Accuracy of Beat-to-Beat Heart Rate Estimation Using the PulseOn Optical Heart Rate Monitor

***Abstract*— Wrist photoplethysmography allows unobtrusive monitoring of the heart rate (HR). Even if it is frequently used for HR estimation, the technology is not yet a popular choice for heart rate variability (HRV) monitoring because optical inter-beat interval (IBI) estimation is highly sensitive to noise. In this paper, we evaluate the PulseOn optical heart rate technology in estimating IBI on a wide range of subjects. Unreliable IBI caused by motion or other types of noise are automatically detected. ECG based R-to-R intervals (RRI) are used for reference. The technology was validated on 494.4 hours of data, from 6 subjects with both sinus rhythm and arrhythmias. 88% of the data was considered reliable during sleep and 32.4% during daily activities. The mean absolute error was 8.84 ms, in close agreement with the reference. The results show that PulseOn provides the IBI reliability and accuracy needed for long-term HRV monitoring and arrhythmia detection.**

I. Introduction

Heart rate variability (HRV) provides information about a person's health status, and can be used for both wellness and clinical applications, such as atrial fibrillation (AF) detection.

The gold standard in HRV analysis is given by ECG devices. These can be in-hospital monitors, ambulatory Holter monitors, chest straps, or electrode patches. Though accurate, they suffer from several limitations. Hospital recordings are usually of short duration and might not detect cases such as paroxysmal atrial fibrillation (AF). Some devices are cumbersome and can limit mobility. If worn for longer durations, the electrodes can easily become uncomfortable and possibly cause skin irritations. In addition, dry skin or poor skin contact often disturb chest strap based HRV monitoring. Monitoring tool obtrusiveness and high cost can also lead to low patient acceptance rate. Thus, there is a clear demand for new technologies, which do not interfere with a person's comfort.

Photoplethysmography (PPG) provides an alternative method for HR and HRV monitoring [1]. Instead of measuring the heart electrical signals, this technology uses light signals to monitor the heart activity. Given that the measuring device can be integrated in a wrist-band, the wrist PPG technology, if proven accurate enough, would provide tremendous benefits in both clinical and home monitoring scenarios: a comfortable, wearable, unobtrusive measurement method suitable for long-term monitoring. Besides analyzing life-style, sleep, and stress levels, it could also be used in the screening of various cardiac anomalies.

Currently, optical heart rate (OHR) devices can provide adequate accuracy for heart rate estimation during rest, sports, and daily activities [2]. In the absence of motion, IBI can be accurately estimated from wrist PPG signals [3, 4].

In this paper, we present the core technology of PulseOn (www.pulseon.com) optical HR monitoring and validate its accuracy for HRV monitoring. As the target goal is not only HR monitoring but also medical applications such as arrhythmia detection, we focus on continuous long-term recordings.

II. PulseOn Technology

A. Optical Heart Rate Monitoring

Optical HR monitoring is based on the PPG technique. The skin is illuminated with a LED and a photodetector measures the intensity of the transmitted or reflected light. This intensity depends on the blood volume in the skin capillaries and the vasculature deeper in the tissue, which, in turn, vary with the pumping actions of the heart. Thus, by analyzing the light intensity, we can determine both HR and inter-beat intervals (IBI).

One of the main problems of PPG measurement is that the useful signal is corrupted by ambient light and other electromagnetic radiations (ambient light artefacts), and by gravity and by voluntary and involuntary subject movements (motion artefacts). The ambient light artefact influence can be measured using multiplexing techniques and eliminated by subtractive techniques. An efficient way to reduce the motion artefacts is to use a motion reference signal provided by an accelerometer and to perform signal enhancement afterwards. In this way, we may obtain reliable HR estimates even under intense physical activities.

This technology has already been used for HR estimation in both medical and wellness domains. However, because IBI estimation is less reliable in the presence of noise, its usability for HRV monitoring or AF detection [5] still needs to be confirmed.

B. PulseOn Technology

The PulseOn OHR solution uses multiple light wavelengths and optimally matched LED-photodetector distances to allow the measurement of blood flow at different tissue depths. The mechanical design of the housing and the strap provides a stable skin-sensor contact in all conditions. This reduces the artefacts without compromising the comfortable use.

The device used in this study is the PulseOn Medical Tracker, shown in Figure 1. It is a wearable wristband OHR monitor designed for clinical use, monitoring HRV, and screening and monitoring arrhythmias and sleep apnea. Easy to use and comfortable to wear for up to one week without recharging, it enables true long term data collection. Additionally, it can log general lifestyle related user data such as sleep quality, steps, and energy expenditure, to aid in developing a more complete view into a person's everyday well-being. The data can be accessed by the health care professional through web based tools for in-depth analysis. The light weight (35g including strap) further reduces the artefact risk and guarantees that the device is not cumbersome and will not interfere with the user's daily activities, thus having a high acceptance rate. Because the device is designed for clinical applications, it does not have a display in order not to distract the users. The sport and wellness version (PulseOn OHR Tracker) is shown in Figure 2.

