Effect of Filtering of Photoplethysmography Signals in Pulse Rate Variability Analysis*

Elisa Mejía-Mejía[1], James M. May[2], *Member, IEEE*, and Panayiotis A. Kyriacou[3], *Member, IEEE*

***Abstract*— Due to the widespread use and simplicity of photoplethysmography (PPG) signals, and because this signal contains information related to pulse rate, several studies have started to propose the use of Pulse Rate Variability (PRV) for the assessment of cardiovascular autonomic nervous activity, instead of using Heart Rate Variability (HRV) obtained with the electrocardiogram (ECG). However, there is a lack of standardisation and guidelines for the measurement of PRV from PPG signals, which might hinder comparability among studies and validation of results. The aim of this study was to evaluate different digital filters on PPG signals and their effects on PRV information, compared to HRV obtained from ECG. PPG and ECG signals obtained from healthy volunteers were used to measure HRV and PRV. PPG signals were filtered using different FIR and IIR digital filters, with several cut-off frequencies. The results indicate that filtering PPG signals using IIR filters and lower low-cut-off frequencies allow for the acquisition of more reliable PRV information, with lower Bland-Altman ratios and higher cross-correlations when compared to HRV. This is a first step in establishing guidelines and standards for the analysis of PRV information using PPG signals.**

***Clinical relevance*— Pulse rate variability might be a useful tool for the assessment of the cardiovascular autonomic nervous system. This study is the first step for establishing standards of measurement of this signal, which helps in the comparability and validation of the technique.**

I. INTRODUCTION

Heart rate variability (HRV) describes the changes in heart rhythm through time, and is considered as a noninvasive, indirect marker of cardiac autonomic activity [1]. HRV has been related to several cardiovascular conditions [2], mental health [3] and emotional states [4], among other applications. HRV is usually assessed using electrocardiograms (ECG) by measuring instantaneous changes in the duration of R to R intervals (RRIs) [5] and standards of measurement have been established in order to allow comparability among studies [6]. Nonetheless, the acquisition and processing of ECG signals is not always feasible in a continuous manner and may limit HRV applications for daily monitoring of cardiac autonomous nervous system (ANS). Hence, several studies have aimed to obtain HRV information from other physiological signals, such as photoplethysmography (PPG) signals.

PPG is a low-cost, noninvasive, optical measurement technique which detects changes in blood volume in peripheral tissue [7]. Since it is easily acquired and allows for a nonintrusive, continuous monitoring of pulse rate, PPG has been widely used in clinical and consumer devices, such as wearables, for the assessment of pulse changes and to obtain an HRV related variable known as Pulse Rate Variability (PRV) [9]. PRV has been derived from PPG for the analysis of cardiovascular ANS changes, and for the identification of different conditions, such as the presence of mental or somatic diseases [9]). Nonetheless, although PRV has been treated as a valid surrogate of HRV, its relationship is not entirely clear, and PRV has been found to significantly differ from HRV under certain circumstances [8], [10]). Some studies have concluded that these differences may be explained from the different nature of PPG and ECG signals, and physiological factors that may affect PRV and HRV differently [8], [9]). However, technical aspects of the analysis of PPG signals for the assessment of PRV information may have a role in explaining the differences between HRV and PRV [14]. Moreover, there is a need of establishing guidelines and standards for the analysis of PRV information from PPG in order to increase the comparability of the results obtained from different studies. Therefore, the aim of this study was to evaluate the differences among PRV information obtained from PPG signals processed with different digital filters and using several cut-off frequencies. PRV features were compared to ECG-obtained HRV indices as a gold-standard measurement, although differences between PRV and HRV were expected due to physiological factors.

II. MATERIALS AND METHODS

A. Data acquisition

PPG and ECG signals were acquired from thirty-four healthy volunteers (14 men, 34.2 ± 7.21 years old, and 20 women, 34.94 ± 7.15 years old), as explained in [11]. The subjects were employees from a university in Medellín, Colombia, and were randomly selected and invited to take part in the study. Subjects with a history of mental or cardiovascular illness, and those who suffered insomnia in the week before the study, suffered any recent major physical or mental stress, or were undergoing any pharmacological treatments at the time of the study, were excluded.

