INSTITUTE OF PHYSICS PUBLISHING PHYSIOLOGICAL MEASUREMENT

Physiol. Meas. 26 (2005) 979–986 doi:10.1088/0967-3334/26/6/008

Heart rate variability: comparison among devices with different temporal resolutions

P J Chellakumar, A Brumfield, K Kunderu and A W Schopper

Engineering and Control Technology Branch, National Institute for Occupational Safety and Health, 1095 Willowdale Road, M/S 2027, Morgantown, WV 26505, USA

E-mail: pic2@cdc.gov

Received 26 May 2005, accepted for publication 7 September 2005
Published 17 October 2005
Online at stacks.iop.org/PM/26/979

Abstract

Several devices based on ECG can acquire beat-to-beat intervals, and some of these devices may be used for heart rate variability (HRV) analysis. Most of these devices and their methods to acquire the beat-to-beat intervals need to be validated for HRV analysis by comparing them against traditional methods. Some of these methods have low temporal resolution, which may be sufficient for certain studies. HRV analysis parameters obtained from two methods differing in temporal resolution were compared to the HRV analysis parameters obtained from a referent method (ECG). One of the methods had a high resolution (<1 ms) and the other method had a low resolution (10 ms). Seven healthy male volunteers participated in the study. The beat-to-beat intervals were collected simultaneously from the three methods and the HRV parameters derived from them were used for our comparisons. The Pearson product–moment correlations were used, which demonstrated an excellent correlation ($r > 0.99$) in time domain, frequency domain and some non-linear HRV measures. The HRV measures were further analyzed using the one-way repeated-measures analysis of variance (ANOVA) and statistically significant differences were observed in some of the HRV parameters obtained from the low-resolution method, especially the mean RR ($p < 0.001$) and the mean heart rate ($p < 0.001$). Since the same software was used for HRV analysis of the three methods, any differences were due to the temporal resolution of the RR intervals measured by the methods. Overall, both the methods correlated very well with the referent method among healthy volunteers in resting conditions and may be used by researchers for HRV studies.

Keywords: heart rate variability, short-term recordings, resolution, time-domain, frequency domain, non-linear analysis, temporal resolution, ECG, armband, chestbelt, HRV analysis software, approximate entropy, sampling rate, Poincare plots, telemetry and HRV devices

0967-3334/05/060979+08$30.00

Introduction

The variations in the intervals between heart beats have been shown to be a valuable marker of the autonomic nervous system activity (Cowan 1995). These variations, also known as heart rate variability (HRV), may offer powerful tools to evaluate relationships between psychological and physiological processes (Berntson *et al* 1997). An appreciation of the history and methods related to HRV may be obtained from the same paper. HRV has been used clinically and in research to assess the prognosis of different pathologies such as myocardial dysfunction, diabetes and arrhythmias (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). Other studies have used HRV as measures of mental activity and mental stress (Bernardi *et al* 2000, Wood *et al* 2002). Holter monitors or computerized electrocardiographs with commercial or special software have been used in the past for HRV analysis but recently other devices mainly based on ECG have been developed for acquiring beat-to-beat intervals. These devices show considerable promise for heart rate variability studies. Some of these devices along with the methods to acquire beat-to-beat intervals have been validated by researchers against traditional methods, to ensure their accuracy and usefulness for HRV analysis (Redespiel-Tröger *et al* 2003, Sandercock *et al* 2004, Kingsley *et al* 2005). Because of their ease-of-use and lower costs, several of these methods are of interest to the research community. We compare two methods using ECG-based telemetry devices, Polar® chestbelt and Bodymedia® armband, to our 'gold standard' method, via the Biopac® ECG system. Time domain, frequency domain, non-linear and approximate entropy analysis were used for our comparisons.

Methods

Study population

Seven healthy male subjects (age = 23.5 (mean) ± 4.5 (SD) years; height = 1.77 ± 0.1 m; weight = 74.7 ± 10.7 kg) volunteered to participate in this study. They received a modest, fixed reimbursement for their participation. The subjects were asked to abstain from alcohol and caffeine for 2 h prior to the start of the study. The test procedures, along with potential risks, were explained and a signed written informed consent was obtained from each subject prior to the start of every test session. The protocol for this study was approved by the Human Subjects Review Board (HSRB) of the National Institute for Occupational Safety and Health (NIOSH).