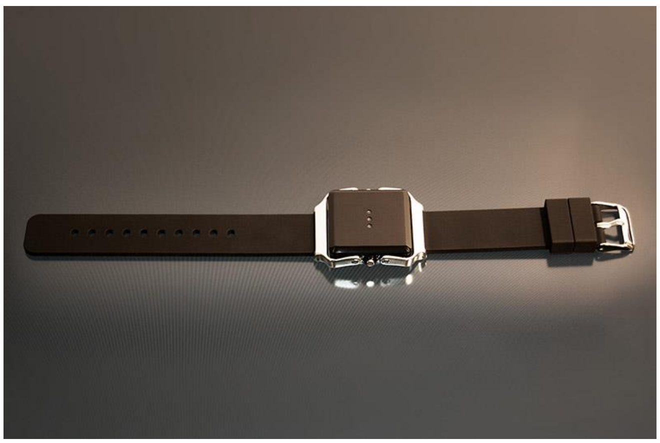

Figure 1. PulseOn Medical Tracker device

Figure 2. PulseOn OHR Tracker for sport and wellness

The HR estimation algorithm applies the accelerometer data to reduce the motion artefacts and provide accurate HR estimation for a range of activities from rest or daily office routine to intensive training. Added to this, the acceleration data is used to determine activity related parameters such as step or calorie count.

In addition to most available optical heart rate monitors, PulseOn also computes the beat-to-beat intervals with millisecond precision. The algorithm has been scientifically validated on subjects of different ages and health conditions [3, 4]. In the absence of motion, the mean absolute error with respect to RR intervals (RRI) obtained from ECG reference is below 8 ms for sinus rhythm (SR) subjects and below 15 ms for subjects suffering of different arrhythmias. This is considerably lower than the difference between consecutive beats and in close agreement with the reference. However, optical IBI estimation is not reliable in the presence of motion, varying ambient light, or other interference. To overcome this, the PulseOn algorithms automatically detect such situations and screen out unreliable data based on the motion level and the PPG wave morphology. Thus, the risk of incorrect HRV or arrhythmia estimation is minimized.

Besides high accuracy, the PulseOn algorithms are designed for low power consumption and to be run in real-time. This reduces the battery consumption and enables continuous long-term monitoring for up to one week.

III. Technology Validation

A. Validation Data

The goal of this study is to validate the PulseOn IBI estimation. As the target scenario is long-term monitoring for arrhythmia detection, the recordings were not limited to sleep or rest periods. Instead, the subjects carried on regular life style for durations of up to 60 hours. Both PPG and ECG signals were continuously monitored during this time.

Because arrhythmia detection algorithms are highly sensitive to IBI errors, it is important to filter out unreliable IBI, but still keep enough data for reliable decision making. Thus, in the following we will first check how much of the recorded data is considered reliable, and continue with IBI statistics for the reliable data.

In total, there were 14 recordings from 6 subjects (4 male, 2 female, 34.6±9.6 years old), accounting for 494.4 hours of data. 4 subjects out of 6 had episodic arrhythmias during the measurement. The test subjects gave their written consent to participate after being informed on the purpose of the study and they had the right to withdraw from the study at any time. The experimental procedures comply with the principles of the Helsinki Declaration of 1975, as revised in 2000.

B. Data Acquisition

Wrist PPG signals were recorded with the PulseOn Medical Tracker device. The device was worn as instructed by the manufacturer, about one finger width from the wrist bone and tightened by the person in charge of data collection so that the skin contact was firm but still comfortable for the whole recording. The IBI and IBI reliability were provided directly by the OHR tracker. The reference ECG RRI signals were measured with the Bittium Faros (www.bittium.com) or Firstbeat Bodyguard 2 (www.firstbeat.com) devices.

C. Data Analysis

The processing block scheme is shown in Figure 3. Firstly, the IBI and IBI reliability (IBI mask) are extracted from the PPG and acceleration signals. Then, as the recording of wrist PPG and reference ECG signals did not start at the same time, we synchronize the IBI and RRI time series by compensating for eventual time drifts between the PulseOn and reference clocks and by minimizing the mean absolute error between the IBI and reference RRI vectors. For final synchronization, we split the data in intervals of one minute and perform a new synchronization for each interval. This is necessary to allow beat-to-beat level synchronization despite slightly differing nominal clock rates of the devices.

