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Validity of Telemetric-Derived Measures of Heart Rate Variability: A Systematic Review

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ABSTRACT

Board EM, Ispoglou T, Ingle, L. Validity of Telemetric-Derived Measures of Heart Rate Variability: A Systematic Review. **JEPonline** 2016;19(6):64-84. Heart rate variability (HRV) is a widely accepted indirect measure of autonomic function with widespread application across many settings. Although traditionally measured from the 'gold standard' criterion electrocardiography (ECG), the development of wireless telemetric heart rate monitors (HRMs) extends the scope of the HRV measurement. However, the validity of telemetric-derived data against the criterion ECG data is unclear. Thus, the purpose of this study was twofold: (a) to systematically review the validity of telemetric HRM devices to detect inter-beat intervals and aberrant beats; and (b) to determine the accuracy of HRV parameters computed from HRM-derived inter-beat interval time series data against criterion ECG-derived data in healthy adults aged 19 to 62 yrs. A systematic review of research evidence was conducted. Four electronic databases were accessed to obtain relevant articles (PubMed, EMBASE, MEDLINE and SPORTDiscus. Articles published in English between 1996 and 2016 were eligible for inclusion. Outcome measures included temporal and power spectral indices (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996). The review confirmed that modern HRMs (Polar® V800™ and Polar® RS800CX™) accurately detected inter-beat interval time-series data. The HRV parameters computed from the HRM-derived time series data were interchangeable with the ECG-derived data. The accuracy of the automatic in-built manufacturer error detection and the HRV algorithms were not established. Notwithstanding acknowledged limitations (a single reviewer, language bias, and the restricted selection of HRV parameters), we conclude that the modern Polar®

HRMs offer a valid useful alternative to the ECG for the acquisition of inter-beat interval time series data, and the HRV parameters computed from Polar® HRM-derived inter-beat interval time series data accurately reflect ECG-derived HRV metrics, when inter-beat interval data are processed and analyzed using identical protocols, validated algorithms and software, particularly under controlled and stable conditions.

Key Words: Heart Rate Variability, Wireless Telemetric Heart Rate Monitors, Inter-Beat Interval Time Series, Modern Polar® HRMs, ECG-Derived HRV Metrics

INTRODUCTION

Afferent and efferent, pathways of the autonomic nervous system (ANS), play a vital role in the regulation of internal organ function. Through integrated physiological adjustments, the ANS maintains a state of dynamic internal stability in response to changes in the internal and external environments. Autonomic dysfunction, evident in multiple clinical pathologies, affects the ANS itself directly, or indirectly through impact on end-organ function (61,97,111). Anatomic location complicates the direct measurement of autonomic function in humans, however cardiovascular reflex responses, provoked by simple, non-invasive physiological challenges that alter the beat-to-beat rhythm of the heart, have become the cornerstone of clinical investigation into autonomic function (29,111).

Assessment of end-organ responses provides a simple, safe, non-invasive and indirect insight to autonomic function, and potential dysfunction (29,65). However, the ANS is complex and no single protocol precisely reflects the function of either the parasympathetic nervous system (PNS) or the sympathetic nervous system (SNS) (27). Heart rate variability (HRV), the beat-to-beat fluctuations in the time period between successive ventricular contractions, originating from a sinus node stimulus, is widely accepted as an indirect measure of autonomic function and enjoys widespread application across multidisciplinary settings (99).

Traditionally measured from 'gold standard' criterion electrocardiogram (ECG) recordings (99), the development and availability of inexpensive, simple-to-use, wireless telemetric heart rate monitors (HRMs), with built-in functional capability to eliminate artefacts and instantaneously compute common HRV indices, has extended the scope of HRV measurement beyond the clinical or research settings (106). In sport and exercise, telemetric HRMs provide a valuable tool for coaches and athletes to assess and monitor the natural connections between cardiac autonomic regulation and a number of constructs: (a) cardiorespiratory fitness (34,35,83); (b) health (56,66,102); (c) training load, type and volume (26,34,37); (d) programed periodization (52); (e) sporting performance (16,17,92); (f) training status and recovery (4,18,15,46,91); (g) physiological and psychological capacity to adapt to training (5,6,20,23,32,76), and (h) environmental stressors (4,54,59,60,109).

It is speculated that HRV may provide valuable insight into the capacity of an individual to function with optimal efficiency in complex environmental, physiological and psychological conditions (100), where high HRV reflects good ANS adaptability and function indicative of good health. Conversely, an attenuated HRV is thought to reflect impaired or diminished ANS adaptability, autonomic dysfunction and ill-health. In athletes, the imbalance between long-term, inappropriate or high training volumes and inadequate time for recovery, has been associated with alterations in resting HRV and overtraining (45,53,56).

