Autocorrelation Function-Based Signal Quality Assessment on Photoplethysmographic Recordings for Opportunistic Accurate Estimation of RR Time Series

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Abstract

Interbeat Interval (IBI) from photoplethysmographic recordings (PPG) is usually employed as a surrogate measure of R-to-R (RR) time series measured using the electrocardiogram. This work focuses on the relationship of the IBI and RR time series agreement with the PPG quality using the PPG's autocorrelation function (ACF) as a signal quality assessment (SQA) index. We monitored 31 subjects for 25 minutes each by measuring PPG using two systems (Biopac PPG sensor sampled at 1 kHz (BS) and Empatica wristband measured PPG sampled at around 64 Hz (ES)) while the BS was also employed to measure ECG. This work also provides ways to synchronize both systems and correct some sampling frequency disparities before performing the agreement assessment and fair comparison between measuring systems. The agreement between IBI and RR for ACF SQA larger than 0.85 (good quality, (GQ)) is significantly different than for ACF SQA lower than 0.85 (fair quality (FQ)) for both systems (BS: 2.74 ms ± 1.18 ms (GQ) vs 3.68 ms ± 2.06 ms (FQ); $p<8.2\cdot10$-5 and ES: 7.94 ms ± 8.03 ms (GQ) vs 14.1 ms ± 11.7 ms (FQ); $p<2.6\cdot10$-6). Identifying PPG signal segments with high ACF SQA opportunistically provides IBI time series with better agreement.

1. Introduction

Interbeat interval (IBI) estimation from finger or wrist photoplethysmography (PPG) is currently used as a surrogate for R-to-R intervals (intervals between consecutive QRS waves in an electrocardiogram) time series [1]. Some studies have focused on the agreement of the IBI compared with the RR time series using established fiducial points for the PPG pulse detection [2] or proposing new ones to maximize agreement [3]. A few have stressed the importance of a good PPG signal quality (SQ) to have a good agreement between time series [4],[5]. Still, these studies have been mostly devoted to robust methods for PPG pulse detection to avoid outliers.

In some applications, it may be interesting to take IBI measurements only when the PPG SQ is exceptionally good [6]. This opportunistic approach benefits from the ease with which we can detect the PPG pulse in these circumstances. On the other hand, the degradation of SQ may still provide valid IBIs, but the agreement can also worsen.

This work aims to use a simple PPG SQ assessment (SQA) index that also directly measures average IBI to recognize good-quality PPG signal segments. We hypothesize that the SQA index can aid in locating PPG segments where the agreement between IBI and RR time series is high enough.

2. Materials and methods

The autocorrelation function (ACF) definition of an $x(n)$ signal with N samples that we will use in this work is:

$$R_{xx}(k) = \frac{\sum_{n=0}^{N-k-1}[x(n+k)-\mu_x]\cdot[x(n)-\mu_x]}{\sum_{n=0}^{N-1}(x(n)-\mu_x)^2} \quad (1)$$

where μ_x is the mean of the signal. Note that $R_{xx}(0)=1$ and $R_{xx}(-k)=R_{xx}(-k)$. Because a purely periodic signal has an autocorrelation function that reaches 1 for each fundamental period delay, the level of the first peak of the autocorrelation for $k>0$ ($R_{xx\ max}$) can be employed as SQA index [7] if it is understood that our ideal signal has a strict periodic behavior. Noise, artifacts, breathing amplitude modulation, and heart rate variability will reduce $R_{xx\ max}$. Moreover, the presence of arrhythmia will also provide low values of $R_{xx\ max}$. Figure 1 shows an example of 10 s segments of PPG signals showing very good quality and movement drifts. Additionally, the delay where $R_{xx\ max}$ happens is an estimate of the mean heart period.

To measure $R_{xx\ max}$, we used the *xcorr* and *findpeaks* functions in MATLAB® R2023b. Moreover, all signal processing was done using this software. An autocorrelation peak was judged relevant if it had a minimum height of 0.2 and corresponded to delays longer than 0.4 s. If no relevant peak was found, $R_{xx\ max}$ was set to zero.

