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ORIGINAL ARTICLE

Validity of the Polar V800 monitor for measuring heart rate variability in mountain running route conditions

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Abstract

Purpose This study was conducted to test, in mountain running route conditions, the accuracy of the Polar V800™ monitor as a suitable device for monitoring the heart rate variability (HRV) of runners.

Method Eighteen healthy subjects ran a route that included a range of running slopes such as those encountered in trail and ultra-trail races. The comparative study of a V800 and a Holter SEER 12 ECG Recorder™ included the analysis of RR time series and short-term HRV analysis. A correction algorithm was designed to obtain the corrected Polar RR intervals. Six 5-min segments related to different running slopes were considered for each subject.

Results The correlation between corrected V800 RR intervals and Holter RR intervals was very high ($r = 0.99$, $p < 0.001$), and the bias was less than 1 ms. The limits of agreement (LoA) obtained for SDNN and RMSSD were (−0.25 to 0.32 ms) and (−0.90 to 1.08 ms), respectively. The effect size (ES) obtained in the time domain HRV parameters was considered small (ES < 0.2). Frequency domain HRV parameters did not differ ($p > 0.05$) and were well correlated ($r \geq 0.96$, $p < 0.001$).

Conclusion Narrow limits of agreement, high correlations and small effect size suggest that the Polar V800 is a valid tool for the analysis of heart rate variability in athletes while running high endurance events such as marathon, trail, and ultra-trail races.

Keywords Validation · Polar V800 heart rate monitor · HRV · Open field running conditions

Abbreviations

ECG	Electrocardiogram
ES	Effect size
GPS	Global positioning system
HF	Power in the high-frequency band
HFn	Normalized HF power
HRM	Heart rate monitors
HRV	Heart rate variability
LF	Power in the low-frequency band
LFn	Normalized LF power
LF/HF	Low-frequency-to-high-frequency ratio.
LoA	Limits of agreement
NN	Normal-to-normal intervals
pNN50	Proportion of differences between adjacent NN intervals of more than 50 ms
P	Total power of the spectral density
RMSSD	Root mean square of differences of successive NN intervals
SDNN	Standard deviation of all NN intervals
T(1–6b)	Error type 1 to 6b
VLF	Power in the very low-frequency band

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Introduction

Heart rate variability (HRV) is the variation over time of the period between consecutive heartbeats and reflects the autonomous nervous system outflow to the heart. Measurement of HRV usually requires an electrocardiogram (ECG)

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system and a consequential R-peak detector. The analysis of heart rate variability has emerged as a powerful tool for assessing the status of the cardiovascular autonomic function in different diseases (Mainardi 2009; Rocha et al. 2014; Voss et al. 2013, 2015). In sports medicine, HRV is considered useful for evaluating the exercise response of the autonomic nervous system to different physical effort in both training and competition. Exercise training may decrease cardiovascular mortality and sudden cardiac death (O'Connor et al. 1989). Regular exercise training is also thought to be capable of modifying the autonomic balance (Arai et al. 1989; Furlan et al. 1993; Hynynen et al. 2006). Decreases and increases in vagal-derived indices of HRV have been suggested to indicate negative and positive adaptations, respectively, to endurance training regimens (Plews et al. 2013). Cardiac autonomic imbalance has been observed in over-trained athletes, but only a few studies are available (Aubert et al. 2003). Monitoring HRV changes in athletes during high endurance events, as marathons and ultra-trail races, could bring new knowledge of the related physiological changes. Analyses of this type currently necessitate the use of heart rate monitors capable of measuring HRV, while the athletes run long distances on mountains or in the open field.

Ambulatory recording of the ECG signal for clinical use is routinely performed using Holter monitors. High cost, difficulty of access, discomfort, and complexity of electrode placement restrict their use in the sports field, especially in high endurance events as marathon, trail, and ultra-trail races. For monitoring heart rate during exercise, several wireless heart rate monitors (HRM) have been developed and wrist-portable HRM devices have become common, permitting the detection of RR intervals with a resolution of 1 ms.

The Polar range (Polar Electro OY, Kempele, Finland) of Vantage/Advantage, S810, RS800 and, more recently, the V800, are practical devices that are widely used, available worldwide, and less expensive than an ambulatory ECG system. They thus represent a very interesting alternative to classic Holter monitors. However, most of the literature refers to Polar HRM validations in subjects during the at rest state. This includes the vantage/advantage (Radespiel-Tröger et al. 2003), S810 (Gamelin et al. 2006, 2008; Nunan et al. 2008, 2009; Porto and Junqueira 2009), the RS800 (Wallén et al. 2012), and the V800 (Giles et al. 2016).

