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ORIGINAL ARTICLE

RR interval signal quality of a heart rate monitor and an ECG Holter at rest and during exercise

Rahel Gilgen-Ammann[1] · Theresa Schweizer[1] · Thomas Wyss[1]

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Abstract

This study was designed to examine the RR interval signal qualities of a Holter device and a heart rate chest belt monitor at rest and during exercise. Ten healthy individuals completed five low- to high-intensity activities while simultaneously using the medilog® AR12plus Holter monitor and the Polar H10 heart rate monitor. The RR interval signal quality was based on the quantification of the missing RR intervals and RR interval detection errors. Therefore, both measurement systems were compared against visual inspection of the raw electrocardiography signal. The missing and wrong R-wave peak detections were counted manually for both measurement systems. RR interval signal quality was defined as the relative number of correctly detected RR intervals. Overall, RR interval signal qualities of 94.6% and 99.6% were demonstrated for the medilog® AR12plus and the Polar H10. During the high-intensity activities, the RR interval signal quality of the medilog® AR12plus dropped to 89.8%, whereas the Polar H10 maintained a signal quality of 99.4%. The correlation between both systems was high ($r = 0.997$, $p > 0.001$). The excellent RR interval signal quality during low- to moderate-intensity activities in the medilog® AR12plus and during low- to high-intensity activities in the Polar H10 demonstrates both measurement systems' validity for the detection of RR intervals throughout a wide range of activities. A simple chest strap such as the Polar H10 might be recommended as the gold standard for RR interval assessments if intense activities with strong body movements are investigated.

Keywords Validity · Low- to high-intensity activities · Gold standard · Heart rate measurement

Abbreviations

ECG	Electrocardiography
HR	Heart rate
HRV	Heart rate variability
LoA	Limits of agreement
PPG	Photoplethysmography

Introduction

The heart rate (HR) and heart rate variability (HRV) are common measures in clinical settings and increasingly in healthy people in sport settings, because they are powerful biomarkers that are sensitive to the physiological and psychological conditions (Hedelin et al. 2000; Malliani et al. 1994; Mourot et al. 2004; Rompelman et al. 1980; Tulppo et al. 1998). The measurement accuracy of these parameters depends on tracking the time elapsing between two consecutive R-waves in the electrocardiogram, which are called RR intervals. Therefore, the RR signal quality is crucial for measurement devices quantifying HR and HRV.

The gold standard for the quantification of RR intervals is electrocardiography (ECG), which registers each electrical impulse of the heart (Task Force 1996). An established reference method for assessing the RR intervals in an ambulatory clinical setting is an ECG Holter monitor (Giles et al. 2016; Kingsley et al. 2005; Nunan et al. 2009). However, in sport-related studies, high cost, difficulty of access, discomfort, and complexity of electrode placement restrict their use in endurance events such as marathon and trail races (Caminal et al. 2018). While multi-lead ambulatory ECG devices have served as the gold standard, multiple alternative devices, mainly based on single-lead ECG and photoplethysmography (PPG), are more convenient and practical for measuring HRV parameters (Singh et al.

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✉ Rahel Gilgen-Ammann
rahel.gilgen@baspo.admin.ch

[1] Swiss Federal Institute of Sport Magglingen SFISM, Hauptstrasse 247, 2532 Magglingen, Switzerland

2018). Indeed, recent HR monitors using a chest strap for ECG detection claim to accurately measure RR intervals as well. These monitors are simple to use, and they enable the HR and HRV data to be recorded in situations in which it was not previously feasible with lab-based or even ambulatory ECGs. Recently, several validation studies in different populations have compared the RR intervals obtained by ECG devices and HR monitors (Barbosa et al. 2016; Gamelin et al. 2006; Giles et al. 2016; Weippert et al. 2010; Costa et al. 2016). Their results demonstrated good agreement in the RR interval recordings of HR monitors with small, but acceptable levels of variation when compared to simultaneously recorded 2-, 3-, or 12-lead ECGs, respectively. However, the majority of these investigations were conducted using data obtained during resting activities, such as lying down, sitting, or standing still (Gamelin et al. 2006; Giles et al. 2016; Parrado et al. 2010). In contrast, the RR interval signal quality obtained during exercise might be in a less favorable context with regard to the HR monitor movements inducing noise in the measured electric signal (Cassirame et al. 2017). The few studies investigating the RR interval signal quality in ECG Holter and HR monitors obtained during moderate- to high-intensity activities mainly assessed these devices using cycling, with one using mountain running (Caminal et al. 2018; Cassirame et al. 2017; Kingsley et al. 2005). As such, Kingsley et al. (2005) revealed increased limits of agreement (LoA) between the RR interval measurements using a Polar 810 s and a Holter device with higher exercise intensity. These authors recommend a protocol with diverging activities and intensity levels to test the accuracy of the RR interval detection. However, a Holter monitor is potentially the best reference device for measuring the RR interval and HR during resting and low-intensity activities. For assessments during high-intensity activities, with increased body movements, the Holter monitor has yet to prove its position as the gold standard for RR interval measurement.