Two common approaches are adopted for the acquisition of HRV data: ***Long-term ambulatory recordings***, collected over a 24-hr time period, and ***short-term recordings***, for which various definitive time periods are evident, such as 2 or 5 min (99), 5 to 15 min (87), <60 min (40), and

<24 hrs (87). More recently the value of ultra-short recordings (<60 sec) has come under scrutiny in healthy individuals (93), athletes (27), clinical settings (71,72), and diverse cross-sectional populations (3,67), with mixed outcomes. Protocols may embrace *stable, resting* measures, where test conditions remain consistent throughout the test period, and *provocative* measures, where the individual is subjected to a physical, cognitive or psychological stimulus that activates an ANS response with measurable changes in HR or HRV indices. Both stable and provocative measures are suited for general and clinical application to stratify health risk or evaluate the impact of an intervention (90).

The HRV measurement is not without controversy. A number of well-known confounders and measurement related issues complicate the interpretation and comparison of outcomes. A detailed discussion of each is beyond the scope of this current review but eloquent discussions are provided elsewhere (15,40,70,75,79,80,87,99,106). Given the rapid developments in technology and the widespread application of HRV data derived from HRMs in healthy, active individuals and athletes, few studies have evaluated the concurrent validity of telemetric-derived data against the gold standard criterion - ECG data - in these populations. Therefore, the aims of the current review were twofold: (a) to review the validity of telemetric HRM devices to detect inter-beat intervals and aberrant beats against criterion ECG measures under stable and provocative conditions; and (b) evaluate the validity of HRM-derived indices of HRV against ECG-derived HRV measures in the temporal and power spectral domains under stable and provocative conditions in healthy adults aged 19 to 65 yrs.

METHODS

A systematic review approach was adopted to address a clear and explicit research question: “Are short-term temporal and spectral measures of heart rate variability, recorded using contemporary Polar® heart rate monitors, at rest, during exercise and during the immediate post-exercise recovery period, valid in healthy adults?” Current authoritative guidelines for systematic reviews were sourced and followed (41,64).

Validity was evaluated on two levels. First, the detection of inter-beat interval and error data was compared between the HRM-derived and ECG-derived data. Subsequently, the HRV indices computed from the HRM-derived and ECG-derived inter-beat interval data were compared. The HRM and the ECG derived inter-beat intervals, or RR intervals, are determined from myocardial electrical signals, notably the R waves from successive QRS complexes. The review included data gathered at rest in stable conditions, during orthostatic provocation, exercise and during the immediate post-exercise recovery time period.

Search Strategy

Four two electronic databases were assessed by the primary investigator (EB) to source relevant research evidence. PubMed and Discover, the institute’s platform for electronic databases, which included access to EMBASE, MEDLINE and SPORTDiscus were used for this purpose. Titles and abstracts of citations identified through the primary search were screened for relevance to identify articles suitable for full text retrieval. Citations were exported and saved in a Microsoft® Word™ document. The duplicate references were removed. Further evidence was then obtained via snowballing, which entailed a manual search of reference lists presented in relevant articles to identify additional citations that did not appear through the electronic database searches.

The search process including the key terms and the number of articles retrieved from one search (PubMed) are detailed in Figure 1. Eligible articles were identified, filtered and read in full by one reviewer (EB). Replicates, where authors presented data from the same participant population, but published in different articles, were identified by closely cross-checking the names of authors against sample sizes, sample characteristics, protocols and cited intervention(s). Where potential

replication was identified unique data were included or the data from the study with the closest relevance to the research question were included. Only two studies (68,69) were identified as potential replicates, based on participants and methods. Each presented unique data, thus both were included in the review.

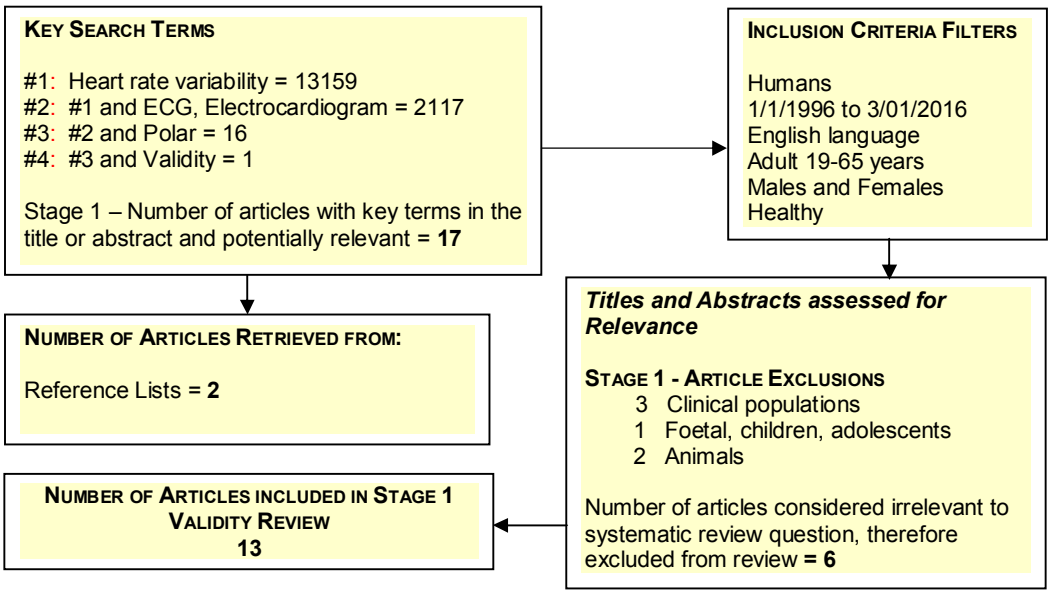

Figure 1. Schematic to Illustrate the Systematic Review Search Process.