Each participant of the study was asked to attend a 20-min test and signed an informed consent for participation in the study, which was approved by Universidad CES's Ethics

*This work was not supported by any organization

[1]Elisa Mejía-Mejía is with the Research Centre for Biomedical Engineering, City, University of London, London, United Kingdom. elisa.mejia-mejia@city.ac.uk

[2]James M. May is with the Research Centre for Biomedical Engineering, City, University of London, London, United Kingdom. james.may.1@city.ac.uk

[3]Panayiotis A. Kyriacou is with the Research Centre for Biomedical Engineering, City, University of London, London, United Kingdom. p.kyriacou@city.ac.uk

Committee. During the test, the subject was connected to a signal acquisition system (g.USBamp, Guger Technologies, Austria). ECG and PPG signals were acquired and sampled at 512 Hz. Signals were stored in a personal computer for further analyses. ECG was obtained using skin-contact electrodes in a lead I configuration, whereas PPG was measured using a standard probe located on the forefinger of the nondominant hand. ECG and PPG signals were filtered by the g.USBamp with a band-reject, high-quality notch 60-Hz filter, and with bandpass filters with cutoff frequencies of 0.1 and 60 Hz, and 0.1 and 30 Hz, respectively.

The 20-min test was divided into four 5-min stages. The first stage of the test was a baseline measurement stage, in which subjects were seated comfortably and held their hands over a table, almost at heart level. Subjects were asked to refrain from talking or moving as much as possible during this time. The second and third stages of the test consisted of laboratory-induced stress tasks, while during the last stage subjects were asked to breath following a slow, deep breathing pattern. For this study, only data acquired during the first stage of the test were considered due to the effects mental stress and deep breathing can have in PRV and HRV, and their relationship [9].

B. Signal processing

1) Design and application of filters: Several filters were designed in MATLAB® for the processing of PPG signals. Filters were designed for the combination of different low ($f_{c,low}$) and high ($f_{c,high}$) cutoff frequencies. $f_{c,low}$ were selected as 0, 0.5, 1 and 2 Hz, while $f_{c,high}$ were 5, 8, 10, 12 and 15 Hz. Table I summarises the different parameters used for the design of these filters. ECG signals were filtered with a bandpass, 4th order, Butterworth filter with cutoff frequencies at 0.5 and 35 Hz. All filters were then applied to the original PPG and ECG signals using zero-phase digital filtering.

2) Pulse and heart rate variability analysis: The intersection point between the tangent lines crossing the point of maximum slope and the valley of the pulse waveform was used as fiducial point for segmenting the cardiac cycles from the PPG signals (Fig. 1(b)). This has been suggested as a more reliable indicator of cardiac cycles than other fiducial

TABLE I

FILTERS DESIGNED FOR THE PROCESSING OF PHOTOPLETHYSMOGRAPHIC SIGNALS

Filter type	Design method	Order	PB ripple (dB)	SB ripple (dB)
FIR	Hanning window	512	-	-
	Parks-McClellan	1667 (f_{c_low} = 0, 1 and 2 Hz), 1684 ($f_{c,low}$ = 0.5 Hz)	0.02	60
IIR	Butterworth	4 (LPF), 2 (BPF)	-	-
	Elliptic		0.2	40

FIR: Finite impulse response. IIR: Infinite impulse response. PB: Passband. SB: Stopband. LPF:Low-pass filter. BPF: Bandpass filter. $f_{c,low}$: Low cut-off frequency.

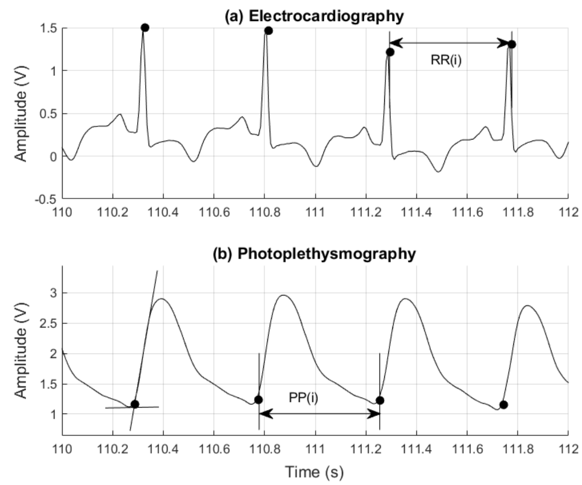

Fig. 1. Example of (a) the measurement of Heart Rate Variability from the R peaks of the electrocardiogram, and (b) the assessment of Pulse Rate Variability from the intersection points between the tangent lines crossing the maximum slope point and the valley of the photoplethysmogram.