Polar Electro Oy (Kempele, Finland) has released a new generation of Polar HR technology. The Polar H10 claims to offer improvements in the HR and HRV measurements compared to the previous generation of H7 technology, whose performance has been acclaimed, and it has been widely used as a reference for wearable HR measurement systems (Cheatham et al. 2015; Plews et al. 2017; Giles et al. 2016). Nevertheless, the Polar H10 has to be validated as a reference device for measuring RR interval over a range of different activity intensities as well.

The aim of the present study was therefore to test the RR interval signal quality of the medilog® AR12plus ECG Holter monitor and the Polar H10 HR chest belt monitor at rest and during various exercises in a cohort of healthy individuals by comparing their results against visual ECG inspection.

Methods

Participants

Ten (five females and five males) healthy, lean, and physically fit volunteers (age 24.7 ± 1.9 years old, body height 172.5 ± 8.4 cm, body weight 67.5 ± 9.7 kg, body mass index 22.6 ± 1.3 kg m^{-2} and chest circumference 80.3 ± 6.8 cm) agreed to participate in this study. None of the participants were known to be taking any medications affecting the HR or metabolism, and there were no known abnormalities in their ECGs. The participants completed the written informed consent forms and physical activity readiness questionnaires prior to taking part in the study. Approval for this study was granted by the Ethics Committee Bern, Switzerland (Study ID: 2018-00309), and it conformed to the principles of the Declaration of Helsinki.

Procedure and instruments

An ECG Holter monitor and a HR chest belt were investigated in this study. The RR intervals were recorded simultaneously with a Schiller medilog® AR12plus ambulatory 3-lead ECG Holter monitor (Schiller Medizintechnik GmbH, Baar, Switzerland) and a Polar H10 HR monitor with a Pro Strap (Polar Electro Oy, Kempele, Finland) during different activities. To detect the RR intervals, the change in the electrical polarity of the heart must be assessed by these measurement systems. The five medilog® AR12plus electrodes were placed on the cleaned skin and the wires were taped to the skin to reduce movement artifacts (noise induced due to wire movement). The Polar H10 with the Pro Strap has seven distinct areas that are engineered to protect against electrical noise and to conduct a proper ECG measurement.

Both devices provide raw ECG and RR time intervals with a resolution of 1 ms. The medilog® AR12plus "scientific" and "open end recording" settings were used to record the data. Prior to the sensor placement, each participant's skin was cleaned and shaved where necessary. Five Ambu® BlueSensor L ECG electrodes (Ambu A/S, Ballerup, Denmark) were attached on the left axillary line sixth rib, centered on the manubrium, left mid-clavicular line, left shoulder, and xiphoid process (Fig. 1). In all the participants, the electrode placement and signal check were performed as recommended by the user manual. Additionally, for the Polar H10, a moistened elastic electrode strap was applied below the participant's chest muscles, and the strap length was fitted to the participant's chest circumference as described by the manufacturer. Moreover, each participant wore a Polar

