2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Photoplethysmography Based Blood Pressure Monitoring Using the Senbiosys Ring

Serj Haddad, Assim Boukhayma, Gilles Di Pietrantonio,
Anthony Barison, Gilles de Preux, and Antonino Caizzone

Abstract— **In this work, we evaluate the accuracy of our cuff-less photoplethysmography based blood pressure monitoring (PPG-BPM) algorithm. The algorithm is evaluated on an ultra low power photoplethysmography (PPG) signal acquired from the Senbiosys Ring. The study involves six male subjects wearing the ring for continuous finger PPG recordings and non-invasive brachial cuff inflated every two to ten minutes for intermittent blood pressure (BP) measurements. Each subject performs the required recordings two to three times with at least two weeks difference between any two recordings. In total, the study includes 17 recordings 2.21 ± 0.89 hours each. The PPG recordings are processed by the PPG-BPM algorithm to generate systolic BP (SBP) and diastolic BP (DBP) estimates. For the SBP, the mean difference between the cuff-based and the PPG-BPM values is -0.28 ± 7.54 mmHg. For the DBP, the mean difference between the cuff-based and the PPG-BPM values is -1.30 ± 7.18 mmHg. The results show that the accuracy of our algorithm is within the 5 ± 8 mmHg ISO/ANSI/AAMI protocol requirement.**

I. INTRODUCTION

Hypertension is a long-term medical condition in which the blood pressure (BP) in the arteries is persistently elevated. It is the main risk factor for cardiovascular diseases and a major cause of premature death worldwide [1]. According to the World Health Organization (WHO), the number of people with hypertension around the world is estimated to be 1.13 billion. More than two-thirds of the population with hypertension live in average and low income countries. Unfortunately, less than 20% of hypertensive people have the problem under control. According to WHO, one of the global targets regarding diseases that are noncommunicable is that by the year 2025 we have a 25% reduction (baseline 2010) in the prevalence of hypertension [1].

Based on the key facts mentioned, the potential solution to the prevalence of hypertension must address the following issue: hypertension is largely asymptomatic, hence the name - silent killer, which requires accurate, long-term, and continuous monitoring for a large number of populations. This means that the proposed solution should be 1) cheap to make it available to the widest possible population, 2) unobtrusive and comfortable to enable continuous long-term monitoring during regular daily activities, and most importantly, 3) *sufficiently* accurate compared to the clinically accepted BP monitoring devices.

The arterial line is an invasive method and the gold standard to measure BP values continuously and accurately, yet it is not suitable for daily ambulatory use [3]. On the other hand, cuff-based, auscultatory and oscillometric, BP monitoring, which is the gold non-invasive method, is intermittent and occludes the blood flow in arteries resulting in uncomfortable and unpleasant feelings [2]. Frequent cuff inflation and blood flow occlusion become painful and prevent a proper monitoring especially during sleep [3].

Photoplethysmography (PPG) was proposed as a promising low-cost, non-invasive, and non-occlusive technique for continuous BP estimation [4], [5]. PPG involves using a light-emitting diode (LED) to illuminate the skin and measuring the intensity of either the transmitted or the reflected light to a photo-diode. This optical solution detects the volumetric changes in the blood flow. It is already available in many wearable devices and smart phones. Many studies confirm the accuracy of PPG-based solutions to monitor heart rate (HR) and heart rate variability (HRV) [6], stress levels [7], irregularity in heart beats [9], [10], sleep quality [11], etc. For BP monitoring, PPG-based methods rely on either pulse wave velocity (PWV) techniques [13], [14] or pulse wave analysis (PWA) methods [15], [16]. PPG-based BP monitoring solutions that rely on PWV techniques require the use of auxiliary sensors, such electrocardiography (ECG), which limits its practicality and usability. For this reason, in this work, we focus on PPG-based BP estimation based on pulse wave analysis (PWA) technique which solely requires PPG signals acquired using the ultra low power SB200 PPG sensor [17].

The paper is organized as follows. Section II presents the methods used for this study. This includes information about the participants of the study, the statistics of the acquired data, and the methods utilized to process the collected data. Section III evaluates the accuracy of our PPG-based blood pressure monitoring technology (PPG-BPM) [18] in estimating the systolic blood pressure (SBP) and the diastolic blood pressure (DBP) compared to the cuff oscillometric measurements. Section IV analyzes the results of the study and presents some observations. Finally, Section V summarizes our conclusions.

