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Validation of a wrist monitor for accurate estimation of RR intervals during sleep

Ph. Renevey, J. Solà, P. Theurillat, M. Bertschi, J. Krauss, D. Andries and C. Sartori

Abstract— **While the incidence of sleep disorders is continuously increasing in western societies, there is a clear demand for technologies to asses sleep-related parameters in ambulatory scenarios. The present study introduces a novel concept of accurate sensor to measure RR intervals via the analysis of photo-plethysmographic signals recorded at the wrist. In a cohort of 26 subjects undergoing full night polysomnography, the wrist device provided RR interval estimates in agreement with RR intervals as measured from standard electrocardiographic time series. The study showed an overall agreement between both approaches of 0.05 ± 18 ms. The novel wrist sensor opens the door towards a new generation of comfortable and easy-to-use sleep monitors.**

I. Introduction

Modern lifestyles are irremediably associated with increased incidence of sleep disorders. Only in the US more than 18 Million people are accounted to suffer from chronic sleep apnea, and 70 Million from insomnia. Unfortunately, the diagnosis and follow-up of sleep disorders requires still nowadays the use of bulky and cumbersome monitoring devices (Figure 1). There is a clear demand for new technologies that allow assessing vital signs during sleep without interfering with population's comfort.

RR intervals are defined as the elapsed time between two consecutive heart beats, and are typically measured as the delay between two R-Waves of an Electro-Cardiogram (ECG). In sleep medicine, RR interval series are further analyzed in the time- or frequency-domain in order to provide non-invasive information about the autonomic nervous system [1]. Accordingly, physiological complex variables such as stress level, physical recovery, and sleep quality are estimated from the analysis of RR interval series [2].

ECG signals are classically acquired by placing Ag/AgCl electrodes on defined anatomical locations, and by connecting them to a cumbersome monitoring system. Three electrodes are typically required to record one ECG lead [3]. Holter monitors are portable solutions permitting to collect the ECG signals in ambulatory conditions. However, skin irritations caused by the electrodes make this solution only suitable for short periods of time, *i.e.* some days [3].

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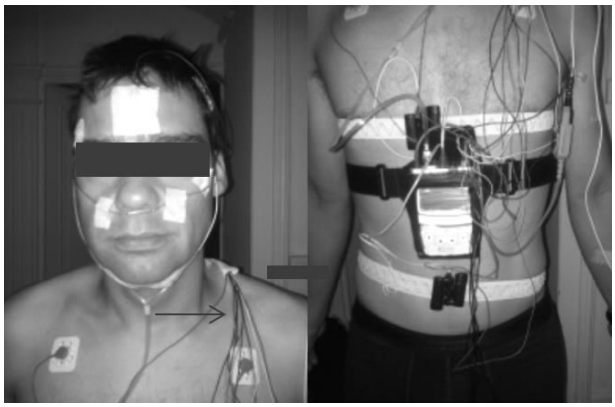

Figure 1. State of the art setup required for polysmonogric studies. Sleep comfort is severly reduced during the monitored nights.

Alternative devices for acquisition of RR interval series in ambulatory conditions are heart rate monitors employed during sport activities. Based on the dry electrode principle [3], these devices have the advantage to be simple and cheap (compared to Holter monitors), but not appropriate for a continuous monitoring in daily-life situations: chest straps remain neither comfortable nor robust (especially during sleep). Textile approaches have been proposed as well [4], but they all require the use of dedicated obtrusive garments in contact with the skin of the thorax. Finally, there exists a family of strapless approaches that detect ECG signal by asking users to place one or two fingers on sensor buttons [5]. Such approaches provide hear rate estimation only on demand for very short periods of time, and do not support continuous recording and processing of RR intervals.

There is thus a lack for technologies allowing the continuous and comfortable measurement of RR intervals, to be introduced in every-day ambulatory campaigns. This paper relies on the use of an alternative technology that catches today the attention of several companies and research institutes: the Photo-Plethysmographic (PPG) technology. PPG is based on a spectrographic technology well-known in the medical community to assess arterial oxygen saturation, so-called pulse oximetry [6]. In order to monitor cardiac activity, a PPG sensor simply requires the placement of an infrared LED and a photo detector on the skin surface [6]. Depending on the geometry of the sensor, PPG measurements can be performed in transmission (infrared light traverses a body flap) or in reflection (infrared light is reflected and travels back towards the skin). In its most common configuration, PPG sensors are integrated into finger or ear clips, or other devices such as finger rings, head patches, arm bands, *etc.* [7-9]. At each cardiac cycle, an arterial pressure pulse propagates along the arterial tree resulting in a generalized increase of the light absorption of

perfused tissues. Accordingly, cardiogenic blood volume changes modulate the absorption properties of tissues, resulting in a fluctuation of the observed PPG signal. PPG sensors measure thus changes of the blood volume of illuminated tissues [10].