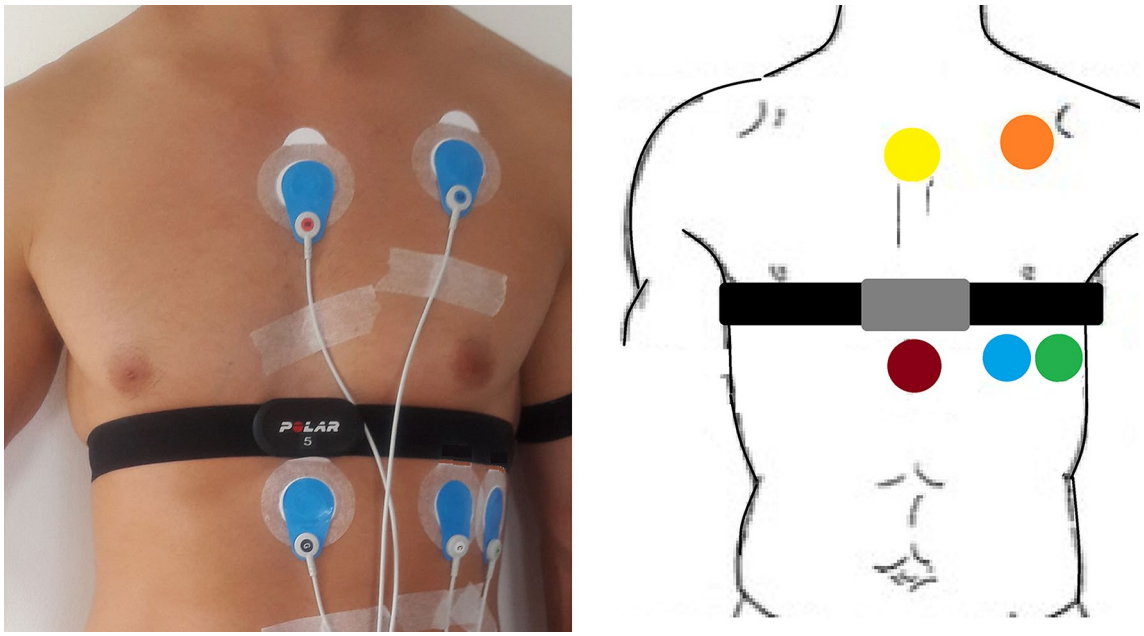

Fig. 1 Schematic of electrodes and HR chest strap placements on participant

M600 sport watch, which was used as a Polar H10 data logger. The supervisor ensured that the electrodes and the chest strap did not interfere with each other. After the data collection, the raw ECG signals and the RR intervals provided by the respective software were compared by visual inspection. Thereof, the missing and wrong R-wave peak detections were counted manually for both measurement systems (see chapter data processing and analysis).

The participants were scheduled during the daytime (8 am–5 pm; temperature 20.7 ± 1.2 °C and humidity 39.3 ± 2.9%), and they were told not to abstain from any kind of nutrition or activity. Initially, the body weight, body height, and chest circumference were assessed, and both the questionnaires and informed consent form were controlled. The measurements were conducted in a performance-testing lab with areas prepared to perform five different tasks ranging from resting to moderate-intensity to high-intensity activity. This protocol was chosen to investigate whether the RR interval signal quality was stable across a wide range of activities. In accordance with the guidelines of the European Society of Cardiology and The North American Society of Pacing and Electrophysiology to standardize physiological and clinical studies, investigating short-term HRV, each activity lasted 5 min, with a 60 s break in between (Task Force 1996). The five activities and their order were as follows: (1) sitting in a chair and reading (sedentary activity); (2) wiping the floor with a mop and hanging out the laundry at a self-guided order and pace (household chores); (3) normal walking on a treadmill (Pulsar, h/p/cosmos; Cosmos Sports & Medical Ltd., Nussdorf-Traunstein, Germany) at 5.5 km/h (gait activity); (4) jogging on a treadmill at 11 km/h (gait activity); and (5) a strength training circuit of five aligned 60 s cycles with 45 s workouts and 15 s rests, including squats, shoulder shrugs, bicep curls with a dumbbell in each hand (4.5 ± 1.6 kg), lunges, and sit-ups (Horton et al. 2017; sports activity). Immediately after the termination of each task, the individual Borg scale values were reported to rate the perceived exertion (Borg 1970).

Data processing

With the medilog® AR12plus, the R-wave peaks were detected automatically in the ECG series using Medilog Darwin Enterprise Software detection algorithm (V2.7.2; Schiller Medizintechnik GmbH, Baar, Switzerland). The RR intervals were exported in milliseconds. Similarly, the data from the Polar H10 were streamed to the M600, uploaded to a cloud server and exported as RR intervals in milliseconds. Both measurement devices were programmed to use the exact same clock time. Still, the raw RR signal start points were visually controlled and where necessary manually synchronized to the best signal fit for each participant before further data analyses.

For each measurement system, the RR interval signal quality was investigated separately. RR interval signal quality was defined as the relative number of correctly detected RR intervals. Therefore, the raw ECG signal and the RR intervals provided by the measurement system were compared by visual inspection. With that method, the missing and wrong R-wave peak detections were counted and

classified manually. With regard to recognizing missing or wrong R-wave peak detections, abnormal RR intervals were previously defined as any interval differing by more than 20% from the previous RR interval (Nunan et al. 2008, 2009). An elaborated visual investigation of the raw ECG signal was conducted by two independent experts wherever an intradevice RR interval differed by more than 20% from the previous RR interval (Task Force 1996). If a difference between experts' visual R-wave peak detection and software output occurred, the RR interval detection error was classified as either: (a) missing RR interval (existing R-wave peak was not detected by the software), (b) R-wave detection error due to wrong peak detection (wrong signal peak allocated as R-wave peak) and (c) R-wave detection error due to signal noise (no clear R-wave peak can be assigned by visual inspection of the ECG raw signal; Fig. 2). The overall RR interval signal quality was calculated by 100% minus the number of missing RR intervals and RR interval detection errors as a percentage of the total number of recorded RR intervals. A RR interval signal quality of 99%, for example, means that 1% of RR intervals were detected wrongly and 99% were correct.

