Comparison of Polar® RS800CX heart rate monitor and electrocardiogram for measuring inter-beat intervals in healthy dogs

Ann Essner^{a,b,*}, Rita Sjöström^{c,d}, Erik Ahlgren^b, Pia Gustås^e, Laurie Edge-Hughes^f,
Lena Zetterberg^a, Karin Hellström^a

^a Uppsala University, Department of Neuroscience, Uppsala, Sweden

^b Evidensia Djurkliniken Gefle, Gävle, Sweden

^c Strömsund Health Centre, Jämtland County Council, Strömsund, Sweden

^d Department of Health Sciences, Mid Sweden University, Östersund, Sweden

^e Swedish University of Agricultural Sciences, Uppsala, Sweden

^f The Canine Fitness Centre, Calgary, Canada

HIGHLIGHTS

- Series of inter-beat intervals from Polar® RS800CX were compared to electrocardiogram.
- Polar® RS800CX validity and reliability measures varied in the dogs studied.
- Polar® RS800CX agreement varied in the dogs studied.
- Detection of measurement errors is fundamental.

ARTICLE INFO

Article history:

Received 30 May 2014

Received in revised form 28 October 2014

Accepted 30 October 2014

Available online 6 November 2014

Keywords:

Behavior

Dogs

Heart rate variability

Physiotherapy

Reliability

Validity

ABSTRACT

The aim of the present study was to assess the criterion validity, relative reliability and level of agreement of Polar® RS800CX heart rate monitor measuring inter-beat intervals (IBIs), compared to simultaneously recorded electrocardiogram (ECG) in dogs.

Methods: Five continuous minutes of simultaneously recorded IBIs from Polar® RS800CX and Cardiostore ECG in 11 adult healthy dogs maintaining standing position were analyzed. Polar® data was statistically compared to ECG data to assess for systematic differences between the methods. Three different methods for handling missing IBI data were used. Criterion validities were calculated by intraclass correlation coefficients (ICCs) and corresponding 95% confidence intervals (CIs). Relative reliabilities and levels of agreement were calculated by ICCs and the Bland and Altman analysis for repeated measurements per subject.

Results: Correlation coefficients between IBI data from ECG and Polar® RS800CX varied between 0.73 and 0.84 depending on how missing values were handled. Polar® was over- and underestimating IBI data compared to ECG. The mean difference in log transformed (base10) IBI data was 0.8%, and 93.2% of the values were within the limits of agreement. Internally excluding three subjects presenting IBI series containing more than 5% erroneous IBIs resulted in ICCs between 0.97 and 0.99. Bland and Altman analysis ($n = 8$) showed mean difference was 1.8 ms, and 98.5% of the IBI values were plotted inside limits of agreement.

Conclusion: This study showed that Polar® systematically biased recorded IBI series and that it was fundamental to detect measurement errors. For Polar® RS800CX heart rate monitor to be used interchangeably to ECG, by showing excellent criterion validity and reliable IBI measures in group and individual samples, only less than 5% of artifacts could be accepted.

© 2014 Elsevier Inc. All rights reserved.

1. Introduction

Heart rate variability (HRV) is defined as the variability of time intervals in consecutive heart beats. Fluctuations between heart beats are caused by autonomic cardiac modulations, mainly via increased sympathetic or reduced vagal activity in efferent nerves, to the sinoatrial node of the heart. By analyzing fluctuations in series of inter-beat intervals

* Corresponding author at: Evidensia Djurkliniken Gefle, Norra gatan 1, SE - 803 21 Gävle, Sweden. Tel.: +46 70 6927562; fax: +46 26 10 63 18.
E-mail address: ann.essner@gmail.com (A. Essner).

(IBIs), various parameters are indicating modulations and activity in the autonomic nervous system [1,2].

Heart rate variability analysis has been used as a quantitative marker of autonomic activity in behavioral, clinical and experimental research in humans [3,4] and different animal species [5–7]. The interplay between the sympathetic and the parasympathetic nervous systems is complex and HRV analysis allows detailed information about modulations in the autonomic nervous system [2].

Performing HRV analysis requires a series of normal-to-normal IBIs. One IBI is the time in milliseconds (ms) between two consecutive R-peaks, in an electrocardiogram (ECG) or in a heart rate monitor, such as a Polar® RS800CX. The equipment of choice depends on the purpose of the examination, if the subject is at rest or ambulatory, or whether the recording is supposed to be short-term or long-term (24 h). In order to standardize studies on short-term HRV analysis, IBI series of 5 min has been recommended [1,2].

The cost and complexity of ECG have made HRV analysis difficult outside laboratory environment. Although, in the last two decades a number of studies have used different Polar® heart rate monitors to record cardiac activity in dogs [8–12], horses [13,14] and sheep [7,15] during physical exercise, to evaluate the level of stress and under the influence of pain.

