“*Why the PPG signal fidelity is crucial in vitals extraction?*”

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Photoplethysmography (PPG) is the most promising of the technologies that provides a comfortable and low-cost alternative for the extraction of many vital signs, such as heart rate, heart rate variability, breathing rate, oxygen saturation, and blood pressure and so. 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 photodiode. This optical solution detects the volumetric changes in the blood flow.

PPG-based extraction of physiological signals is based on the detection of specific characteristic points of the analog PPG signal. These characteristics are used to identify the features of the PPG morphology that are correlated with the extracted physiological signals. Any PPG-based technology aiming at accurate extraction of physiological signals requires a good algorithm capable of accurately identifying and mapping the features of the PPG morphology. However, irrespective of how good an algorithm is, it will have inadequate performance if the input PPG signal morphology lacks the resolution necessary for the detection of the required characteristic. Therefore, any PPG technology/algorithm is only *as good* as the *fidelity* of the PPG signal itself.

Senbiosys conducted several studies to evaluate the performance of its PPG-based proprietary algorithm to validate the high fidelity of the Senbiosys PPG signal. In this note we provide some technical details pertaining to PPG-based algorithms and some of the results obtained from the Senbiosys PPG recordings.

I. Beat Detection

The volumetric variations in blood measured using a PPG signal can be analyzed to approximate inter-beat intervals (IBI), which then enables pulse-rate variability (PRV) analysis. In the past decade, PPG wearable devices garnered vast interest among researchers who studied their effectiveness for heart rate variability (HRV) analysis. These studies show that PRV analysis using PPG is sufficiently accurate compared to HRV analysis using ECG. However, this is only accomplished if the PPG signal has a sufficiently high signal-to-noise ratio (SNR) with well-defined pulse peaks and/or maximal pulse upslope values. Please refer to our application note *“Every photon counts?”* for further details.

Beat detection can be either through peak detection or maximum slope detection of the PPG signal. In both cases, it is important to have a high SNR signal. A high SNR signal reduces the degree of filtering required to identify the mentioned characteristics for beat detection. As a result, the peaks detected will be very close to the exact systolic peaks of the cardiac cycle, which is essential for accurate IBI detection and HRV analysis.

We evaluated the performance of the Senbiosys PPG sensor over ~100,000 heartbeats at a sampling frequency of 122 Hz. This evaluation consists of characterizing 1) the beat detection rate (*presented in Table 1*) and 2) the accuracy of the correctly detected beats (*presented in Table 2)*.

Table 1. IBI Detection Performance

Metrics	Senbiosys	Shimmer3
Missed Beats (%)	0.73	0.52
Extra Beats (%)	0.84	1.41
Correct Beats (%)	99.27	99.48

Table 2. IBI Estimation Performance

Metrics	Senbiosys	Shimmer3
Mean Error (ms)	0.4	0.29
Mean Abs. Err. (ms)	6.58	7.27
Mean Abs. Perc. Err. (%)	0.73	0.82
Root Mean Sq. Err. (ms)	16.08	16.03

We compared the performance of the Senbiosys PPG to that of the Shimmer3 Consensys GSR optical development kit PPG (operating at a sampling frequency of 128 Hz). Figure 1 illustrates how low the Senbiosys PPG LED brightness is compared to the Shimmer3 device. Despite the low brightness, corresponding to a lower emitted LED optical power, the IBI detection of the Senbiosys module has a similar performance to the Shimmer3 PPG, with a detection rate of 99.27% (vs. 99.48% for the Shimmer3 PPG) and a lower percentage of extra beats of 0.84% (vs. 1.41% for the Shimmer3 PPG). Moreover, as shown in Table 2, both PPG devices show a comparable performance in terms of IBI estimation accuracy. The Senbiosys module has a slightly better mean absolute error value (6.58 ms) than the Shimmer3 PPG (7.27 ms) and the Shimmer3 PPG has a slightly better mean error value (0.29 ms) than the Senbiosys module (0.40 ms).