Further, the measurement agreement between the two investigated ECG measurement systems was analyzed based on the quantification of the deviation errors, correlations and descriptive statistics. The data analysis was based on the previous literature (Caminal et al. 2018; Task Force 1996; Gamelin et al. 2006; Giles et al. 2016; Nunan et al. 2008). With regard to the deviation error, when the difference between each simultaneously obtained RR interval measured using the medilog® AR12plus and Polar H10 exceeded ± 2%, the measurement agreement was not considered for that particular RR interval (Caminal et al. 2018; Gamelin et al. 2006; Giles et al. 2016). Previously, an error was defined as a difference between the measurement systems exceeding 20 ms. However, this cutoff was applied to the RR intervals obtained at rest only, and it should not be applied to data obtained during high-intensity activities. Assuming an average RR interval of 1,000 ms at rest, a 20 ms difference represents a relative deviation of approximately 2%.

Statistical analysis

The statistical analyses were conducted using Microsoft Excel (2016) and IBM SPSS Statistics for Windows version 24.0 (IBM Corp., Armonk, NY, USA). The level for accepting statistical significance was set at $p < 0.05$ for all the analyses. Due to not normally distributed RR interval data for the medilog® AR12plus and the Polar H10 (Kolmogorov–Smirnov: $p < 0.001$), measurement agreement between the two systems was investigated by nonparametric methods such as Wilcoxon and Spearman tests. The Spearman tests were used to assess the correlations, and the Wilcoxon tests were used to assess the differences between RR intervals obtained from the medilog® AR12plus and the Polar H10. The systematic bias between RR interval data of the medilog® AR12plus and the Polar H10 was calculated by

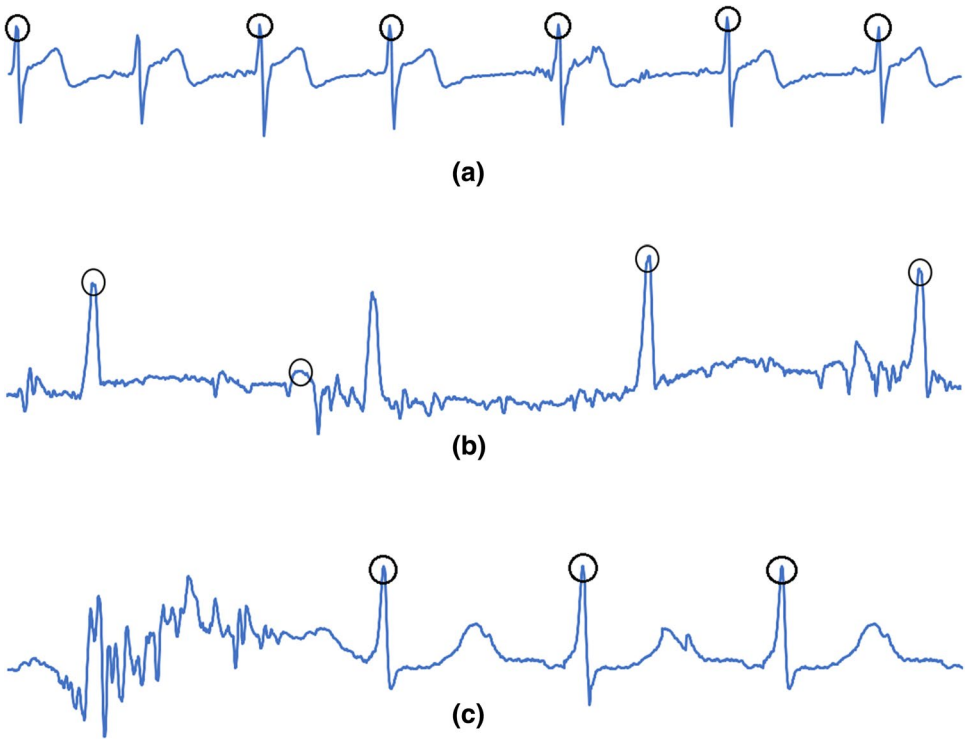

Fig. 2 Three categories of RR interval detection errors based on comparison between RR intervals provided by software (circles) and visual investigation of electrocardiograph (ECG) signals: **a** a missing RR interval, when existing R-wave was not detected by the software, **b** an R-wave peak detection error due to wrong peak detection. **c** An R-wave peak detection error due to noise in the ECG signal

the absolute difference between mean data of both measurement systems, and as values for the random errors, the limits of agreement (LoA) were calculated using the standard deviations of the differences, multiplied by 1.96 (Bland and Altman 1986).