II. MATERIALS AND METHODS

A. Data acquisition

1) Participants and Protocol: Six healthy male subjects with a mean age of 32 ± 2.61 years participated in this study. All the recordings were done during daytime. The participants are asked to wear the ring on the index finger, as shown in Fig. 1, to collect PPG data. They are also asked to wear the cuff of an Omron Automatic BP monitor (M7 Intelli

---

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

978-1-7281-1178-0/21/$31.00 ©2021 IEEE

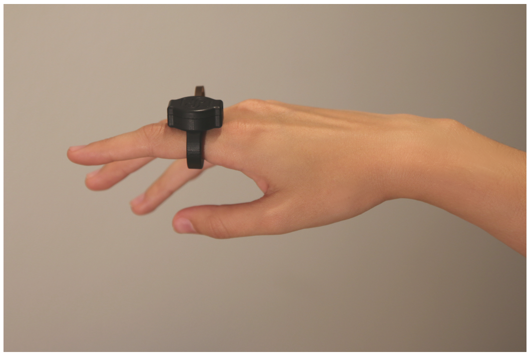

Fig. 1. The ring on the index finger.

TABLE I
THE STATISTICS OF THE CUFF-BASED BP RECORDINGS.

	Systolic BP	***Diastolic BP***
Mean (mmHg)	115.20	66.73
Standard deviation (mmHg)	10.68	6.59
Range (mmHg)	88-158	48-88

IT) on the arm opposite to the ring wearing hand. BP values are recorded every 2 to 10 minutes. The participants are asked to perform some activities like leg stretching, climbing stairs, etc. to introduce fluctuations in their blood pressure values without increasing their heart rate as much as possible.

Each recording includes morning, afternoon, and evening data with a mean duration of 2.21 ± 0.89 hours. Each subject performs two to three recordings (distinct days) with at least two weeks difference between any two recordings. The study includes 17 recordings with an approximate total duration of 37.5 hours. Regarding the reference BP data, the brachial cuff is inflated every two to ten minutes. The subjects are asked to increase the number of cuff recordings after they perform light exercises to track the BP fluctuations. In total, the study includes 413 cuff-based reference SBP and DBP data.

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.

2) Signals: The available signals in this study are finger PPG and cuff-based BP recordings. The sampling frequency of the PPG signal is 122 Hz. The reference data from the cuff recordings contains 413 SBP and DBP labels. The statistics of the reference cuff-based BP recordings is summarized in Table I.

The evaluation metrics used in the study include: mean absolute error (MAE, in mmHg), mean error (ME, in mmHg), standard deviation of error (SDE, in mmHg), and percentage of estimated BP values with absolute error $\leq Y$ mmHg, $Y = (5, 10, 15)$.

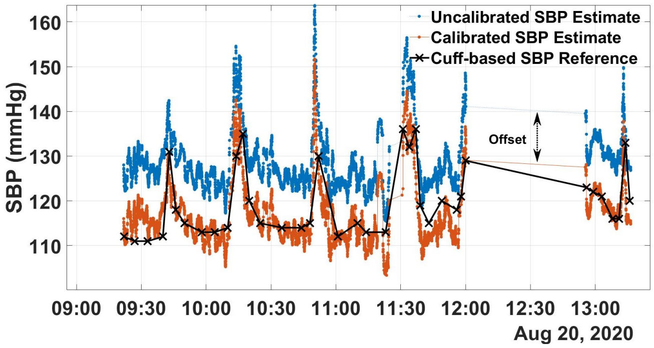

Fig. 2. A negative offset of 12mmHg separates between uncalibrated and calibrated SBP estimates generated by the PPG-BPM algorithm.

B. Signal Processing

This section presents a general overview of the PPG-BPM algorithm used to process the PPG signal from the ring. The technical details of the algorithm are disclosed in [18].

1) Pre-processing: The raw PPG signal is filtered using a band-pass filter with cutoff frequencies of 0.3 Hz and 4.5 Hz to remove the undesired frequency components. The Senbiosys proprietary beat-to-beat detection algorithm [17] is applied on the filtered PPG signal to identify the PPG pulses. Each of the detected PPG pulses is further associated with a signal quality index (SQI) to indicate the quality of the detected pulse.

