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REVIEW

Can Wearable Devices Accurately Measure Heart Rate Variability? A Systematic Review

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Background: A growing number of wearable devices claim to provide accurate, cheap and easily applicable heart rate variability (HRV) indices. This is mainly accomplished by using wearable photoplethysmography (PPG) and/or electrocardiography (ECG), through simple and non-invasive techniques, as a substitute of the gold standard RR interval estimation through electrocardiogram. Although the agreement between pulse rate variability (PRV) and HRV has been evaluated in the literature, the reported results are still inconclusive especially when using wearable devices.

Aim: The purpose of this systematic review is to investigate if wearable devices provide a reliable and precise measurement of classic HRV parameters in rest as well as during exercise.

Materials and methods: A search strategy was implemented to retrieve relevant articles from MEDLINE and SCOPUS databases, as well as, through internet search. The 308 articles retrieved were reviewed for further evaluation according to the predetermined inclusion/exclusion criteria.

Results: Eighteen studies were included. Sixteen of them integrated ECG - HRV technology and two of them PPG - PRV technology. All of them examined wearable devices accuracy in RV detection during rest, while only eight of them during exercise. The correlation between classic ECG derived HRV and the wearable RV ranged from very good to excellent during rest, yet it declined progressively as exercise level increased.

Conclusions: Wearable devices may provide a promising alternative solution for measuring RV. However, more robust studies in non-stationary conditions are needed using appropriate methodology in terms of number of subjects involved, acquisition and analysis techniques implied.

BACKGROUND

Monitoring and analysis of heart rate (HR) provide valuable information regarding health status and have been extensively investigated in various activities of healthy subjects as well as in patients suffering from various diseases.[1,2] Heart rate variability (HRV) has emerged as a non-invasive tool to estimate the vagal activity in several conditions, including monitoring of athletic responses to training. Decreased HRV has been reported as a predictive factor for adverse outcomes in disease states and has been found to be associated with fatigue, stress, and even burnout during athletic performance.[3-5] High HRV is an indication of a better general health status as it allows better adjustment to external and internal stimuli.[6]

Due to the fact that traditional HRV recording methods, such as using electrocardiography (ECG) and specialized software, often involve expensive equipment, which is primarily found in research laboratories, alternative methods have been used, yet, with variable results. Photoplethysmography (PPG) is a simple and low-cost method used to detect volumetric changes in the peripheral blood circulation at the skin surface.[7]

In recent years, several wearable pulse rate monitors using PPG technology have been developed and have become widely available. The general concept of operation of these small, robust and user-friendly devices is that they contain sensors which reliably monitor minor changes in the intensity of light from high intensity light emitting diodes (LEDs) that is transmitted through or reflected from the human tissues. Although they have obvious advantages over the classical ambulatory ECG recording, the fact that they use PPG, i.e. a different detecting approach, raises the question of how much accurate and reliable are their results when compared to the gold standard ECG method?

The purpose of this systematic review is to present the available literature comparing the ECG derived RR and HRV with that of the wearable commercially available devices in terms of accuracy and reliability as well as to reveal their strengths and limitations in the everyday clinical practice.

MATERIALS AND METHODS

Search Strategy

This systematic review was conducted by searching medical literature in MEDLINE and SCOPUS. The search was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement in conjunction with the PRISMA explanation and elaboration document.[8,9] The last search was conducted in April 2017. All the retrieved article titles and abstracts were screened for relevant manuscripts. Full texts were then retrieved for the relevant articles and these were thoroughly read to judge if they meet the inclusion criteria of the current systematic review.

Medical Subject Heading (MeSH) terms and text words were used based on the following search strategy:

Group A terms: (HRV) OR heart rate variability

Group B terms: ((((smart) OR Smartphone$) OR wearable$) OR phone$ OR plethysmography OR photoplethysmography OR impedance)

Group C terms: (((((holter) OR continuous ECG) OR continuous electrocardiogram) OR continuous electrocardiography) OR ambulatory ECG) OR ambulatory electrocardiogram OR ambulatory electrocardiography.

Group A, group B, and group C were combined and humans' studies and English language limits were applied.

We also searched the reference lists of retrieved full text review manuscripts for the relevant articles (regardless of their publishing date) and included these in our systematic review.

Well defined inclusion/exclusion criteria were applied to filter the retrieved literature. Of the articles retrieved through the above described search strategy only those that met the following criteria were considered for this systematic review:

Inclusion criteria:

Studies related to human subjects.