points [12]. The interbeat intervals (PPs) were measured as the time difference between consecutive fiducial points. RRIs were obtained from ECG signals using the algorithm described by Pan and Tompkins [13], as is shown in Fig. 1(a). Outliers were detected and replaced with the median value of duration in both cases. Time- and frequency-domain indices, and nonlinear features for PRV and HRV analysis were extracted. Frequency-domain analysis was performed applying the fast Fourier transform (FFT) after interpolating the PPs or RRIs time series using a 4 Hz sampling rate and a cubic spline. The extracted time-domain indices were AVNN, SDNN, RMSSD and pNN50. From frequency-domain analysis, LF, HF, nLF, nHF, and LF/HF were obtained. Nonlinear indices obtained were SD1, SD2, SD1/SD2 from Poincaré plot, sample entropy (SampEn) and multi-scale entropy (MSE), and α_1 and α_2 from Detrended Fluctuation Analysis (DFA).

C. Statistical analysis

The maximum cross-correlation value between HRV and each PRV time series were obtained to evaluate the correlation between HRV and PRV, when PRV is measured from PPG signals processed using the different filters. Also, Bland-Altman analysis of agreement was used to assess the agreement between HRV and PRV indices. From these analyses, a ratio (BAR) was measured as described in [10]. Agreement was considered as good (BAR $\leq$ 10%), moderate (10% $\leq$ BAR $\leq$ 20%) or insufficient (BAR $\geq$ 20%).

III. RESULTS

Figure 2 shows the absolute value of the maximum cross-correlation values obtained from comparing HRV and PRV time series. Results from the Bland-Altman analysis for each extracted index are shown in Figures 3 to 6.

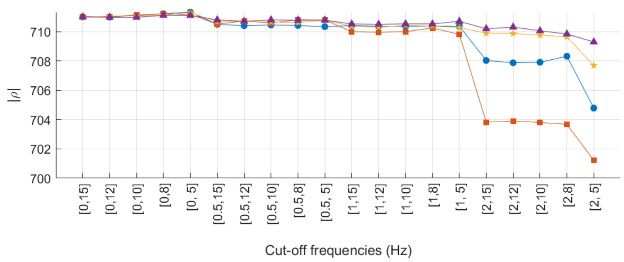

Fig. 2. Mean value of the absolute maximum cross-correlation coefficients ($|\rho|$) obtained when comparing Heart and Pulse Rate Variability time series,, after filtering photoplethysmographic signals with different cut-off frequencies and different filter designs. Applied filters were Hanning window FIR filter (blue circles), Parks-McClellan FIR filter (orange squares), Butterworth IIR filter (yellow stars), and elliptic IIR filter (purple triangles).

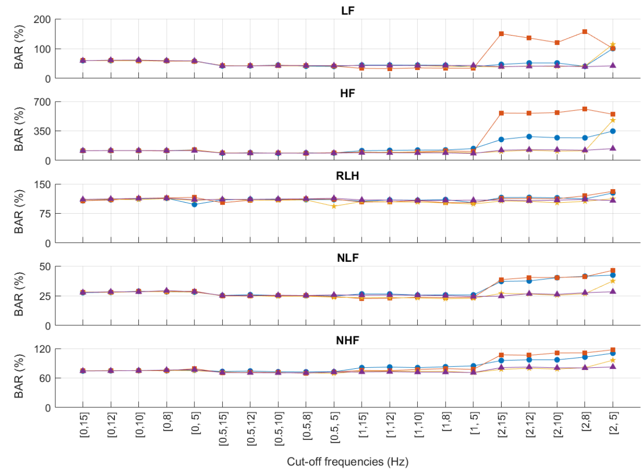

Fig. 4. Bland-Altman ratio for the comparison between frequency-domain indices extracted from Heart and Pulse Rate Variability, after filtering photoplethysmographic signals with different cut-off frequencies and different filter designs. Applied filters were Hanning window FIR filter (blue circles), Parks-McClellan FIR filter (orange squares), Butterworth IIR filter (yellow stars), and elliptic IIR filter (purple triangles).