Inclusion and Exclusion Criteria

Studies published between 1996 (publication of ESC Task Force Recommendations) to March 2016 were eligible for inclusion in this review. Studies that assessed short-term HRV (i.e., where short-term was officially defined as inter-beat interval time epochs <1 hr) were included (40). Inter-beat interval data derived from 2-lead, 3-lead, 5-lead, and 12-lead ECG recordings were accepted as suitable criterion measures. The review included both stability HRV measures at rest and responses to ANS provocation. Selected articles were restricted to those published in the English language due to limited access to translation services. Also, all articles were restricted to healthy, active adult males and females, aged 19 to 65 yrs.

Outcome Measures

Outcome measures included 11 standard temporal and spectral power indices of HRV (Table 1) (99). These included the normalized RR interval and HR. Given the dubious nature of very low frequency (VLF) power values derived from short-term recordings (99), we chose to exclude this measure from the review. We also excluded the normalized low frequency (LF) and high frequency (HF) HRV indices expressed as a percentage (LF% and HF% respectively) given that VLF power is integral to their computation (LF% = LF / VLF + LF + HF and HF% = HF / VLF + HF + LF, respectively), but did include alternative normalized LF and HF indices (expressed in normalized units [nu]) where LFnu equates to [LF / (LF + HF) * 100] and HFnu to [HF / (LF + HF) * 100]. Studies which presented non-linear derived HRV indices were excluded.

Table 1. Temporal and Power Spectral Measures of Short-Term Heart Rate Variability (ESC Task Force, 1996).

VARIABLE	DESCRIPTION	UNITS
Temporal Measures		
RR Interval	Time between adjacent normal R-R intervals	ms
SDNN	Standard deviation of all NN intervals	ms
RMSSD	The square root of the mean sum of squares of differences between adjacent NN intervals	ms
pNN_{50}	Percentage of successive NN intervals over the temporal segment that differ by more than 50 ms.	ms
Power Spectral Measures		
Total Power	The variance of the NN intervals over the temporal segment (approximately ≤0.4 Hz)	ms^2
VLF	Power in the very low frequency range (<0.04 Hz)	ms^2
LF	Power in the low frequency range (0.04 – 0.15 Hz)	ms^2
LFnu	LF power in normalized units (LF/[LF + HF])*100	nu
HF	Power in the high frequency range (0.15 – 0.4 Hz)	ms^2
HFnu	HF power in normalized units (HF/[LF + HF])*100	nu
LF/HF	Ratio of LF[nu] / HF [nu]	

Risk of Bias

We accounted for differences in methodological quality and the risk of bias and imprecision between studies. Definitive criteria were identified to ease and standardize the appraisal of methodological bias associated with extraneous variables in the individual research studies. Highly controlled measures reduced bias and strengthened the value of the research outcomes. Simultaneous recordings of inter-beat intervals using ECG and HRM were regarded more favorably than sequential measures. The use of temporal event markers to clearly demarcate the exact start and finish times was viewed as evidence of good control as was the reporting of beat-to-beat count data for both ECG and HRM derived methods. Food and fluid (water) intake was judged to be highly controlled if participants were assessed in a fasted state, or if they had consumed a light meal or fluids provided or advised no less than 2 hrs prior to trials (40). *Ad libitum* water intake was deemed as a high bias risk and not considered controlled (40). Stimulatory beverages, foods or sports gels, for example, those containing caffeine (tea, coffee, and energy drinks) were deemed controlled if restricted for at least 12 hrs. Strenuous or vigorous exercise and smoking habits were regarded as controlled if restricted for at least 24 hrs, ideally 48 hrs prior to the HRV assessment. Finally, the effects of ventilation on HRV were controlled if a set

(paced) breathing frequency was evident, ideally above 0.15 or 0.16 Hz, 9 to 10 breaths·min^{-1} (84). Where a specific methodological control (e.g., breathing pattern, posture, or duration of time series sample) was not explicitly stated, it was assumed to be absent and therefore a potential source of bias.

Statistical Analyses

Analyses, which independently quantified the magnitude of systematic bias, random error, and agreement, as recommended by Atkinson and Nevill (2), Hopkins, (43) and Weir (108) were judged to be of high methodological quality. The intra-class correlation co-efficient (ICC) quantifies the strength of linear association between two sets of data. The standard error of measurement (SEM), typical error (TE), within-subject standard deviation (WS_{SD}), and co-efficient of variation (CV) quantify the magnitude of random error. In addition, given that calculations are mere estimates from a sample and not population data, the citing of 95% confidence intervals (95% CI) was deemed good practice (2,108). A significant outcome ($P<0.05$) from paired *t*-tests or a within-subjects analysis of variance (ANOVA) confirmed the presence of systematic bias. The effect size (ES) statistic (defined as the pooled standard deviation of the differences divided by the mean difference) was accepted as a valid measure for quantifying the magnitude of differences (33). A small effect size indicates that there is greater agreement between measures. The assumption of homoscedastic data was evaluated by correlating individual difference scores between test and retest variables (Test 2 –Test 1) and against their respective mean ([Test 2 + Test 1]/2). A zero correlation confirms homoscedasticity. Finally, Bland-Altman Limits of Agreement were also accepted as measures to quantify the magnitude of random and systematic bias (12).