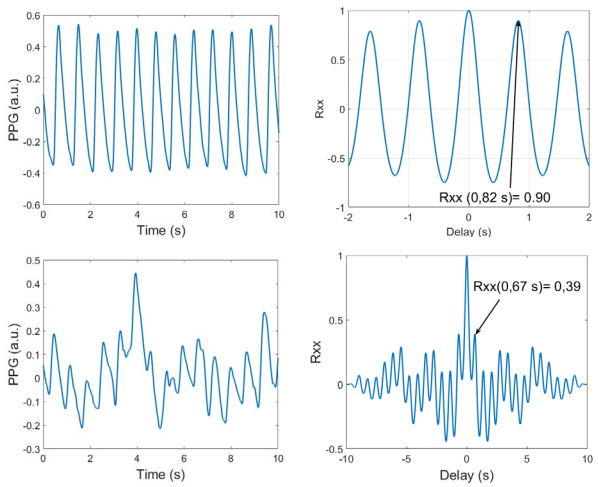


Figure 1. Examples of good (upper panels) and poor (lower panels) quality PPG signals. The right panels show the acquired signals, while the left panels show the ACF.

We used the recordings of 31 healthy subjects (18 male and 13 female) with a mean age of 31.8 years and standard deviation of 10.8 years who participated in a previous experiment [8]. The subjects included in the study were either sedentary or moderately physically active, with a body mass index (BMI) of 25.04 ± 3.0 kg m^2 in men and 23.35 ± 3.1 kg m^2 in women. All subjects in this investigation provided informed consent before participating, and the study was carried out according to the Declaration of Helsinki. We used a BIOPAC MP36 recording unit to measure, among other signals, an ECG Std II lead and the non-dominant hand index finger PPG signal, both sampled simultaneously at 1 kHz. At the same time (although the start of the recordings was not synchronized), an Empatica E4 wristwatch was employed to measure, at nominally 64 Hz, the PPG at the wrist of the non-dominant arm. The experiments, which required moving and clicking a mouse with the dominant hand during two 5-minute periods, lasted around 25 minutes. Subjects were asked not to move except for the mouse operating periods, where movements were kept to a minimum. These precautions guarantee the quality of the recordings is good to very good. Only in some short periods, when the voluntary switch from rest to mouse operation, SQ could degrade. The non-dominant hand rested in the same position on a table during the whole experiment.

The first rough detection of QRS complexes and pulse arrival in the PPG was made using the procedures described in [3]. For the QRS detection, the ECG signal was filtered with a bidirectional 4th-order Butterworth band pass filter with 10 Hz and 30 Hz cut-off frequencies. After filtering, a maximum filter with a window of 600 ms was applied to the signal. The R peak locations correspond to the samples where the maximum filter output equals the value of the filtered ECG. The E4 PPG was previously resampled at 1 kHz before any processing step. For the pulse arrival detector, a bidirectional 4th-order Butterworth band pass filter with cut-off frequencies between 2 Hz and 15 Hz was applied separately to both PPG signals. Next, a maximum filter with the same characteristics as the QRS detectors was used to locate the peaks of the filtered PPG. After rough pulse detection, the fiducial points of every pulse detected in any PPG signal were refined by adjusting a hyperbolic tangent to the systolic rise [9], as explained in [3].

RR time series were defined as the interval between consecutive QRS complexes. Each RR interval was assigned a timestamp referenced to the recording start, equal to the average time of the two QRS complexes that defined the RR time interval. The same procedure was employed for the two IBI time series, using the fiducial points signaling the pulse arrival.

The beat-to-beat agreement between the RR and the Biopac IBI time series was assessed by identifying which IBI time interval timestamp was nearest in time to each RR interval timestamp and obtaining the difference between the corresponding intervals, as explained in [10].

Because the measurements using the Biopac system and those of the E4 wristband are not synchronized, it was necessary to align the time series before measuring the agreement. We noted that the sampling frequency of the E4 system was not exactly 64 Hz. Moreover, it slightly drifted from day to day. Hence, a correction in the E4 IBI time series timestamps was obtained by summing a constant delay and multiplying the timestamp by a constant that corrects the sampling frequency drift. Both delay and drift correction constants were obtained by minimizing the standard deviation of the differences between the E4 IBI time series and the RR time series. A beat-to-beat agreement was obtained once the correction was applied, similar to when comparing RR and the Biopac IBI time series. In this way, two beat-to-beat agreement time series for each recording are obtained with the same number of samples as the number of detected RR time intervals. Figure 2 shows an example of the three time series, once synchronized, and the two beat-to-beat agreement time series.