Studies reported in full text English language.

Studies related to HRV. Studies on HRV detection and/or analysis and/or interpretation and/or filtering were included.

Studies that compare ECG/Holter recordings of HRV with any other wearable HRV detection and capture method(s) were included.

Original papers were only included; however, reference lists from other kind of manuscripts were used to retrieve any relevant original studies.

Exclusion criteria:

Studies that did not include HRV were excluded.

Studies that did not use commercially available wearable hardware were excluded.

In addition, we performed Google search for wearable devices which claimed that they can measure HRV via plethysmography HR and are available on the market. Our search spanned the last 5 years. The devices list **(Table 1)** was used as an additional retrograde search tool for any relevant studies through manufacturers' commercial websites.

Two of the authors (KEG and AL) independently applied the above described search strategy to retrieve and screen the articles. Any disagreements were resolved by a third author (AJG) and a final decision was made accordingly.

RESULTS

Applying the search strategy described in the methods section, we retrieved 57 articles from MEDLINE and 269 from SCOPUS. Exclusion of duplicates yielded 308 articles. Of these articles, 272 were excluded after title and abstract screening according to the predefined criteria. Thirty-six articles were selected for full text review. Full text reading resulted in exclusion of further 30 articles, which were found to be either irrelevant (n=28) or non-comparison papers (n=2). The remaining six articles were included in the study. Additionally, 12 relevant peer-reviewed articles were identified from the reference list of the reviews and from manufacturers' commercial websites and added to the study. So, 18 articles were finally included in this systematic review. The flow diagram of the selection process is shown in **Fig. 1**.

Table 1. Capable to measure HRV wearable models: sensor location, release year and connectivity type

	Model	Sensor site	Company	Release Year	Connectivity
1	4IIII VIIIIVA	chest	4IIII	2013	B & A
2	60beat HR Monitor	chest	60beat	2016	B & A
3	HRM Blue	chest	BlueLeza	2016	B & A
4	Dash Earphones	ear	Bragi	2014	B
5	TP3	chest	Cardiosport	2015	B & A
6	Hexoskin	torso	Carre Technologies	2014	B & USB
7	Empatica E4 Wristband	wrist	Empatica	2016	B
8	R2 Smart Fitness HRM Wristband	chest	Cositea	2016	B & A
9	EQ02 LifeMonitor	chest	Equivital	2012	B, P & USB
10	Forerunner 935	wrist	Garmin	2016	B & A
11	HRM Tri	wrist	Garmin	2016	B & A
12	Premium Heart Rate Monitor	chest	Garmin	2016	B & A
13	Vívoactive HR+	wrist	Garmin	2015	B & A
14	910XT	wrist	Garmin	2016	B, P & A
15	920XT	wrist	Garmin	2016	B, P & A
16	HeartMath emWave Pro	ear	HeartMath	2015	B & A
17	Athos	torso, legs & thighs	Mad Apparel	2015	B
18	HxM Smart HR	chest	Medronic	2017	B & Gateway
19	Alpha 2	wrist	Mio	2015	B & A
20	Oxstren	hand	Oxstren	2015	B
21	H7 Heart Rate Monitor	chest	Polar	2012	B & WiFi
22	H10	chest	Polar	2016	B & WiFi
23	QardioCore	chest	Qardio	2017	B
24	SmartBand 2	wrist	Sony	2016	B
25	Smart Sensor	chest	Suunto	2017	B & A
26	Spartan Sport	wrist	Suunto	2017	B & A
27	DGYAO® Mobile HR Monitor	ear	Top Yao	2016	B
28	Tickr Heart Rate Monitor	chest	Wahoo Fitness	2015	B & A
29	Tickr X Workout Tracker	chest	Wahoo Fitness	2017	B & A
30	WHOOP Strap 2.0	wrist	Whoop	2016	B
31	Tinké Fitness & Wellness Tracker	fingers	Zensorium	2016	B & A