For every PPG-detected beat, we check how many reference beats are detected in the interval $[t - 0.5l, t + 0.5l]$, where t is the time when the beat was detected and l is the length of the corresponding IBI. If there is only one reference beat, then it is associated to the IBI. This method ensures that more than 97% of the IBI are correctly associated to a reference RRI [4].

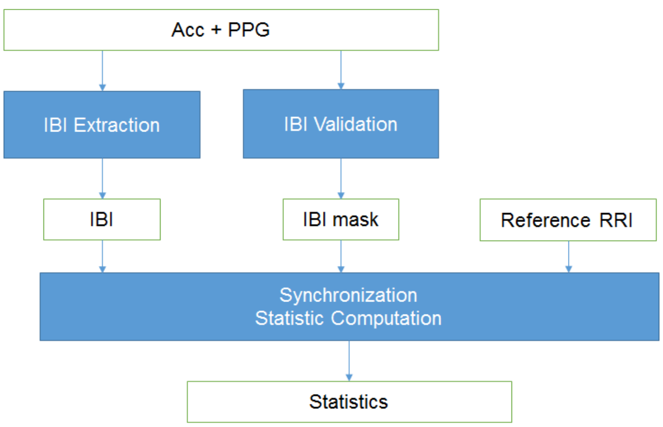

Figure 3. Data analysis block scheme

The IBI reliability, or signal quality estimation (SQE) is computed as the percentage of beats considered reliable from the total number of beats. To obtain a better view of the SQE behavior, we compute it separately for periods of sleep and for periods of activity.

The IBI estimation performance is evaluated by the following parameters:

- Mean error (ME): average of the difference between the estimated IBI and the reference RRI
- Mean absolute error (MAE): average of the absolute difference between the estimated IBI and the reference RRI
- Mean absolute percentage error (MAPE): average of the absolute percentual difference between the estimated IBI and the reference RRI
- Root mean square error (RMSE): square root of the average of squared errors between the estimated IBI and the reference RRI

The effect of IBI accuracy influence on HRV analysis is shown by computing two HRV parameters:

- Root mean square of successive differences (RMSSD)
- The percentage of successive IBI that differ by more than 50 ms (pNN50)

These values were estimated with two different approaches: first considering all detected beats with a one-to-one correspondence to the reference RRI, and then considering only reliable beats.

IV. Results and Discussion

A. Beat Reliability

Figure 4 illustrates how the proposed method works. In the 160 - 165 s interval, motion, depicted as variations in the 3D acceleration signal, generates artefacts in the PPG signal. In these situations, IBI estimation is inaccurate, as seen in the comparison with the ECG reference. The IBI validation block detects this and marks the beats as unreliable (the IBI mask from the lower panel is set to > 0). Afterwards, when the movement stops, the PPG signal quality increases and the IBI are considered reliable again (the IBI mask is set to 0).

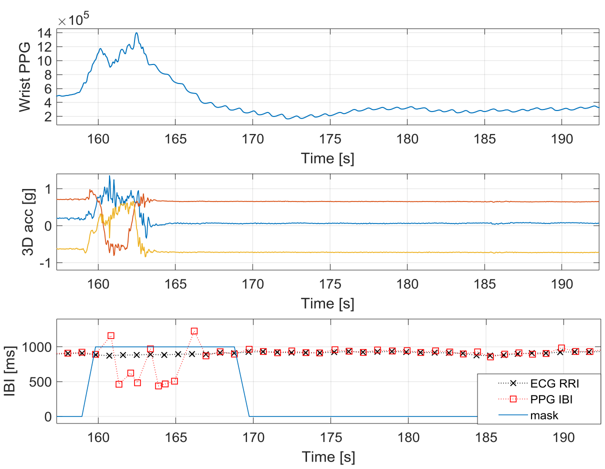

Figure 4. Effect of motion, depicted as variations in the 3D acceleration signal, on the estimation of IBI from wrist PPG signals

The percentage of beats considered reliable is presented in Table I. During sleep, most detected beats (88%) are reliable. As it was expected, this percentage decreases during daily activities due to the presence of motion. Overall, in an interval of 24 hours, 50.9% beats are expected to be reliable (considering 8 hours as sleep).

TABLE I. BEAT RELIABILITY

	Time [h]	Reliable IBI [%]
Daily activities	345.1	32.4
Sleep	149.3	88.0
Total	494.4	50.9

B. IBI Estimation

In Figures 5 and 6, we illustrate examples of 50 consecutive beats extracted from the PPG signals as well as from the ECG reference, and the error between IBI and RRI. Figure 5 is for an SR subject with one ectopic beat. Figure 6 is for an AF subject. For both scenarios, the PPG-derived IBI are in very close alignment with the reference RRI. The error is higher when the RRI variation is higher, but considerably lower than the difference between consecutive IBI.