Results

All participants completed all the activity tasks, and no technical failures were reported. The reported Borg values were 6.0 ± 0.0 for sitting and reading, 6.6 ± 0.7 for household chores, 8.7 ± 1.5 for walking, 13.2 ± 1.9 for jogging, and 11.9 ± 2.3 for strength training. The averaged HR values during each activity task were 63.7 ± 12.1 bpm for sitting and reading, 79.6 ± 10.9 bpm for household chores, 91.4 ± 13.8 bpm for walking, 143.0 ± 19.2 bpm for jogging, and 114.6 ± 18.3 bpm for strength training.

In total, 25,015 RR intervals were obtained by both systems. Of these, 1,082 (4.3%) and 90 (0.4%) missing RR intervals were detected in the medilog® AR12plus and the Polar H10, respectively. Further, the medilog® AR12plus and the Polar H10 recorded 268 (1.1%) and 2 (0.0%) RR interval detection errors, respectively (Table 1). The combination of the missing RR intervals (R-wave peak was not detected) and RR interval detection errors (R-wave peak was wrongly detected) represented overall signal qualities of 94.6% and 99.6% of all the RR intervals assessed by the medilog® AR12plus and the Polar H10, respectively. For both measurement systems, the highest (and very similar) signal quality was achieved during the low-intensity activities. During the high-intensity activities (jogging and strength training), the medilog® AR12plus reported 1,332 RR interval missing or detection errors (signal quality of 89.8%), whereas the Polar H10 reported 74 total RR interval errors (signal quality of 99.4%), respectively.

Table 1 RR interval signal qualities for the medilog® AR12plus and Polar H10 as absolute and relative numbers, *N* (%)

	Total RR intervals *N*	Total RR interval errors *N* (%)		Missing RR intervals *N* (%)		RR interval detection error due to wrong R-wave peak detection *N* (%)		RR interval detection error due to noisy ECG signal *N* (%)	
		medilog® AR12plus	Polar H10	medilog AR12plus	Polar H10	medilog® AR12plus	Polar H10	medilog® AR12plus	Polar H10
Sitting and reading	3248	5 (0.15)	4 (0.12)	4 (0.12)	4 (0.12)	0 (0.00)	0 (0.00)	1 (0.03)	0 (0.00)
Household chores	4047	11 (0.27)	10 (0.24)	2 (0.04)	10 (0.24)	7 (0.17)	0 (0.00)	2 (0.04)	0 (0.00)
Walking	4673	2 (0.04)	4 (0.08)	2 (0.04)	4 (0.08)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Jogging	7229	878 (12.15)	52 (0.72)	662 (9.16)	52 (0.72)	189 (2.61)	0 (0.00)	27 (0.37)	0 (0.00)
Strength training	5818	454 (7.80)	22 (0.38)	412 (7.08)	20 (0.34)	13 (0.22)	0 (0.00)	29 (0.50)	2 (0.03)
Overall	25,015	1,350 (5.40)	92 (0.37)	1,082 (4.33)	90 (0.36)	209 (0.84)	0 (0.00)	59 (0.24)	2 (0.01)

RR interval detection errors were quantified as missing RR intervals (R-wave peak was not detected), RR interval detection errors due to wrong R-wave peak detection and RR interval detection errors due to noisy ECG signal

Table 2 Measurement agreement between the medilog® AR12plus and Polar H10

	RR intervals Mean ± SD (ms)		Deviation errors[a] *N* (%)	Mean RR interval differences between systems (LoA)[b] (ms)	Spearman correlation (*r* value, *p* value)	Wilcoxon test (*Z* value, *p* value)
	medilog® AR12plus	Polar H10				
Sitting and reading	927.8 ± 216.9	927.9 ± 216.8	0 (0.0)	< 0.1 (2.3)	*1.000*, < 0.001	*− 1.367*, 0.174
Household chores	744.1 ± 138.8	744.8 ± 138.8	16 (0.4)	0.7 (33.3)	*0.993*, < 0.001	*− 0.673*, 0.501
Walking	646.0 ± 101.7	646.0 ± 101.7	1 (0.0)	< 0.1 (3.3)	*1.000*, < 0.001	*− 0.376*, 0.707
Jogging	422.2 ± 62.5	422.6 ± 59.8	501 (6.9)	0.4 (38.6)	*0.953*, < 0.001	*− 0.210*, 0.834
Strength training	521.9 ± 101.8	522.0 ± 101.3	213 (3.7)	< 0.1 (23.2)	*0.992*, < 0.001	*− 0.873*, 0.382
Overall	611.7 ± 208.6	611.9 ± 208.3	731 (2.9)	0.23 (26.8)	*0.997*, < 0.001	*− 1.259*, 0.208