As changes in cardiac activity are influenced by psychological and emotional states there are potential clinical applications for short-term HRV parameters as outcome measures for the relief of pain and/or stress in humans [16,17] and animals [18]. Within the field of canine behavioral science, a growing number of professionals and scientists are including physiological outcome measures such as heart rate and short-term HRV analysis to report autonomic responses [6,19–23]. The relationship between short-term HRV parameters and the level of stress [12,24], responses to human–dog contact [19,21] and physical as well as mental activities [23] have been studied in dogs of various breeds and of differing ages.

In addition, HRV has been used as an outcome measure in various physical interventions and exercise regimens for the possible effect on the autonomic nervous system in humans [25–27] and in dogs [28].

Different Polar® heart rate monitors have been tested for validities and reliabilities, against ECG, for recording short-term HRV data in humans [29–32], dogs [33,34] and horses [35,36]. Results are conflicting and researchers have raised concerns whether Polar® heart rate monitors should be used interchangeably with ECG [35,37,38]. The time- and frequency-based parameters in HRV analysis may easily be biased by measurement errors in IBIs. It is recommended to assess the accuracy of IBI measurements from a device designed to record IBI series by comparing to a gold standard method (i.e. ECG) [1]. Preferably only segments of IBIs that are completely free from error and/or non-sinus beats should be included in an HRV analysis. Marchant-Forde et al. [37] presented that even a small amount of errors in IBI data may bias the outcome of time- and frequency-based parameters of an HRV analysis in five pigs. The Polar® RS800C heart rate monitor has also been shown to present errors in IBI data in dogs [33]. Some of the errors may be explained as artifacts originating from interruption of the transmission of the cardiac signal or distortions from a burst of physical activity. Yet, there are errors described that are unexplainable and therefore the criterion validity of Polar® heart rate monitors has been questioned [33,37]. The error detection process is fundamental as a small amount of errors may seriously affect HRV analysis parameters. Von Borell et al. [2] suggest that IBI series containing more than 5% errors, should not be included in HRV analysis.

Recently two studies have shown that Polar® RS800CX heart rate monitor is valid and reliable for measuring heart rate, defined as heart beats per minute, in dogs [33,34]. Jonckheer-Sheehy et al. [33] identified a number of errors in Polar® data from a homogeneous group of ten Beagle dogs, and showed there were no significant differences between either time- or frequency-domain data collected from Polar® RS800CX and ECG. However, to the authors' knowledge, there is a lack of research

on the validity and reliability of Polar® RS800CX for measuring IBIs in dogs. The data accumulated to date, suggest there is more to assess before Polar® RS800CX may be used interchangeably with ECG for recording IBI data and performing HRV analysis in dogs. If the Polar® RS800CX heart rate monitor is valid and reliable in measuring IBIs in dogs there are obvious potential benefits in using the Polar® device instead of ECG. The Polar® RS800CX is easily accepted by dogs and is less expensive than ECG, and thereby potentially useful for collection of IBI data for further analysis of HRV parameters in clinical settings such as canine physiotherapy units or in veterinary facilities. The accuracy of the Polar® RS800CX remains to be determined before considering any further clinical application of HRV analysis.

The objectives of the present study were to assess the criterion validity, relative reliability and level of agreement of Polar® RS800CX heart rate monitor measuring IBIs, compared to simultaneously recorded ECG, in dogs during stationary standing position.

2. Methods and materials

2.1. Study design

This study was an observational study with a methodologically standardized approach [39]. One group of dogs, on a consecutive sample, was studied with the objective to compare simultaneously recorded IBI data from two measurement devices. A priori power analysis, conducted before data acquisition to the present and a previously published article [34], showed that eight to ten dogs were required to detect true differences and avoid the occurrence of type II errors, when implementing the study.

2.2. Study group

Data from eleven (six female and five male) dogs from various breeds, with mean $\pm$ standard deviation (SD) age of 3.8 ± 1.3 years and mean $\pm$ SD weight of 29.9 ± 7.2 kg were included in the study. None of the dogs had a history or current evidence of cardiovascular or systemic diseases, as assessed by a veterinarian. None of the dogs seemed to react with aggression or fear during the study. As the dogs were privately owned, the owners were informed as to the procedures and objectives of the study and informed owner consent was obtained. The study was approved by the Local Ethical Committee in Uppsala, Sweden (C81/12).

2.3. Data acquisition

Two IBI recording devices were applied to the dogs. Polar® RS800CX (Polar® Electro Oy), consisted of electrode belt and transmitter W.I.N.D. and heart rate monitor RS800CX. The electrode belt and transmitter supported recording and processing of IBIs at a frequency of 1000 Hz and 2.4 GHz transfer between the belt and heart rate monitor. The coat was clipped at all electrode sites and the skin was cleaned with alcohol and air-dried. Cefar® electrode transmission gel (Cefar-Compex Scandinavia AB) was applied liberally to promote conductivity. The electrode belt was strapped around the chest of the dogs with the transmitter placed ventrally and the electrodes on each side of the sternum. Cardiorec digital ECG (Vetronic Services Ltd.) was attached by three adhesive ECG electrodes (Kruuse Svenska AB). Electrodes were placed: 1) on the right side of the thorax, slightly caudal and dorsal to the point of the elbow and caudal to Polar® electrode belt, 2) on the left side of the thorax in level with the xiphoid process of sternum and at the lowest point on the side of the dog without being ventral and, 3) at the dorsal side of the neck (Fig. 1) [40]. The ECG recorded cardiac activity at a frequency of 600 Hz.