A priori criteria, or analytical goals, for each statistical measure were defined. The ICC's were interpreted using Hopkins (44) criteria: Small (≤0.30), moderate (0.31-0.49), large (0.50-0.69), very large (0.70-0.89), and near perfect (>0.90). An ICC >0.75 (lower 95% CI boundary) was acknowledged as the minimal level of agreement accepted for the interchangeable use of two methods (55,68,86). The magnitude of ES was evaluated using Hopkins (43) criteria: Trivial (<0.2), small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0), and very large (>2.0). To summarize, statistical criteria that strengthen support for validity include a small systematic bias, narrow 95% limits of agreement, small effect sizes (<0.20) and ICC (>0.75) between the Polar® HRM-derived and criterion ECG-derived data.

RESULTS

Twelve relevant validity studies that compared the performance of the Polar® V800™, Polar® RS800CX™, Polar® 810™, and Suunto T6 HRM to ECG were identified. One additional article (104) was included, although it did not fully meet *a priori* inclusion criteria. Vasconcellos et al. (104) assessed the validity of the Polar® RS800CX™ to ECG, but in an adolescent population. Given the paucity of available validity data it was deemed important to include. Twelve studies evaluated stable responses in the supine posture. Three studies assessed provocative responses to either an orthostatic (stand) or exercise challenge.

As is clearly evident from data presented in Table 2 (refer to Tables 2 and 3), there was a distinct contrast in the number of HRV variables reported, protocols adopted and sample demographics (age, sex, BMI, and physical activity status of participants) between studies. Thus, the heterogeneity of the individual studies prevented pooling of data for in-depth meta-analysis. Consequently, the review emphasis was placed on variables deemed to have major physiological importance in sport and exercise, and also on variables reported repeatedly, as consistency of results across multiple independent studies supports the validity of an outcome (19).

A total of 595 participants were included in the review. A slight sex distribution bias was evident (322 males and 273 females). The mean age of participants was 33 (range 21 to 57) yrs with a

distinct bias towards the younger age groups in 9 studies. Mean body mass was consistent across studies. Few studies reported data for body fat percentage or body mass index. The sample size range for individual studies was between 11 and 318 participants.

Inter-Beat Interval Detection

Six studies assessed the validity of inter-beat interval count in rested supine conditions and two in response to standing (Table 3; refer to Tables 2 and 3). Of these studies, four assessed the validity of the Polar® S810™ and two the Polar® RS800CX™. The data from one study was limited (106). In the supine position, systematic bias (±LOA) varied between studies and between HRM models: Polar® S810™, median -2.0 beats (77) and 1.4 ± 23.2 beats (68); Polar® RS8000CX™, -0.14 ± 7.3 beats (104). In the standing position, one study reported a mean inter-beat interval detection bias of -2.6 ± 0.93 beats (77). No studies examined the validity of inter-beat interval count in response to exercise or during the immediate post-exercise recovery time period.

Aberrant Beat Detection

Six studies assessed error detection rates (Table 3; refer to Tables 2 and 3). Five studies quantified the number of errant beats as a percentage of the total number of inter-beat intervals. One study quantified the number of error beats incorrectly detected by the HRM (106). This accounts for the large discrepancy in comparison to other studies. Error detection rates in the supine position varied: 0.082%, Polar® V800™ (33); 0.32%, Polar® S810s™ (51); 0.40%, Polar® S810™ (31); and 6.93%, Polar® S810i™ (103). The Polar® RS800CX™ failed to detect 18 of the 21 (85.7%) errant beats identified from the ECG recordings (106). In the standing position, a single study reported an error detection rate of 0.089% (33) for the Polar® V800™. An error rate of 0.10% was reported for the Polar® 810™ during sub-maximal exercise (103). There are no available data for aberrant beats in the post-exercise recovery period.

Inter-Beat R-R Interval Time Period

Nine studies assessed and compared the accuracy of the inter-beat (RR) interval time period (Table 3; refer to Tables 2 and 3). The mean bias between the Polar® V800™ and the ECG-derived inter-beat interval time period was 0.06 ms and 0.59 ms for the supine and the standing postures, respectively (33), -10 ms to 10 ms for the Polar® RS800CX™ (104 and 65, respectively), and between -0.06 ms (51) to 2.5 ms. (68) for the Polar® S810™. In the standing position, the inter-beat interval detection bias was 0.59 ms (LOA, -1.70 to 2.87) for the Polar® V800™ (33) and between -0.70 ms (LOA, -3.89 to 2.50) and 1.0 ms (LOA, -6.0 to 8.5) for the Polar® S810™ (77 and 31, respectively). Intra-class correlation coefficients for the supine position ranged between 1.00 for Polar® V800™ (33); 0.94 to 0.99 for Polar® RS800CX™ (65,104); 0.95 to 1.00 for Polar® S810™ (31,68,69,107); and 0.99 to 1.00 for standing (Polar® S810™ (31) and Polar® V800™ (33). Inter-beat interval bias during exercise is dependent upon intensity (51) (Table 3; refer to Tables 2 and 3). Intra-class correlation coefficients during exercise ranged between 0.93 (<80-100% VO_2 max) to 1.00 (<40% VO_2 max).