[a]Number of RR intervals with a difference between measurement systems > 2%

[b]LoA = limits of agreement = standard deviations (SD) of mean RR interval differences between both systems multiplied by 1.96

The measurement agreement between the two systems is represented in Table 2. On average, the mean RR intervals were 611.7 ± 208.6 ms and 611.9 ± 208.3 ms for the medilog® AR12plus and the Polar H10, respectively. In 2.9% of the RR intervals, a difference higher than 2% between the RR intervals obtained by the two systems was registered. High Spearman correlations were demonstrated for RR interval detection between the two measurement systems for the overall and specific activity tasks (Table 2). Furthermore, the Wilcoxon test revealed no significant differences between the two systems for the overall and specific activity tasks. The systematic bias was 0.23 ms with a lower limit of 26.61 ms and an upper limit of 27.08 ms.

Discussion

The present study investigated the RR interval signal quality of the medilog® AR12plus ECG Holter monitor and the Polar H10 HR monitor with the Pro Strap over a broad range of activities in a healthy cohort. The RR interval measurement agreement between these two systems was also examined. Overall, good signal quality was demonstrated in 94.6% and 99.6% of all the RR intervals from the medilog® AR12plus and the Polar H10, respectively. In terms of the measurement agreement, a high correlation was found ($r = 0.997$), and in 97.1% of the measured RR intervals, the values provided by both systems differed less than 2% among each other.

To the authors' knowledge, the present study was the first to investigate the RR intervals in different low- to high-intensity activities. Consequently, the results of the present study are only partly comparable to the previous findings in which the RR intervals were obtained mainly at rest or on a cycle ergometer, with a rather calm upper body, at submaximal intensities. More precisely, in the present study, both measurement systems demonstrated similar and perfect signal quality during the sitting and reading, household chores, and walking activities. The medilog® AR12plus and the Polar H10 showed error rates in the RR interval detection obtained during low- to moderate-intensity activities of 0.16% and 0.15%, respectively. These were even higher RR interval signal qualities than those found in previous investigations showing detection errors ranging from 0.27 to 2.20% (Cassirame et al. 2017; Gamelin et al. 2006; Giles et al. 2016; Parrado et al. 2010; Ruha et al. 1997). During the jogging and strength training, the Polar H10 showed a 0.56% RR interval detection error. This was in line with 0.32–0.71% detection errors for the graded exercise tests conducted on a cycling ergometer using a Polar H7 or during mountain running using a Polar T61 chest belt (Caminal et al. 2018; Kingsley et al. 2005). The medilog® AR12plus showed a reduced RR interval signal quality during those specific, intense activities with a total of 10.21% RR interval detection errors in jogging and strength training. However, no comparable data on RR interval signal quality during intense activities with strong body movements were published for ECG Holter systems so far. The increased RR interval detection error in the Holter monitor during the high-intensity activities could be explained by the more exigent nature of the task conditions when compared to resting activities. Movement artifacts might induce more noise in the electric signal of a Holter monitor where electrodes are connected to a board by wires compared to a simple but compact chest belt.

When a loss in the RR interval signal quality occurred within the Polar H10 measurement system, it was caused to 98% by missing R-wave peak detections while reading the ECG raw signal. A wrong R-wave peak detection or not interpretable, noisy ECG signal did rarely occur. When a loss in the RR interval signal quality occurred within the medilog® AR12plus system, it was caused to 80% by missing R-wave peak detections while reading the ECG raw signal, to 15% due to wrong R-wave peak detection and to 4% due to not interpretable, noisy ECG signal. These results are in line with previous research, showing that the missing RR intervals were the most commonly recurring errors. The usual reasoning concerning elastic electrode straps included the lack of or decrease in contact between the skin and the elastic electrode strap and the different R-wave detection algorithms between the measurement systems (Gamelin et al. 2006; Giles et al. 2016). However, in the present study, the medilog® AR12plus using ECG electrodes registered more missing RR intervals when compared to the Polar H10 with the electrode strap during high-intensity activities.