2) Pulse Wave Analysis: The PPG pulses with high SQI values are eligible to be processed by the PWA block of the PPG-BPM algorithm. The PWA block extracts several time-related and amplitude-related features, as proposed in the state-of-the-art [15], [16], from the qualified PPG pulses. The extracted features are then mapped to two values using a multiple linear regression (MLR) model. Note that the MLR model that maps the extracted features to BP estimates is generated using publicly available data-sets and it is oblivious to the data of the current study. The two values generated by the MLR model represent the uncalibrated SBP and DBP estimates of the PPG-BPM algorithm corresponding to a specific PPG pulse.

The generated beat-to-beat BP estimates are then grouped into intervals/epochs of 40 seconds each. Epochs containing sufficient number of BP estimates, called clean epochs, are kept and the remaining epochs are discarded. Finally, the algorithm generates uncalibrated SBP and DBP estimates for each clean epoch using the beat-to-beat BP estimates available in the given epoch. In this study, the PPG-BPM algorithm identifies a total of 2250 clean epochs, thus generating 2250 uncalibrated SBP and DBP estimates from the PPG recordings.

C. Calibration

For each subject, we use an offset value (simple shift) to calibrate the SBP estimates and another offset value to calibrate the DBP estimates. The same SBP and DBP offset values are used for all the recordings belonging to the same subject. For example, in Fig. 2, a negative offset of 12

TABLE II

PERFORMANCE EVALUATION OF THE PPG-BPM ALGORITHM.

	Systolic BP	***Diastolic BP***
ME (mmHg)	-0.28	-1.30
SDE (mmHg)	7.54	7.18
MAE (mmHg)	5.86	5.69
$\leq$ 5**mmHg** (%)	54.23	52.78
$\leq$ 10**mmHg** (%)	82.32	83.05
$\leq$ 15**mmHg** (%)	92.49	94.67

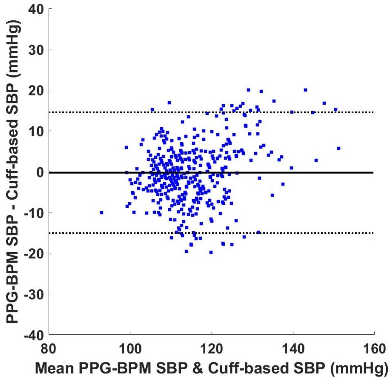

Fig. 3. Bland-Altman plot for SBP shows the 95% confidence interval $\mu \pm 1.96\sigma = \{-15.0584$ mmHg, 14.4984 mmHg$\}$.

mmHg is used to calibrate the SBP estimates generated by the algorithm. The same offset is used for all the recordings belonging to the same subject. Recall that for each subject there are at least two recordings with at least 14 days delay between the two. Finally, we identify the calibration offset based on the arithmetic difference between the BP estimate of a single epoch and its corresponding BP reference. To evaluate the accuracy of the PPG-BPM algorithm we consider the clean epochs that contain cuff recordings. This means that we only use 413 (number of cuff-based recordings) out of the available 2250 clean epochs.

III. RESULTS

The performance evaluation of the PPG-BPM algorithm is summarized in Table II. The obtained results confirm the accuracy of our algorithm in estimating both systolic and diastolic blood pressures with a respective mean error of -0.28 ± 7.54 mmHg and -1.30 ± 7.18 mmHg. The results also show that more than 80% of both SBP and DBP estimates have an absolute error of less than 10 mmHg compared to the cuff-based BP recordings.

We present the Bland-Altman plots for both SBP and DBP estimates in Figs. 3 and 4, respectively. For SBP, Fig. 3 shows the 95% limits of agreement -15.0584 mmHg to 14.4984 mmHg. For DBP, Fig. 4 shows the 95% limits of agreement -15.3728 mmHg to 12.7728 mmHg.

IV. DISCUSSION

A. *Accuracy Analysis*

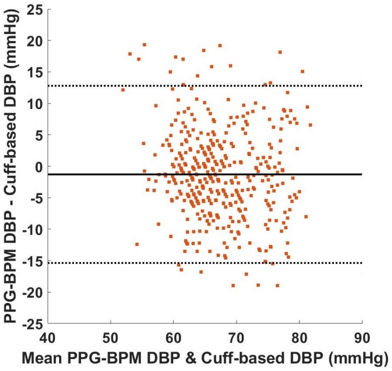

Fig. 4. Bland-Altman plot for DBP shows the 95% confidence interval $\mu \pm 1.96\sigma = \{-15.3728$ mmHg, 12.7728 mmHg$\}$.