Some studies have performed validations between different monitors in subjects in an active state (Kingsley et al. 2005; Vanderlei et al. 2008; Weippert et al. 2010). Despite movement or exercise being considered in these works, the experimental conditions were far from representing mountain or open field conditions. All their experiments were conducted in controlled lab conditions, which significantly differed from those that athletes encounter while running. To take advantage of the potential of new technologies in this area, the analysis of runner's HRV, based on the RR intervals obtained from a HRM device, would require a prior comparison of the device with a state-of-the-art clinical measurement (Holter electrocardiographic monitoring) during field exercise conditions. Specifically, when considering the feasibility of the V800 monitor for measurements during outdoor exercise conditions, as opposed to lab-based exercise experiments, sensor movement and the movement of the physiological heart axis may occur and are the main factors that might affect its R-wave peak detection.

The aim of the current work was to test, under mountainous running conditions, the accuracy and feasibility of the V800 monitor as an alternative device for monitoring the heart rate variability of runners. The comparative study of the V800 and a Holter monitor included the comparative analysis of RR time series and the comparative analysis of heart rate variability parameters during running. The results of this work will enable future studies of the HRV in athletes while running high endurance events as marathon, trail, and ultra-trail races. To our knowledge, the studies of Sumi et al. (2006) and Melia et al. (2014) are the only two that have analysed HRV during exercise in the field; all other studies of HRV in athletes during exercise have been analysed under controlled laboratory conditions.

Study group

A group of 22 consecutively recruited volunteers aged 20–30 years gave their written informed consent to participate in this study. Data from four participants were not used because of a low signal-to-noise ratio in the Holter ECG during running. Consequently, results are reported on 18 participants, 9 males and 9 females (age 23 ± 2 years; height 1.73 ± 0.11 m; weight 65.58 ± 9.83 kg). None of the participants had any known cardiovascular disease and none were taking any medication or substance that might have influenced HRV during the study. All participants exercised at least 3 h per week.

Experimental design

Data were collected during running. The running route started at the Ciutadella Park, in Barcelona, continued to the top of Montjuic Mountain, and ended at the Ciutadella Park. Figure 1 shows the route map and the elevation profile. The total distance of the running route was 9.87 km. Minimum and maximum elevations were 2 and 174 m, respectively. The running route was designed to include a range of running slopes as in trail and ultra-trail races and to be long enough to include a range of situations that can be found in open field running.

Fig. 1 Route map and elevation profile. Ciutadella Park—top of Montjuic Mountain—Ciutadella Park, in Barcelona

Short-term HRV analysis was performed in 5-min segments, as recommended by the Task Force of the European Society of Cardiology and by the North American Society of Pacing and Electrophysiology (1996). To analyse the short-term heart rate variability, the following 5-min RR interval series were considered during the running route of each subject: S1, during the first stage of the course with a running slope lower than 4.5%; S2, with a positive running slope between 4.5 and 10%; S3, just before arriving at the top of the mountain, with an average positive running slope of 12%; S4, just after the top of the mountain, with an average negative running slope of − 12%; S5, with a negative running slope between − 10 and − 4.5%; S6, during the last stage of the course with running slope lower than 4.5%. These six selected 5-min segments for each subject covered a wide heart rate and heart rate variability ranges to assess whether agreement among the different devices was stable across the whole measurement range. Consequently, 108 5-min segments (6 segments for each of the 18 subjects) were considered in this study.

Instrumentation and data acquisition

A Polar V800 HRM with a Polar H7 Heart Rate Sensor chest strap (henceforth, V800) recorded the RR intervals at a sampling frequency of 1000 Hz. A 12-lead GE SEER 12 Holter (GE Healthcare Inc., Milwaukee, WI, USA. Henceforth, Holter) simultaneously recorded the ECG signal at a sampling frequency of 128 Hz. The position of the runner was recorded by the V800, with a GPS sampling frequency of 1 Hz.

Electrodes were placed in the standard configuration for a 12-lead ECG. The V800 HRM elastic electrode belt was placed in accordance with the manufacturer's guidelines. Electrodes were moistened before placement, but no conductive gel was applied.

Data analysis

The data analysis included: (1) a comparative analysis of the RR intervals obtained from the V800 and the Holter; (2) a comparative analysis of Heart Rate Variability parameters obtained from the data recorded with the V800 and the Holter. The data sets with the RR intervals obtained from the V800 and the Holter are included in this published article as additional supporting files. In the first analysis, the raw data obtained from the V800 were considered, as well as the corrected RR intervals obtained after applying a correction algorithm to the raw data.

Two signals of interest were obtained from the V800: GPS signal and RR interval data series. Running slope information of each subject during running was necessary to select each one of the previously described segments (S1–S6). Altitude measurement precision from the Polar HRM is relatively low and pressure changes due to weather conditions may affect such measurements. Hence, the GPS elevation data were corrected for all the subjects using the GPS Visualizer, a utility that creates maps and profiles from geographic data. Data were taken from the NASA database of Shuttle Radar Topography Mission (SRTM).