One person was responsible for all measurements. The dogs came from their routine activities and were fed not less than 2 h before the

test. The experiment was conducted in a calm examination room at a veterinary clinic and at a room temperature of 18–22 °C.

Each dog fully completed the recordings in standing position on an examination table. Seven minutes of recording was manually started when cardiac activity could be visually inspected in the display of each device. Polar® data was transmitted at the end of each recording to a laptop computer via a bidirectional infrared interface using the Polar® software Polar Protrainer 5.

2.4. Data preparation and analysis

Computer software Cardiorestore 1.33 was used to visually inspect raw ECG data and to calculate IBIs. The first 5-minute recordings from both devices were extracted and visually inspected by a veterinarian to identify technical and physiological artifacts [1]. No non-sinus beats were present in the ECG recordings. Polar® and Cardiorestore software were each respectively used to export IBIs as text files to Microsoft Excel. Corresponding ECG and Polar® IBIs from each subject were aligned to enable pairwise comparisons and the difference between each ECG IBI and corresponding Polar® IBI was calculated. A measurement error was considered when the difference between ECG and corresponding Polar® IBI was more than 50 ms. When the difference was more than 50 ms, the IBIs were checked against the ECG tracings [33,37]. The Polar® measurement errors were labeled anomalous and assigned to one out of eight previously described error categories [33].

2.5. Statistical analysis

Raw IBI data was analyzed with SPSS (Version 20, IBM Statistical Package for Social Science Statistics for Windows, Armonk, NY: IBM Corp). Stata Statistical Software (Release 13, College Station, TX: StataCorp LP) was used to estimate correlation between the measurement methods. Mean, SD, maximum and minimum IBI were calculated in IBI data. Distribution of ECG and Polar® data was tested for normality by performing Kolmogorov–Smirnov and Shapiro–Wilks tests. Inter-beat intervals from ECG were slightly positively skewed in the group of 11 dogs. During the synchronization procedure, extra or missing IBIs in type 4, 5, 6 and 8 errors [33] from Polar®, resulted in empty cells in either ECG or Polar® IBI series. Incomplete pairwise data, produced by Polar®, was assumed to be missing at random. In order to allow us to discuss our results compared to previously reported research on validity and reliability of Polar® heart rate monitors, three different methods for handling missing IBI data were used. Empty cells were kept blank, (i.e. pairwise deletion), zero-values were added in the empty cells (i.e. worst case analysis), and mean imputations. The mean imputations were calculated as previously described by

Jonckheer-Sheehy et al. [33]. When a missing value occurred in either ECG or Polar® IBI series, the mean of the two immediately preceding IBIs differences was calculated. The missing value was replaced by the sum of the estimated IBI difference and the observed ECG or Polar® IBI.

The level of agreement between ECG and Polar® data was assessed in Bland and Altman plots with 95% limits of agreement (LoA) [41] using the Bland–Altman method accounting for repeated measurement per subject. In order for Polar® being used interchangeably to ECG, 95% of the differences were expected to fall within LoA and in addition the width of LoA was expected to be clinically acceptable.

A multilevel model was fitted for the IBI measures to obtain estimates of within-subject and between-rater variances [42,43]. Inter-beat intervals by ECG and Polar® (level 1) were nested within measurement methods (i.e. Polar® or ECG) (level 2) and within the same dog (level 3). A three-level nested model with random intercepts was used. By using the three-level nested model we took into account the possible correlation between the repeated IBI measurements within the same subject. From the nested model level-2 intraclass correlation coefficients (ICC), with 95% confidence intervals (CI), were calculated to represent the correlation between measurement methods in simultaneously recorded IBI data. Intraclass correlation coefficients were also calculated separately for each dog. Correlation between ECG and Polar® within the group of dogs studied was calculated using intraclass correlation coefficients of a single measure and in absolute agreement with two-way random effects (ICC_{2,1}). Intraclass correlation coefficients >0.75 indicates excellent reliability [44].

3. Results

A total amount of 4814 IBIs from ECG and 4794 IBIs from Polar® RS800CX were analyzed. The ECG and Polar® IBIs were synchronized to a total of 4851 pairs in order to allow statistical pairwise comparisons. A total of 595 errors were identified in the Polar® data, representing involvement in 12.3% of the pairwise data set. As the errors were not present in the ECG tracings, none of the artifacts in the Polar® data were non-sinus in origin. The amounts of errors were unequally distributed among the eleven dogs (Table 1 and Fig. 2). Within the individual IBI series, the incidence of errors ranged from 0% to 74.5%. Due to the synchronization procedure, pairwise IBI data from all dogs in the study group consisted of 1.9% missing values. Mean $\pm$ SD IBI from ECG was 686.6 $\pm$ 174.5 ms and from Polar® 691.2 $\pm$ 162.0 ms. In ECG data maximum and minimum IBI were 1530 ms and 307 ms respectively. Maximum and minimum IBIs obtained from Polar® were 1482 ms and 307 ms.

