Evaluation of agreement between temporal series obtained from electrocardiogram and pulse wave.

GM Leikan¹; E Rossi¹; MCuadra Sanz²; D Delisle Rodríguez³; MC Mántaras¹; J Nicolet¹; D Zapata¹; I Lapyckyj¹; L Nicola Sirì¹ & MS Perrone¹
¹Facultad De Ingeniería-Bioingeniería-Universidad Nacional de Entre Ríos-Argentina.
²Centro de Investigación y DesarrolloTecnológico de la Industria de la Electrónica y la Informática-Colombia.
³Centro de Biofísica Médica-Universidad de Oriente-Cuba.
E-mail: msperrone@bioingenieria.edu.ar

Abstract. Heart rate variability allows to study the cardiovascular autonomic nervous system modulation. Usually, this signal is obtained from the electrocardiogram (ECG). A simpler method for recording the pulse wave (PW) is by means of finger photoplethysmography (PPG), which also provides information about the duration of the cardiac cycle. In this study, the correlation and agreement between the time series of the intervals between heartbeats obtained from the ECG with those obtained from the PPG, were studied. Signals analyzed were obtained from young, healthy and resting subjects. For statistical analysis, the Pearson correlation coefficient and the Bland and Altman limits of agreement were used. Results show that the time series constructed from the PW would not replace the ones obtained from ECG.

1. Introduction

It has been shown a significant relationship between the autonomic nervous system (ANS) and the operation of the cardiovascular system [1]. To quantify this relationship, the development of quantitative indicators of autonomic activity has been necessary [2].

A common way to estimate certain aspects of cardiovascular function is through a surface electrocardiogram (ECG) at rest. It is used for diagnosis of various cardiovascular diseases by analyzing, among other things, the morphology of the signal. Extract the average heart rate, defined as the number of beats per minute, is also possible, and the average period defined as the average length of RR intervals per minute, although this indicator is rarely used in clinical practice.

Since RR intervals are not constant and these fluctuations are influenced by the respiratory cycle and ANS activity, variations of the consecutive RR intervals can be studied using time series constructed from the sequences of such intervals. From these time series is possible to obtain indicators that describes what is known as heart rate variability (HRV).

The quality of measurements of biological variables is crucial in clinical practice. The inherent variability of the variable itself, the associated physiological process, the measuring system and the operator are determining the value of conclusions that emerge from measurements obtained. This reinforces the need of ensure that new measurement techniques be reliable and, eventually, interchangeable [3], [4], [5],[6].
While ECG signal is a reliable primary source for obtaining the intervals associated with heartbeat, there are other physiological signals which also contains information of heart rate, as pulse wave (PW) obtained by Photoplethysmography (PPG). To obtain the PW, normally used to get information of cardiovascular physiology, requires a much simpler patient’s instrumentation than that used in ECG recordings, as it consumes less time and its implementation is less complex, besides being more comfortable for the patient [7].

However, it is necessary know how reliable is the information obtained from PW signal to generate equivalent time series to those obtained from ECG. There are several publications where PW is used as a primary source of information for HRV study. Some of those publications considered that both methods are equivalent for this purpose [8], [9], [10], [11], [12].

The aim of this study is to determine if time series obtained from PPG and those obtained from ECG are interchangeable. Then, the series were analyzed using Pearson’s correlation coefficient and Bland-Altman’s agreement method[3].

2. Materials and methods

Studies were conducted in young, healthy subjects, in supine position. 13 recordings were performed, each between 5 and 8 minutes long. Sample consists of 7 women and 6 men, aged between 19 and 27 years (mean 23.7 ± 2.3 years). The applied protocol establishes a rest period of 5 minutes before data acquisition start. The ANGIODIN V2-Plus was used as acquisition device, previously validated [13]. Each recording consists of 3 signals, ECG (Lead I) and PPG (left and right) acquired simultaneously with 10-bit resolution and 1 [kHz] sampling frequency per channel. This sampling frequency is higher than minimum recommended by the Task Force[14].

The equipment used performs an analog filtering of signals before digitalization. A digital processing which includes filtering and detection of fiduciary points is then performed. In case of ECG's time series, the fiduciary point used is QRS complex's R wave's maximum. In PPG signal, three possible fiduciary points were studied: the systolic point (P), the maximum positive derivative point (D) and the diastolic point (F). P and D points are commonly used [15], but diastolic point's detection is very uncertain when the signal is affected by motion artifacts, so it was discarded. The detection's algorithms and the construction of time series were implemented in Matlab®, where PPG and ECG records were processed with the same techniques of signal analysis.