Study protocol

Subjects were acclimated in a dark, ambient environment for 15 min and subsequently the data were collected simultaneously from the three methods for another 15 min. The subjects were instructed to sit and remain stationary for the duration of the test. Sound-attenuating headphones were worn to minimize interference from the external environment.

Instrumentation

A three-lead system (BIOPAC Systems Inc., CA) was used to acquire the ECG signal. It was sampled at 1000 Hz (Hejjel and Roth 2004) by a 16-bit A/D converter, NI DAQCard-6036E (National Instruments, TX). The ECG data were stored in an uncompressed text file. RR intervals were calculated from the text file using AcqKnowledge software (BIOPAC Systems Inc., CA). This method is referred to as the ECG method and has a temporal resolution of 1 ms.

Additionally, the subjects wore a Polar® T31 chestbelt transmitter (Polar Electro Inc., Kempele, Finland) from which electromagnetic pulses were digitized by a Polar® receiver unit placed directly in front of the subject. A 32-bit counter card, PCI-6602 (National Instruments, TX), running at 80 MHz, was used to collect the pulse data. Custom software written in LabVIEW (National Instruments, TX) was used to derive the RR time intervals from the pulses. This method is referred to as the Chestbelt–Counter method and has a temporal resolution of 0.0125 μs. To investigate the differences in HRV measurements associated with the use of a lower resolution device, a SenseWear PRO™ armband (Bodymedia Inc., PA), with its own receiver, was used. The armband also uses the signals from the T31 chestbelt transmitter. The armband then calculated the RR intervals using its own free-running 8 kHz timer-based counter. This method is referred to as the Chestbelt–Armband method and has a temporal resolution of 10 ms.

HRV analysis

A 5 min window of data, devoid of movement artifacts, was selected based on visual inspection. The data within this timeframe for each of the three methods were used for analysis. Analysis methods, including time-domain, frequency-domain and non-linear methods, were accomplished using HRV analysis software, Biosignal Analysis and Medical Imaging Group (Niskanen *et al* 2004). Time-domain measures included measures of the mean of RR intervals (mean RR), the standard deviation of normal RR intervals (SDNN), the mean heart rate (mean HR), the root-mean-square of differences of successive RR intervals (RMSSD) and the percentage value of consecutive RR intervals that differ by more than 50 ms (pNN50). Frequency analysis provided low-frequency (LF) and high-frequency (HF) parameters including LF peak, HF peak, LF power, HF power and the ratio of LF to HF band powers. As recommended elsewhere (Bernston *et al* 1997), the frequency bands for LF and HF were 0.04–0.15 Hz and 0.15–0.4 Hz, respectively. Since RR series are irregularly time sampled, cubic interpolation at 4 Hz was used by the HRV analysis software for frequency analysis. Detrending of the RR series was accomplished using the smoothness priors method (Tarvainen *et al* 2002). For non-linear analysis, Poincare plots and approximate entropy were used (Woo *et al* 1992). Two limitations need to be noted on Poincare plots; geometric methods are suggested for at least several 10 min long records, and SD1 and SD2 parameters do not bring the non-linear features as proved in Brennan *et al* (2001). The short-term approximate entropy also should be treated carefully.

Approximate entropy

The fast algorithm for the approximate entropy (ApEn) calculations (Yang *et al* 2001) was implemented on the selected 5 min segments of beat-to-beat intervals using a custom LabVIEW (National Instruments, TX) software. The data were normalized by subtracting the mean and dividing by the standard deviation. The embedding dimension, $m = 2$, and the threshold, $r = 0.2$, were used in all computations.

Statistical analysis

RR data obtained from the same 5 min window of the ECG, Chestbelt–Counter and Chestbelt–Armband methods related to each subject were analyzed using HRV analysis software (Niskanen *et al* 2004). The HRV parameters associated with short-term recordings, as recommended elsewhere (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996), were selected and used

Table 1. Statistical comparison of the time domain, frequency domain, non-linear and approximate entropy values derived from the ECG, Chestbelt–Counter and Chestbelt–Armband methods. The explanation for the parameters can be found in the methods section.