The use of an advanced HR chest belt monitor for RR interval detection seems promising because of its feasibility in an ambulatory, especially in a sport setting. In addition to this, the Polar H10 demonstrated the same RR interval signal quality as the well-established ECG Holter monitor during the low- to moderate-intensity activities, and even a better RR interval signal quality during the high-intensity activities in healthy subjects. If this result is equally valid for chest belts of other manufacturers has yet to be discussed and further investigated. Since RR interval signal quality as defined in the present study was not assessed for other HR chest belts, this discussion has to rely on the measurement agreement between chest belts and ECG Holter data. The present study observed a very high measurement agreement between both systems. The non-significant systematic bias (mean ± SD) was 0.23 ± 13.69 ms, which was comparable to the results found in other ECG Holter monitors and HR chest belts (Table 3). Therefore, one can also expect good RR interval signal quality in other advanced chest belts.

Table 3 Measurement agreement between HR chest belts and ECG Holter monitors

References	*N*	HR chest belt (connected watch)	ECG Holter monitor	Activities	RR interval mean bias ± LoA (ms)
Present study	10	Polar H10 (M600)	Medilog® AR12plus	Sitting	0.0 ± 2.3
				Household	0.7 ± 33.3
				Walking	0.0 ± 3.3
				Jogging	0.4 ± 38.6
				Strength training	0.0 ± 23.2
				Overall	0.2 ± 26.8
Caminal et al. (2018)	18	Polar H7 (V800)	GE SEER 12	Running	0.0 ± 0.1
Giles et al. (2016)	20	Polar H7 (V800)	MP36, Biopac Systems Ltd	Supine	0.1 ± 4.4
				Standing	0.6 ± 2.3
Kingsley et al. (2005)	8	Polar T61 (S810)	Reynolds	Cycling ergometer	0.1 ± 9.1
Nunan et al. (2008)	33	Polar T61 (S810)	CardioPerfect	Supine	2.5 ± 61.8
Weippert et al. (2010)	19	Polar T61 (S810i)	Cardiolight S	Overall (supine, walking, isometric exercise)	− 0.4 ± 14.7
Weippert et al. (2010)	19	Suunto ANT (t6)	Cardiolight S	Overall (supine, walking, isometric exercise)	− 0.4 ± 12.0
Cassirame et al. (2017)	11	Garmin HRM (Forerunner 920XT)	BioAmp and Powerlab system	Supine	0.0 ± 2.3
				Standing	0.0 ± 3.1
				Moderate exercise	0.0 ± 4.4

Different to the present study, all comparative studies excluded the RR interval detection errors due to artifacts or aberrant beats before the investigation of measurement agreement

Conclusion

As initially pointed out, the medilog® AR12plus is a medical device. The present study underlines the assumption that such ECG Holter instruments are still the best gold standard for RR interval measurements during resting and low-intensity activities, especially in clinical settings. However, in sport settings, they might be not the most suitable monitors to accurately assess the RR intervals during high-intensity activities. The present study showed, that in healthy subjects, advanced HR chest belts like the Polar H10 are as accurate as the gold standard during low- and moderate-intensity activities and even of higher RR interval signal quality than the Holter monitor during intense activities with strong body movements. Based on the present results, the Polar H10 can be recommended as the gold standard for RR interval assessments during intense activities to obtain HR and HRV. Due to its high degree of practical applications, these findings are of great interest in the sport setting and it might provoke similar studies to be performed on subjects with heart diseases in the clinical setting. One should keep in mind that the value of Holter monitors is not only to reliably detect RR intervals for HR and HRV assessment, but also to quantify ectopic beats or health-threatening abnormalities in the ECG signals. Since the present study was performed on healthy subjects only, results do not allow to draw a conclusion on the quality of measurement devices in the detection of ectopic beats or health-threatening abnormalities in the ECG signals.

Author contributions RGA and TW conceived and designed the research. RGA and TS conducted the experiments. RGA analyzed the data and wrote the manuscript. All authors read and approved the manuscript.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical standards All procedures performed in this study were in accordance with the ethical standards of the cantonal ethics committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

References

Barbosa MP, da Silva NT, de Azevedo FM, Pastre CM, Vanderlei LC (2016) Comparison of Polar(R) RS800G3 heart rate monitor with

Polar(R) S810i and electrocardiogram to obtain the series of RR intervals and analysis of heart rate variability at rest. Clin Physiol Funct Imaging 36(2):112–117. https://doi.org/10.1111/cpf.12203

Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1(8476):307–310

Borg G (1970) Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med 2(2):92–98

Caminal P, Sola F, Gomis P, Guasch E, Perera A, Soriano N, Mont L (2018) Validity of the Polar V800 monitor for measuring heart rate variability in mountain running route conditions. Eur J Appl Physiol 118(3):669–677. https://doi.org/10.1007/s00421-018-3808-0

Cassirame J, Vanhaesebrouck R, Chevrolat S, Mourot L (2017) Accuracy of the Garmin 920 XT HRM to perform HRV analysis. Australas Phys Eng Sci Med 40(4):831–839. https://doi.org/10.1007/s13246-017-0593-8