RR interval comparison

The RR interval comparison was analysed considering the 108 described previously 5-min segments. The ECG signal recorded with the Holter was resampled from 128

to 1000 Hz, as recommended by the Task Force (1996), through spline interpolation, providing a temporal resolution of 1 ms, the same as the V800 resolution. R-wave peaks were detected automatically in the ECG signal using a custom peak detection algorithm in Matlab (Mathworks, Natick, MA, USA). The R-wave peaks detected were manually assessed to ensure that they had been correctly detected. Alignment of the two RR data series (from the V800 and the Holter) was done using minimum distance criteria.

A V800 acquisition error was considered to have occurred when the difference between the Holter and V800 intervals exceeded 20 ms (Gamelin et al. 2006), with the addition of T6 (a and b) described in (Giles et al. 2016). Then, the V800 RR interval was assigned to one of six identified error categories according to the classification presented in (Gamelin et al. 2006) and (Giles et al. 2016): A T1 error was defined as a single point of discrepancy, either positive or negative, between the Holter and the V800 RR interval; a T2 error was defined as a long interval immediately followed by a short interval and the magnitude of the difference between the two Holter and the V800 RR intervals being similar; a T3 error was defined as a short interval immediately followed by a long interval with the magnitude of the difference between the two Holter and V800 RR intervals being similar; a T4 error was defined when the V800 RR interval was equivalent to a multiple of Holter RR interval; a T5 error occurred when the V800 detected two or more short RR intervals, whereas the Holter detected one interval; a T6-a error was defined when a RR interval was entirely missed by the V800: T6-a were not detectable without the simultaneous ECG recording, whilst T6-b were identified by a discrepancy between the time stamp in the first column and the length of the interval in the second column of the file exported from the V800 data.

To obtain the corrected V800 RR intervals, a correction algorithm was designed, based on the algorithms developed by Gamelin et al. (2006) and Giles et al. (2016). The correction algorithm applied to the V800 raw data did not consider information from the simultaneous Holter recording. Otherwise, it would not represent the typical use of the V800 (Nunan et al. 2008; Giles et al. 2016), because simultaneous recording of Holter during trail and ultra-trail races is not possible. The present study avoided the correction of unidentifiable errors without a simultaneous ECG recording (T6-a), and corrects errors (T1–T5 and T6-b) considering exclusively the Polar raw data.

If a T1 error was detected, as a deviation from the mean value of the last samples higher than a given threshold, the RR was replaced by the median value of the last samples. When T2 or T3 errors were present, the two uncorrected different RR intervals were averaged and replaced by the average value. In the case of T4 error, the erroneously measured RR interval was equivalent to k times the mean of previous samples, and the measured RR value was replaced by k consecutive values of the measured RR divided by k. T5 errors were corrected replacing the measured short RR intervals by the addition of these detected intervals. Correction of T6-b errors was not applied, because in the data recorded in this study, no T6-b error was observed. Once abnormal RR intervals were replaced, the signal was considered to be normal, and to provide normal-to-normal (NN) intervals.

Short-term HRV analysis: time and frequency domain measures

Short-term heart rate variability analysis was performed in 5-min segments, as recommended by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996).

The following short-term HRV parameters were analysed in the time domain: mean NN interval, the standard deviation of all NN intervals (SDNN), and the root mean square of differences (RMSSD) of successive NN intervals. The proportion of differences between adjacent NN intervals of more than 50 ms (pNN50) was not considered, because, during strenuous exercise, the value of this parameter is nearly zero (Mateo et al. 2001).

Spectral analysis was performed using a parametric autoregressive model with the Burg method (Burg 1975) and a 16-order model. The RR interval time series was resampled at 4 Hz (Boardman et al. 2002; Broersen 2000; Gomis et al. 2012). The following HRV spectral indices were computed: Total power of the spectral density (P), power in the very low-frequency band (VLF; 0.00–0.04 Hz), power in the low-frequency band (LF; 0.04–0.15 Hz), power in the high-frequency (HF; 0.15–0.40 Hz) band, normalized LF power [$\mathrm{LFn} = 100 \times \mathrm{LF}/(\text{total power} - \mathrm{VLF})$], normalized HF power [$\mathrm{HFn} = 100 \times \mathrm{HF}/(\text{total power} - \mathrm{VLF})$], and the LF/HF ratio.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 20.0. Statistical significance was set at $p = 0.05$ level for all analyses. A Wilcoxon matched-pair test was used to detect the presence of a systematic difference in RR intervals from the V800 and the Holter.

Correlation between repeated measurements was assessed by the Pearson's product–moment correlation coefficient or, when appropriate, by the Spearman rank-order correlation. In this case, repeated measurements were Holter measurements and V800 measurements, and they were expected to be the same.

Bland–Altman plots of all measures from both systems were constructed and the 95% limits of agreement (LoA), where the true value varies, were computed (Bland and

Altman 2007). The Bland–Altman plot analysis is a simple way to evaluate a bias between the mean differences, and to estimate an agreement interval, within which 95% of the differences of the second method, compared to the first one, fall (Giavarina 2015). The magnitude of the difference of the RR intervals and the HRV parameters was calculated by determining the effect size (ES) which represented the mean difference over the standard deviation of the difference (Thomas et al. 2015); the difference was considered small when ES < 0.2, moderate when ES ≤ 0.5, and great when ES > 0.8 (Cohen 1988).