	Mean (SD) ($n = 7$)			
Parameter	ECG	Chestbelt–Counter	Chestbelt–Armband	Median SD[a]
Time domain				
Mean RR (ms)[b]	842.3 (150.3)	842.2 (150.3)	837.3 (150.3)	2.90
SDNN (ms)	55.4 (23.9)	55.3 (23.9)	55.5 (23.9)	0.15
Mean HR (bpm)[b]	73.58 (11.84)	73.59 (11.84)	74.05 (11.99)	0.28
RMSSD (ms)	46.0 (29.1)	45.7 (29.0)	46.0 (28.8)	0.28
pNN50 (%)	22.6 (24.1)	22.4 (24.0)	22.4 (23.7)	0.36
Frequency domain				
LF peak (ms^2)	899.8 (691.6)	899.5 (691.9)	894.1 (684.5)	3.30
LF power (nu)	69.1 (15.8)	69.3 (15.9)	69.0 (15.7)	0.36
HF peak (ms^2)	533.2 (651.3)	528.2 (652.5)	530.0 (649.6)	2.61
HF power (nu)	30.9 (15.8)	30.7 (15.9)	31.0 (15.7)	0.36
LF/HF	3.2 (2.3)	3.2 (2.4)	3.1 (2.2)	0.06
Non-linear Poincare plot				
SD1 (ms)	32.7 (20.7)	32.5 (20.6)	32.7 (20.5)	0.23
SD2 (ms)[c]	92.7 (42.0)	92.6 (42.0)	92.8 (41.9)	0.12
Approximate entropy				
ApEn[d]	1.07 (0.10)	1.07 (0.10)	0.99 (0.09)	0.05

[a] Median value of the within-subject standard deviations evidenced for each parameter across the three methods.
[b] $p < 0.001$.
[c] $p = 0.027$.
[d] $p < 0.005$.

for statistical analysis. The differences among the three methods were evaluated for the data via the use of a one-way repeated-measures analysis of variance (ANOVA). The more conservative Greenhouse–Geisser value was used in place of the traditional F-test when sphericity assumptions could not be met. The Bonferroni procedure was used in performing all *post hoc* analyses when a significant ANOVA effect ($p < 0.05$) was evidenced.

Results

Table 1 provides the mean values for each of the HRV parameters obtained from each of the methods along with the between-subject variability that was evidenced, expressed as the standard deviation. To provide some appreciation of variability between the methods, table 1 also provides the median value of the within-subject standard deviations evidenced for each parameter across the three methods.

None of the frequency-domain HRV parameters considered yielded any statistically significant effect between the three methods. Among the 13 parameters considered, there were four parameters for which the ANOVA yielded a statistically significant effect ($p < 0.05$): mean RR and mean HR at $p < 0.001$, ApEn at $p < 0.005$ and SD2 at $p = 0.027$. The *post hoc* analyses performed revealed that there were no statistically significant differences between the mean values for the referent ECG-based values and any of those derived from the Chestbelt–Counter method. With the exception of the SD2 finding, the parameters' mean RR, mean HR and ApEn derived from the Chestbelt–Armband method were significantly lower than those of the referent ECG values. As related to the relatively less-pronounced SD2

finding ($p = 0.027$), the *post hoc* analyses revealed that neither the Chestbelt–Counter method value nor the Chestbelt–Armband value differed significantly from the ECG values; however, the armband value was indicated to be suggestively higher ($p = 0.062$) than the Polar value.

Pearson product–moment correlations were also computed to assess the degree of correspondence between each pair of instruments for each parameter. In all instances, the correlations are high (generally $r > 0.99$) indicating that data obtained from the two methods correlate well with the ECG and with each other.

