
BRIEF REPORT

Comparison of finger plethysmograph to ECG in the measurement of heart rate variability

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Abstract

Two experiments compared finger plethysmograph (FP) to electrocardiogram (ECG) in providing accurate heart periods for use in heart rate variability (HRV) calculations. In Experiment 1, simultaneous ECG and FP recordings were taken from 16 healthy subjects at rest. In Experiment 2, 10 additional healthy subjects were recorded at rest and during the Stroop Color-Word Test. In both studies, high correlations were found between FP-derived and ECG-derived band variance for high and low frequency HRV at rest. But, during the Stroop task, correlations were strongly diminished. In addition, under both conditions, HRV measures were significantly higher using the FP signal. Thus, FP may be adequate for determining HRV at rest, but, for experimental use, ECG may still be recommended. Nonetheless, further studies that include test–retest reliability assessment of both data collection techniques are warranted before a more certain determination can be made.

Descriptors: Heart rate variability, Electrocardiogram, Finger plethysmograph

Measures of heart rate variability are becoming increasingly prominent in psychophysiological research and clinical practice as an index of cardiac autonomic control. Although an electrocardiogram (ECG) is assumed to provide greater accuracy, and is thus recommended to measure cardiac interbeat intervals (Berntson et al., 1997), some researchers (e.g., James, Panerai, & Potter, 1998; Laude, Weise, Girard, & Elghozi, 1995; Omboni et al., 1993; Veerman, Imholz, Weiling, Karemaker, & van Montfrans, 1994) and many practitioners use the distal measurement of arterial pulse (e.g., finger reflectance plethysmograph) for this purpose, either implicitly or explicitly suggesting that the resulting measures are comparable to those derived from ECG.

Accurate determination of individual heart periods is the first step, and presumably essential, to the calculation of heart rate variability measures. Most agree that measurement to the nearest millisecond is optimal (Berntson et al., 1997; Task Force, 1996). Nonetheless, there are some potential obstacles to obtaining precise interbeat intervals from arterial pressure pulses, especially when measured from a distal source (e.g., fingertip). Blood pressure pulses lack the sharp peak found in the R-wave of the ECG, making precise determination of a fiducial point in these records more difficult. Also the shape and timing of the pulse waveform

may be influenced by ventricular pressure, flow rate, time period, or other parameters of cardiac output. Peripheral effects, such as changes in vascular tone, may also influence distal pulse peak detection.

In their report on the origins, measurement, and interpretation of heart rate variability, Berntson et al. (1997) note these potential pitfalls and, so, strongly advise using R-R intervals from an ECG signal to determine interbeat intervals. They do include, though, that “the use of intra-arterial pressure pulses and a sophisticated peak detection algorithm may be acceptable,” but add, “More indirect measures, such as photoplethysmograph signals or Finapres-type measures, require further validation.” (p. 631).

In this report, we present the results of two experiments in which the simultaneous measurement of ECG and finger plethysmograph was used to compare heart rate variability measures calculated from interbeat interval times series derived from each source.

EXPERIMENT 1

Method

Participants

Sixteen healthy young adults participated in Experiment 1. Their ages ranged from 23 to 35 years of age ($M = 28.1$ years, $SD = 4.4$). Nine of the participants were male and 94% were Caucasian. Participants were all nonsmokers and none had a positive history of cardiovascular disease. They were not paid for their participation.

We are grateful to Dr. J. Richard Jennings for providing us with the computer software to run the vanilla baseline and Stroop Color-Word tasks. Address reprint request to: Dr. Paul Lehrer, Department of Psychiatry, University of Medicine and Dentistry of New Jersey–Robert Wood Johnson Medical School, Piscataway, NJ 08854, USA. E-mail: lehrer@umdnj.edu.

Procedure

Participants were seated in an upright chair and asked to sit quietly and breath normally for 5 min.

Apparatus and Measures

Data were recorded with the use of a Beckman Type RM Dynograph. Electrocardiogram was recorded from a three-lead placement, amplified through an AC coupler at a time constant of 1.0. Blood pressure pulse was measured using an LED light source and cadmium sulfide photoresistor secured to the pad of the third finger of the left hand. An output from the amplified plethysmograph triggered an analog cardiometer (Beckman Coupler 9857). All signals (ECG, finger plethysmograph, and cardiometer) were acquired on-line at 1,000 samples per second and stored for further processing.