Fiduciary points that were studied are indicated in Figure 1: R points obtained from ECG, D and P points obtained from PW.

![Figure 1: Fiduciary points on ECG and PW signals.](image)

**R**: wave from ECG; **D**: maximum positive derivative point; **P**: systolic point from PPG.

Time series corresponding to each recording are constructed after event detection. According to recording’s duration and individual's heart rate, each series has between 250 and 400 samples. For this study, time series of all subjects were concatenated, to verify correlation in the detection of intervals;
thus a single time series with 4500 intervals for each fiducial point was obtained. The time series obtained from ECG is called RR, whereas in case of PPG signals, are called PP (PPG1), PP (PPG2), DD (PPG1) and DD (PPG2), being PPG1 and PPG2 the signals obtained from left hand and right hand, respectively.

Were calculated Pearson's correlation coefficients and Bland-Altman's limits of agreement [2] of these series, with RR as reference.

Bland-Altman's limits of agreement assesses if the proposed measurement method can replace the reference method by analyzing the differences between one or another method measurements. In turn, this method can identify trends and behavior of the measuring system. The decision about the interchangeability of methods depends on the application field; in our case, we assessed if differences between them were significant.

3. Results and discussion
The results of correlation and agreement analysis are presented in numerical and graphical form to facilitate understanding. As shown in Table 1, all correlation coefficients are greater than 0.9988, which indicates excellent correlation.

| Compared series     | r      |
|---------------------|--------|
| RR vs DD (PPG1)     | 0.9988 |
| RR vs PP (PPG1)     | 0.9990 |
| RR vs DD (PPG2)     | 0.9989 |
| RR vs PP (PPG2)     | 0.9991 |

Table 1: Pearson’s correlation coefficient between temporal RR series (obtained from ECG) and temporal PP and DD series (from PPG1 -left hand- and PPG2 -right hand-).
High correlation does not imply agreement, so it was decided to implement Bland Altman agreement’s graphics, a method which represents average of measurements in abscissa and difference between measurements in ordinate. In Figure 2 the Bland Altman analysis between time series of RR intervals (ECG) and DD intervals (PPG1) can be seen. The average of measurements is close to zero, 8.4 [$\mu$s], and the standard deviation (SD) is around 5.5 [ms], as is shown in the figure.

Figure 2: Agreement analysis between time series of RR intervals (ECG) and DD intervals (PPG1).

The same analysis performed between time series of RR intervals (ECG) and PP intervals (PPG1) is shown in Figure 3. The average difference between measurements is close to zero, -9.6 [$\mu$s], and SD is around 4.9 [ms].

Figure 3: Agreement analysis between time series of RR intervals (ECG) and PP intervals (PPG1).
The agreement analysis between time series of RR intervals (ECG) and DD intervals (PPG2) show an average difference between measurements of -1 [µs] and SD of 5 [ms] (Figure 4).

![Figure 4](image)

Figure 4: Agreement analysis between time series of RR intervals (ECG) and DD intervals (PPG2).

The results shown in Figure 5 belongs to agreement analysis between time series of RR intervals (ECG) and PP intervals (PPG2). The average difference is around -7.57 [µs] and SD of 4.8 [ms].

![Figure 5](image)

Figure 5: Agreement analysis between time series of RR intervals (ECG) and PP intervals (PPG2).

Discrepancies between either method’s measurements have a SD between 2.2 [ms] and 5.5 [ms]. Limits of agreement (average ± 1.96 SD) exceeds the maximum sampling period suggested by reference bibliography (4 [ms], corresponding to 250 [Hz]) [14].

It is known that autonomic modulation over PW is more complex than heart rate regulation and is affected by other regulation systems, so it is necessary to elucidate if discrepancies between measurements are inherent to the physiological process or to the measurement methodology.
If it is considered that the cause of differences can be attributed to ANS vasomotor regulation, but also to the neurohumoral systemic regulation (catecholamines, angiotensin, vasopressin, etc.) and neurohumoral local regulation (prostaglandins, histamine, nitric oxide, etc.) [16], it is possible that time series obtained both from ECG and PW can reflect different dynamics and mechanisms associated to peripheric vascular regulation.

4. Conclusions
Considering that ECG and PPG signals contains information of cardiac cycle duration, it could be infer that results of analysis both signals, in this aspect, would be equivalent. Although Pearson’s correlation coefficients shows high correlation, limits of agreement exceeds maximum sampling period recommended by Task Force in HRV analysis. This work’s results suggests that PW’s obtained time series can’t replace those arising from ECG to HRV analysis, but they can be useful to investigation of vasomotor regulation.

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