Discussion

Resolution

One particular concern at the beginning of this study was the potential impact of the differences in resolution, among the three methods, on the HRV measures. The Chestbelt–Counter method, which used a counter and an 80 MHz clock, had the highest resolution at 0.0125 μs. The ECG system was sampled at 1000 Hz and had a resolution of 1 ms. Although the armband receiver had a 0.125 ms resolution, it truncated each RR interval value internally for bandwidth reasons, giving a resolution of 10 ms. Thus, the Chestbelt–Armband method had the least resolution among the three methods. The differences in resolution did not show any significant statistical difference in most of the HRV parameters for the three methods. These resolution differences were more apparent in Poincare plots' analysis and can be inferred from the plots (figure 1). The Poincare plot for HRV provides a visual assessment of beat-to-beat variability and is obtained by graphing each RR interval against subsequent RR interval as explained in Woo *et al* (1992).

The Poincare plots showed considerably less distinct points for the Chestbelt–Armband method compared to the ECG method which in turn showed lesser distinct points than the Chestbelt–Counter method. This is a direct result of the resolution of the methods. For example, if one RR interval shows up as 700 ms and the subsequent RR intervals show up as 708 ms and 705 ms in the ECG method, these RR intervals will be truncated in the armband and all three of them will show up as 700 ms in the Chestbelt–Armband method. This results in considerably less distinct points in the Poincare plots for the Chestbelt–Armband method. The short-term heart rate variability parameter, SD1, calculated from Poincare plots evidenced no statistical significant differences among the devices, whereas the long-term heart rate variability parameter, SD2, evidenced some difference for the armband (Brennan *et al* 2001). The SD2 parameter represents long-term variability and is not pertinent to short-term recordings.

Movement artifacts and skin preparation

The ECG system is sensitive to movement which resulted in the need to search the 15 min dataset to find a 5 min window, devoid of movement artifacts and noise. The electrode areas in the subject's body needed to be devoid of hair, and these areas had to be cleaned with abrasive pads before application of electrodes to ensure good contact. Minute movements were not much of an issue with the chestbelt or the armband since they fit quite snugly to the subject by means of elastic straps. The snug fit of the chestbelt and the armband ensured good contact with the subject's skin throughout the test session.

Window selection

Given the different temporal resolutions of the methods, acquiring the same 5 min window from the RR data files for the three methods was of concern. The Polar–Counter method and