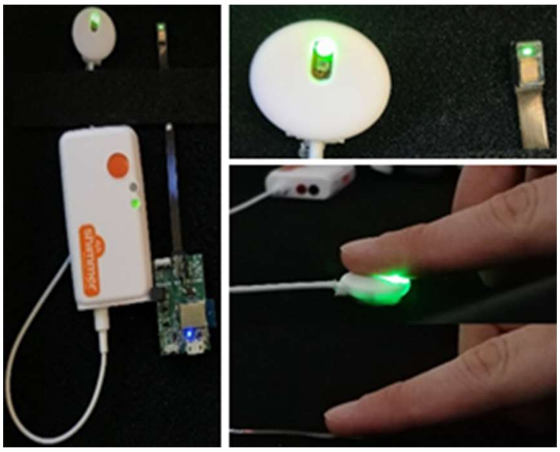

Figure 1. Shimmer3 PPG vs Senbiosys PPG

The details of this study can be found in [1].

II. Pulse Wave Analysis

The Senbiosys blood pressure monitoring algorithm (SB-BPM) uses only a PPG signal to determine blood pressure values. The technology is based on pulse wave analysis (PWA) of PPG signals retrieved from different body locations to continuously estimate the systolic blood pressure (SBP) and the diastolic blood pressure (DBP). The technical details of the SB-BPM algorithm can be found in [2].

Pulse wave analysis is a lot more complicated than the beat detection. It requires the detection of a larger number of characteristics points of the PPG waveform and its 1st and 2nd derivative waveforms. This includes the velocity PPG (VPPG), the acceleration PPG (APPG), the maximum pulse upslope, the systolic peak, the half amplitude points, the dicrotic notch, the diastolic peak, the *a*, *b*, *c*, *d*, and *e* waves of the APPG and so forth. PWA techniques include a morphological analysis of the PPG pulse waveform to extract features that can be used to estimate the blood pressure. Several time-related and amplitude-related features are proposed in the state-of-the-art. The extracted features are then mapped to blood pressure values using different techniques.

Since PWA relies primarily on accurately identifying numerous characteristics of the PPG signal such as the VPPG, and the APPG waveforms, it requires high fidelity PPG signals. It was therefore important to conduct a study to evaluate the performance of the SB-BPM algorithm on the Senbiosys PPG module [3]. The study included 17 Senbiosys PPG recordings 2.21±0.89 hours each together with cuff-based blood pressure measurements. The PPG recordings were processed by the SB-BPM algorithm to generate systolic blood pressure (SBP) and diastolic blood pressure (DBP) values to be compared with the cuff-based measurements. The study included 413 cuff measurements and the results are summarized in Table 3.

Table 3. Performance Evaluation of the SB-BPM Algorithm

	Systolic Blood Pressure	**Diastolic Blood Pressure**
Mean Error (mmHg)	0.28	1.30
Std. Dev. of Err. (mmHg)	7.54	7.18
Mean Abs. Err. (mmHg)	5.86	5.69
% of Abs. Err. < 5 mmHg	54.23	52.78
% of Abs. Err. < 10 mmHg	82.32	83.05
% of Abs. Err. < 15 mmHg	92.49	94.67

The results show that the Senbiosys PPG module provides the high fidelity required by the SB-BPM algorithm to ensure accurate blood pressure monitoring within the 5±8 mmHg ISO/ANSI/AAMI protocol requirement.

References:

1. S. Haddad *et al.*, "Beat-to-beat detection accuracy using the ultra low power senbiosys ppg sensor," 8th European Medical and Biological Engineering Conference (EMBEC), 2020
2. S. Haddad *et al.*, "Continuous ppg-based blood pressure monitoring using multi-linear regression," *submitted to* IEEE Journal of Biomedical and Health Informatics
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