A time series consisting of Rxx max values were obtained using a sliding window of 10 s duration and 0.3 s time increments for the Biopac and E4 PPG signals. A beat-to-beat $R_{xx\ max}$ time series was obtained for each time series by concatenating the Rxx max values closer to the RR timestamps. Figure 3 shows an example of these time series for the recording in Figure 2.

Statistical tests were applied on the beat-to-beat agreement time series and $R_{xx\ max}$ time series to check the hypothesis that large values of $R_{xx\ max}$ correspond to better agreement between the IBI and RR time series (small differences).

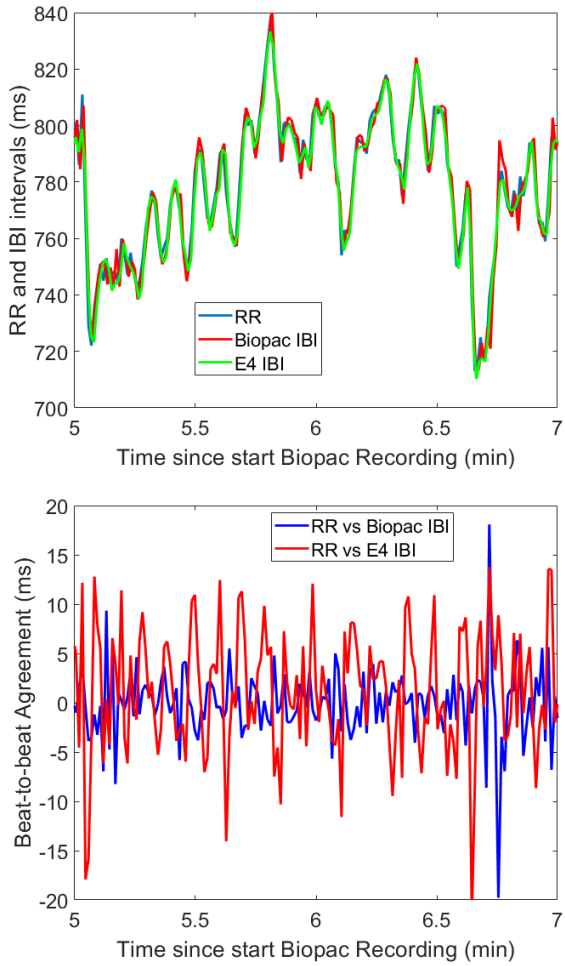


Figure 2. The upper panel shows an example lasting 2 minutes of the RR time series obtained from the ECG and the two IBI time series obtained from the Biopac system and the E4 wristband after synchronizing all three time series. The lower panel shows the agreement of each IBI time series compared with the reference RR time series.