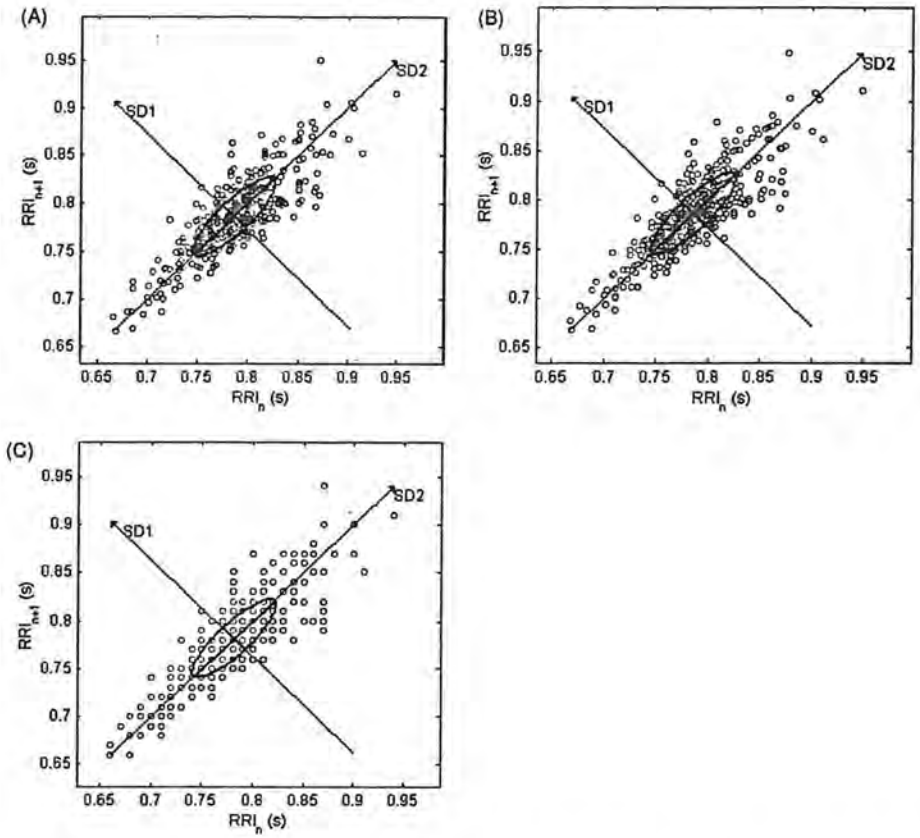

Figure 1. Poincare plots of a 5 min window of data for (A) ECG, (B) Chestbelt–Counter and (C) Chestbelt–Armband methods of one test subject. It is observed from the plots that there are considerably less distinct points for the Chestbelt–Armband method.

(This figure is in colour only in the electronic version)

the ECG method used computers, which enabled remote control of the computers from the server. The computers were simultaneously started and stopped after 15 min from the server. The armband is an independent standalone system and hence event markers, made possible by subjects pressing a button on the armband, were used to mark the beginning and end of the test session. Although the data windows appeared to be identical in the HRV software, closer scrutiny revealed the presence of slight offsets. The Chestbelt–Counter method also had a minor window offset but this was due to its higher resolution. For example, setting the window between 150 and 450 s and starting with the first RR after 150 s could have an offset if the ECG's first RR was at 150.000 s, while the same pulse registered at 149.9998 s on the Chestbelt–Counter system. Therefore, the window for the Chestbelt–Counter method would start with the next pulse to follow and the window would not be the same as in the ECG method. To avoid these errors, the window of the RR files for Chestbelt–Counter and Chestbelt–Armband had to be realigned to the ECG using custom software before running HRV analysis. This ensured that both the HRV analysis and statistical analysis were free from

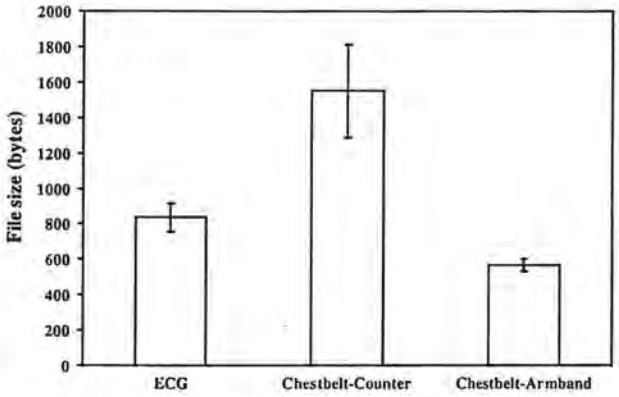

Figure 2. Results obtained from Lempel–Ziev compression of 5 min RR interval series files from the three methods for one test subject. It is observed that compressed files from the Chestbelt–Counter method have the least compression, followed by the ECG method and then the Chestbelt–Armband method.

window-offset errors. A separate two-way, mixed, repeated-measures ANOVA was performed to determine if correcting the initially observed minor phase differences had an impact. This analysis revealed no significant main or interaction effect due to the phase correction on any of the parameters. The correction was precautionary and performed particularly because of the short data window. It confirmed that such a minor offset had no impact on a 5 min window analysis and would be of lesser concern with longer datasets.

Spectral analysis

The frequency-domain results from the Chestbelt–Counter and Chestbelt–Armband methods were exceptionally consistent with the frequency-domain results obtained from the ECG. The LF parameters, HF parameters and the LF/HF values did not indicate any statistically significant difference. This is particularly important since frequency-domain parameters are favored for short-term HRV studies (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996).