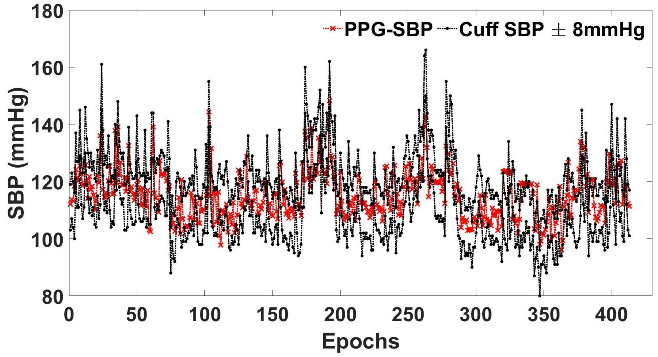

Fig. 5. All SBP estimates with ± 8 mmHg limits of the cuff-based reference.

For both the SBP and the DBP estimates, the accuracy metrics (ME ± SDE) of our algorithm are within the ISO/ANSI/AAMI protocol 5 ± 8 mmHg requirement. In Figs. 5 and 6, all the SBP and the DBP estimates (in chronological order) of the algorithm are shown. Out of the 413 estimates, 306 SBP estimates (74.09%) and 303 DBP estimates (73.37%) are within the ± 8 mmHg region of the cuff-based reference.

B. *Heart Rate vs Blood Pressure*

One of the methods to obtain continuous blood pressure values using cuff-based BP measurements is to interpolate the BP measurements using the heart rate variations, which

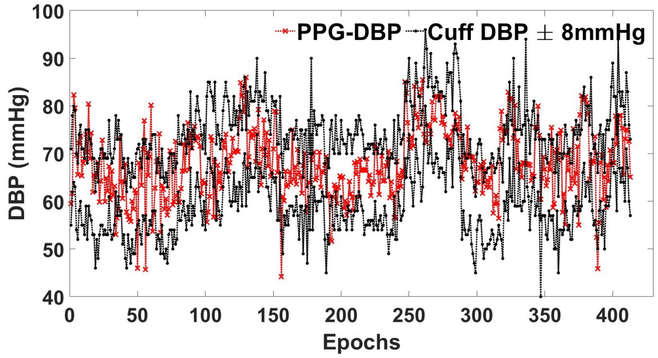

Fig. 6. All DBP estimates with ± 8 mmHg limits of the cuff-based reference.

can be continuously and accurately monitored using the subject's ECG or PPG. Despite that the heart rate often varies in agreement with the blood pressure, it cannot act as a reliable substitute. For example, in Fig. 7, we illustrate a scenario where there are two heart rate plateaus, one in the range of $[60-70]$ beats per minute (bpm) before $16:45$ and the other in the range of $[80-100]$ bpm after $16:45$. In both cases, the steady SBP values are in the range of $[100-120]$ mmHg. As shown in Fig. 7, the output of the PPG-BPM algorithm is consistent with the reference BP measurements indicating that our algorithm is robust and insusceptible to the described scenario.

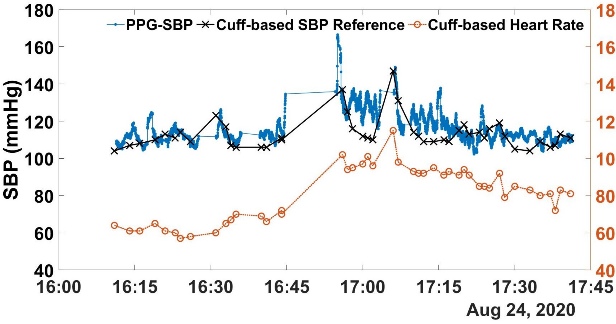

Fig. 7. Blood pressure vs heart rate variations.

C. Power Consumption

The Senbiosys ring SBF2003 embeds the ultra-low power SB200 PPG sensor. The LED deployed in the sensor is driven with a very low current. The sensor chip itself requires a significantly low current consumption compared to commercially available PPG sensors.. At a sampling frequency of 122Hz, the total current consumption of the PPG sensor is only $189\mu A$ ($109\mu A$ by the LED and $80\mu A$ by the sensor chip) [17]. The low power consumption of the ring ensures a long battery life, which makes it suitable for long-term continuous recordings.