Validity of Computed HRV Indices in Temporal and Power Spectral Domains

The validity of computed HRV indices is variable between HRM models (Table 3; refer to Tables 2 and 3). Near perfect validity is confirmed for temporal and spectral power HRV measures computed from inter-beat interval data captured using the most contemporary Polar® V800™ HRM model [ICC (lower boundary of 95%CI) = 0.98 for LF/HF and 1.00 for all other variables] (33). In contrast, one study suggested the Polar® S810™ portrayed poor levels of interchangeable agreement [ICC (lower boundary 95% CI), R<0.75] (68).

Evidence to support the validity of the Polar® RS800CX™ HRM varied from moderate [ICC (lower 95%CI); R>0.75] to near perfect [ICC (lower 95%CI); R>0.90] with narrow LOAs for temporal domain variables (22,65,106). The validity of pNN50 and spectral power HRV measures derived

from the Polar® RS800CX™ were poor (ICC, <0.75 and wide LOA), for pNN50 (106), LFms (22), HFms (106), LFnu (22,104;106), and HFnu (104).

Excellent ICC correlations were found between the Polar® V800™ and the Polar® RS800CX™ derived and ECG-derived HRV time domain parameters during an orthostatic challenge [ICC (lower boundary 95%CI): active stand R = 0.99-1.00, (33)] and passive tilt; [R = 0.89-1.00, (65)]. The RMSSD and HF indices appeared to be sensitive and valid measures of ANS function.

DISCUSSION

The purpose of this systematic review was twofold: (a) evaluate the validity of Polar® HRMs to detect inter-beat intervals and aberrant beats against the criterion ECG; and (b) compare Polar® HRM-derived indices of heart rate variability against criterion ECG-derived measures in the temporal and power spectral domains.

This systematic review is the first to offer an up-to-date comprehensive review and comparison of HRM-derived HRV validity data. The current review supports the validity of Polar® HRMs (S810™ series, RS800G3 ™, RS800CX™, and V800™ models) to detect and record inter-beat interval time series data against the 'gold standard' electrocardiogram (ECG), using 12-lead (77), 5-lead (107), 3-lead (51), and 2-lead (31) recordings in normal ambient conditions. The low mean bias, narrow limits of agreement, and high ICC values observed in the more carefully controlled studies strongly suggests that HRM-derived inter-beat interval data are interchangeable with ECG-derived data. The evidence supports the improved accuracy of the more contemporary Polar® RS800CX™ and V800™ HRM devices in comparison to the previously validated Polar® S810™ model. The Polar RS800CX HRM may not be sufficiently sensitive to satisfactorily detect aberrant beats of a clinical nature, but the evidence on which this assertion is made is limited to one study (106). Therefore, caution is advised since validity outcomes are not consistent in the studies that were reviewed. Where dispute has arisen, regarding Polar® S810 (68) and Polar® RS800CX (106), this is likely due to the methodological inconsistencies related to: (a) poor bias control measures within the research design; (b) use of customized Polar software for HRV computations; (c) the casual adoption of default manufacturer settings; and (d) the use of corrected or uncorrected inter-beat interval time series data of which all the inconsistencies may contribute substantially to the poor outcome data (22,81,104,110).

Sub-division of the entire HRV process into three sequential stages (such as inter-beat interval data acquisition, data editing, and HRV analysis) enables the user/researcher to better appreciate the impact of methodological inconsistencies on reported validity outcomes. In particular, error detection and its removal or correction is a crucial part of the process. At any stage the artifacts (error) will impact the quality of the data moving forward to the next sequential step, which will substantially alter the final analyses of the HRV parameters.

Error detection rates in the supine position varied: 0.082%, Polar® V800™ (33); 0.32%, Polar® S810s™ (51); 0.40%, Polar® S810™ (31); >85.0%, Polar® RS800CX™ (15); and 6.93%, Polar® S810i™ (103). In the standing position, a single study reported an error detection rate of 0.089% (33) for the Polar® V800™. No studies reported inter-beat interval counts for short-term time series during exercise or recovery from exercise. Wallén et al. (106) questioned the validity of the Polar® RS800CX™ HRM for use with the clinical populations, given its poor ability to detect non-sinus beat data. With error detection rates of 0.082% (10/12247) and 0.089% (10/11240) in the supine and standing postures, respectively, the Polar® V800™ HRM offers the most accurate inter-beat data on the commercial, non-clinical market. Discrepant outcomes between studies are likely attributed to population characteristics, methodological variations, control measures for internal validity, and the competency of observers responsible for the filtering, processing, interpolation, and de-trending of time series data.