3.1. Relationship and relative reliability between ECG and Polar® IBI measurements ($n = 11$)

ICC revealed strong association between IBI data from ECG and Polar® RS800CX. Using the criteria of Shrout and Fleiss [44] the assessment of relative reliability showed strong to excellent agreement; the values of ICC were between 0.73 and 0.84 depending on how missing values were handled (Table 1). 95% CI for ICC varied moderately, ranging from 0.74–0.95, 0.62–0.82 and 0.72–0.90 indicating that the true difference between these measures was moderate. Table 1 shows within-subject mean $\pm$ SD IBI and individual relative reliability investigated by estimating ICC using pairwise deletion, inserted zero “0” values, and mean imputation, in order to address and replace missing IBI values.

Bland and Altman plots were constructed to assess the presence of systematic over- and underestimations in the group and in individual IBI data respectively (Fig. 2). The Bland and Altman plots of the differences between the ECG and Polar® IBI data against their means illustrate the discrepancies between the devices in individual subjects and the group ($n = 11$) data, when missing values were pairwise deleted. As the difference between methods increased with the magnitude of

Fig. 1. Picture of one of the dogs in the study group showing ECG and Polar® electrode placement in the subjects.

Table 1Individual descriptive statistics (mean IBI $\pm$ SD), individual and group intraclass correlation coefficient for IBI measures obtained by ECG and Polar®.

Subject	ECG, mean IBI (SD)	Polar®, mean IBI (SD)	ICC blank	ICC zero	ICC imputation	Error rate %
1	739.9 (75.7)	739.5 (72.2)	0.92	0.85	0.90	2.6
2	646.4 (72.3)	649.3 (69.0)	0.94	0.90	0.93	1.9
3	469.8 (62.6)	473.9 (60.4)	0.96	0.87	0.96	2.7
4	731.5 (61.7)	733.4 (61.8)	1.00	0.87	0.96	0.2
5	922.3 (176.4)	922.0 (153.2)	0.64	0.53	0.61	26.4
6	649.6 (59.9)	651.5 (59.5)	0.99	0.99	0.99	0.2
7	782.4 (119.1)	782.1 (113.5)	0.95	0.90	0.94	4.2
8	618.9 (73.4)	620.2 (73.6)	1.00	1.00	1.00	0.0
9	599.9 (55.2)	601.4 (55.0)	0.99	0.99	0.99	0.0
10	876.3 (270.9)	878.0 (192.8)	0.23	0.32	0.22	74.5
11	768.0 (198.2)	807.7 (156.9)	0.58	0.49	0.55	44.9
Total ($n = 11$)*			0.84	0.73	0.82	12.3
			95% CI: 0.74–0.95	95% CI: 0.62–0.82	95% CI: 0.72–0.90	
Total ($n = 8$)**			0.99	0.97	0.99	1.5
			95% CI: 0.97–0.99	95% CI: 0.94–0.98	95% CI: 0.97–0.99	

Missing IBI values were handled with blanks, zeros, and imputation. Error rate (percentage of IBI pairs involved in measurement errors) within individual and group IBI series obtained by Polar. SD = standard deviation. CI = confidence intervals. IBI = inter-beat intervals. *All 11 dogs ($n = 11$). **Subject 1, 2, 3, 4, 6, 7, 8, and 9 in a subgroup and subject 5, 10 and 11 internally excluded ($n = 8$).

the measurements, another Bland and Altman analysis was performed on log (base 10) transformed IBI values. The mean difference between the methods was 0.8%. Lower LoA was 0.807 and upper LoA was 1.258, indicating that for about 95% of cases Polar® measurement of IBI was between 19% lower and 26% higher than the ECG measurements of IBIs. 93.2% of the values were within the limits of agreement.

3.2. Relationship and relative reliability between ECG and Polar® IBI measurements ($n = 8$)

Despite overall high ICC values and moderate confidence intervals on group level, the relative reliability and agreement were not acceptable individually in three of the subjects. According to the recommendations of von Borell et al. [2] and of the “Heart Rate and Heart Rate Variability Task Force” [1], three dogs (subject 5, 10 and 11) were internally excluded as their error rates also were more than 5% (Table 1).

Consequently, the relationship between ECG and Polar® IBI measurements in the subgroup ($n = 8$) was stronger and the relative reliability, estimated with ICC, was excellent (Table 1). The values of ICC in the subgroup ($n = 8$) were between 0.97 and 0.99 depending on how missing values were handled. In addition, 95% CI for ICC were narrow, ranging from 0.97–0.99, 0.94–0.98 and 0.97–0.99 indicating that the true differences between these measures were small (Table 1).

