

## Pulse rate variability compared with heart rate variability in children with and without sleep disordered breathing

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**Abstract**—Heart Rate Variability (HRV), the variation of time intervals between heartbeats, is one of the most promising and widely used quantitative markers of autonomic activity. Traditionally, HRV is measured as the series of instantaneous cycle intervals obtained from the electrocardiogram (ECG). In this study, we investigated the estimation of variation in heart rate from a photoplethysmography (PPG) signal, called pulse rate variability (PRV), and assessed its accuracy as an estimate of HRV in children with and without sleep disordered breathing (SDB). We recorded raw PPGs from 72 children using the Phone Oximeter, an oximeter connected to a mobile phone. Full polysomnography including ECG was simultaneously recorded for each subject. We used correlation and Bland-Altman analysis for comparing the parameters of HRV and PRV between two groups of children. Significant correlation ( $r > 0.90$ ,  $p < 0.05$ ) and close agreement were found between HRV and PRV for mean intervals, standard deviation of intervals (SDNN) and the root-mean square of the difference of successive intervals (RMSSD). However Bland-Altman analysis showed a large divergence for LF/HF ratio parameter. In addition, children with SDB had depressed SDNN and RMSSD and elevated LF/HF in comparison to children without SDB. In conclusion, PRV provides the accurate estimate of HRV in time domain analysis but does not reflect precise estimation for parameters in frequency domain.

### I. INTRODUCTION

Heart rate variability (HRV), the variation in the interval between consecutive heartbeats, is widely used to evaluate the function of the autonomic nerve system and balance between the sympathetic and parasympathetic activities that control heart rate. The spectral analysis of HRV quantifies this evaluation. Three frequency bands are usually of interest: very low ( $< 0.04$  Hz, VLF), low (0.04 – 0.15 Hz, LF) and high frequency band (0.15 – 0.4 Hz, HF). The physiological interpretation of the components in the VLF band is debatable. The LF components reflect the sympathetic control of heart rate, and the HF components represent respiratory sinus arrhythmia and are more related to parasympathetic control of the heart rate [1].

Pulse oximeter photoplethysmography (PPG) is a simple and low-cost measurement technique for non-invasively detecting blood volume variation in the body tissues (e.g.

fingertip or earlobe). The pulsatile feature of the PPG waveform, called the AC component, is synchronized with each heartbeat and its fundamental frequency depends on heart rate. The pulse waves arise from blood volume changes in arterial tissues due to each heartbeat and can be used to estimate the variation of heart rate. Pulse-to-pulse variability, called pulse rate variability (PRV), can be calculated from peak to peak time intervals of the PPG signal. The AC component of the PPG signal is overlaid on a large DC component which varies slowly due to respiration [2].

Childhood sleep-disordered breathing (SDB) includes children with obstructive sleep apnea syndrome (OSAS), the syndromes of central hypoventilation, and children with disorders of the respiratory muscles [3]. OSAS, the most prevalent type of SDB, is characterized by periodic interruption of breathing (apnea / hypopnea) during sleep and is generally caused by a collapse in muscles of the upper airway. Untreated SDB disturbs normal respiration, oxygenation and sleep quality. Symptoms of SDB include daytime sleepiness, fatigue, poor school performance, inattention, hyperactivity, and other behavioral disturbances [3].

A wide range of studies have suggested that apnea, hypopnea and arousals induce changes in normal variation of heart rate during sleep. These studies have showed that increased heart rate [4], elevated sympathetic activity [5] and higher LF to HF ratio (LF/HF) [6] are apparent during sleep disordered breathing.

Additionally, several studies have investigated the accuracy of PRV as an estimate of HRV in healthy subjects. PRV has been shown to be sufficiently an accurate estimate of HRV in healthy subjects at rest [7]. However, the studies have shown that there was a positive bias in the estimation by PRV variables, especially for HF components [8] and the LF/HF parameter [9]. Recently, Khandoker et al. [10] compared PRV variables with HRV parameters during obstructive sleep apnea in adults and showed that PRV was different from HRV for a number of variables during apneic episodes.

In this study, we investigate the accuracy of PRV measured from PPG as an estimate of HRV in children with and without sleep disordered breathing. The PPG signals were recorded in a sleep laboratory using the Phone Oximeter [11], an oximeter sensor connected to a mobile phone. Polysomnography was recorded simultaneously for each subject. Although in a standard sleep laboratory, the PPG signal is recorded as a part of full channel polysomnography, we used the Phone Oximeter for recording the PPG signal as it provided us a high resolution raw signal with an

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opportunity to examine the feasibility of the Phone Oximetry as a convenient, low cost and standalone technology for monitoring the variation of heart rate during sleep disordered breathing.