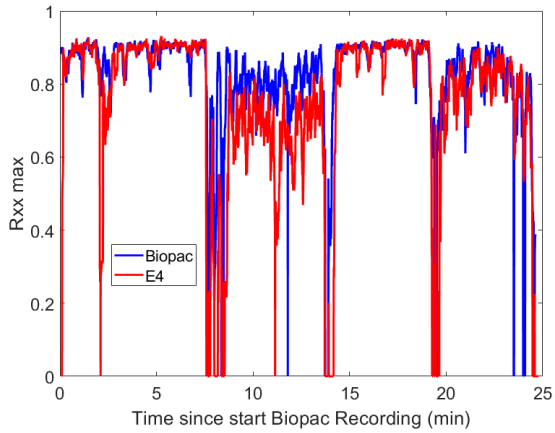


Figure 3. An example illustrating the $R_{xx\ max}$ time series

3. Results

First, SQ was compared between the E4 (ES) and the Biopac (BS) PPG measuring systems. When comparing the average of the $R_{xx\ max}$ time series between measuring systems for the whole recording and each subject, the Wilcoxon Signed Rank Test (WSRT) shows very significant differences ($p<1.2\cdot10^{-6}$, n=31) between the average of the $R_{xx\ max}$. These values' median ± interquartile range are 0.81 ± 0.09 for the BS and 0.77 ± 0.07 for the ES. The average $R_{xx\ max}$ is only larger in the ES for one subject out of 31. A raw comparison by pooling the $R_{xx\ max}$ time series of all the subjects (n=59317) and taking the paired differences shows that SQ is better for BS than ES in 61.7% of the SQA cases. In summary, these results show a better average quality for BS than for ES. Similarly, the average for the whole recording of the absolute value of the differences between the RR and the IBI time series (MAE) for each subject was very significantly lower for BS (4.5 ms ± 4.0 ms) than for ES (24.0 ms ± 21.6 ms) ($p<1.2\cdot10^{-6}$, WSRT). If before averaging the agreement, the beats showing a difference in agreement larger than 20 ms (outliers) are rejected, the results still hold ($p<1.6\cdot10^{-6}$, WSRT): 2.28 ms ± 1.58 ms for BS against 8.58 ms ± 3.35 ms for ES. These results show that, on average, the agreement for BS is also better than for ES.

To relate $R_{xx\ max}$ to the agreement, we pooled all the agreement time series and associated each detected beat with the nearest available $R_{xx\ max}$. We identified pairs of agreement and $R_{xx\ max}$ where the absolute value of the agreement was below 20 ms, and $R_{xx\ max}$ was higher than 0.1. These criteria avoid including outliers and noise segments. Because agreement can change from one beat to the next, a moving average filter of 100 is needed to capture central tendency relationships. Figure 4 shows a graph displaying the agreement versus $R_{xx\ max}$ for BS and ES. A linear regression shows that the negative slope of the linear fitting for each cloud of points in Figure 4 is very statistically significant ($p<<0.001$). However, the residuals are large, as reflected by the low value of R^2 (0.32 for BS and 0.13 for ES).

4. Discussion

As can be seen in Figure 4, the higher the $R_{xx\ max}$, the better the agreement is. Nevertheless, the relationship between both parameters is not simple, as judged by the low value of R^2. The agreement between IBI and the RR Time series does not only depend on how accurate the determination of the pulse arrival (that is affected by noise and morphology changes, both factors accounted for in the proposed SQA), but it changes directly with beat-to-beat changes in pulse transit time. Hence, the proposed SQA locates sections where it is feasible to obtain IBI showing good agreement with the RR, but beat-to-beat modulations

of the PTT can worsen this agreement [3].

In Figure 4, each dot cloud's central location also reveals the ES's poorest agreement compared to the BS agreement. Although the time series have been carefully synchronized, this worsening in agreement could be attributed to the lower original sampling frequency of the PPG or remaining errors in the synchronization, noticeably, the drift in the sampling frequency of the ES.

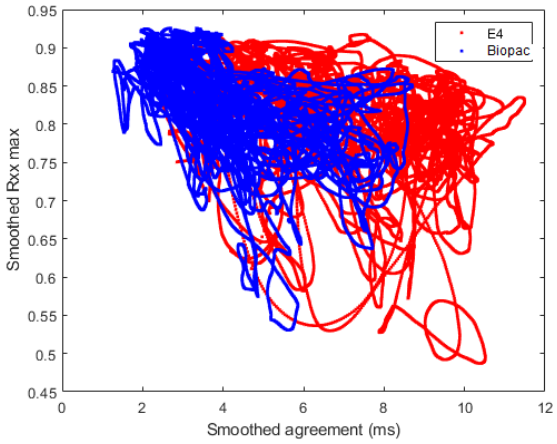


Figure 4. Relationship between the agreement and the SQ $R_{xx\,max}$ for the ES and BS.

5. Conclusion

The proposed SQA ($R_{xx\,max}$) shows promising results for easily locating segments on the PPG signal where IBI shows good agreement with the RR. Moreover, the computation of Rxx max also provides a direct estimate of the mean heart period. On average, Rxx max modulates the agreement between the IBI and RR time series. Nevertheless, other factors different from SQ worsen the agreement. Moreover, results show that the IBI obtained from the Biopac system has better agreement than the Empatica Wristband.

Acknowledgments

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