Descriptive statistics were performed to calculate mean values and standard deviations for all HRV indices in all the groups and skewness of differences between Holter and Polar V800 RR interval values. Normal distribution of the indices was assessed with the Kolmogorov–Smirnov test. A *t* test or a Wilcoxon matched-pair test, depending on whether normality distribution and homoscedasticity were fulfilled or not, was used to detect the presence of differences in HRV indices.

Comparative analysis of RR time series

The total number of RR intervals detected with the V800 was 91,825 during the 108 5-min running segments considered in this study. Type and number of obtained errors, described in "Data analysis" section, are detailed in Table 1, in both absolute and relative terms. The total error rate was 0.71%. Error T4 type was the most frequent error type, with an error rate of 0.56%. It represented 79% of the total errors in the analysed 5-min segments during the mountain running route.

The number of RR intervals analysed for each participant ranged from 4638 to 5590. In all but four runners, the difference between Holter and uncorrected Polar V800 RR interval values presented a symmetrical pattern [skewness median (interquartile range) = − 0.09 (0.76)]. Two patterns of difference values between monitor systems showed a markedly positive skewness (62.52 and 25.64), while other two had a negative skewness (− 9.97 and − 52.16). Differences between Holter and uncorrected Polar RR intervals were non-normally distributed according to the Kolmorogov–Smirnov test.

No systematic differences were found in RR intervals from V800 and the Holter in the Wilcoxon matched-pair test ($p < 0.05$). Figure 2a, b represents Bland–Altman plots for combined Holter and uncorrected V800 RR intervals and the Holter and corrected V800 RR intervals, respectively. The Spearman rank-order correlations were 0.97 and 0.99 for the uncorrected and the corrected V800 RR intervals with the Holter, respectively ($p < 0.01$). Limits of agreement (LoA) for uncorrected and corrected data, considering the Bland Altman analysis with multiple and non-constant observations per individual, were − 60.53 to 60.54 and − 3.61 to 3.63, respectively. The bias obtained when comparing Holter and corrected V800 RR intervals was less than 1 ms.

Heart rate variability indices analysis

No significant differences were found for time domain and frequency domain parameters obtained from the corrected V800 and Holter signals, except for the power in the low-frequency band ($p < 0.05$). Bland–Altman plots of all measures from both systems were constructed and the 95% limits of agreement (LoA) computed. Detailed results are presented in Table 2, which includes the correlations of the HRV parameters obtained from the corrected V800 and Holter signals, as well as the bias, the 95% interval LoA, and the effect size. Normally distributed data are presented as means ± one standard deviation (SD) and non-normally distributed data are expressed as medians and the interquartile ranges (Gomis et al. 2012).

Discussion

This study was conducted to compare RR time series and heart rate variability parameters obtained from a Polar V800 heart rate monitor and a Holter ECG recorder under running conditions in the field. The present results provided consistent measurement of heart rate variability from RR intervals derived from the V800 in a running route. The results

Table 1 Classification of measurement errors by the Polar V800 monitor

Type	Description of error	Number	Error rate (%)
T1	Single interval of discrepancy	7	0.01
T2	Long interval and short interval	20	0.02
T3	Short interval and long interval	98	0.11
T4	Too few intervals detected	515	0.56
T5	Too many intervals detected	0	0
T6-a	RR interval(s) missed by the V800, undetectable	7	0.01
T6-b	RR interval(s) missed by the V800, detectable	0	0
		647	0.71