## II. MATERIALS AND METHODS

### A. Participants

Following ethics approval and informed consent, 72 children referred to the British Columbia Children's Hospital for polysomnography were recruited. The sleep studies of 9 subjects were excluded from study due to inadequate length of sleep or absence of PPG or ECG signals. Using the PSG outcomes and diagnostic report of the paediatric respiratory specialist, the subjects were divided into two groups: subjects with more than 5 apnea / hypopnea per hour (SDB group) and normal children (Non-SDB group) with less than 5 apnea / hypopnea per hour (AHI<5). Table I shows the PSG outcome of the studied subjects.

TABLE I  
SUBJECTS DEMOGRAPHICS AND PSG METRIC *Mean ± SD*

	<b>Total (n = 63)</b>	<b>Non-SDB (n = 36)</b>	<b>SDB (n = 27)</b>
Age(years)	8.56 ± 4.69	8.05 ± 4.65	9.22 ± 4.75
BMI(kg/m <sup>2</sup> )	19.51 ± 8.73	17.41 ± 6.43	22.32 ± 4.69
AHI	7.97 ± 10.88	1.3 ± 0.99	16.78 ± 11.88

### B. Data Collection

Each PSG included electroencephalogram (EEG), left and right electrooculogram, leg movements, body positions, thoracic and abdominal wall movement (from respiratory inductive plethysmography), oronasal airflow (from nasal pressure), arterial oxygen saturation SpO<sub>2</sub>, PPG and ECG lead I and II (recorded at 256 Hz).

In addition, PPG (62.5 Hz), HR (1 Hz), and SpO<sub>2</sub> (1 Hz) were recorded with the Phone Oximeter.

## III. DATA ANALYSIS AND PROCESSING

### A. Heart Rate Analysis

Raw ECG recorded through lead II was used for obtaining HRV. The ECG was passed through a second order Butterworth low-pass filter with a cut-off frequency of 11 Hz, in order to remove high frequency noise. To remove baseline wandering, a second order Butterworth high-pass filter with a cut off frequency of 0.5 Hz was applied to the ECG with a forward-backward technique.

After preprocessing, each ECG signal was divided into 1 minute long segments with 50% overlap between adjacent segments. For each segment, the peaks of normal R-waves were detected using a filter bank based algorithm developed by Afonso and Tompkins [12]. Later, the durations between successive peak locations were calculated to produce RR intervals. The RR intervals with the length less than 0.33 second and more than 1.5 were deleted from time series.

HRV was obtained by evenly resampling RR intervals at 4 Hz using a cubic spline interpolation.

The power spectral density (PSD) of the HRV was calculated through a parametric PSD based on autoregressive modeling, with 1024 points and order 7. Subsequently, the power in the LF and HF band was calculated.

### B. Pulse Rate Analysis

The Phone Oximeter PPG was used for obtaining PRV. After baseline removal and smoothing with a Savitzky-Golay FIR smoothing filter (order 3, frame size 11 samples), each PPG signal was divided into 1 minute segments with 50% overlap between adjacent segments. A signal quality index, obtained by an adaptive version of the algorithm developed by Karlen et al. [13] was performed for automatic rejection of segments with artifacts. After detecting the peak of each pulse wave, the time series of PP intervals (interval between two adjacent pulse peaks) for each segment were estimated. As the same for RR intervals, the PP intervals with the length less than 0.33 second and more that 1.5 were deleted. By performing even resampling of PP intervals at 4 Hz, the PRV signal was obtained.

As with HRV, the power of the PRV in the LF and HF band was calculated through the parametric PSD.

### C. Time and Frequency Domain Parameter

To compare the indices calculated for PRV and HRV signals, the widely used time and frequency domain parameters were calculated according to the standard definitions of HRV parameters [1]. In the time domain, for each overlapped segment of RR or PP intervals, the mean RR and PP intervals (mean NN interval), the standard deviation of all RR and PP intervals (SDNN) and the root mean square of the difference of successive RR or PP intervals (RMSSD) were calculated.

The ratio of the low-to-high frequency spectra (LF/HF) was determined in the frequency domain.

### D. Statistical analysis

Results were expressed as means and standard deviations (SD). Correlation between PRV and HRV parameters was assessed with the Pearson correlation, and their agreement and bias were compared using a Bland-Altman analysis [14].

## IV. RESULTS

Descriptive data, correlation and Bland Altman analysis for the parameters obtained from PRV and HRV are given in Table II for normal subjects (n = 27, AHI = 16.78 ± 11.88) and the subjects with sleep disordered breathing (n = 36, AHI = 1.3 ± 0.99).