V. CONCLUSION

In this work, we study the accuracy of the PPG-BPM algorithm for continuous blood pressure monitoring using the ultra-low power Senbiosys ring. Indeed, the obtained results confirm that our PPG-based BP monitoring solution is capable of accurately estimating systolic and diastolic blood pressure. For the SBP, the algorithm achieves a mean absolute error of 5.86 mmHg and a mean error of -0.28 ± 7.54 mmHg compared to the cuff-based recordings. A similar performance is achieved for the DBP with a mean absolute error of 5.69 mmHg and a mean error of -1.30 ± 7.18 mmHg. The accuracy achieved by the algorithm fulfills the ISO/ANSI/AAMI protocol requirement of mean error 5 ± 8 mmHg. In the near future, these results will be complemented by clinical trials to evaluate the performance of the PPG-BPM algorithm with respect to the invasive arterial line.

REFERENCES

[1] WHO, "Hypertension," September 2019. https://www.who.int/news-room/fact-sheets/detail/hypertension.

[2] A. K. Park, S. W. Menard, and C. Yuan, "Comparison of auscultatory and oscillometric blood pressures," *Archives of Pediatrics & Adolescent Medicine*, vol. 155, no. 1, pp. 50–53, 2001.

[3] R. J. O. Davies, N. E. Jenkins, and J. R. Stradling, "Effect of measuring ambulatory blood presure on sleep and on blood pressure during sleep," *British Medical Journal*, vol. 308, pp. 820–23, March 1994.

[4] X. F. Teng and Y. T. Zhang, "Continuous and noninvasive estimation of arterial blood pressure using a photoplethysmographic approach," in *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE Cat. No.03CH37439)*, vol. 4, pp. 3153–3156, 2003.

[5] A. D. Choudhury, R. Banerjee, A. Sinha, and S. Kundu, "Estimating blood pressure using windkessel model on photoplethysmogram," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4567–4570, 2014.

[6] U. R. Acharya, K. P. Joseph, N. Kannathal, C. M. Lim, and J. S. Suri, "Heart rate variability: a review," in *Medical & Biological Engineering & Computing*, vol. 44, pp. 1031–1051, 2006.

[7] J. Sztajzel, "Heart rate variability: a noninvasive electrocardiographic method to measure the autonomic nervous system," vol. 134(35-36), pp. 514–522, Swiss Med Wkly, 2004.

[8] J. Thayer, F. Åhs, M. Fredrikson, J. J. Sollers III, and T. D. Wager, "A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health," in *Neuroscience and Biobehavioral Reviews*, vol. 36(2), pp. 747–756, 2012.

[9] 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.

[10] 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.

[11] P. Renevey, R. Delgado-Gonzalo, A. Lemkaddem, M. Proença, M. Lemay, J. Solà, A. Tarniceriu, and M. Bertschi, "Optical wrist-worn device for sleep monitoring," in *EMBEC & NBC 2017*, (Singapore), pp. 615–618, Springer Singapore, 2018.

[12] T. Myllymäki, H. Rusko, H. Syväoja, T. Juuti, M.-L. Kinnunen, and H. Kyröläinen, "Effects of exercise intensity and duration of nocturnal hear rate variability and sleep quality," *European Journal of Applied Physiology*, vol. 122, pp. 801–809, 2012.

[13] Y. Choi, Q. Zhang, and S. Ko, "Noninvasive cuffless blood pressure estimation using pulse transit time and hilbert-huang transform," *Computers and Electrical Engineering*, vol. 39, pp. 103–111, January 2013.

[14] Y. Liang, D. Abbott, N. Howard, K. Lim, R. Ward, and M. Elgendi, "How effective is pulse arrival time for evaluating blood pressure? challenges and recommendations from a study using the mimic database," *Clinical Medicine*, vol. 8, March 2019.

[15] K. Atomi, H. Kawanaka, S. Bhuiyan, and K. Oguri, "Cuffless blood pressure estimation based on data-oriented continuous health monitoring system," in *Computational and Mathematical Methods in Medicine*, vol. 2017, 2017.

[16] S. Shimazaki, S. Bhuiyan, H. Kawanaka, and K. Oguri, "Features extraction for cuffless blood pressure estimation by autoencoder from photoplethysmography," in *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 2857–2860, July 2018.

[17] 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.

[18] S. Haddad, A. Boukhayma, and A. Caizzone, "Continuous ppg-based blood pressure monitoring using multi-linear regression," https://arxiv.org/abs/2011.02231.