IV. DISCUSSION

PRV, measured from the intervals between consecutive pulse cycles detected in pulse waves such as the PPG, has been proposed as an alternative measurement from HRV [9], which has been used as a non-invasive marker of cardiac autonomic activity, due to the effects sympathetic and parasympathetic activity have on the control of heart rhythm [5], and which is measured from the intervals between consecutive R peaks identified in the ECG signal. The relationship between PRV and HRV is not straightforward, and the use of PRV as a surrogate of HRV is still under debate [8], [9]. Nonetheless, the assessment of cardiovascular autonomic activity from PRV obtained using PPG signals is expected to be a popular tool for the identification of different events related to cardiovascular and mental health using wearable devices, due to the widespread use and simplicity of PPG technology [15]. Hence, standardising the methodology for PRV extraction from pulse waves, specifically PPG, is a significant factor in order to facilitate comparisons between studies and validation of results. In this study, the aim was to analyse the effects of different digital filters applied on the PPG signal for the assessment of PRV information. The application of filters in the PPG signal is essential to improve the signal-to-noise ratio (SNR) of the signal, which tends to be low due to the multiple artifacts that may affect the signal [16]. However, these filters may generate changes in the PPG waveform that could affect the identification of fiducial points from the signal and, hence, affect the reliability of the PRV information.

From the obtained results, it can be observed that HRV and PRV series tended to show a better cross-correlation

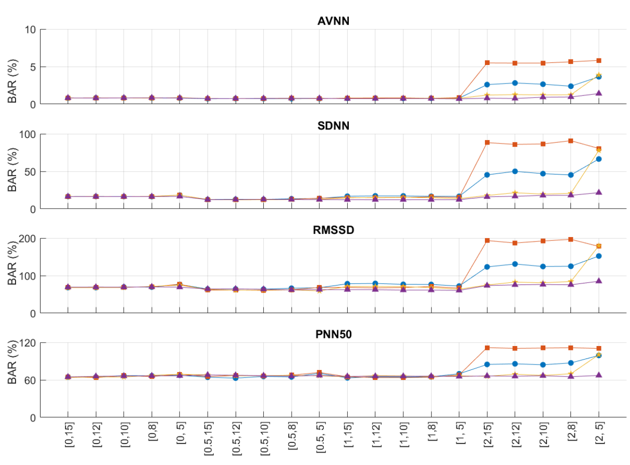

Fig. 3. Bland-Altman ratio for the comparison between time-domain indices extracted from Heart and Pulse Rate Variability, after filtering photoplethysmographic signals with different cut-off frequencies and different filter designs. Applied filters were Hanning window FIR filter (blue circles), Parks-McClellan FIR filter (orange squares), Butterworth IIR filter (yellow stars), and elliptic IIR filter (purple triangles).

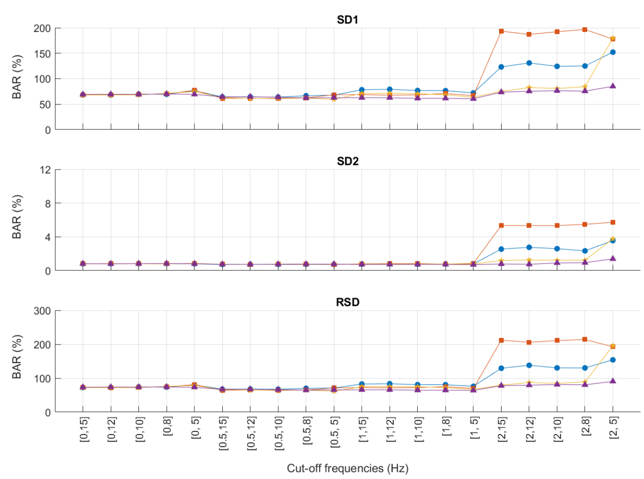

Fig. 5. Bland-Altman ratio for the comparison between Poincaré plot indices extracted from Heart and Pulse Rate Variability, after filtering photoplethysmographic signals with different cut-off frequencies and different filter designs. Applied filters were Hanning window FIR filter (blue circles), Parks-McClellan FIR filter (orange squares), Butterworth IIR filter (yellow stars), and elliptic IIR filter (purple triangles).