As summarized in Table II, mean NN intervals (mean RR and PP intervals) demonstrated a strong correlation (p < 0.05) for both SDB group and non-SDB group. The Bland-Altman analysis of mean RR and PP intervals exhibited a close agreement for both groups. In normal children, the bias estimated as 0.0012 seconds and the 95% upper and lower limits of agreement were -0.0091 and 0.0116 seconds, respectively (Figure 1a). For children with SDB, the bias

TABLE II

DESCRIPTIVE RESULTS, CORRELATION AND BLAND ALTMAN ANALYSIS FOR THE PARAMETERS OBTAINED FROM PRV AND HRV FOR TWO GROUPS OF SUBJECTS WITH AND WITHOUT SLEEP DISORDERED BREATHING

Condition	Parameters			Correlation		Lower limits	Upper limits	Standard Error
		HRV	PRV	Coefficient	Bias	of agreement	of agreement	
Non-SDB	Mean NN intervals	0.797(0.16)	0.799(0.16)	1	0.0012	-0.0091	0.0116	0.0010
	SDNN	0.052(0.032)	0.055(0.035)	0.94	0.0038	-0.0183	0.0260	0.0021
	RMSSD	0.062(0.046)	0.070(0.055)	0.95	-0.0064	-0.0387	0.0257	0.0031
	LF/HF Ratio	0.57(0.46)	0.56(0.41)	0.98	-0.026	-0.2263	0.1723	0.0195
SDB	Mean NN intervals	0.73(0.14)	0.737(0.14)	1	0.0017	-0.0096	0.0131	0.0011
	SDNN	0.046(0.024)	0.048(0.021)	0.91	0.0019	-0.0175	0.0215	0.0019
	RMSSD	0.05(0.028)	0.054(0.025)	0.90	0.0045	-0.0201	0.029	0.0025
	LF/HF Ratio	0.70(0.52)	0.59(0.43)	0.96	-0.091	-0.4243	0.2085	0.0322

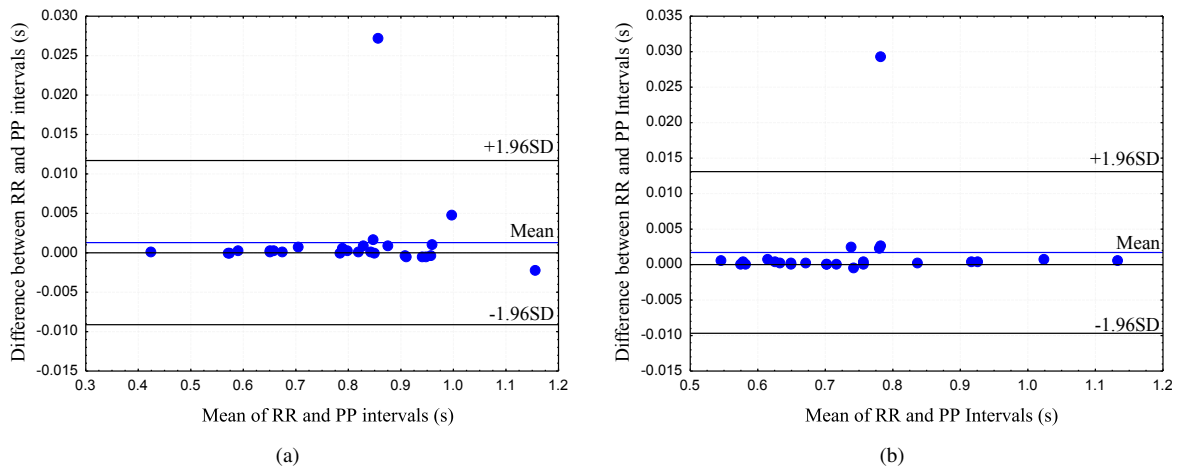


Fig. 1. The Bland-Altman plot of mean NN intervals for a) subjects without sleep disordered breathing (mean = 0.0012) with upper and lower limits of agreements (-0.0091 and 0.0116 respectively) b) subjects with sleep disordered breathing (mean = 0.0017) with upper and lower limits of agreements (-0.0096 and 0.0131 respectively).

