart. Section III presents the materials and the methods used for this study. Section IV presents the performance of the IBI detection and estimation algorithm applied to the Senbiosys ear and finger PPG signals. Finally, Section V concludes this work.

All authors (corresponding author: serj.haddad@senbiosys.com) are with Senbiosys SA, Neuchâtel, Switzerland.

## II. Motivation

Acquiring PPG signals from different body locations has many advantages and is attracting a significant amount of interest with the flourishing of the wearable devices market. One of the advantages of having two PPG signals is to introduce redundancy, as shown in this work. Another advantage is to determine how fast the pulse wave propagates from one body location to another.

### A. HRV Monitoring

For accurate HRV analysis, it is important to have accurate IBI estimation with high beat detection rate to ensure sufficient number of consecutively accurate IBI values. Sometimes it is challenging to achieve this goal by relying solely on one PPG sensor due to motion artifacts. Having an auxiliary PPG signal from another body location introduces redundancy especially if the two body locations are far apart and have a certain degree of independence in terms of movement and motion artifacts.

### B. Blood Pressure Monitoring

Arterial stiffness directly affects the blood pressure. The stiffening of the arteries increases the velocity of the pressure wave propagation through the arterial tree and results in an increased blood pressure. Pulse wave velocity (PWV) techniques aim at estimating the blood pressure by computing the propagation velocity. Some of these techniques estimate the pulse transit time (PTT) [6], which is the time delay between proximal and distal arterial waveforms and is inversely proportional to the PWV. This can be achieved by using two PPG sensors in two different body locations.

## III. Materials and Methods

### A. Participants

This study includes 43 recordings, 7 night recordings during sleep ($\sim$ 5 to 6 hours of recording per participant) and 36 day recordings of different lengths. The total duration

(a) (b)

Fig. 1. (a) AThe earbud SBE2200 vs the ring SBF2200. (b) PPG data acquisition setup using the earbud and the ring.

TABLE I
THE STATISTICS OF THE REFERENCE RR INTERVALS.

| | |
|---|---|
| **Number of RRI's** | 213072 |
| **Mean ± SD (ms)** | $1040 \pm 170$ |
| **pNN50 (%)** | 29.40 |
| **pNN20 (%)** | 71.13 |

of the recordings is 72.21 hours. The *sleep* and the *wake* measurements comprise 37.10 and 35.11 hours of recording, respectively. Seven male subjects with a mean age of $34.29 \pm 5.28$ years participated in this study. One of the subjects has many ventricular ectopic beats (premature ventricular contractions (PVC)).

The procedures followed in this work comply with the guidelines of the Helsinki Declaration of 1975, as revised in 2000. The subjects provided an informed consent to participate in the study and could have withdrawn from the study at any time. Prior the analysis, all data is rendered anonymous.

### B. Data acquisition

Ear and Finger PPG signals are recorded simultaneously using the Senbiosys devices, namely the earbud SBE2200 and the ring SBF2200, as shown in Fig. 1(a). The participants are asked to wear the earbud in the left ear and the ring in the middle finger, as shown in Fig. 1(b). For both of the PPG devices, the sampling frequency is set to 122 Hz and the LED driving current is set to 4.1 mA. For the reference ECG recordings, the Shimmer3 Consensys ECG development kit is used to monitor 4 ECG channels. The sampling frequency for the ECG recordings is set to 1024 Hz.

The Senbiosys proprietary IBI detection software is used to extract the IBI values from the ear and the finger PPG signals. On the other hand, the ConsensysPRO Software version 1.6.0 is utilized to extract the RR intervals (RRI) from the ECG signals. The statistics of the reference RRI values is summarized in Table I. The mean RRI value is $1040 \pm 170$ ms, which means that the average heart rate of the participants is $< 60$ beats per minute. Moreover, the average heart rate variability of the participants is relatively high with a respective pNN50 and pNN20 values of 29.40% and 71.13%, where pNN50 and pNN20 denote the percentage of the RR intervals with a successive difference exceeding 50 ms and 20 ms, respectively.

### C. Signal Processing

The raw PPG signals from the earbud and the ring are filtered using a band-pass filter with cutoff frequencies of 0.3 Hz and 4.5 Hz to remove the undesired frequency components. The beat-to-beat detection algorithm presented in [5] is applied on the filtered PPG signal. To evaluate the beat detection accuracy, we identify the correctly detected beats, the missed beats, and the extra beats. To achieve this, we match the PPG-based IBI's to their corresponding ECG-based RRI's. The approach used in [5] is also followed in this work.