B: Bluetooth, A: ANT+, P: proprietary

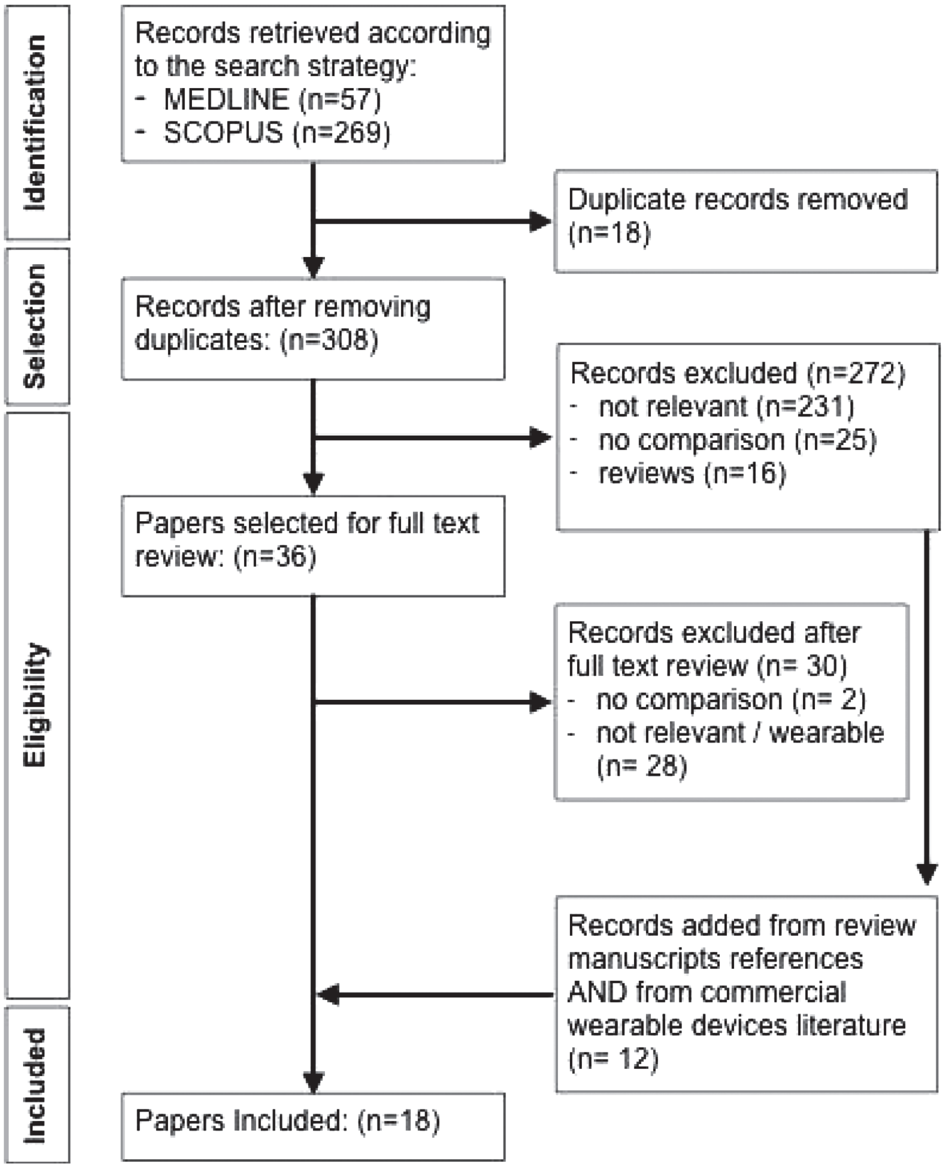

Figure 1. Flow diagram.

Table 2 summarizes the quantitative and qualitative methodology used and the categorization (measurement, position, location, sample number, technology used) as well as the main findings of the included studies.

The total number of subjects involved in the included studies was 686, with one study having 339 subjects.[10] All 18 articles have examined healthy subjects except one: Vasconcellos et al. (2015) who studied obese adolescents.[11] Also, one study examined children.[12] In most of the articles (n=16), a chest device was used,[10-25] while a finger device was used in two studies[26,27]. Sixteen of the studies utilized a similar to ECG - HRV technology[10-25] and the remaining two integrated PPG - PRV technologies[26,27].