Data Reduction

Interbeat interval time series were created using three separate data sources (cardiometer, finger plethysmograph, and ECG), each at four simulated sampling rates (1,000, 100, 20, and 10 samples per second), for each 5-min epoch. For all three records, fiducial points (R-waves or pulse peaks) were detected using an idiographic peak-detection algorithm taken from Friesen et al. (1990). The maximum slope for each record was determined using the following first derivative formula calculated for each point of the sampled EKG or plethysmograph signal:

$$Y(n) = -2X(n - 2) - X(n - 1) + X(n + 1) + 2X(n + 2).$$

A slope threshold was then defined as 70% of the maximum value obtained for $Y(n)$. The signals are then searched for sequences that exceeded the slope threshold, the first point of which is taken as the peak onset.

In the first approach, each detected plethysmograph pulse peak triggered the sampling of the cardiometer level 0.2 s after the peak detection. Each sampled heart rate value was then converted to a heart period by taking its reciprocal. The second method calculated the time interval between each blood pressure pulse peak directly. The third method determined the time between successive R-wave detections from the ECG signal. Additional simulated sampling rates of 200, 20, and 10 per second were created for each subject and for each time-series derivation method (i.e., R-R interval, pulse peak interval, and cardiometer sampling) by utilizing only every 5th, 50th, and 100th stored data point for 200, 20, and 10 samples per second rate simulations, respectively. For example, extracting every 5th data point from a signal originally digitized at 1,000 samples per second is essentially the same as sampling the analog signal 200 times per second.

Further processing of IBI data was carried out using MXEDIT, a PC-based program that allows editing of data for faulty R-wave detection and calculation of band variance. Heart rate variability measures were calculated using the standard fast fourier transform (FFT) method of Berger, Akselrod, Gordon, and Cohen (1986). This method consists of first converting IBI records to an instantaneous heart rate time series, which is sampled at 4 Hz. A Hamming window is then applied and spectral analysis is performed using a standard FFT algorithm (Berger et al., 1986). A frequency range of 0.15–0.40 Hz was used for high frequency (HF) variability calculations and 0.07–0.15 Hz used for low frequency (LF) variability. A computer program that performed these functions was generously supplied by Dr. William Craelius (Craelius, Akay, & Tangella, 1992; Curcie & Craelius, 1997).

Band variances were also determined using the Porges–Bohrer method (Porges & Bohrer, 1990) for band-pass filtering of inter-beat interval time series in order to allow for greater generalization of our findings. This method applies a moving polynomial filter to remove aperiodic trends in the data set and then calculates the natural logarithm of the heart period variance within a selected frequency band. The algorithm applied band-pass frequencies of 0.15 Hz to 0.40 Hz, with 21 polynomial coefficients for high frequency, and band-pass frequencies of 0.07 to 0.15 Hz, and 51 polynomial coefficients for low frequency variability.

Date Analysis

Product-moment correlation coefficients and mean differences between ECG- and finger plethysmograph-derived heart rate variability measures were calculated. Because the use of correlations may be misleading when comparing two measurement techniques (i.e., high correlation may not mean high agreement), we plotted the difference between log-transformed HRV measures against the mean of both measures for each observation and also computed 95% limits of agreement and 95% confidence intervals for upper and lower limits of agreement (Bland & Altman, 1986).

Results

Results obtained using FFT and Porges–Bohrer calculation methods did not differ; therefore only the former will be reported. Correlations between data acquisition methods are presented in Table 1 and pictured in Figure 1. High correlations were found between plethysmograph-derived band variances and ECG-derived band variances for both high and low frequency bands, especially at higher sampling rates. However, plethysmograph-derived band variances were consistently higher than ECG-derived variances in the high frequency and, to a lesser extent, low frequency bands. Plethysmograph-derived high frequency variances were, on average, 22% higher than ECG-derived values (Table 2). The mean difference of the natural log of plethysmograph- and ECG-derived HF was 0.21 ($SD = 0.05$), with 95% limits of agreement 0.10–0.31. HF values for all but one subject fell between these limits. The 95% confidence intervals for the lower and upper limits of agreement were 0.05–0.16 and 0.26–0.36, respectively. Finally, differences between the two measures were negatively correlated