Ectopic beats and premature atrial contractions (physiological artifacts) in addition to sweating, motion, loose HRM chest belts, and poor electrode attachment (technical artifacts) are widely acknowledged sources of error and have been shown to significantly influence subsequent HRV computations. Short term inter-beat interval time-series are particularly sensitive to artifacts and editing (49,50). A single aberrant beat may influence computed HRV indices (7,8). Ideal time-series inter-beat interval data would include only beats of sinus node origin, but this is rarely observed even in healthy individuals (48,73). As such, error detection and inter-beat interval time-series editing procedures are crucial to identify, remove, and correct errant beats and other noise artifacts. Errant beats may be distinguished from sinus rhythm beats by variations in the length of the corresponding inter-beat intervals. As such, an accurate inter-beat interval time-series is reliant on an accurate R-peak signal detection algorithm from which inter-beat time periods may be determined.

Error detection is not straight-forward and there is no consensus or clearly defined, standardized method to guide the identification, correction, and removal of errant beats. Inter-beat interval errors have been sub-categorized into five specific types (31). More recently, two further error sub-types have been demarcated (33). Detailed discussion of error correction types and methods are beyond the scope of this review, but can be found elsewhere (31,62). In the validity studies presented in this review, aberrant beats and other artifacts were either visually and manually detected or identified through in-built automated algorithms integral to the measurement devices. Few studies explicitly detailed the pre-processing and de-trending procedures and error definitions were inconsistent. Errors between HRM and ECG derived time-series data were defined as inter-beat interval discrepancies greater than 20 ms (31,68) or greater than 20% between successive beats (99) and, perhaps erroneously, as a difference greater than 2000 ms between consecutive inter-beat intervals (51, page 40). Errant data may be deleted or it may be corrected manually or automatically using customized software interpolation algorithms. Strategies for inspecting and pre-processing the inter-beat interval time-series data vary among the studies with resultant discrepant outcomes (31,51,68).

The criteria applied to correct or remove errant beats in inter-beat interval time-series recordings also vary between instruments and software programs. Correction usually involves linear and non-linear interpolation methods to replace errant beats (48,57). To ease the process, Polar® HRM models have an automatic, integrated detection and removal or correction function, although this has been criticized as insufficiently sensitive to identify all aberrant or missing beats (106). Kubios HRV software also facilitates automated artefact detection and correction. It integrates visual inspection via a graphical interface with a flexible filter that allows for the correction of differences between successive inter-beat intervals of variable magnitude ranging from very low [450 ms] to very strong [50 ms]. These corrections are scaled to a HR of 60 beats·min^{-1} to accommodate variations in HR within the inter-beat interval time-series recording. Schäfer et al. (90) suggested the choice of automated error filter should be the lowest that removes all errors, although the default value (moderate) is recommended, and it is deemed appropriate for most applications (47). Either way, automated detection and correction using an accurate algorithm is recommended to avoid manual errors (73) and yet, visual error inspection remains an important step in the pre-processing step of HRV analysis (99).

Temporal and power spectral analyses are sensitive to signal length, where wider LOA have been reported when errant beats were corrected (31) rather than deleted (51). Others have reported no significant impact on computed mean bias (90). Corrected data may differ significantly from uncorrected data (33). However, the trivial effect sizes (0.000 to 0.004), which accompanied the narrow LOA and near perfect correlations led the authors to conclude that the inter-beat sample size (12247 for supine and 11240 for standing) was the most likely determinant of the significant outcome. Beat deletion shortens the length of the time-series data sample and may alter

computed HRV parameters, therefore interpolation methods that preserve the length of the inter-beat interval time-series are preferred (47). Power spectral HRV indices are also sensitive to non-stationarity in the inter-beat interval time-series, thus de-trending corrections such as the smoothness priors approach (98) that lessens any baseline non-stationarity in an inter-beat interval epoch.

The HRV analysis requires sophisticated computations. The HRV measures may be determined through automated, equipment in-built algorithms, or the ECG-derived and HRM-derived inter-beat interval data may be downloaded and exported for analysis through external HRV software. Evidence appears to support the use of automated corrected time-series data over uncorrected data for the subsequent computation of HRV parameters in both the temporal and power spectral domains (31,51). The relative agreement between Polar® HRM-derived and ECG-derived data for the computation of temporal and spectral HRV parameters at rest in the supine posture is controversial. Wallén et al. (106) supported the interchangeable use of HRM-derived data in place of ECG-derived data for HRV analysis for males but not for females in those aged under 45 yrs but not for those aged over 60 yrs. Poorer levels of agreement were generally observed, once again where methodological controls were less defined and where the HRV indices were derived from dissimilar individual manufacturer-customized ECG and Polar® software packages (68,106).