Rest

All studies examined the HRV/PRV at rest as baseline. Overall, agreement between the several indices of HRV and PPG as measured by Holter and wearable devices, respectively, was very good to excellent (ranging from 0.85 to 0.99). The RR interval correlation ranged from 0.91 to 0.999. Moreover, in two studies,[12,15] the error rate in detection of R waves was evaluated and found to range between 0.28 and 0.4%. This was estimated as an accepted ratio. Regarding time domain indices of HRV, correlations ranged from 0.98 to 0.99, while in the frequency domain the correlation was

Table 2. Results

#	Study	Rest	Supine	Upright / Sitting	Walking / Running / Exercise	Wearable device Location	n	Wearable device Technology	Comparison	Details
1	Akintola et al., 2016	Y	Y	Y	Y	Chest (Belt)	18	ECG	Correlation depends on artifacts	Average artifact % → 19%. AMV (r: 0.967), SDNN (0.393), RMSSD (0.285), SDANN (0.680), pnn50 (0.982).
2	Esco & Flatt 2017	Y	Y	Y	N	Finger (silicone sheath)	30	PPG	Good agreement	LOA Ln RMSSD constant error ± SD: -0.13 ± 2.83 for the supine values, -0.94 ± 3.47 for the seated values, -1.37 ± 3.56 for the standing values. (r values from 0.98 to 0.99).
3	Flatt & Esco, 2013	Y	Y	N	N	Chest (Belt)	25	ECG	Total agreement	No significant difference, correlation nearly perfect for RMSSD (r: 0.99).
4	Gamelin et al, 2006	Y	Y	Y	N	Chest (Belt)	20	ECG	Good agreement	Supine vs. standing: differences for uncorrected & corrected RR coefficient correlation: 0.88 & 0.91 for supine & standing. No differences except RMS-SD, SD_1 in standing. Detection Error Rate of R waves: 0.4%.
5	Gamelin et al, 2008	Y	Y	N	N	Chest (Belt)	12	ECG	No difference	Correlation between ECG & Polar RR intervals (corrected & uncorrected) was 0.80. No significant differences for Time Domain, FFT & Poincare plot except for $SD_{2.}$ R waves detection error rate: 0.28%.

6	Giles et al, 2016	Y	Y	Y	N	Chest (Belt)	18	ECG	Accurate. Good agreement	No significant differences for SDNN, RMSSD, pNN50, VLF, LF, HF, nnLF
7	Heathers, 2013	Y	N	Y	Y	Finger (silicone sheath)	20	PPG	Good agreement at rest. Mildly reduced agreement during exercise.	Experiment 1: Close agreement – small overall bias & acceptable limits of agreement. RR & PP correlation coefficient (0.988 – 0.999). All HRV from SPRV > than ECG. Experiment 2: Close agreement between RR & PP (highest at rest, r: 0.993 – 0.997, slightly attenuated in exercise (0.965 – 0.998).
8	Hernando et al, 2016	Y	N	Y	Y	Chest (Belt)	23	ECG	As exercise increases, correlation decreases	19/23 had high correlation at rest (r> 0.8). Discrepancy increased from 1.67% (at rest) → 4.8% at the exercise peak. As exercise increases, reliability & agreement indices drop below 0.5.
9	Hong et al, 2009	N	N	N	Y	Chest (Bioshirt)	18	ECG	As exercise increases, correlation decreases (artefacts)	Coefficient correlation of HRV (r^2: 0.965 or higher), HF, LF
10	Kingsley et al, 2005	Y	N	Y	Y	Chest (Belt)	8	ECG	High agreement higher at rest. Reduced agreement at exercise.	Short relationship between RR internals during exercise. Similar results obtained for the RR internal but significant differences occurred for HRV indices.
11	Nunan et al, 2008	Y	Y	N	N	Chest (Belt)	33	ECG	Accurate / Good agreement	No significant differences for HRV indices – LOA for mean RR, LFnn, HFnn, LF/HF
12	Nunan et al, 2009	Y	Y	N	N	Chest (Belt)	33	ECG	Good agreement Not for all indicators	Correlation coefficient: 0.99, 0.86, 0.85 for mean RR, LFnn, HFnn respectfully. Near perfect correlation for SDNN, RMSSD (0.99, 0.37). Good correlation for LF (0.92), HF (0.94), LF/HF (0.87). All measures of HRV ranged from 0.85-0.99.