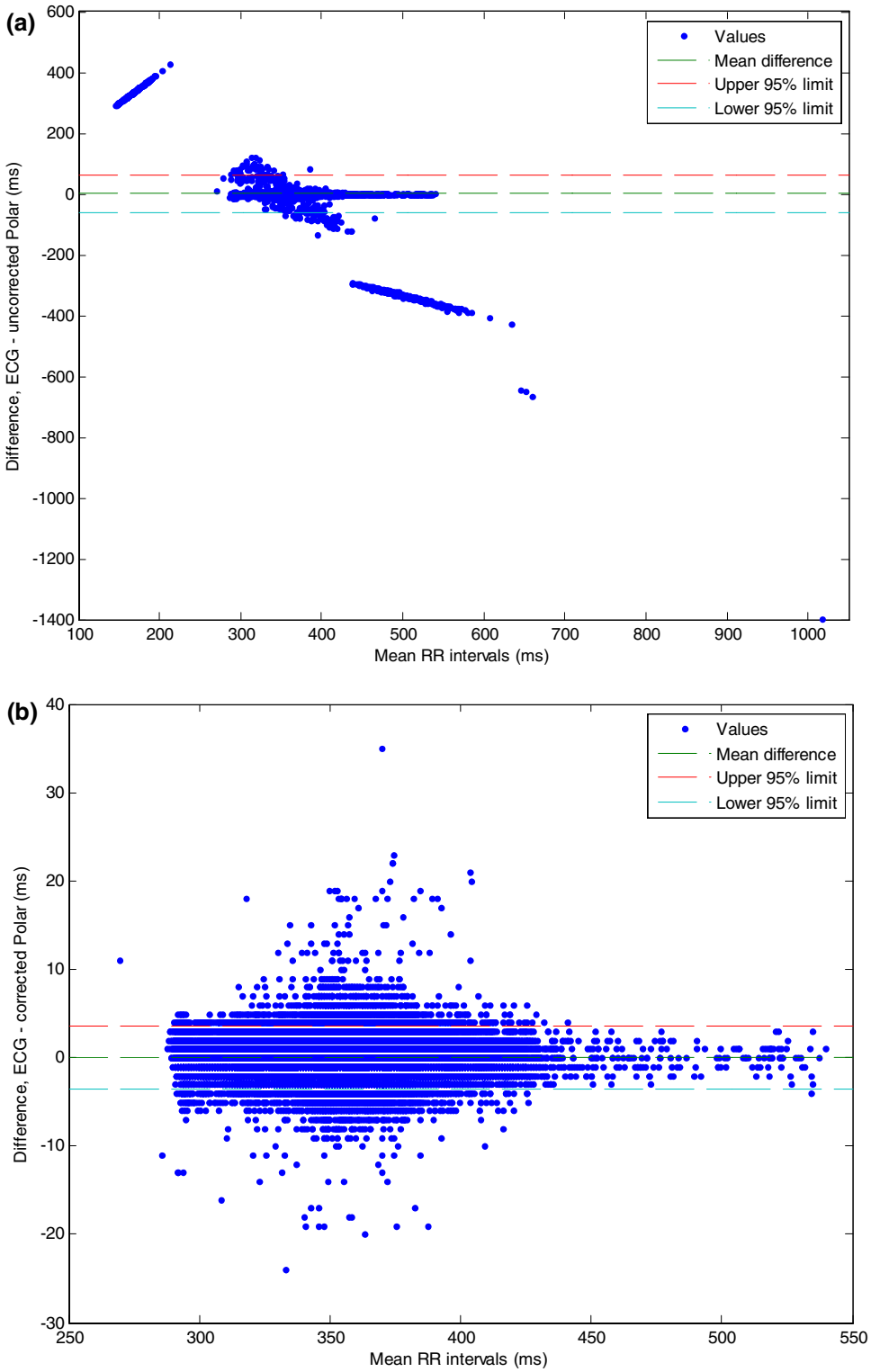

Fig. 2 Bland–Altman plots for combined Holter and uncorrected V800 RR intervals (**a**) and the Holter and corrected V800 RR intervals (**b**), during running. Center dot–dash line equals mean difference between the two devices to detect RR intervals

showed that this device is practical and feasible for recording RR interval time series for HRV analysis as compared to the RR interval series recorded by a conventional Holter system. The experimental design used for the comparison was worth noting; a mountain running route of about 10 km, including running slopes in the range of trail and ultra-trail races. The purpose was to recreate real conditions of athletes during training or competition, since most previously available studies were conducted in the at rest state or in controlled lab conditions.

Table 2 Heart rate variability parameters obtained from the corrected V800 and Holter data (data expressed as means ± SD or median and interquartile range), correlation between V800 and Holter parameters, bias, limits of agreement (LoA), and effect size

							Magnitude of the bias	
		Holter	V800	Correlation*	Bias	LoA	Effect size	Interpretation
TD	MeanNN (ms)	353.26 ± 25.04	353.25 ± 25.04	1.00	0.01	− 0.11 to 0.13	0.000	Small
	SDNN (ms)	7.47 ± 3.05	7.43 ± 3.06	1.00	0.04	− 0.25 to 0.32	0.012	Small
	RMSSD (ms)	3.54 (2.99–4.65)	3.53 (2.99–4.25)	0.87	0.09	− 0.90 to 1.08	0.044	Small
FD	VLF (ms^2)	17.49 (7.83–29.33)	17.49 (7.88–29.40)	1.00	− 0.07	− 1.95 to 1.81	0.004	Small
	LF (ms^2)	1.54 (0.68–2.76)	1.71 (0.72–2.87) [a]	0.99	− 0.04	− 0.42 to 0.34	0.018	Small
	HF (ms^2)	0.61 (0.33–1.23)	0.65 (0.31–1.17)	0.96	0.01	− 0.60 to 0.61	0.004	Small
	P (ms^2)	20.88 (9.90-34.99)	20.98 (10.06–35.01)	1.00	− 0.05	− 2.19 to 2.08	0.003	Small
	LFn	57.98 ± 19.83	58.46 ± 20.44	0.96	− 0.48	− 11.05 to 10.09	0.024	Small
	HFn	30.00 ± 14.42	30.43 ± 15.87	0.96	− 0.43	− 8.99 to 8.14	0.028	Small
	LF/HF ratio	2.01 (1.13–3.55)	1.99 (1.20–3.67)	0.98	− 0.13	− 1.44 to 1.18	0.003	Small