Finally Bland and Altman plots of the differences between the ECG and Polar® IBI data ($n = 8$) against their means (Polar® + ECG / 2) were constructed with missing data being handled in three different ways (pairwise deletion, worst case analysis and mean imputation). Fig. 3 shows a Bland and Altman plot on pairwise deleted missing data. The dotted lines on the scatter plot indicate the upper and lower LoA, stretching from 40.3 ms to –36.8 ms. Bland and Altman analysis showed that Polar® was over- and underestimating IBIs compared to ECG. Mean difference in the Bland and Altman analysis, adjusted for multiple measurements per individual, was 1.8 ms. A total of 3703 (98.5%) out of 3756 values were plotted inside LoA (Fig. 3). Limits of agreement and number of measures within LoA varied depending on method used to handle missing IBI data (Table 2).

4. Discussion

In the present study comparisons between Polar® RS800CX and simultaneously recorded ECG IBI show strong associations between methods, with high ICCs in the initial group of eleven dogs studied. However, the relative intra-subject reliability was poor in three of the subjects, due to large amounts of errors. Intraclass correlation coefficients showed the association was as low as 0.22 in subject 10. Despite a highly standardized protocol and that the dogs were maintaining a

standing position in our study, there are various sources of artifacts that can interfere with the signals and make it difficult for the devices to recognize IBIs. Loss of contact of the electrodes to the skin surface or bursts of muscle activity when subjects are non-stationary may lead to displacement of the electrodes respectively false peaks in the ECG and/or Polar® signals.

In our study, there were no corresponding artifacts or non-sinus beats in the ECG tracings and Polar® did not show any continuous sequences of non-registered IBIs. Despite a highly standardized study protocol and stationary dogs, the Polar® heart rate monitor repeatedly overlooked the intervals revealed by the ECG tracings. In subject 5, 10 and 11 the Polar® heart rate monitor commonly triggered sequences of rather invariable Polar® IBIs, resulting in smaller estimated SD in Polar® than in ECG. Consequently the validity of time-based parameters in a HRV analysis may be threatened, as one of the common parameters estimated is the standard deviation of the inter-beat intervals. In addition, the Polar® device manipulated consecutive Polar® IBIs by either adding (e.g., ECG IBI 980 ms, 960 ms; Polar® IBI 649 ms, 649 ms, 649 ms) or withdrawing (e.g., ECG IBI 695 ms, 515 ms, 585 ms; Polar® IBI 900 ms, 900 ms) IBIs, thus measurement errors similar to those previously described by Jonckheer-Sheehy et al. [33] were identified in the present study.

Researchers who previously tested Polar® on validity have been handling missing data in different ways. Jonckheer-Sheehy et al. [33] previously used pairwise deletion to estimate if there were any differences between Polar® and ECG measures in ten Beagle dogs. The same research group used mean imputation to construct a Bland and Altman plot on the differences against their means. Whereas Parker et al. [35] and Marchant Forde et al. [37] inserted zero values where there was missing data in their studies on six horses [35] and five pigs [37].

As ICC estimates only the association between two variables, Bland and Altman plots were constructed to evaluate the differences obtained from the same subjects, using two devices measuring the same criteria and we decided to handle missing data in three different ways. Blank values are handled by SPSS by pairwise deletion. To create a worst case analysis, zero values were inserted in empty cells instead of missing data, and we also used the same mean imputation as Jonckheer-Sheehy et al. [33].

A strength in the present study is that we are able to present varying results depending on which way missing data was handled. In the study group of eleven dogs the CI intervals in the worst case analysis are stretching down to 0.62. Thereby erroneous IBI series from Polar® may not be valid enough to measure the same criteria as ECG [44]. Internally excluding erroneous IBI series in three subjects consequently reveals that the results on individual level reflected on the results on

Fig. 2. Bland–Altman plot illustrating the agreement between ECG and Polar® IBIs in the individual data and in all dogs ($n = 11$). x-axis showing the mean of Polar® and ECG ($\text{Polar®} + \text{ECG} / 2$) is plotted against y-axis showing differences between the methods (Polar® minus ECG). Dotted lines represent mean differences.

group level. Internally excluding three subjects with errors rates $>5\%$ made obvious differences to the confidence intervals of the ICC.

In the subgroup containing eight dogs the CI were higher and had more narrow widths, despite method for handling missing data. Altogether high ICCs stretching from 0.97–0.99 ($n = 8$), narrow CIs and narrow LoA suggest criterion validity for Polar® measuring IBI in IBI series containing $<5\%$ errors was excellent. Though it should be noted that limits of agreement, even in the subgroup of eight dogs, are stretching over and under 50 ms. This may interfere with the parameters in a subsequent HRV analysis, as some of the time-based parameters involve normal-to-normal IBIs >50 ms. Limits of agreement

estimated in the present study were considerably more narrow compared to LoAs presented by Jonckheer-Sheehy et al. [33]. Even though, LoAs estimated by Jonckheer-Sheehy et al. [33] stretched from -126.8 ms to 127.6 ms, they suggested Polar® to be used interchangeably to ECG in stationary dogs.