Although PPG sensors are medically accepted as a means to assess average Heart Rate (HR) values in pulse oximetres, little is known about the reliability of PPG signals to provide accurate beat-by-beat estimates of RR intervals. The present validation study evaluates the performance of a reflectance PPG sensor integrated into a wrist device to derive RR estimates during sleep.

II. Materials and Methods

A. Materials

This study was conducted during 2012 in La Paz (Bolivia) following the experimental protocol approved by the institutional review boards on human investigation of the University of Lausanne, Switzerland. All participants provided written informed consent.

In total 26 subjects participated to the study (age: 48.1±14.4, BMI: 28.3±5.2, indian). From the 26 subjects, 22 had been previously diagnosed with chronic mountain sickness and sleep-disordered breathing.

After preparation for a full-night sleep monitoring via a polysomnograph system (Titanium recorders and Somnologica biosignal analysis software, Embla, Broomfield, CO), a wrist monitor integrating infrared PPG technology was placed at the right wrist. ECG time series from the polysomnograph were acquired at 256Hz. PPG time series were acquired by the CSEM proprietary wrist monitor prototype at 21.33 Hz. The portable sensor (Figure 2) includes one infrared LED (940nm) and three photodiodes in contact with wrist skin. The total weight of the device is of less than 25g, and together with its reduced watch-like size (34x40x12mm), it is perceived as a very comfortable and light sensor for sleep studies. The sensor is equipped with an LCD showing cardiovascular indicators in real time, and depicts 12 hours of data logging autonomy.

Data was recorded during the entire night without interfering with subjects, and it was further downloaded into a PC platform for off-line processing. In total, 13'991 minutes of data were recorded, containing a total number of 932'948 heart beats.

B. Methods

The analysis of the recorded dataset was perfomed offline. In a first step, reference intervals were extracted from raw ECG time series by means of the Biosig library in a Matlab environment [11]. In a second step, RR intervals estimates were extracted from the raw PPG signals using the procedure herein described.

Figure 2. CSEM's propietary wrist device for the estimation of RR intervals during night periods.

A first derivative of the PPG signals was obtained by computing the difference between two consecutive samples:

$$y(n) = x(n) - x(n-1) \tag{1}$$

where $x(n)$ is the raw PPG signal, and $y(n)$ is the approximation of the temporal derivate. The amplitude envelop $y(n)$ was obtained using an approximation of the infinity norm estimated over a fixed-duration window.

$$\theta(n) = \left(\sum_{i=0}^{W-1}\left(y(n-i)\right)^{\alpha}\right)^{1/\alpha} \tag{2}$$

where W=40 is the size of the averaging widow and $\alpha = 100$ is the term approximating the infinity norm. The amplitude envelop was further used to detect regions where a heart-beat could be detected, the condition for the detection being:

$$y(n) < \beta \cdot \theta(n) \tag{3}$$

where $\beta = 0.5$ is a factor that controls the detection of the heart-beats. The value of β is a compromise between false-positive (small value) and false negative (large value).

The position of individual heart-beats was finally obtained by searching for the minimal value in every continuous interval that fulfilled the condition given in (3). Due to the low sampling frequency of the original data, the precision of the heart-beat positions (in integer of the sampling period) was not sufficient for HRV analysis. This limitation was overcome by using a second-order polynomial interpolation around the detected minimal value. Accordingly, an estimate of a fractional part of the sampling period that corresponded to the position of the minima was obtained. In particular, *assuming* $y(n_{min})$ to be a detected local minimum, the fractional part of the sampling period was estimated as:

$$n_{frac} = \frac{y(n_{min}-1)-y(n_{min}+1)}{2\cdot\left(y(n_{min}+1)-2\cdot y(n_{min})+y(n_{min}-1)\right)} \tag{4}$$

The position of the heart-beat was thus given by $n_{min} + n_{frac}$, and a series of RR intervals was calculated from the difference between consecutive positions of detected heart-beats. The expression of said RR in *ms* was obtained by

dividing the values of the RR series by the sampling frequency in Hz and by multiplying the results by 1000.