In method comparison studies, the adoption of identical software for pre-processing, editing, and subsequent HRV analyses appears to enhance validity. The application of dissimilar methods for HRV editing, interpolation, and HRV analysis as alluded to earlier in the discussion may amplify errors (68,73,74,82,86,106,107). In the current review, the software used for the final HRV analysis was not always stated. A number of bespoke software programs with integral beat and error detection capabilities and interpolation algorithms are now freely available for more general use (47). To further enhance validity, it may be argued that time-series data for individual cases may be excluded from final analysis if the proportion of error in the inter-beat interval time-series exceeds a certain threshold, although a clear threshold has not been established yet. Schäfer et al. (90) applied a more stringent 10% non-sinus (errant) beat error threshold, whereas others commonly adopt a 20% threshold (28,47,95). Salo et al. (85) have showed that errors <5% in a short-term inter-beat interval time series will influence HF, LF, RMSSD, and pNN50 HRV parameters. Where outliers are identified and data removed, reasons must be clearly articulated and justified. A recent review recommended more accurate reporting of data pre-processing and editing methods (73).

Most studies included in this review implemented standard control measures with participants rested in a supine position, in a quiet, dimly lit room with few distractions and a climatic controlled temperature (20 to 24^{o}C) and relative humidity (50 to 55%). However, other methodological factors were less well controlled. Participant instructions to refrain from stimulants (e.g., caffeine-related products) and other recreational substances with a stimulatory effect on the ANS were inconsistent and varied from the vague [‘no clear instructions’ (14,24,107)], ‘on the morning of the test’ (65,105), ‘prior to the test’ (33), and ‘on test day’ (68)] to more specific, such as ‘for 12 hrs’ (103) or ‘24 hrs’ (65) prior to testing. Strenuous or vigorous intensity was prohibited for 24 hrs (105) and 48 hrs (68,69) before tests, or not restricted. Instructions regarding food or fluid intake varied between fasting for 10 to 12 hrs (105) to a light meal permitted 2 hrs before trials (33,103). Participants prescribed medications, which influenced cardiovascular autonomic activity were usually but not always excluded (105). Most studies specified smoking within their exclusion criteria but when smokers were recruited, participants were requested to abstain from smoking for between 12 to 24 hrs (86). No studies stated that participants were asked to confirm they had adhered to the pre-trial control measures. Where HRV was assessed in multiple conditions, for example standing and supine or during paced and controlled breathing, no explicitly articulated randomization or blinding procedures were integrated within the study design. However, designs did align well to ESC Task Force recommendations (99).

Time of day was consistently controlled across studies with re-tests scheduled to coincide with the time of the original test data collection (±1 to 2 hrs). Most studies were conducted in the morning hours between 6:00 and 11:30 to control for known circadian variations (13,63). However, evidence to support circadian-induced variations in HRV in healthy individuals is sparse. Morning data collection also facilitated an overnight fast to control for the potential confounder aligned to food and beverage consumption. As reported by Lu et al. (58), the post-prandial, sympathetic activation, thermogenesis, and vasodilation provoke a coordinated autonomic response reflected by a diminished HF and increased LF/HF. Conversely, Ambarish et al. (1) reported no effect of food intake on any HRV index 15 min, 1 hr, and 2 hrs post-prandial. More recent evidence (89) reported no significant effect of meal intake on HRV measures with the exception of HF in the 2 hrs post-prandial period. Vögele et al. (105) suggested dietary restriction, i.e., fasting will increase HF and decrease LF components. Given the conflicting evidence, the more recent 2 hrs post-prandial recommended control measure (96) appears as a sensible compromise to an overnight fast.

In a recent review of normal HRV values, Nunan et al. (70) conservatively defined a discrepant value as one that was greater than 1.5 SD from the mean publication value. In a similar manner, an attempt was made in this review to quantify the magnitude of bias and identify acceptable levels of bias using the available data. The mean bias and the mean LOA data for individual HRV indices from independent studies were calculated. Outcomes of the current review suggest that the data published by Vasconcellos et al. (103), Wallen et al. (106), and Nunan et al. (68) should be treated cautiously as the level of bias does not support the interchangeable use of HRM and ECG devices. However, the near perfect agreement for both time domain and frequency domain HRV data in the Giles et al. (33) improves upon outcomes from previous research exploring the validity of earlier Polar S810 HRM model (31,69,77,103,107).

The studies conducted by Gamelin et al. (33), Weippert et al. (107), and Giles et al. (33) suggest that controlled breathing improves the validity of HRV outcome data. Given the observed fluctuations in HRV parameters with respiratory sinus rhythm (RSA) (42,78), the integration of controlled breathing protocols at a pre-determined breathing frequency are generally recognized as a good practice for the assessment of HRV, particularly in the HF power spectral domain. However, counter-arguments suggest breathing controls are not necessary, particularly for HRV measured in the rested state (21,84). It is also argued that the transition from spontaneous (a largely unconscious process) to controlled breathing (a conscious process) induces fluctuations in tidal volume and breathing frequency that inadvertently lead to inaccurate estimations of HRV and misinterpretations that do not reflect the true ANS activity on the heart (88). It may also be argued that controlled breathing does not reflect real-world fluctuations. The respiration-cardiovascular debate remains an active and current area of research. Detailed discussions on the close coupling between the respiratory and cardiac systems and the impact on HRV are beyond the scope of this current review but eloquent contrasting arguments are debated elsewhere (9,10,11,21,25,36,101).