13	Plews et al, 2017	Y			N	Chest (Belt)	29	ECG	Acceptable agreement	Almost perfect correlation all HRV indices (RMSSD)
14	Romagnoli et al, 2014	Y	N	Y	Y	Chest (Vest)	12	ECG	Good agreement for RR / unequal results for HRV.	Mean RR, SDNN & SD_2, excellent LOA. RMSSD, HF, LF/HF, HF & SD_1 worst LOA.
15	Vanderlei et al, 2008	Y	N	Y	Y	Chest (Belt)	15	ECG	As exercise increases, correlation decreases.	HRV indices assessed: PNN50, RMSSD, LFnu, HFnu, LF/HF.
16	Vasconcellos et al, 2015	Y	Y		N	Chest (Belt)	14	ECG	Very good correlation	Moderate to strong agreement (0.68-0.98) for HR, RR, pNN50, rMSSD, LF, HF, LF/HF. In general moderate agreement for frequencies domain measures.
17	Wallen et al, 2012	Y	Y	N	N	Chest (Belt)	339	ECG	Good to excellent agreement	328 subjects. Gender & age dependent: females especially > 60 yrs old present reduced correlation). ICC coefficients ↓ in women than men → more pronounced in SDNN.HRV from Polar → Gender + Age dependent. ICC > 0.8 on all HRV parameters among men. Agreement moderate on all HRV among men.
18	Weippert et al, 2010	Y	Y	N	Y	Chest (Belt)	19	ECG	Limited agreement	Good correlation (narrow LOA & small bias). ICC for HRV frequencies were high, however in most cases LOA showed unacceptable discrepancies.

LOA: level of agreement

found to range from 0.85 to 0.94. Finally, in the non-linear multivariate analysis, the correlation was found to be > 0.9.

Exercise

Eight out of the 18 examined studies used an exercise protocol, with a total of 131 participants. All of them reported that although there was an excellent correlation between HRV and PPG as measured by Holter and wearable devices at rest, this seemed to decrease up to 0.85 as the level of exercise and/or motion increased. Overall, RR agreement was moderate to excellent ranging from 0.786 to 1. Regarding time domain, HRV parameters correlation was found to range from 0.786 (at the exercise peak) to 1 (rest and exercise 1st phase). Similar pattern occurred in the frequency domain HRV parameters where the correlation was found to range from 0.8 to 1. Also, RR to pulse pressure (PP) wave correlation was ranging from 0.8 to 0.998.

DISCUSSION

In recent years, technology advances have been used to capture HRV through wearable devices during daily activities. The accuracy of these devices versus classical methods like ECG is still under evaluation.

This systematic review aims to present the available relevant literature and discuss their findings, their limitations as well as to provide possible explanations for these findings.

It is important to realize that the basic difference between PPG and ECG is the captured signal per se: the electrical activity of the heart is depicted by ECG, whereas the PPG is a mechanical signal measuring the propagation of the peripheral pulse wave. Therefore, the time of propagation of the PP wave from the heart to the distal arterioles is called pulse transit time (PTT). It is a measure of the time that elapsed between the R-wave of QRS complex in the ECG and the arrival point to PPG device.[28] Several studies have shown that PTT seems to be a surrogate marker of ANS in parallel to HRV[29] and that PTT is dependent on the properties of the pulse wave velocity, the vascular path from the heart to the location of the detector and is negatively correlated with blood pressure, arterial stiffness and age.[7]

Therefore, we will discuss HRV and PPG fundamentals as well as the factors affecting them in order to elaborate PPG versus ECG for HRV measurement.

HRV fundamentals

HRV analysis is a widely available and accurate non-invasive technique used as a quantitative assessment tool of the autonomic nervous system (ANS) function.[30] Studies have shown that reduced HRV indices, as assessed by the RR interval analysis, is associated with increased cardiovascular morbidity and mortality in patients with various diseases as well as in the general population.[31] In addition, heart rate and HRV analysis have been used for estimation of mental stress and athlete's fitness levels, fatigue and overload.[5]

The quantification of ANS function is feasible by calculating several HRV parameters according to time-domain, frequency-domain and nonlinear analysis of consecutive RR intervals.[1] These indices represent different components of the sympathetic and/or parasympathetic system of the ANS. For instance, the high frequency (HF) component derived by the frequency domain analysis represents the parasympathetic activity, while the LF/HF ratio represents the balance of sympathetic to parasympathetic activity.[32]

However, it is important to realize that these HRV indices depends on the recording quality, the subject's activity during the recording, the exclusion of artifacts, the detection of arrhythmic beats and the recording duration ranging from seconds (short term HRV) to even days (long term). Some of these indices, like the root mean square of standard deviation (RMSSD) of RR interval can be calculated from a 10-second session while others need more than one-hour recording time.[33]