We start by synchronizing the time vectors of the different devices by introducing time shifts between the IBI and the RRI time series that minimize the mean absolute error (MAE) between the two vectors. Each PPG beat is marked as a correct beat, a missed beat, or an extra beat, based on the number of ECG beats identified in the vicinity of the given PPG beat. We count the number of beats detected using the ECG signal in the interval $[t-0.5l, t+0.5l]$, where $t$ is the time when the PPG beat was detected and $l$ is the length of the corresponding IBI. If only one reference ECG beat is detected, then the PPG beat is labeled as a correct beat. A PPG beat without a reference beat in the specified interval is said to be an extra beat. Finally, the ECG beats that are not referenced by a PPG beat are considered to be missed PPG beats. Since our recordings do not include motion detection signals, we discard the noisy intervals using the following strategy. We divide the PPG recordings into 10-second intervals. We keep the intervals where more than 80% of the reference beats are correctly detected. This is justified by the fact that the intervals containing many missed beats also contain, with high probability, motion artifacts. This procedure is applied separately on the finger PPG IBI vector and the RRI vector pair and on the ear PPG IBI vector and the RRI vector pair. Finally, after identifying the correctly detected beats, we evaluate the accuracy of the IBI estimation. For our analysis we use the following evaluation metrics: mean absolute error (MAE, in ms), mean error (ME, in ms), root mean square error (RMSE, in ms), and mean absolute percentage error (MAPE).

### D. Algorithm

In what follows, we provide a brief description of our beat detection algorithm implemented on the ear and the finger PPG signals independently. Moreover, we explain our fusion scheme that combines the two independent beat detection and estimation outputs of the two PPG signals.

*1) Beat Detection:* The PPG-based beat detection block implements the beat-to-beat detection algorithm presented in [5]. It is based on identifying the peaks of the first derivative of the PPG signal, known as the velocity PPG (VPGG). The identified points represent the maximum slope of the PPG pulse. Each of the detected PPG pulses is further associated

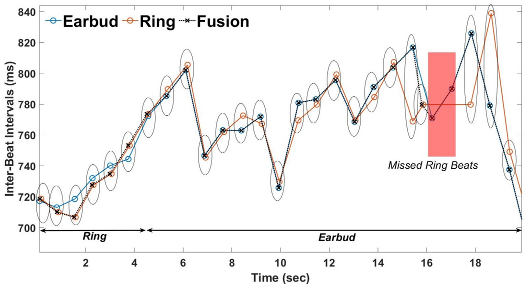


Fig. 2. An illustration of the fusion scheme between the IBI values generated using the earbud PPG and the IBI values generated by the ring PPG. The black ovals in the plot represent the IBI matching of the scheme.

with a signal quality index (SQI) to indicate the quality of the detected beat. The SQI index is a value between 0 and 1 that indicates the reliability of the beat estimation, with larger index values indicating higher reliability. The SQI value is based on: 1) the eligibility of the detected beat length, 2) how much the detected beat interval deviates from the previous beat intervals, 3) the skewness of the corresponding PPG pulse.

*2) IBI Fusion:* We propose a simple IBI fusion scheme that combines the IBI outputs of the earbud PPG with the that of the ring PPG. The scheme is based on two main steps, namely, IBI matching and IBI fusing. The IBI matching is based on the same approach as that of the PPG IBI and the ECG RR matching. Note that the earbud provides the proximal PPG signal and the ring provides the distal PPG signal. Since the pulse wave requires more time to travel from the heart to distal locations, such as the finger, the beat detection happens earlier with the ear PPG. The IBI matching block of the fusion scheme synchronizes the values of the earbud IBI buffer with that of the ring IBI buffer. After IBI matching, the IBI fusing is based on the SQI values of the detected beats. For each IBI match, the fusion scheme votes for the IBI value that has a larger SQI. In other words, the fusion scheme votes for the earbud IBI if its SQI value is larger than that of the ring IBI, and votes for the ring IBI otherwise. In the case of a missing IBI match, the fusion scheme obviously selects the available IBI value. In Fig. 2, we illustrate the described fusion mechanism: 1) The IBI matching is illustrated using the black ovals. Note that the red rectangle shows a missing IBI match, where there are only IBI values from the ear PPG. 2) The IBI fusing is illustrated by the black line plot, which shows that the fusion scheme votes for the ring IBI values for the first 7 IBI's and votes for the earbud IBI values for the remaining IBI's.

## IV. Results

The results of this work can be divided into three categories: IV-A) A comparison of the performance of the beat detection/estimation algorithm between the earbud and the ring. IV-B) The performance enhancement that the proposed fusion scheme provides. IV-C) A comparison of the performance metrics between the day (wake) and the night (sleep) recordings.