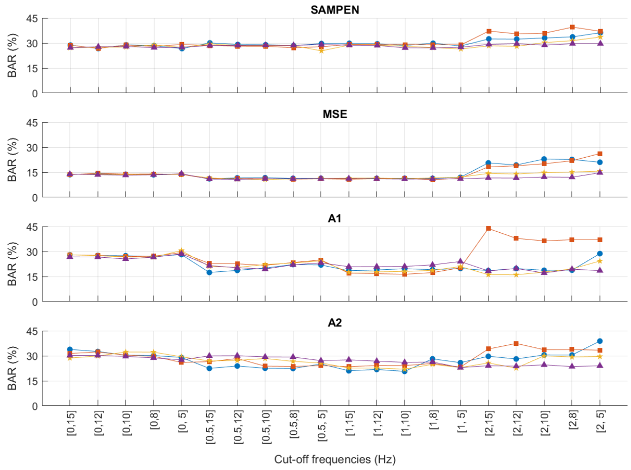

Fig. 6. Bland-Altman ratio for the comparison between entropy and detrended fluctuation analysis indices extracted from Heart and Pulse Rate Variability, after filtering photoplethysmographic signals with different cut-off frequencies and different filter designs. Applied filters were Hanning window FIR filter (blue circles), Parks-McClellan FIR filter (orange squares), Butterworth IIR filter (yellow stars), and elliptic IIR filter (purple triangles).

when lower $f_{c,low}$ tends to zero, while changing $f_{c,high}$ does not have a very remarkable effect. Similarly, BAR's showed a better agreement between HRV and PRV indices when PRV is measured from PPG signals filtered using lower $f_{c,low}$. Regarding the different filter designs studied, it can be observed that the cross-correlation between time series and the agreement between indices is better when using IIR filters, even for lower $f_{c,low}$. This might be due to the passband ripple, which might alter the location of the fiducial points, or due to the larger orders of the FIR filters. Other studies have aimed to understand the effects of digital filtering on PRV. Akar et al concluded that using a Butterworth filter and a nonlinear weighted Myriad filter did not have a significant difference on PRV analysis [14]. Kim and Ahn evaluated the effects of Butterworth and elliptic filters for the assessment of PRV from PPG signals, and concluded that there were no significant differences between HRV and PRV time series, although small differences were observed in some extracted indices [17]. The results obtained in this study have a similar trend, although it is evident that using IIR filters might improve the performance of PRV extraction, especially for higher values of low cut-off frequencies. Also, even if Butterworth and elliptic filters have similar behaviour, indices extracted from PRV obtained from PPG signals filtered using elliptic filters tend to show slightly lower BAR's and higher cross-correlation than those filtered using Butterworth filters. Hence, the use of these filters is recommended for PRV analysis, especially when higher $f_{c,low}$ needs to be used. This study presents some limitations that need to be considered for the analysis of the results. Firstly, PPG and ECG signals were sampled using a 512 Hz, which might not be ideal for PRV and HRV analysis. Nonetheless, using these sampling rate should suffice specially for the detection of PPG fiducial points. Secondly, PRV was compared to HRV, and these signals are not necessarily the same. However, they were measured from healthy, young, and resting subjects, which might diminish the differences between HRV and PRV [8], [9]. Finally, the sample size is small for the establishment of guidelines, and more studies should aim to prove the results obtained in this study using a larger data set.

References

[1] F. Shaffer, and J.P. Ginsberg, "An Overview of Heart Rate Variability Metrics and Norms", *Front. Public Heal.*, vol. 5, 2017, pp. 258. DOI: 10.3389/fpubh.2017.00258.

[2] B. Xhyheri, O. Manfrini, M. Mazzolini, C. Pizzi, and R. Bugiardini, "Heart Rate Variability Today", *Prog. Cardiovasc. Dis.*, vol. 55, 2012, pp. 321-331. DOI: 10.1016/j.pcad.2012.09.001.