In order to avoid the comparison of the two RR series to be biased by outlier values, a non-causal rejection procedure was applied based on the following filter for consecutive RR time series:

$$RR_{med}(k) = Median(RR(k+i));\ i \in \left[-M/2, M/2\right], \quad (5)$$

where $M = 30$ is the size of the median window and k is the index of the detected heart-beats. The RR intervals whose absolute difference with the median value exceeds 200 *ms* were rejected from the series.

Finally, the reference and the estimated RR time series were aligned via a Viterbi algorithm [12] in order to compensate for the difference between the time-bases (offset and clock drifts) of the two measuring systems.

III. Results

Figure 3 illustrates 100 consecutive heart-beats, as extracted from the reference ECG device and the novel PPG wrist monitor. While the upper plot shows the extracted and estimated RR intervals, the lower plot depicts the temporal difference between synchronous RR-pairs.

Table 1 provides a statistical summary of the comparison between reference and PPG-estimated RR time series, as compiled for the entire dataset. Accordingly, the overall error when comparing RR_{ECG} and RR_{PPG} is of 0.05 ± 17.96 ms. Additionally, Figure 4 summarizes the same information in a Bland-Altman plot.

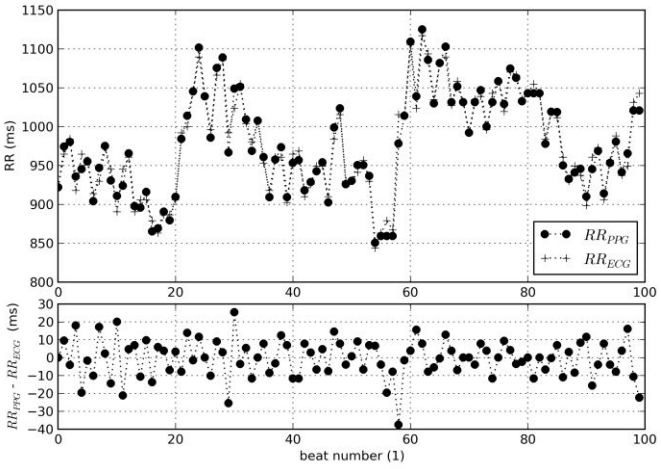

Figure 3: Illustrative example showing 100 heart beats of reference RR intervals (RR_{ECG}), and the associated RR intervals as estimated by the wrist device (RR_{PPG}). Lower plot depicts the instantaneous difference between synchronous RR intervals.

TABLE I. Statistical summary for the results evaluated on the entire dataset (N=932'948).

	Difference between RR_{ECG} and RR_{PPG}		
	mean and std (ms)	***min (ms)***	***max (ms)***
mean	0.05 ± 0.55	-1.41	0.97
Std	17.96 ± 2.36	14.29	23.29

IV. Discussion and Conclusion

The results depicted in Table 1 and Figure 4 demonstrates that RR intervals estimated via the novel wrist monitor are in agreement with the reference ECG measurements. In particular, the Bland-Altman analysis of Figure 4 illustrates that: 1) there is no correlation between the RR difference and the value of the RRs, and b) the estimation error is unbiased (mean difference of 0.05 ms). Yet, the standard deviation of the estimation error is of 18 ms. The analysis of typical examples such as the one provided in Figure 3 better illustrates the nature of such RR_{ECG}-RR_{PPG} difference. Accordingly, the origin of such dispersion is to be explained by the following phenomena:

- The ECG signal is recorded at a sampling frequency of 256 Hz. The estimated RR values are expressed in integer multiples of the sampling intervals. A bounded sampling noise of ± 4 ms with a triangular distribution is thus expected.
- The second order interpolation used in the estimation of the RR from the PPG signals is an approximation, and is dependent on the quantization steps of the signal. A numerical simulation of this effect shows that a Gaussian error with a standard deviation of around 4 ms is expected.
- While RR_{ECG} intervals are directly related to the electrical stimulation of the heart, RR_{PPG} intervals are in addition affected by changes of artery diameters induced by autonomic nervous system vasomotion. The influence of such modulation is not quantifiable with the current dataset, but might account for the resting 10 ms of estimation error. Further experimental data will be required to validate this hypothesis.
- And finally, PPG signals are sensitive to motion-artifacts and these artifacts irremediably introduce errors in the estimation of the heart-beat temporal positions.