*Significant correlation with $p < 0.001$

[a]Significantly different from the Holter data

The comparative analysis of the RR intervals obtained from the V800 and the Holter gave an error rate of 0.71%. This was in accordance with the previous studies in adults which reported a rate of between 0.09 and 6.93% (Ruha et al. 1997; Kingsley et al. 2005; Gamelin et al. 2006; Vanderlei et al. 2008; Giles et al. 2016). The error results obtained were slightly greater than in the previous studies of adults at rest. This increase of the error rate could be explained by the more exigent nature of the mountain running route conditions. Some 79% of the errors in the uncorrected HRM signal were of type T4 (too few intervals detected by the HRM, with a V800 RR interval equivalent to a multiple of the Holter RR interval). The movement of the sensors and the bad contact of the chest strap with the skin could produce this type T4 error, causing a decrease or an absence in R-wave amplitude and the inability to detect it. Bad contact could be due to lack of moisture, which depended on perspiration of the subject, or by a partial overlapping with the electrodes of the Holter system. In all but four runners, the distribution of bias of the uncorrected Polar V800 RR intervals presented a symmetrical pattern. The skew pattern of differences between the Holter and uncorrected Polar V800 RR interval values observed in these four runners was explained by the type T1 and T6-a errors found (single intervals of discrepancy or RR interval missed by the V800). The other type errors generated symmetric distribution patterns.

To reduce the errors in the detection of R-wave peaks during outdoor exercise conditions, mainly due to movement of the sensors and movement of the physiological heart axis, a correction algorithm was designed to obtain the corrected V800 RR intervals. Errors were easily recognizable in Polar raw data. The algorithm applied to this data did not consider information from the simultaneous Holter recording. Correlation between corrected V800 RR intervals and Holter RR intervals was very high (0.99). The bias was less than 1 ms in the current study, comparable to that already reported in other studies (Kingsley et al. 2005). The observed narrowing of limits of agreement (LoA) after correction (− 61.9 to 61.9 and − 3.55 to 3.57 ms for uncorrected and corrected data, respectively) also suggested that the correction methodology was successful. The LoA obtained for corrected data was narrower than those reported at rest by Gamelin et al. (2006) (− 5.2 to 5.89 ms), and during exercise by Kingsley et al. (2005) (− 13.48 to 13.32 ms). Our limits of agreement for corrected data were slightly wider than those reported by Porto and Juniqueira (2009) (− 3.89 to 2.50 ms) and Giles et al. (2016) (− 1.70 to 2.87 ms), and this difference was to be expected, since our results were obtained in subjects under open field running conditions, which means more adverse conditions, whereas the results of Porto and Juniqueira (2009) and Giles et al. (2016) were obtained in subjects in a rest state. The correlation between corrected V800 RR intervals and Holter RR intervals and the obtained LoA suggested that the V800 was a valid tool for measuring RR intervals during training or competition in a mountain running route. Several factors accounted for any differences between the V800 and Holter RR intervals. As data collection from the V800 monitor and Holter ECG recorder was performed simultaneously, the locations of the elastic band of the V800 monitor and the Holter electrodes were different, implying that the electrocardiographic leads captured by both devices could not be exactly the same. Another factor was the different R-wave detection algorithms used. R-waves were detected automatically in the Holter ECG signal using a custom peak detection algorithm, whereas the RR intervals from the V800 monitor were available with no information on the detection algorithm used.

Regarding time domain heart rate variability, all parameters obtained from the V800 and Holter data showed high correlation, and no significant differences, as reported in several previous articles under other conditions (Radespiel-Tröger et al. 2003; Gamelin et al. 2008; Vanderlei et al. 2008; Giles et al. 2016). The LoA obtained for SDNN (-0.25 to 0.32 ms) was narrower than those reported at rest by Gamelin et al. (2006) (−0.47 to 0.63 ms) and Porto and Juniqueira (2009) (−1.65 to 2.28 ms), and was slightly wider than those reported by Giles et al. (2016) at rest state (−0.22 to 0.24 ms). This difference was to be expected, because our results were obtained in subjects under running conditions in the field. There were no previous LoA results for SDNN during exercise. The LoA obtained for RMSSD (−0.90 to 1.08 ms) was narrower than those reported at rest by Gamelin et al. (2006) (−1.17 to 1.58 ms) and Gamelin et al. (2008) (−1.09 to 1.29 ms). Our limits of agreement for this variable were wider than those reported by Giles et al. (2016) at rest state (−0.32 to 0.32 ms), and there were no previous results of LoA for RMSSD during exercise. The highest effect size (ES) in the time domain HRV parameters was obtained for the RMSSD, with a value of 0.044 that was considered small (ES < 0.2) in Cohen (1988).