TABLE II
The beat detection performance: earbud vs ring.

| | ***Earbud*** | ***Ring*** |
|---|---|---|
| **Correctly Detected Beats** | 209811 | 208539 |
| **Correct Beats (%)** | 98.47 | 97.87 |
| **Missed Beats (%)** | 1.53 | 2.13 |
| **Extra Beats (%)** | 1.84 | 1.40 |

TABLE III
The performance of the IBI Estimation: earbud vs ring.

| | ***Earbud*** | ***Ring*** |
|---|---|---|
| **Number of High Quality IBI's** | 166275 | 152958 |
| **MAE (ms)** | 7.52 | 8.10 |
| **ME (ms)** | 0.65 | 0.24 |
| **RMSE (ms)** | 13.71 | 13.97 |
| **MAPE (%)** | 0.74 | 0.80 |

### *A. Earbud vs Ring*

*1) Beat Detection:* The performance of the IBI detection algorithm using the earbud and the ring is summarized in Table II. The results show that the earbud has a better beat detection rate than the ring. The percentage of the correctly detected beats in the earbud and the ring is 98.47% and 97.87%, respectively. On the other hand, the ring has a lower percentage of extra beats (1.40%) compared to the earbud (1.84%).

*2) IBI Estimation:* For the IBI estimation performance analysis, we only consider the 10-second *clean* windows, equivalently, the windows with beat detection rates greater than 80%, as described in Section III-C. This approach results in discarding more beats for the finger PPG compared to the ear PPG, because the percentage of the missed beats in the ring (2.13%) is larger than that of the earbud (1.53%) (refer to Table II). As shown in Table III, the number of high quality IBI's in the earbud (166275) is larger than that of the ring (152958). Moreover, in terms of the IBI estimation accuracy, the earbud outperforms the ring with an MAE of 7.52 ms versus 8.10 ms for the ring. For the remaining performance metrics, namely, the ME, the RMSE, and the MAPE values, a similar performance is observed in both devices.

### *B. Fusion Scheme*

The beat detection performance and the IBI estimation accuracy of the fusion scheme are summarized in Tables IV and V, respectively. The fusion scheme demonstrates an improved detection rate of 99.22% with a slight increase in the number of extra beats. Note that a small decrease in the percentage of missed beats increases the number of clean windows, which results in a larger impact on the number of high quality IBI's. As shown in Table V, the number of high quality IBI's increases to 173620 for the fusion scheme. This represents a 4.42% and a 13.51% increase compared to the number of high quality IBI's of the earbud and the ring, respectively. Moreover, the enhancement in the beat detection rate of the fusion scheme does not compromise its IBI estimation accuracy. On the contrary, the fusion scheme

TABLE IV

THE BEAT DETECTION PERFORMANCE OF THE FUSION SCHEME.

| | |
|---|---|
| **Correctly Detected Beats** | 211406 |
| **Correct Beats (%)** | 99.22 |
| **Missed Beats (%)** | 0.78 |
| **Extra Beats (%)** | 1.94 |

TABLE V

THE IBI ESTIMATION PERFORMANCE OF THE FUSION SCHEME.

| | |
|---|---|
| **Number of High Quality IBI's** | 173620 |
| **MAE (ms)** | 7.42 |
| **ME (ms)** | 0.63 |
| **RMSE (ms)** | 13.45 |
| **MAPE (%)** | 0.72 |

demonstrates a slightly better IBI estimation than the earbud and the ring, as shown in Table V.

### C. Wake vs Sleep

We present a comparison of the performance of the algorithm between the wake and the sleep recordings for the earbud, the ring, and the fusion scheme in Tables VI and VII. The beat detection performance metrics for the sleep recordings are better than that of the day recordings for all the three cases (earbud, ring, and fusion) (refer to Table VI). This is due to the fact that the day recordings, which are performed during the working hours, contain considerably more motion artifacts than the night recordings. Similarly, the accuracy of the IBI estimation algorithm is higher for the night recordings with a decrease of $\sim 1$ ms in the MAE and a decrease of $\sim 4$ ms in the RMSE (refer to Table VII). It is also worth mentioning that since the total duration of wake and sleep recordings are approximately the same, one would expect larger number of beats for the wake recordings since the heart rate is lower during sleep. However, due the motion artifacts during the day recordings, we had to discard significantly more ECG intervals for the wake recordings.