Nevertheless, the depicted example illustrates that the difference between RR_{ECG} and RR_{PPG} is contained within a well-limited interval, and that it does not show any particular temporal structure (noise like). Therefore, the described differences should not affect, neither bias, the use of wrist-like devices for the estimation of HRV-related parameters.

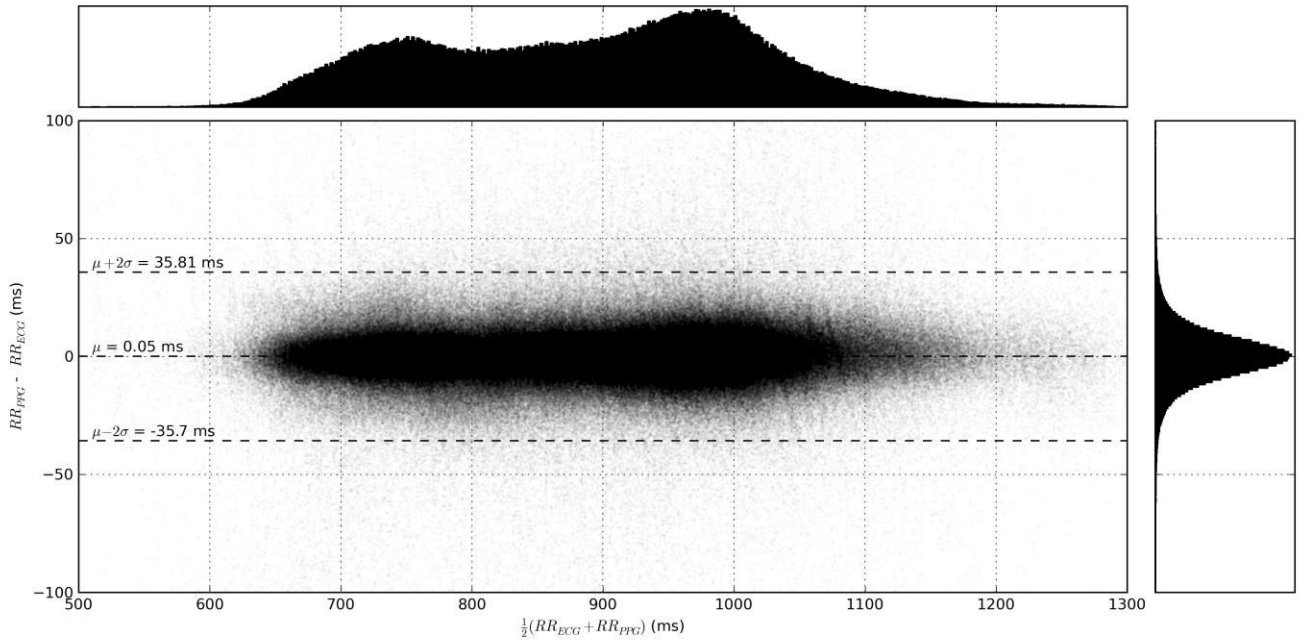

Figure 4: Bland-Altman plot comparing reference ECG-derived RR intervals (as measured by polysomnography) to the associated PPG-derived RR intervals (as estimated by the wrist device). The entire dataset contains a total of N=932'948 heart beats from 26 subjects.

A main limitation of this study remains the fact the RR_{PPG} time series have only been validated during sleeping periods, when motion artifacts are mainly negligible. Although the use of PPG-based sensors to measure heart rate during physically-active periods has been described in the past [13], all existing approaches provide only rough and smooth estimates of heart rate. The present study represents thus a first-ever validation on the use of such technologies for the assessment of beat-by-beat accurate RR intervals.

Even more, the fact that good agreement results were obtained even under cardiovascular stress conditions induced by chronic exposure to high altitude (La Paz is situated at 3600 above the sea), indicates that the novel wrist device approach is robust against non-stationary cardiovascular states.

In conclusion, the present study demonstrated, on cohort of 26 subjects, that the estimation of RR intervals via the analysis of PPG signals recorded at the wrist level is in agreement with simultaneous RR intervals as measured by an ECG. The use of comfortable sensors such as the suggested wrist device might in the future provide novel insights into cardiovascular regulation mechanism occurring during sleep.

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