The frequency domain heart rate variability parameters obtained from the V800 and the Holter showed high correlations, as reported previously when comparing Polar HRM and ECG data in other conditions. In this study, no significant differences were found in any parameter except for LF. This difference was not previously reported when analysing Polar HRM in subjects at rest (Radespiel-Tröger et al. 2003; Gamelin et al. 2006; Giles et al. 2016). The study of Kingsley et al. (2005), in subjects during an active state in controlled lab conditions, presented no differences in frequency domain parameters during low intensity exercise ($< 40\%VO_{2max}$), but significant differences were obtained throughout exercises at intensities greater than $40\%VO_{2max}$. Vanderlei et al. (2008) did not report differences in frequency domain parameters, but the subjects were submitted only to a submaximal effort test. Nevertheless, the correlation coefficient for this LF parameter between the V800 and the Holter is high ($r = 0.99$, $p < 0.001$), and the effect size was small ($0.018 < 0.2$). Considering that 2 weeks of intensive training induced a significant decrease of LF that corresponds to an effect size of 0.43 (Pichot et al. 2000), the measurement error by the V800 could be considered negligible. Limits of agreement for LF and HF (−0.42 to 0.34, and −0.60 to 0.61, respectively) were narrower than those reported in Kingsley et al. (2005) and Gamelin et al. (2006). Limits of agreement for LFn (−11.05 to 10.09), HFn (−8.99 to 8.14), and LF/HF (−1.44 to 1.18) were narrower than those reported in Weippert et al. (2010) and wider than those reported in Gamelin et al. (2006) but, based on Cohen (1988), all the effect sizes were considered small.

In conclusion, narrow limits of agreement, high correlations, and small effect size between the Polar V800 and a Holter ECG suggested that this monitor, after data correction, was a valid tool for the analysis of heart rate variability in athletes while running high endurance events such as marathon, trail, and ultra-trail races. The correction of Polar V800 HRV data was possible without the simultaneous recording from an ECG. Caution must be taken regarding the power in the low-frequency band (LF) parameter. Nevertheless, the slight differences obtained in this HRV parameter, when comparing the values obtained from V800 Holter monitors, were negligible compared to training or overtraining effects.

Conclusion

The evaluation of changes in the autonomic nervous system during high endurance events as marathons, trail, and ultra-trail races needs the use of heart rate monitors capable of measuring the heart rate variability, while the athletes are running these events. Some existing studies have performed validations between different heart rate variability monitors in subjects during controlled lab conditions which significantly differed from those that athletes encounter while running in mountain or open field conditions. This study compared RR time series and heart rate variability parameters obtained from a Polar V800 heart rate monitor and a state-of-the-art clinical measurement (Holter ECG) in mountain running route conditions. Narrow limits of agreement and high correlations between the Polar V800 monitor and a Holter ECG are obtained. They suggested that this monitor, after data correction, is a valid tool for the analysis of heart rate variability in athletes while running high endurance events such as marathon, trail, and ultra-trail races. The correction of Polar V800 monitor data is possible without the simultaneous recording from an electrocardiograph system.

Author contributions Participated in research design: PC, PG, EG, LM, AP and NS. Conducted experiments: FS and NS. Performed data analysis: PC, PG, AP and FS. Wrote or contributed to the writing of the manuscript: PC, PG, EG, LM, AP, FS and NS.

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Compliance with ethical standards

Informed consent A group of 22 consecutively recruited volunteers gave their written informed consent to participate in this study.

Ethical approval The protocol was reviewed and approved by the Healthcare Ethics Committee of the Hospital Clínic of Barcelona (2013/8255).

Conflict of interest Pere Caminal, Fuensanta Sola, Pedro Gomis, Eduard Guasch, Alexandre Perera, Núria Soriano, and Lluis Mont declare that they have no conflicts of interest.

References

Arai Y, Saul JP, Albrecht P et al (1989) Modulation of cardiac autonomic activity during and immediately after exercise. Am J Physiol 256:H132–H141

Aubert A, Seps B, Beckers F (2003) Heart rate variability in athletes. Sports Med 33(12):889–919

Bland JM, Altman DG (2007) Agreement between methods of measurement with multiple observations per individual. J Biopharmaceut Stat 17:571–582

Boardman A, Schlindwein F, Rocha A, Leite A (2002) A study on the optimum order of autoregressive models for heart rate variability. Physiol Meas 23(2):325–336

Broersen P (2000) Finite sample criteria for autoregressive order selection. IEEE Trans Signal Process 48(12):3550–3558

Burg JP (1975) Maximum entropy spectral analysis. Dissertation, Stanford University

Cohen J (1988) Statistical power analysis for the behavioral sciences. Lawrence Eribaum Associates, Hillsdale

Furlan R, Piazza S, Dell'Orto S et al (1993) Early and late effects of exercise and athletic training on neural mechanisms controlling heart rate. Cardiovasc Res 27:482–488

Gamelin FX, Bosquet L, Berthoin S (2006) Validity of the Polar S810 heart rate monitor to measure R–R intervals at rest. Med Sci Sports Exerc 38(5):887–893