There are some possible limitations in the present study. First, the sample in our study was small, even if repeated measures within each subject generated a large amount of pairwise data. The results from our reliability analysis would be better to generalize to mid-size healthy dogs, if the sample size would have been larger and still heterogeneous among breeds. Second, more assumptions on variables influencing the

Fig. 3. Bland–Altman plot illustrating the agreement between ECG and Polar® IBIs, based on subject 1, 2, 3, 4, 6, 7, 8 and 9 ($n = 8$). x-axis showing the mean of ECG and Polar® ($\text{Polar®} + \text{ECG} / 2$) plotted against y-axis showing differences between the methods ($\text{Polar®} \text{ minus ECG}$). Lines represent mean differences and the upper and lower limits of agreement ($\text{mean} \pm 1.96 \text{ SD}$). Missing IBI values are handled as blanks in the data set.

results would have been possible to make if we would have controlled for breathing frequency, respiratory sinus arrhythmia and level of fitness within the study group.

Altogether there seems to be some shortcomings of Polar® RS800CX to reliably measure IBIs in all dogs in our study. The exact cause for the errors produced by Polar® especially in three of the subjects is not possible for us to explain. One assumption is that Polar® may register the depolarization illustrated in the ECG tracing as a P-peak, instead of or followed by the R-peak, in some cases of errors. We agree with the description already stated by Jonckheer-Sheehy et al. [33], that Polar® repeatedly showed sequences of rather invariable IBIs compared to corresponding sequences with great variability in ECG. It thereby should be mentioned that Polar® may have a shortcoming with respiratory sinus arrhythmia in dogs, which may influence the intra-subject reliability especially in healthy and fit dogs. As with ECG tracings and IBI recorded by ECG, Polar® IBI series need to be inspected before further HRV analysis. The skill of the observer to detect measurement errors, independently from ECG tracings, is fundamental as erroneous IBI data seriously threatens the validity of the measurement and has to be either excluded or corrected. There are yet no algorithms to detect and correct canine IBI series from Polar® in the software Polar Protrainer 5, nor in the Kubios HRV software. Thereby it is essential for the validity of Polar® IBI data that the quality of recorded IBI series is high and to a large extent free from errors. We recommend that researchers and clinicians that use Polar® RS800CX, and that do not have access to simultaneous ECG to correct potential measurement errors, should apply the guidelines given by Jonckheer-Sheehy et al. [33]. Hence, greater differences than ± 450 ms between preceding or successive IBI and sequences of two or more identical Polar® IBIs should be treated as measurement errors [33].

Table 2
Mean differences in IBI between Polar and ECG and 95% limits of agreement.

Missing data	Mean difference	Limits of agreement	Amount within limits (as percentage)	Amount outside limits (as percentage)
Blanks	1.8	−36.8–40.3	3692 (98.5%)	55 (1.5%)
Zeros	1.8	−58.9–62.5	3703 (98.6%)	53 (1.4%)
Imputation	1.8	−36.8–40.3	3693 (98.3%)	63 (1.7%)

The amount of values within respectively outside 95% limits of agreement, also presented as a percentage of all values ($n = 8$). Values are presented as mean, limits of agreement, amount and amount as percentage.

Polar® heart rate monitors are easily accepted by different animal species, and we suggest Polar® to develop the equipment and supplied software until sufficient validity in recording and correcting IBI artifacts may be proven.

There is still lack of research on the reliability of both time- and frequency-based parameters in HRV analysis from IBI series recorded by Polar® RS800CX in dogs. Given a data set from Polar®, identified with less than 5% measurement errors, there would be a great value in further assessments on the HRV parameters to be used in clinical settings.

5. Conclusion

This study indicated that regarding IBI measurements Polar® RS800CX heart rate monitor was valid and reliable and may be used interchangeably with ECG in the group of dogs studied, when the recorded IBI series did not contain more than 5% measurement errors. Because of systematic biases produced by Polar® RS800CX, it was fundamental to inspect the IBI series according to measurement errors previously described in the literature. Only less than 5% of artifacts could be accepted for the Polar® RS800CX heart rate monitor to show excellent criterion validity and reliable IBI measures in the group of dogs studied. Further studies on the reliabilities of time- and frequency-based parameters in HRV analysis from IBI series recorded by Polar® RS800CX in dogs are needed.

Acknowledgment

We are grateful to the dogs and their owners who participated in this study. Special thanks to Marianne Mellgren and Linnea Stjernstedt for your support. Thanks also to Mona-Lisa Wernroth for your statistical support.