Despite being accepted as gold standard methods for RR interval monitoring and analysis, both the classical ECG and the ambulatory Holter monitoring have several drawbacks regarding the proper and accurate detection of RR intervals. For example, patients with tremor or elderly patients with fragile skin have bad quality of recordings with a lot of noise and artifacts.[34] Similarly, other factors such as surface electromyography, increased electrode impedance, respiration induced baseline drift, and electrode contact movement can cause noise and motion artifacts.[7] Additionally, morphological variations in the ECG waveform and heterogeneity in the QRS complex can often make difficult to identify the RR interval.[35] Another limitation can be the need for the presence of a specialized technician/doctor, thus increasing the cost and accordingly decreasing the wide applicability. Finally, a reported drawback in ECG wearable devices that do not record standard ECG derivations is their inability to distinguish some arrhythmias and ectopic beats.[10]

PPG fundamentals

Photoplethysmography (PPG), a cheap, simple and widespread technology has been used as an alternative approach to obtain HRV indices.[7] The PPG based devices have a sensor that uses infrared emitter and a detector. This emitter is integrated to a probe which is comfortable to wear in stable places of the body that are rich in microcirculation. Thus, the blood volume changes in the microvascular bed which are synchronous to the heartbeat can be traced without the inconveniences of electrode installation or the need to undress the examinee.[1] The simplicity of the technique, cost-effectiveness, easy signal acquisition and remote monitoring are the main and obvious advantages of the PPG versus the gold standard ECG. Therefore, PPG is often used in conditions of measurements where mobility, simplicity, time efficiency, flexibility and low cost are of paramount importance, e.g., in exercise monitoring, every day motion, monitoring of the elderly, or with disabled patients, etc.[7,36]

In the relevant literature of the wearable PPG devices the terms 'heart rate' and 'pulse rate' are frequently used interchangeably. Also, the term 'pulse rate variability' (PRV), which is derived from PPG, has been suggested as a potential analog of HRV.[37,38]

As PRV is further processed identically to HRV, the derived parameters can be extracted from both methods such as the standard deviation of normal to normal (SDNN) R–R intervals (NN), root mean square of successive differences between adjacent NN intervals (RMSSD), proportion of NN50 in total NN intervals (pNN50), low frequency (LF) power, high frequency (HF) power and LF/ HF ratio (LF/HF).

Recently, latest technology smart phones applications with wearable devices[26,27] use PPG for assessing HRV as an alternative to ECG monitoring in clinical research. More information is available in **Table 2**.

Wavelength used

PPG uses low intensity infrared or green light, which are more strongly absorbed by the blood than the surrounding tissues. It has been shown that 530 nm light (green) PPG showed higher accuracy of pulse rate detection than the 645 (red) and 470 (blue) nm light for monitoring HR.[39]

Measurement site

A flat skin surface with rich microvasculature is required to firmly attach the PPG sensor to obtain an accurate measurement. As such, the usual measurement sites for wearable PPGs are the wrist and the chest. Most of the wearable devices are placed on the wrist and considerably fewer of them on the chest.

However, it is worth noting that there is also a bunch of quasi-wearable devices attached to either the ear lobe or the finger which compared HRV to PRV parameters.

The ear is chosen as a measuring site because it is a natural anchoring point, and it is discrete since the device can be partially hidden by hair. Weinschenk et al.[28] compared PPG to ECG HRV measurements in deep breathing test in 343 female subjects in resting conditions and using appropriate parameters they found an excellent correlation. Finger tips have also been used as a measuring site but only in stationary conditions: it has been shown that HRV derived from fingertip PPG had an excellent correlation to ECG in stationary conditions.[38] However, a comparative study of finger derived PRV and HRV in healthy subjects[40] using a stationary equipment found a poor correlation and suggested that finger derived PRV might not be suitable to substitute ECG derived HRV, as has been mentioned by other authors, too[41].

The use of a smart phone camera as PPG sensor can provide an acceptable agreement for some HRV indices when compared with ECG,[22] but there are increasing differences in HRV and HR detection in the setting of movements or exercise[42]. This is because the application algorithm is cancelled in the filtering process of inaccurate signals as well as due to the difficulty of stabilizing the fingertip on the camera while exercising.