Cheatham SW, Kolber MJ, Ernst MP (2015) Concurrent validity of resting pulse-rate measurements: a comparison of 2 smartphone applications, the polar H7 belt monitor, and a pulse oximeter with bluetooth. J Sport Rehabil 24(2):171–178

Costa RBMPd, Mícolis AF, Marcelo PC, Marques VLC (2016) Comparison of Polar® RS800G3™ heart rate monitor with Polar® S810i™ and electrocardiogram to obtain the series of RR intervals and analysis of heart rate variability at rest. Clin Physiol Funct Imaging 36(2):112–117. https://doi.org/10.1111/cpf.12203

Gamelin FX, Berthoin S, Bosquet L (2006) Validity of the polar S810 heart rate monitor to measure R–R intervals at rest. Med Sci Sports Exerc 38(5):887–893. https://doi.org/10.1249/01.mss.0000218135.79476.9c

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(3):563–571. https://doi.org/10.1007/s00421-015-3303-9

Hedelin R, Wiklund U, Bjerle P, Henriksson-Larsen K (2000) Cardiac autonomic imbalance in an overtrained athlete. Med Sci Sports Exerc 32(9):1531–1533

Horton JF, Stergiou P, Fung TS, Katz L (2017) Comparison of polar M600 optical heart rate and ECG heart rate during exercise. Med Sci Sports Exerc 49(12):2600–2607. https://doi.org/10.1249/MSS.0000000000001388

Kingsley M, Lewis MJ, Marson RE (2005) Comparison of Polar 810 s and an ambulatory ECG system for RR interval measurement during progressive exercise. Int J Sports Med 26(1):39–44. https://doi.org/10.1055/s-2004-817878

Malliani A, Lombardi F, Pagani M (1994) Power spectrum analysis of heart rate variability: a tool to explore neural regulatory mechanisms. Br Heart J 71(1):1–2

Mourot L, Bouhaddi M, Perrey S, Cappelle S, Henriet MT, Wolf JP, Rouillon JD, Regnard J (2004) Decrease in heart rate variability with overtraining: assessment by the Poincare plot analysis. Clin Physiol Funct Imaging 24(1):10–18

Nunan D, Jakovljevic DG, Donovan G, Hodges LD, Sandercock GR, Brodie DA (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. https://doi.org/10.1007/s00421-008-0742-6

Nunan D, Donovan G, Jakovljevic DG, Hodges LD, Sandercock GR, Brodie DA (2009) Validity and reliability of short-term heart-rate variability from the Polar S810. Med Sci Sports Exerc 41(1):243–250. https://doi.org/10.1249/MSS.0b013e318184a4b1

Parrado E, Garcia MA, Ramos J, Cervantes JC, Rodas G, Capdevila L (2010) Comparison of omega wave system and polar S810i to detect R–R intervals at rest. Int J Sports Med 31(5):336–341. https://doi.org/10.1055/s-0030-1248319

Plews DJ, Scott B, Altini M, Wood M, Kilding AE, Laursen PB (2017) Comparison of heart-rate-variability recording with smartphone photoplethysmography, polar H7 chest strap, and electrocardiography. Int J Sports Physiol Perform 12(10):1324–1328. https://doi.org/10.1123/ijspp.2016-0668

Rompelman O, Kampen WHAV, Backer E, Offerhaus RE (1980) Heart rate variability in relation to psychological factors. Ergonomics 23(12):1101–1115. https://doi.org/10.1080/00140138008924817

Ruha A, Sallinen S, Nissilä S (1997) A real-time microprocessor QRS detector system with a 1-ms timing accuracy for the measurement of ambulatory HRV. IEEE Trans Bio-Med Eng 44(3):159–167

Singh N, Moneghetti K, Christle JW, Hadley D, Plews D, Froelicher V (2018) Heart rate variability: an old metric with new meaning in the era of using mHealth technologies for health and exercise training guidance. Part one: physiology and methods. Arrhythm Electrophysiol Rev 7(3):193–198. https://doi.org/10.15420/aer.2018.27.2

Task Force of the European Society of Cardiology the North American Society of Pacing and Electrophysiology (1996) Heart Rate Variability: standards of measurement, physiological interpretation and clinical use. Circulation 93(5):1043–1065

Tulppo MP, Makikallio TH, Seppanen T, Laukkanen RT, Huikuri HV (1998) Vagal modulation of heart rate during exercise: effects of age and physical fitness. Am J Physiol 274(2 Pt 2):H424–H429

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. https://doi.org/10.1007/s00421-010-1415-9