Table 1. Correlations Between Band Variances Derived from Two Methods for Sampling Finger Plethysmograph Records and a Standard ECG Interbeat Interval Detected at 1000 Hz

Heart period variance band	0.15–0.40 Hz	0.07–0.15 Hz
Cardiometer method		
Sampling rate/s		
1,000	.99	.98
200	.99	.96
20	.97	.97
10	.91	.91
Interpeak interval method		
Sampling rate/s		
1,000	.99	.99
200	.98	.97
20	.97	.98
10	.92	.90

$p < .001$ for all values.

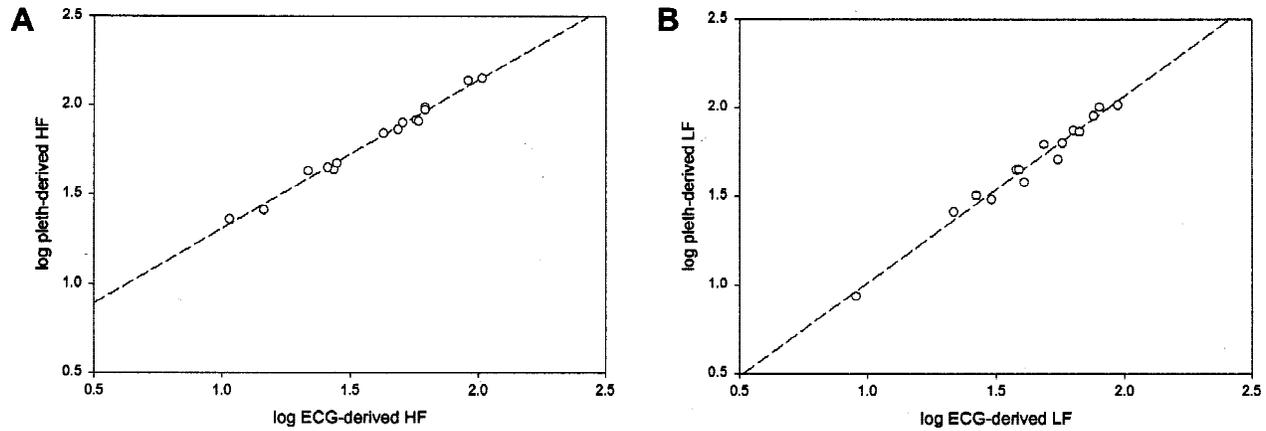


Figure 1. Scatterplots of high frequency (0.15–0.40 Hz; panel A) and low frequency (0.07–0.15 Hz; panel B) heart rate variability calculated from ECG- versus finger plethysmograph (interpeak interval)-derived interbeat interval time series in Experiment 1.

with HF values, $r = -.87$, $p < .001$. That is, discrepancies between the two measures increased as HF values decreased. Differences between ECG- and pleth-derived values versus averages of the two methods are shown in Figure 2.

Discrepancies between low frequency values were smaller, but still significant. The average difference of the natural log of plethysmograph- and ECG-derived LF was 0.04 ($SD = 0.05$), with 95% limits of agreement -0.05 – 0.14 . The 95% confidence intervals for the lower and upper limits of agreement were (-0.09) – (-0.00) and 0.09 – 0.18 , respectively. All LF values fell within the limits of agreement; measure discrepancies and LF values were not significantly correlated, $r = .38$, $p = .16$.

In an attempt to identify the source of inflation in plethysmograph-derived values, we examined the relationship between interbeat intervals from each data source and pulse transit time. It was found that differences between individual ECG- and plethysmograph-derived interbeat intervals were correlated with pulse transit time, $r = -.61$, $p < .001$, in such a way that, for values below the mean pulse transit time, R-R intervals were longer than interpulse intervals. For longer pulse transit times, the converse was true; interpulse interval times were longer than R-R intervals. For transit times around the mean, both values tended to be the same (see Figure 3A). A plot of these difference values over time suggested periodic variability in the time series, so we then subjected the difference values to a fast fourier transformation. This analysis revealed a sharp peak just below 0.20 Hz, the average respiratory frequency (Figure 3B).