TABLE VI

THE BEAT DETECTION PERFORMANCE: WAKE VS SLEEP.

| | | ***Wake*** | ***Sleep*** |
|---|---|---|---|
| **Correctly Detected Beats** | ***Earbud*** | 89087 | 120724 |
| | ***Ring*** | 88916 | 119623 |
| | ***Fusion*** | 89976 | 121430 |
| **Correct Beats (%)** | ***Earbud*** | 97.49 | 99.21 |
| | ***Ring*** | 97.30 | 98.30 |
| | ***Fusion*** | 98.46 | 99.79 |
| **Missed Beats (%)** | ***Earbud*** | 2.51 | 0.79 |
| | ***Ring*** | 2.70 | 1.70 |
| | ***Fusion*** | 1.54 | 0.21 |
| **Extra Beats (%)** | ***Earbud*** | 2.68 | 1.21 |
| | ***Ring*** | 1.92 | 1.00 |
| | ***Fusion*** | 2.85 | 1.26 |

TABLE VII

THE IBI ESTIMATION PERFORMANCE: WAKE VS SLEEP.

| | | ***Wake*** | ***Sleep*** |
|---|---|---|---|
| **Number of High Quality IBI's** | ***Earbud*** | 68667 | 97608 |
| | ***Ring*** | 65778 | 87180 |
| | ***Fusion*** | 70166 | 103454 |
| **MAE (ms)** | ***Earbud*** | 8.23 | 7.01 |
| | ***Ring*** | 8.32 | 7.94 |
| | ***Fusion*** | 8.12 | 6.94 |
| **ME (ms)** | ***Earbud*** | 0.91 | 0.47 |
| | ***Ring*** | 0.79 | −0.17 |
| | ***Fusion*** | 0.76 | 0.54 |
| **RMSE (ms)** | ***Earbud*** | 16.14 | 12.00 |
| | ***Ring*** | 15.96 | 12.48 |
| | ***Fusion*** | 15.65 | 11.97 |
| **MAPE (%)** | ***Earbud*** | 0.77 | 0.72 |
| | ***Ring*** | 0.80 | 0.81 |
| | ***Fusion*** | 0.77 | 0.69 |

## V. CONCLUSION

In this work, we analyze the accuracy of the IBI detection and estimation using ear and finger PPG signals independently and also simultaneously through a fusion scheme that we propose. The obtained results confirm that the earbud PPG enables a higher beat detection rate and a more accurate IBI estimation than the ring. On the hand, our fusion scheme that smartly combines the IBI values from both devices provides an optimal performance with a beat detection rate of 99.22% and an IBI estimation with MAE, ME, RMSE, and MAPE values of 7.42 ms, 0.63 ms, 13.45 ms, and 0.72%, respectively. Furthermore, the beat detection and estimation proved to be significantly better for the sleep recordings compared to the wake recordings with an increase of $\sim 1.5\%$ in the detection rate, a decrease of $\sim 1.5\%$ in the extra beats, a decrease of $\sim 1$ ms in the MAE, and a decrease of $\sim 4$ ms in the RMSE. This confirms the growing interest in PPG devices for continuous HR/HRV monitoring during sleep.

## REFERENCES


[1] S. Lu, H. Zhao, K. Ju, K. S. Shin, M. H. Lee, K. Shelley, and K. H. Chon, "Can photoplethysmography variability serve as an alternative approach to obtain heart rate variability information?," in *2008 Computing in Cardiology (CinC)*, vol. 22, pp. 23–29, 2008.

[2] A. Schäfer and J. Vagedes, "How accurate is pulse rate variability as an estimate of heart rate variability? a review on studies comparing photoplethysmographic technology with an electrocardiogram," *International Journal of Cardiology*, vol. 166, pp. 15–29, June 2013.

[3] A. Tarniceriu, V. Vuohelainen, S. Haddad, T. Halkola, J. Parak, J. Laurikka, and A. Vehkaoja, "Performance of wrist photoplethysmography in monitoring atrial fibrillation in post cardiac surgery patients," in *2019 Computing in Cardiology (CinC)*, pp. 1–4, 2019.

[4] S. Haddad, J. Harju, A. Tarniceriu, T. Halkola, J. Parak, I. Korhonen, A. Yli-Hankala, and A. Vehkaoja, "Ectopic beat-detection from wrist optical signals for sinus rhythm and atrial fibrillation subjects," in *XV Mediterranean Conference on Medical and Biological Engineering and Computing – MEDICON*, pp. 150–158, September 2019.

[5] S. Haddad, A. Boukhayma, and A. Caizzone, "Beat-to-beat detection accuracy using the ultra low power senbiosys ppg sensor," in *8th European Medical and Biological Engineering Conference (EMBEC 2020)*, pp. 178–188, Springer, 2020.

[6] R. Wang, W. Jia, Z. H. Mao, R. J. Sclabassi, and M. Sun, "Cuff-free blood pressure estimation using pulse transit time and heart rate," in *International Conference on Signal Processing*, pp. 115–118, 2014.