Gamelin FX, Baquet G, Berthoin S, Bosquet L (2008) Validity of the Polar S810 to measure R–R intervals in children. Int J Sports Med 29:134–138

Giavarina D (2015) Understanding Bland Altman analysis. Biochem Med 25(2):141–151

Giles D, Draper N, Neil W (2016) Validity of the Polar V800 heart rate monitor to measure RR intervals at rest. Eur J Appl Physiol 116:563–571

Gomis P, Caminal P, Vallverdú M, Warren S, Stein P, Wagner G (2012) Assessment of autonomic control of the heart during transient myocardial ischemia. J Electrocardiol 45(1):82–89

Hynynen E, Uusitalo A, Konttinen N, Rusko H (2006) Heart rate variability during night sleep and after awakening in overtrained athletes. Med Sci Sports Exerc 38(2):313–317

Kingsley M, Lewis M, Marson R (2005) Comparison of Polar 810S and an ambulatory ECG system for RR interval measurement during progressive exercise. Int J Sports Med 26(01/02):39–44

Mainardi L (2009) On the quantification of heart rate variability spectral parameters using time–frequency and time-varying methods. Philos Trans R Soc A 367:255–275

Mateo J, Serrano P, Bailón R et al (2001) Heart rate variability measurements during exercise test may improve the diagnosis of ischemic heart disease. Proc 23rd Ann Int Conf IEEE 503–506

Melia U, Roca E, Brotons et al (2014) Heart rate variability in ultra-trail runners. Comput Cardiol 41:997–1000

Nunan D, Jakovljevic D, Donovan G, Hodges L, Sandercock G, Brodie D (2008) Levels of agreement for RR intervals and short-term heart rate variability obtained from the Polar S810 and an alternative system. Eur J Appl Physiol 103(5):529–537

Nunan D, Donovan G, Jakovljevic D, Hodges L, Sandercock G. Brodie D (2009) Validity and reliability of short-term heart-rate variability from the Polar S810. Med Sci Sports Exerc 41(1):243–250

O'Connor GT, Buring JE, Yusuf S et al (1989) An overview of randomized trials of rehabilitation with exercise after myocardial infarction. Circulation 80:234–244

Pichot V, Roche F, Gaspoz JM et al (2000) Relation between heart rate variability and training load in middle-distance runners. Med Sci Sports Exerc 32(10):1729–1736

Plews D, Laursen P, Stanley J, Kilding A, Buchheit M (2013) Training adaptation and heart rate variability in elite endurance athletes: opening the door to effective monitoring. Sports Med 43(9):773–781

Porto LGG, Junqueira J (2009) Comparison of time-domain short-term heart interval variability analysis using a wrist-worn heart rate monitor and the conventional electrocardiogram. Pacing Clin Electrophysiol 32:43–51

Radespiel-Tröger M, Rauh R, Mahlke C, Gottschalk T, Mück-Weymann M (2003) Agreement of two different methods for measurement of heart rate variability. Clin Auton Res 13(2):99–102

Rocha AP, Almeida R, Leite A, Silva MJ, Silva ME (2014) Long-term HRV in critically ill pediatric patients: coma versus brain death. Comput Cardiol 41:89–92

Ruha A, Sallinen S, Nissila S (1997) A real-time microprocessor QRS detector with a 1-ms timing accuracy for the measurement of ambulatory HRV. IEEE Trans Biomed Eng 44:159–167

Sumi K, Suzuki S, Matsubara M, Ando Y, Kobayashi F (2006) Heart rate variability during high-intensity field exercise in female distance runners. Scand J Med Sci Sports 16(5):314–320

Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996) Heart rate variability: standards of measurement, physiological interpretation and clinical use. Circulation 93: 1043–1065

Thomas JR, Nelson JK, Silverman SJ (2015) Research methods in physical activity. Human Kinetics Publishers, Champaign

Vanderlei L, Silva R, Pastre C, Azevedo F, Godoy M (2008) Comparison of the Polar S810i monitor and the ECG for the analysis of heart rate variability in the time and frequency domains. Braz J Med Biol Res 41(10):854–859

Voss A, Schroeder R, Vallverdú M, Schulz et al (2013) Short-term vs long-term heart rate variability in ischemic cardiomyopathy risk stratification. Front Physiol 4:364–380

Voss A, Schroeder R, Heitmann A, Peters A, Perz S (2015) Short-term heart rate variability. Influence of gender and age in healthy subjects. PLoS One 10(3):e0118308

Wallén MB, Hasson D, Theorell T, Canlon B, Osika W (2012) Possibilities and limitations of the polar RS800 in measuring heart rate variability at rest. Eur J Appl Physiol 112:1153–1165

Weippert M, Kumar M, Kreuzfeld S, Arndt D, Rieger A, Stoll R (2010) Comparison of three mobile devices for measuring R–R intervals and heart rate variability: Polar S810i, Suunto t6 and an ambulatory ECG system. Eur J Appl Physiol 109(4):779–786