Approximate entropy and compression

The approximate entropy is a measure of randomness in a series and it has been used recently in HRV studies (Yang *et al* 2001). The results obtained from the statistical analysis of the ApEn values show that the Chestbelt–Counter method correlates more highly ($r > 0.94$) with the ECG. While the mean values between the three methods are very close and suggest that all methods could be used, the results obtained from the statistical analysis of the RR files from the Chestbelt–Armband method show that the ApEn is significantly lower ($p = 0.005$) than that from the ECG or the Chestbelt–Counter method. Again, this is a resolution difference and is appropriate because any difference between subsequent RR values less than 10 ms will be lost from the data derived from the Chestbelt–Armband method. Hence, there will be fewer unique values using the Chestbelt–Armband method than using the Chestbelt–Counter and ECG systems. The RR files for the three methods were also passed through Lempel–Ziev compression algorithm (Hamilton 2005) and the compressed Chestbelt–Armband data files

were considerably smaller in size than compressed data files from the ECG or the Chestbelt–Counter method. Interestingly, compressed Chestbelt–Counter files were the largest and may be attributed to its high resolution (figure 2).

Conclusions

Two methods of different resolution using modern ECG-based telemetry devices were evaluated for HRV studies by comparing them to the data from a referent ECG-based method. Commonly used HRV parameters were derived and the higher resolution Chestbelt–Counter method was found to be comparable to ECG for HRV studies. This method may be of interest because it is easy to use and is less sensitive to minor movements. The low-resolution method performed well in frequency-domain analysis and may be acceptable for time-domain analysis as well. Even though differences in some of the HRV parameters were observed in the low-resolution method, this method gave very good results among healthy volunteers in resting conditions in all of the analyses and may also be given appropriate consideration by researchers.

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

References

Bernardi L *et al* 2000 Effects of controlled breathing, mental activity, and mental stress with or without verbalization on heart rate variability *J. Am. Coll. Cardiol.* **35** 1462–9

Berntson G G *et al* 1997 Heart rate variability: origins, methods and interpretive caveats *Psychophysiology* **34** 623–48

Brennan M, Palaniswami M and Kamen P 2001 Do existing measures of Poincare plot geometry reflect nonlinear features of heart rate variability? *IEEE Trans. Biomed. Eng.* **48** 1342–7

Cowan M J 1995 Measurement of heart rate variability *West. J. Nurs. Res.* **17** 32–48

Hamilton J 2005 File compression *LabVIEW Tips, Tricks and Download* http://hamiltondesign-consulting.com/labuseful.html

Hejjel L and Roth E 2004 What is the adequate sampling interval of the ECG signal for heart rate variability analysis in the time domain? *Physiol. Meas.* **25** 1405–11

Kingsley M, Lewis M J and Marson R E 2005 Comparison of Polar 810s and an ambulatory ECG system for RR interval measurement during progressive exercise *Int. J. Sports Med.* **26** 39–44

Niskanen J, Tarvainen M P, Ranta-aho P O and Karjalainen P A 2004 Software for advanced HRV analysis *Comput. Methods Programs Biomed.* **76** 73–81

Redespiel-Tröger M, Rauh R, Mahlke C, Gottschalk T and Mück-Weymann M 2003 Agreement of two different methods for measurement of heart rate variability *Clin. Auton. Res.* **13** 99–102

Sandercock G R H, Shelton C, Bromley P and Brodie D A 2004 Agreement between three commercially available instruments for measuring short-term heart rate variability *Physiol. Meas.* **25** 1115–24

Tarvainen M P, Ranta-aho P O and Karjalainen P A 2002 An advanced detrending method with application to HRV analysis *IEEE Trans. Biomed. Eng.* **49** 172–5

Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996 Heart rate variability: standards of measurement, physiological interpretation, and clinical use *Eur. Heart J.* **17** 354–81

Woo M A, Stevenson W G, Moser D K, Trelease R B and Harper R M 1992 Patterns of beat-to-beat heart rate variability in advanced heart failure *Am. Heart J.* **123** 704–10

Wood R, Maraj B, Lee C M and Reyes R 2002 Short-term heart rate variability during a cognitive challenge in young and older adults *Age Ageing* **31** 131–5

Yang F, Bo H and Qingyu T 2001 Approximate entropy and its application to biosignal analysis *Nonlinear Biomedical Signal Processing: Dynamic Analysis and Modeling* vol 2 ed M Akay (New York: IEEE Press) pp 72–91