Author contribution

All authors contributed to the paper. A.E. and R.S. made substantial contributions to conception and design of the paper. A.E. and E.A. were responsible for the data acquisition. A.E. and R.S. processed the data. In addition R.S., P.G., L.E.H, L.Z. and K.H. contributed in drafting the article and revising it critically. All authors discussed the results, commented on the manuscript and gave final approval of the version to be published.

References

- [1] Task Force of the European Society of Cardiology and the North American Society of Pacing. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *Eur Heart J* 1996;17(3):354–81.
- [2] Von Borell E, Langbein J, Després G, Hansen S, Leterrier C, Marchant-Forde J, et al. Heart rate variability as a measure of autonomic regulation of cardiac activity for assessing stress and welfare in farm animals—a review. *Rev Physiol Behav* 2007;92(3):293–316.
- [3] Weissman A, Zimmer EZ, Aranovitch M, Blazer S. Heart rate dynamics during acute pain in newborns. *Pflügers Arch* 2012;464(6):593–9.
- [4] Hallman DM, Lyskov E. Autonomic regulation, physical activity and perceived stress in subjects with musculoskeletal pain: 24-hour ambulatory monitoring. *Int J Psychophysiol* 2012;86(3):276–82.
- [5] Billman GE. Cardiac autonomic neural remodeling and susceptibility to sudden cardiac death: effect of endurance exercise training. *Am J Physiol Heart Circ Physiol* 2009;297(4):H1171–93.
- [6] Manzo A, Ootaki Y, Ootaki C, Kamohara K, Fukamachi K. Comparative study of heart rate variability between healthy human subjects and healthy dogs, rabbits and calves. *Lab Anim* 2009;43(1):41–5.
- [7] Stubbs SM, Flø AS, Moe RO, Janczak AM, Skjerve E, Valle PS, et al. Exploring non-invasive methods to assess pain in sheep. *Physiol Behav* 2009;98(5):640–8.
- [8] Hampson BA, McGowan CM. Physiological responses of the Australian cattle dog to mustering exercise. *Equine Comp Exercise Physiol* 2007;4(01):37–41.
- [9] Rehn T, McGowan RTS, Keeling LJ. Evaluating the Strange Situation Procedure (SSP) to assess the bond between dogs and humans. *PLoS One* 2013;8(2):e56938.
- [10] Vincent IC, Leahy RA. Real-time non-invasive measurement of heart rate in working dogs: a technique with potential applications in the objective assessment of welfare problems. *Vet J* 1997;153(2):179–83.
- [11] Fallani G, Prato Previde E, Valsecchi P. Behavioral and physiological responses of guide dogs to a situation of emotional distress. *Physiol Behav* 2007;90(4):648–55.
- [12] Hydbring-Sandberg E, von Walter LW, Hoglund K, Svartberg K, Swenson L, Forkman B. Physiological reactions to fear provocation in dogs. *J Endocrinol* 2004;180(3):439–48.
- [13] Munsters CC, Visser EK, van den Broek J, Sloet van Oldruitenborgh-Oosterbaan MM. Physiological and behavioral responses of horses during police training. *Anim Int J Anim Biosci* 2013;7(5):822–7.
- [14] Von Lewinski M, Biau S, Erber R, Ille N, Aurich J, Faure J-M, et al. Cortisol release, heart rate and heart rate variability in the horse and its rider: different responses to training and performance. *Vet J* 2013;197(2):229–32.
- [15] Stubbs SM, Bohlin J, Skjerve E, Valle PS, Zanella AJ. Applying fractal analysis to heart rate time series of sheep experiencing pain. *Physiol Behav* 2010;101(1):74–80.
- [16] Appelhans BM, Luecken LJ. Heart rate variability and pain: associations of two interrelated homeostatic processes. *Biol Psychol* 2008 Feb;77(2):174–82.
- [17] Lane RD, McRae K, Reiman EM, Chen K, Ahern GL, Thayer JF. Neural correlates of heart rate variability during emotion. *Neuroimage* 2009 Jan 1;44(1):213–22.
- [18] Rietmann TR, Stauffacher M, Bernasconi P, Auer JA, Weishaupt MA. The association between heart rate, heart rate variability, endocrine and behavioural pain measures in horses suffering from laminitis. *J Vet Med A Physiol Pathol Clin Med* 2004;51(5):218–25.
- [19] Kuhne F, Hößler JC, Struwe R. Behavioral and cardiac responses by dogs to physical human–dog contact. *J Vet Behav Clin Appl Res* 2014;9(3):93–7.
- [20] Maros K, Dóka A, Miklósi Á. Behavioural correlation of heart rate changes in family dogs. *Appl Anim Behav Sci* 2008;109(2–4):329–41.
- [21] Gácsi M, Maros K, Sernkvist S, Faragó T, Miklósi Á. Human analogue safe haven effect of the owner: behavioural and heart rate response to stressful social stimuli in dogs. *PLoS One* 2013;8(3):e58475.