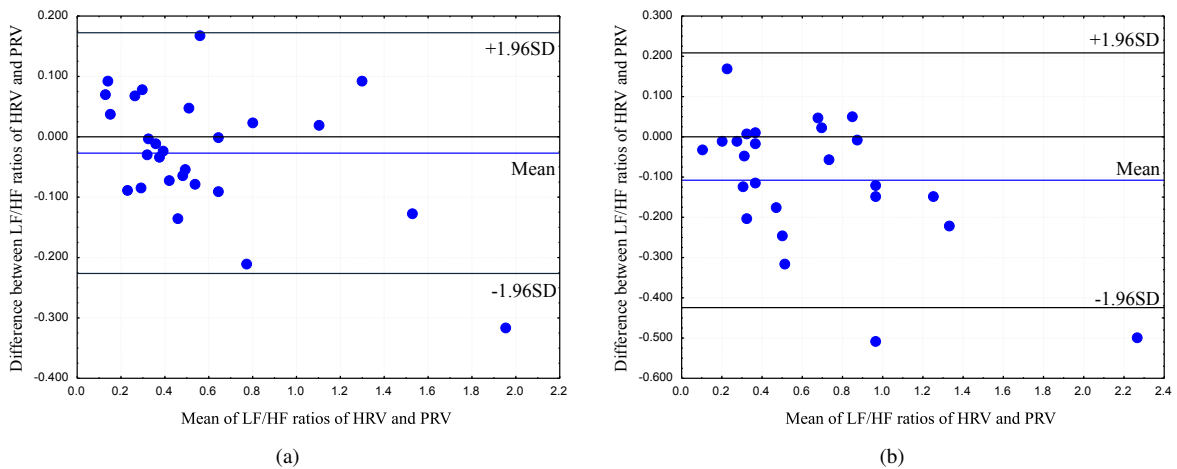


Fig. 2. The Bland-Altman plot of the LF/HF ratio for a) subjects without sleep disordered breathing (mean = -0.026) with upper and lower limits of agreements (-0.227 and 0.172 respectively) b) subjects with sleep disordered breathing (mean = -0.091) with upper and lower limits of agreements (-0.424 and 0.208 respectively).

was 0.0017 seconds and the 95% upper and lower limits of agreement were -0.0096 and 0.0131 seconds, respectively

(Figure 1b).

Results displayed in Table II indicate a significant correla-

tion ( $p < 0.05$ ) and good agreement for SDNN and RMSSD parameters for the two groups of children. For LF/HF ratio, there is a significant correlation for non-SDB group ( $p < 0.05$ ,  $r = 0.98$ ) and also for SDB group ( $p < 0.05$ ,  $r = 0.96$ ) but Bland-Altman Analysis shows a large divergence for SDB group (Figure 2).

## V. DISCUSSION

Simplicity, mobility and comfort of pulse oximetry make it ideally suited non invasive monitoring of patients, especially at home. Furthermore the PPG signal recorded by the pulse oximeter can be used as an alternative signal for estimating respiratory rate [15], heart rate and heart rate variability [8], [9]. In this study, we assessed the accuracy of PRV as an estimate of HRV in children with and without sleep disordered breathing.

Sympathovagal balance is typically reflected in the ratio of low-to-high frequency components (LF/HF ratio). In this study, for both groups of children, the Bland-Altman analysis showed a large divergence between LF/HF ratio estimated from HRV and PRV. This deviation is more significant for children with SDB (Figure 2b). For both groups, the LF/HF ratio from PRV decreased in comparison with the LF/HF ratio estimated from HRV. This decrease could be related to the RSA components or originated from the low sampling frequency of PPG signal. The RSA components (high frequency activity) might be more pronounced in the PPG signal [15] and accordingly, the LF/HF index of PRV may reduce. On the other hand, the low sampling frequency of ECG signal induces the bias and uncertainty in the estimation of HF and LF/HF parameters [16]. Due to low sampling frequency (less than 128 Hz), the HF parameter is underestimated and consequently, the LF/HF ratio is overestimated. In this study, the low frequency of the PPG signal (62.5 Hz) may cause the diminution of the LF/HF parameter of PRV.

In children with SDB, the mean NN interval decreased when compared to the normal children, which reflects an increased heart rate during sleep disordered breathing. SDNN which is mathematically similar to the total power of the spectrum was found to be an order of magnitude lower for the SDB group in comparison with the normal children. As a measure derived from interval differences, we calculated RMSSD, the square root of the mean squared differences of successive NN intervals. The RMSSD which reflects high frequency variations in heart rate, decreased in children with SDB, indicating less parasympathetic activity during SDB. In the group of children with SDB, the LF/HF ratio, regardless of the source, increased in magnitude. This increase reflects more sympathetic activity during SDB.

When comparing our results with previous studies on the effects of SDB on the normal variation of heart rate, we can confirm both a reduction in time parameters and an increase in LF/HF ratio. However, since HRV varies normally over different stages of sleep [17], it is more appropriate to analyze the impact of SDB on HRV during a particular stage of sleep.

## VI. CONCLUSION

In this study, we have demonstrated that PRV provides an accurate estimate of HRV in children with and without sleep disordered breathing for time domain analysis. However the result of the frequency domain analysis should be used with care.

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