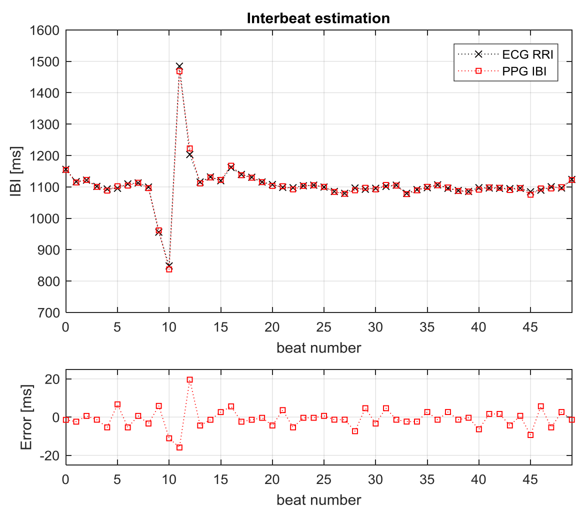

Figure 5. Example of IBI and RRI time series for an SR case. The lower panel shows the instantaneous error between RRI and IBI

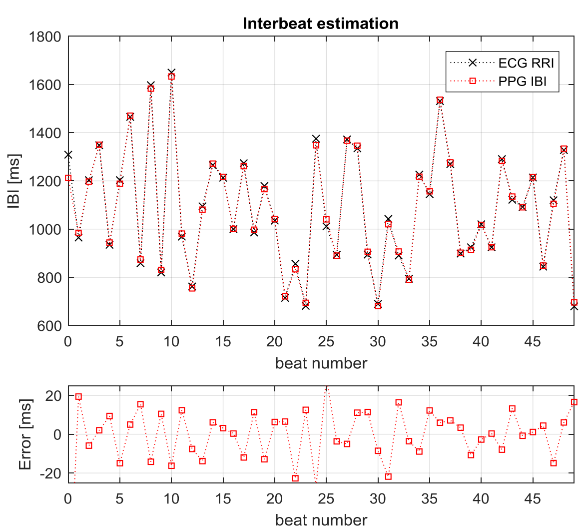

Figure 6. Example of IBI and RRI time series for an AF case. The lower panel shows the instantaneous error between RRI and IBI

Table II summarizes the IBI estimation results. When discarding the unreliable IBI, the MAE is 8.84 ms, which is suitable for HRV applications such as sleep or stress analysis, or arrhythmia detection. The MAE when considering all beats with a one-to-one RRI correspondence is significantly higher, of 56.42 ms.

TABLE II. IBI ESTIMATION PERFORMANCE

	All IBI	Reliable IBI
ME [ms]	0.96	-0.66
MAE [ms]	56.42	8.84
MAPE [%]	7.17	0.97
RMSE [ms]	132.36	28.21

In Table III, we show two parameters used to describe HRV, namely pNN50 and RMSSD, and the importance of discarding unreliable data. For the reliable IBI, these are close to the reference-computed values. However, the differences are clearly visible when using all IBI. Given the sensitivity of HRV algorithms to inaccurate inputs, this could easily cause unwanted results as, e.g., false arrhythmias detected.

TABLE III. HRV PARAMETER ESTIMATION

	All IBI	Reliable IBI	Reference RRI
	PPG	PPG	ECG
pNN50 [ms]	43.63	25.20	23.36
RMSSD [ms]	190.82	77.05	65.98

V. CONCLUSION

This study evaluates the accuracy of the PulseOn IBI estimation from wrist PPG signals during continuous long-term monitoring. As IBI estimation from optical signals is highly sensitive to noise, unreliable beats are automatically detected. The MAE for beats classified as reliable is 8.84 ms, which is suitable for HRV analysis.

The method to distinguish between reliable and unreliable data has also been validated. The MAE decreases from 56.42 ms when considering all IBI to 8.84 ms when considering only reliable IBI. The amount of reliable data is 88% during sleep and 32.4% during daily activities, which translates to 50.9% reliability ratio during a 24 hour period. It is unavoidable that some data is discarded in order to obtain an accurate solution, but this is naturally preferred to having a wrong interpretation.

In conclusion, the present study confirms the accuracy and reliability of PulseOn IBI estimation. During low motion periods, IBI from wrist PPG signals are in close agreement with RRI obtained from the ECG reference. The estimated values can be used for both HRV analysis and clinical applications such as AF detection. This provides a promising alternative to current monitoring technologies, and an important step towards wearable, comfortable, 24/7 monitoring.

References

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