- [22] Schöberl I, Wedl M, Kotrschal K. Heart rate and heart rate variability in owners and their dogs. *J Vet Behav Clin Appl Res* 2013;8(4):e34.
- [23] Kortekaas K, Range F, Virányi Z, Kotrschal K. Heart rate and heart rate variability of dogs (*Canis lupus familiaris*) during physical and mental activities. *J Vet Behav Clin Appl Res* 2013;8(4):e45–6.
- [24] Bergamasco L, Osella MC, Savarino P, Larosa G, Ozella L, Manassero M, et al. Heart rate variability and saliva cortisol assessment in shelter dog: human–animal interaction effects. *Appl Anim Behav Sci* 2010;125(1–2):56–68.
- [25] Haker E, Egekvist H, Bjerring P. Effect of sensory stimulation (acupuncture) on sympathetic and parasympathetic activities in healthy subjects. *J Auton Nerv Syst* 2000;79(1):52–9.
- [26] Farinatti PTV, Brandão C, Soares PPS, Duarte AFA. Acute effects of stretching exercise on the heart rate variability in subjects with low flexibility levels. *J Strength Cond Res* 2011;25(6):1579–85.
- [27] Takamoto K, Sakai S, Hori E, Urakawa S, Umeno K, Ono T, et al. Compression on trigger points in the leg muscle increases parasympathetic nervous activity based on heart rate variability. *J Physiol Sci* 2009;59(3):191–7.
- [28] Wang H, Litscher G, Shi X, Jiang YB, Wang L. Effects of acupuncture on heart rate variability in beagles; preliminary results. *Evid-Based Complement Altern Med* 2013;2013:419212.
- [29] Nunan D, Donovan G, Jakovljevic DG, Hodges LD, Sandercock GRH, Brodie DA. Validity and reliability of short-term heart-rate variability from the Polar S810. *Med Sci Sports Exerc* 2009;41(1):243–50.
- [30] Gamelin FX, Berthoin S, Bosquet L. Validity of the polar S810 heart rate monitor to measure R–R intervals at rest. *Med Sci Sports Exerc* 2006;38(5):887–93.
- [31] Gamelin F-X, Baquet G, Berthoin S, Bosquet L. Validity of the polar S810 to measure R–R intervals in children. *Int J Sports Med* 2008;29(2):134–8.
- [32] Porto LGG, Junqueira Jr LF. Comparison of time-domain short-term heart interval variability analysis using a wrist-worn heart rate monitor and the conventional electrocardiogram. *Pacing Clin Electrophysiol* 2009;32(1):43–51.
- [33] Jonckheer-Sheehy VSM, Vinke CM, Oortolani A. Validation of a Polar® human heart rate monitor for measuring heart rate and heart rate variability in adult dogs under stationary conditions. *J Vet Behav* 2012;7(4):205–12.
- [34] Essner A, Sjöström R, Ahlgren E, Lindmark B. Validity and reliability of Polar® RS800CX heart rate monitor, measuring heart rate in dogs during standing position and at trot on a treadmill. *Physiol Behav* 2013;114–115:1–5.
- [35] Parker M, Goodwin D, Eager RA, Redhead ES, Marlin DJ. Comparison of Polar® heart rate interval data with simultaneously recorded ECG signals in horses. *Comp Exercise Physiol* 2010;6(04):137–42.
- [36] Ille N, Erber R, Aurich C, Aurich J. Comparison of heart rate and heart rate variability obtained by heart rate monitors and simultaneously recorded electrocardiogram signals in nonexercising horses. *J Vet Behav Clin Appl Res V* 2014;9(6):341–6. <http://dx.doi.org/10.1016/j.jveb.2014.07.006>.
- [37] Marchant-Forde RM, Marlin DJ, Marchant-Forde JN. Validation of a cardiac monitor for measuring heart rate variability in adult female pigs: accuracy, artefacts and editing. *Physiol Behav* 2004;80(4):449–58.
- [38] Wallén MB, Hasson D, Theorell T, Canlon B, Osika W. Possibilities and limitations of the Polar RS800 in measuring heart rate variability at rest. *Eur J Appl Physiol* 2012;112(3):1153–65.
- [39] Carter RE, Domholdt E. Rehabilitation research: principles and applications. 4th ed. Philadelphia, Pa: Saunders; 2011.
- [40] Tilley LP. Essentials of canine and feline electrocardiography: interpretation and treatment. 2nd ed. Philadelphia, Pa: Lea and Febinger; 1992.
- [41] Bland JM, Altman DG. Agreement between methods of measurement with multiple observations per individual. *J Biopharm Stat* 2007;17(4):571–82.
- [42] Bates D, Pinheiro J. Computational methods for multilevel modelling. Technical Memorandum BL0112140-980226-01 TM. Murray Hill, NJ: Bell Labs, Lucent Technologies; 1998.
- [43] Rabe-Hesketh S, Skrondal A. Multilevel and longitudinal modeling using Stata. 3rd ed. College Station, TX: Stata Press; 2012.
- [44] Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. *Psychol Bull* 1979;86(2):420–8.