Parameters involved in PPG measurements

Several parameters have to be considered when interpreting PPG measurements. These include:

1. *Motion artifact*: Special attention must be exercised during data PPG acquisition to eliminate motion-induced artifacts.[7] The contact force between the site and the sensor should be considered as PPG is vulnerable to such type of artifacts. However, despite the importance of this factor, we found only one study in 16 male ischemic patients measuring the accuracy of a smart phone derived pulse rate versus ECG, where an excellent correlation was found at rest, which was slightly deteriorated during exercise.[42]

2. *Respiration*: Since respiration alters the intrathoracic pressure and causes blood flow variations

in both the veins the DC component of the PPG waveform shows minor changes with respiration.[43] Thus, it has been shown that the short-term variability (RMSSD, SD1, and HF) and LF/HF agreement between PRV and HRV deteriorates as a result of the vulnerability to respiratory changes.[44]

3. Age, gender and environmental factors: Normal HRV values for various age and gender groups are still not available in the literature. However, it is well known that the elderly have increased arterial stiffness which leads to faster pulse transmission in the periphery and thus pulse transit time (PTT) differences observed between HRV and PRV could be attributed to aging.[45] The reviewed articles, except one,[23] involved young population (mean range from 20.9 to 39.2 years).

Regarding gender influence, in our review, just one study showed that measuring HRV at rest was age and gender dependent, the correlation with ECG being lower in women than men and further decreasing in older women.[10] As there is no strong evidence provided so far that age and/or gender can play a role in the studied correlations, further studies are needed to investigate these two variables in different populations while using appropriate sampling and prospective study design with a longitudinal follow-up.[28]

Environmental factor effects such as temperature was investigated in one of the studies. This study concluded that ambient temperature could induce a difference in the short-term variables that reflect the parasympathetic activity between HRV and PRV.[38]

4. Software analysis: Some proprietary software systems for collection and analysis of RV data exist like the PPT5 or the Ithlete™ software application[14,26,27] or freely available software may be used e.g. Kubios (http://www.kubios.com)[46]. According to guidelines[2], manual editing should be preferred instead of automated data analysis as automatic filters are known to be unreliable and may potentially introduce errors. In our review only six studies used automated analysis only whether the rest used both manual and automated analysis.

5. *Statistical analysis*: The Bland-Altman plot must be used to compare the agreement among a new measurement technique with a gold standard, as even a gold standard does not imply to be without error. This plot allows the identification of any systematic difference between the measurements.[47]

In our review only 17 studies used this technique while four studies did not apply the Bland-Altman analysis and therefore only the correlation, but not agreement between the two methods, could be determined from these publications.

6. Sampling rate: The sampling rate is a matter of difference between the two approaches. Sampling rate of PPG is usually 20 Hz much less than that of ECG which is 125 to 250 Hz. This obviously implies weaker ability of the PPG devices for events detection.[36]

Comparison of PPG vs. ECG for HRV measurement

There are several studies examining the correlation between HRV and PRV with inconclusive results.[40] This may be due to different experimental settings or to the absence of standardization of the methods of analysis used.[44] It is worth noting that the disagreement between the two methods does not apply to the same extent to all HRV parameters. Additionally, PPG is susceptible to motion artifacts. As such, the accuracy of PRV as obtained from PPG should be interpreted with caution.[36]

Rest

Our search revealed that the comparison studies performed in stationary conditions have generally revealed that PRV is a good surrogate of HRV. This is in line with other studies not involving wearable devices, which also found an acceptable agreement between HRV and PRV at sitting and resting positions.[48]

PRV becomes stronger at a standing than at a supine position, as it reflects the mechanical coupling between respiration and thoracic vasculature tone. Therefore, when a subject changes his/her position from supine to upright, even in resting conditions, a PRV divergence from HRV becomes apparent. Additionally, HRV indices derived from PPG data are very sensitive to different factors including noise, artifacts, stature, atherosclerosis, location of sensor and sampling rate. It is probably due to these reasons that some studies comparing the two methods found differences among normal healthy subjects[7,36,45] as well as in patients[40].

Exercise

There are many non-stationary situations where autonomic balance significantly changes like in stress, during motion or exercise. Unfortunately, in such situations where PRV would be more useful as a surrogate measurement of HRV, its clinical value is questionable: a moderate agreement was observed in some studies about the factors affecting the measurements when the subject is exercising or having mental stress i.e. increased noise production, contraction of muscles which are in contact with the sensors, sweating, increased intrathoracic pressure altering the venous return, increased peripheral vasoconstriction and the respiratory effort during exercise.