As illustrated in Table 2 (refer to Tables 2 and 3), the risk of methodological bias is interpreted as high for most studies included in this review. This is attributed to poor or variable study designs that failed to adequately control for known confounds, which have previously been shown to dramatically alter HRV. However, it may be argued that real-world applications are not rigorously controlled, therefore, the validity data under strictly controlled conditions are unrealistic and do not portray an ecologically valid representation of HRV. We suggest validity data should be interpreted with this ideation in mind. The magnitude of observed real-world changes should be used to guide the interpretation of validity data, as may normative data. With no clear consensus as to what constitutes ‘normative data’, magnitude of bias interpretations are somewhat thwarted. This is an important area for future research, that is, to explore the impact of the female hormonal cycle on the validity of HRV measures.

This systematic review presented here is scientifically robust in both process and outcomes. However, it is not without limitations. We acknowledge only one independent reviewer was used to search, appraise and select the studies for inclusion. Similarly, the same individual acted as the sole reviewer for the articles selected. Exclusive attention to articles published in the English language potentially excludes relevant articles written in other languages. Although the review focused on Polar® HRMs, we do not believe this to significantly bias the general validity of the conclusions (given that much of the practical application and published research in sport and exercise is monopolized by Polar® HRM technology). That is not to say HRMs produced by other manufacturers are any more or any less effective. There simply is not the available evidence. Similarly, we acknowledge the availability of alternative methods for inter-beat interval data acquisition that were excluded (e.g., digital photoplethysmography).

Also, this study did not examine signal pre-processing specifications, automated algorithms, and interpolation procedures used for detection and correction of inter-beat interval data and HRV parameter computations. This was beyond the scope of the current review, but does presents a real and pertinent threat to the validity of HRV parameters. Detailed discussions are available elsewhere (40,49,50,80). We limited the review to short-term HRV analyses in the time and frequency domain. Exciting but more complex, non-linear methods are emerging although linear analyses remain the most commonly reported method in the extant literature. The recent development of smartphone devices and apps (14,27,39) makes the utility of HRV more accessible on a population level. The routine use of ultra-short term HRV recordings in clinical practice (67) offers a practical alternative to short-term measures. Future research should examine the validity of these contemporary measures and devices across different population groups and incorporate larger sample sizes. Little is known about the validity of HRV parameters measured in the afternoon or evening. Similarly, there is a need to closer assess the confounding influence of the female hormonal cycle on the validity of HRV parameters at distinct phases of the menstrual cycle. Studies have yet to be conducted that compares the simultaneous recording of HRM and ECG derived inter-beat time-series data during exercise and during the post-exercise recovery period. The validity of HRV parameters derived from HRM and ECG inter-beat time-series data in different environments, e.g., at altitude, also remain to be established.

Advancements in computing technology and miniaturization have eased the telemetric detection, recording, and analysis of inter-beat interval data and, therefore, have extended the practical application of HRV measurements beyond the clinical and research arena to more diverse settings and audiences in sport, exercise, and fitness. However, as evident from the validity studies included in this systematic review, the complex mathematical computations involved in HRV analysis, the uncertainty surrounding the physiological origin of HRV indices, the diversity of methodological approaches, and the presence of numerous influential confounders complicate the HRV interpretation and expose significant risk for outcome misinterpretation. Based on the evidence reviewed, temporal measures, particularly those widely used in sport and exercise applications (RMSSD and HFnu), appear to show good to excellent interchangeability with ECG and present as valid measures of parasympathetic autonomic activity. As such, these indices derived from HRM inter-beat interval time series data offer valid and useful measures for monitoring fatigue and recovery in athletes or levels of daily or occupational stress in the wider population. It is evident that the validity of data and the quality of HRV outcomes are improved when methodological controls are implemented.

CONCLUSIONS

The validity of HRMs has been evaluated in this systematic review in laboratory-based research settings. The accuracy of inter-beat interval recognition derived from modern Polar HRMs compares well to the gold-standard ECG criterion methods at rest (33,65,106) and during

orthostasis (33,65). Hence, it may be concluded that more modern Polar HRMs (Polar® V800™ and Polar® RS800CX™) provide a valid measurement tool for HRV analyses. Little is known about the validity of HRV measures during exercise and the post-exercise recovery time period in adults.

Previous reviews have evaluated the validity of ECG-derived inter-beat interval data. In this study, we focused on HRM-derived measures. The review confirms the validity of Polar® HRMs for the detection of inter-beat interval data. It questions the accuracy of aberrant beat detection, which is more of a concern for clinical applications than for common sport and exercise uses (80). The review highlights the lack of rigorous controls for known confounders. We acknowledge this may be a reporting issue rather than poor methodological practice, but we do emphasize the need for accurate reporting of control measures in HRV research publications.

We conclude that for healthy adults aged 19 to 65 yrs in ambient conditions at rest the Polar® HRMs: (a) present a valid method for the detection of inter-beat intervals; (b) Polar® HRM-derived inter-beat interval time series are valid for subsequent HRV analysis using validated Kubios HRV software; and (c) currently, there is a lack of available evidence to support the validity of integral Polar® HRV analysis software to compute HRV parameters from Polar® HRM-derived time series data.

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