[3] J. Koenig, A.H. Kemp, T.P. Beauchaine, J.F. Thayer, and M. Kaess, "Depression and resting state heart rate variability in children and adolescents - A systematic review and metaanalysis", *Clin. Psychol. Rev.*, vol. 46, 2016, pp. 136–150. DOI: 10.1016/j.cpr.2016.04.013.

[4] K.-H. Choi, J. Kim, O.S. Kwon, M. Ji Kim, Y. Hee Ryu, and J.-E. Park, "Is heart rate variability (HRV) an adequate tool for evaluating human emotions? – A focus on the use of the International Affective Picture System (IAPS)", *Psychiatry Res.*, vol. 251, 2017, pp. 192-196. DOI: 10.1016/j.psychres.2017.02.025.

[5] G.D. Clifford, F. Azuaje, and P.E. McSharry, Advanced Methods and Tools for ECG Data Analysis. Norwood, MA: Artech House, 2006.

[6] Task Force of the European Society of Cardiology and The North American Society of Pacing and Electrophysiology, "Heart rate variability: Standards of measurement, physiological interpretation, and clinical use", *Eur. Heart J.*, vol. 17, 1996, pp. 354–381.

[7] P.A. Kyriacou, "Pulse oximetry in the oesophagus", *Physiol. Meas.*, vol. 27, 2006, pp. R1-35. DOI: 10.1088/0967-3334/27/1/R01.

[8] A. Schäfer and J. Vagedes, "How accurate is pulse rate variability as an estimate of heart rate variability? A review on studies comparing photoplethysmographic technology with an electrocardiogram", *Int. J. Cardiol.*, vol. 166, 2013, pp. 15-29. DOI: 10.1016/j.ijcard.2012.03.119.

[9] E. Mejia-Mejia, J.M. May, R. Torres, and P.A. Kyriacou, "Pulse rate variability in cardiovascular health: A review on its applications and relationship with heart rate variability", *Physiol. Meas.*, vol. 41, 2020, pp. 07TR01. DOI: 10.1088/1361-6579/ab998c.

[10] E. Mejía-Mejía, K. Budidha, T.Y. Abay, J.M. May, and P.A. Kyriacou, "Heart Rate Variability (HRV) and Pulse Rate Variability (PRV) for the Assessment of Autonomic Responses", *Front. Physiol.*, vol. 11, 2020, pp. 779. DOI: 10.3389/fphys.2020.00779.

[11] E. Mejía-Mejía, R. Torres, and D. Restrepo, "Physiological coherence in healthy volunteers during laboratory-induced stress and controlled breathing", *Psychophysiology*, vol. 55, 2018, pp. e13046. DOI: 10.1111/psyp.13046.

[12] M.C. Hemon and J.P. Phillips, "Comparison of foot finding methods for deriving instantaneous pulse rates from photoplethysmographic signals", *J. Clin. Monit. Comput.*, vol. 30, 2016, pp. 157-168. DOI: 10.1007/s10877-015-9695-6.

[13] J. Pan and W. Tompkins, "A real-time QRS detection algorithm", *IEEE Trans. Biomed. Eng.*, vol. 32, 1985, pp. 230-236. DOI: 10.1109/TBME.1985.325532.

[14] S.A. Akar, S. Kara, F. Latifoğlu, and V. Bilgiç, "Spectral analysis of photoplethysmographic signals: The importance of preprocessing", *Biomed. Signal Process. Control*, vol. 8, 2013, pp. 16-22. DOI: 10.1016/j.bspc.2012.04.002.

[15] Y.S. Can, N. Chalabianloo, D. Ekiz and C. Ersoy, "Continuous stress detection using wearable sensors in real life: Algorithmic programming contest case study", *Sensors (Basel)*, vol. 19, 2019, pp. E1849. DOI: 10.3390/s19081849.

[16] J. Allen, "Photoplethysmography and its application in clinical physiological measurement", *Physiol. Meas.*, vol. 28, 2007, pp. R1-R39. DOI: 10.1088/0967-3334/28/3/R01.

[17] J.K. Kim and J.M. Ahn, "Digital IIR Filters For Heart Rate Variability; A Comparison Between Butterworth And Elliptic Filters", *Int. J. Sci. Res.*, vol. 8, 2019, pp. 3509-3513.