RR interval variables of Bioshirt ECG were compared to those from conventional ECG and found that R-peak detecting capabilities of these two devices were largely similar. However, as the level of exercise was increasing, the correlation was decreasing due to artifact production. It must also be noted that a disadvantage of chest band wearable devices during intense exercise is the discomfort that a subject senses as the chest expands with deep breathing.[18]

Hernando et al. (2016)[17] observed that although an agreement between the detected R-peaks and the RR intervals from the Polar wearable and ECG existed, as the exercise intensity level was increased, the discrepancy of the RR pairs Bland-Altman plot also increased. They noticed a good correlation in some but not in all of the HRV indices, due to the disagreement of the relative error of the Polar derived high frequency with that of the ECG, as the level of the exercise increases.[17]

Akintola et al. (2016) used a chest wearable device detecting ECG and HRV and reported enormous amount of artifacts during daily activities in 18 healthy subjects and they concluded that this is a limitation of the wearable device used.[13]

In agreement with all of the above, another study showed that the limits of agreement were deteriorating as the exercise was intensified, implying an influence of adrenergic input, respiratory effort and unreliable algorithm detection and recording RR ability.[19]

In contrast to the many negative results reported during intense exercise, there are other researchers who reported an overall stronger agreement.[49] Also, some other research groups reported that PPG yielded higher HRV values.[36] However, all these studies involved only a sample size of few subjects.

Unfortunately, most of the findings from our review showed that the correlation was fading out as the level of exercise and/ or motion increases. Furthermore, the data from the reviewed studies are not able to support an in-depth quantitative analysis due to the differences in their methodology.

Future directions

As wearable healthcare technology and the research of light propagation in human tissues are progressing, it is expected that PPG applications will expand. For instance, there is a growing interest to remotely depict PPG through imaging such as contactless video-photoplethysmography (vPPG)[50] or imaging PPG (IPPG)[51].

It is essential to develop advanced wearable devices with higher accuracy, to minimize motion artifacts as well as improved algorithms to better detect and identify errors that may occur during exercise and higher intensity motion.

Additionally, as the availability of wearable devices is expanding, more research is obviously warranted to establish age- and sex-dependent normal PRV values as well as to standardize both acquisition protocols and analytical methods in order to get reliable and accurate results, thus permitting these methods to become a valid surrogate for HRV parameters.

CONCLUSION

Our systematic review revealed that wearable devices, especially those using PPG, may provide a promising alternative solution for measuring HRV. However, it is evident that more robust studies in non-stationary conditions are needed with appropriate methodology in terms of number of subjects involved, acquisition and analysis techniques implied, before being able to recommend any of the commercially available devices. Therefore, so far wearable devices can only be used as a surrogate for HRV at resting or mild exercise conditions, as their accuracy fades out with increasing exercise load.

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Возможности переносных приборов для точного измерения вариабельности сердечного ритма. Систематическое обозрение

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Введение: Утверждается, что всё большее количество переносных приборов обеспечивает установление точных, недорогих и легко применимых показателей вариабельности сердечного ритма (ВСР). В основном это обеспечивается приборами переносной фотоплетизмографии (ФПГ) и/или электрокардиографии (ЭКГ) с помощью простых и неинвазивных методов в качестве заместителей золотого стандарта оценки интервала RR с помощью электрокардиограммы. Хотя соответствие между вариабельностью частоты пульса (ВЧП) и ВСР было исследовано в литературе, полученные результаты по-прежнему неубедительны, особенно в отношении использования переносных устройств.

Цель: Целью настоящего систематического обозрения является установление возможностей переносных приборов обеспечивать надёжное и точное измерение классических параметров ВСР как в состоянии покоя, так и во время физической нагрузки.

Материалы и методы: Была использована стратегия сбора данных для нахождения соответствующих статей в базах данных MEDLINE и SCOPUS, а также в Интернете. Найденные 308 статей были рассмотрены для дальнейшей оценки в соответствии с заранее определёнными критериями включения / исключения.

Результаты: Восемнадцать исследований были включены. В шестнадцати из них применялась технология ЭКГ – ВСР, а в двух из них - технология ФПГ – ВЧП. Все они исследовали точность переносных приборов при измерении СР во время отдыха, а только восемь из них во время физической нагрузки. Корреляция между классической ВСР, полученной от ЭКГ, и переносной ВСР варьировалась от очень хорошей до превосходной во время отдыха, но она постепенно снижалась по мере увеличения нагрузки.

Заключение: Переносные приборы могут обеспечить альтернативное решение для измерения ВСР. Тем не менее, необходимы более надёжные исследования в нестационарных условиях с использованием соответствующей методологии в отношении количества участвующих в исследовании субъектов, использованных методов измерения и анализа.