Table 2. Mean Values of ECG- and Plethysmograph-Derived Heart Rate Variability in Experiment 1 (1000 Hz, Interpeak Interval Method)

	Mean (bpm ² /Hz)	SD	<i>t</i>	<i>p</i>
High frequency (0.15–0.40 Hz)				
ECG	5.11	1.36		
Plethysmograph	6.23	1.41	29.11	<.001
Low frequency (0.07–0.15 Hz)				
ECG	5.29	1.23		
Plethysmograph	5.55	1.36	3.88	.002

Conclusion

The data reported in Experiment 1 addressed the need to validate finger plethysmograph as a method for heart period determination in the measurement of heart rate variability. Correlational analysis demonstrated a very strong association between the plethysmograph-derived and ECG-derived band variances, especially at high sampling rates, supporting the adequacy of finger plethysmograph for this purpose in physically healthy subjects at rest.

However, high frequency and, to a lesser extent, low frequency heart rate variabilities were consistently higher when derived from the plethysmograph signal. Also, discrepancies between methods increased as HF values decreased. Our subsequent analyses revealed that differences between cardiac interbeat intervals calculated from each data source varied in relation to pulse transit time and also periodically, at respiratory frequencies.

EXPERIMENT 2

Most psychophysiological research is concerned with changes in heart rate variability under varying conditions. Therefore, in Experiment 2, we extended our investigation to assess ECG and plethysmograph data collection methods under conditions of experimental challenge.

Method

Participants

Ten healthy adults participated in Experiment 2. They ranged in age from 25 to 50 years ($M = 41$ years, $SD = 6.6$). Six of the participants were male and 90% were Caucasian. Participants were all nonsmokers and none had a positive history of cardiovascular disease. They were not paid for their participation.

Apparatus and Measures

Data were recorded with the use of the Flexcomp Biomonitoring System 1.5B (Thought Technology Ltd., Montreal). Electrocardiogram was recorded from a three-lead chest placement. Distal pulse was recorded, as in Experiment 1, using a photoresistor secured to the pad of the third finger of the left hand. Both signals were acquired on-line at 991 samples per second and stored for further processing.

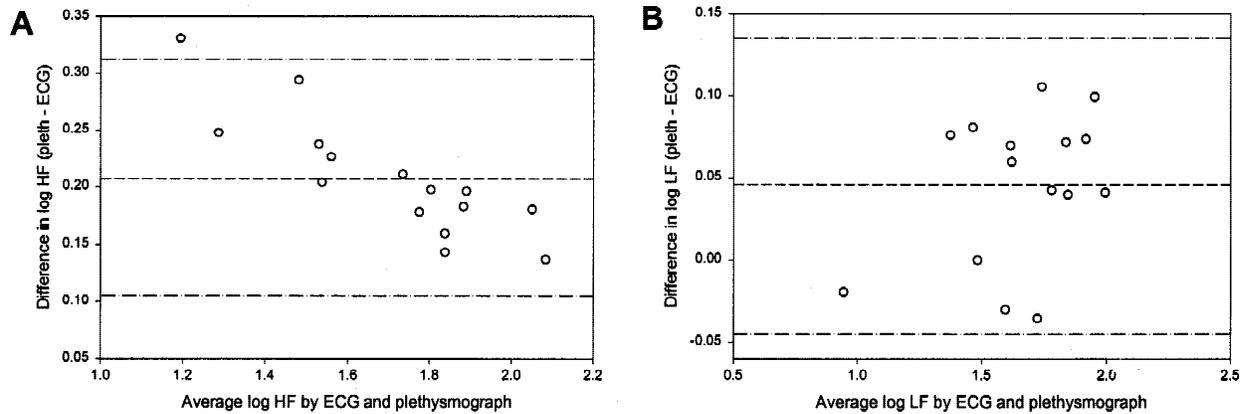


Figure 2. Experiment 1. Difference (pleth-derived – ECG-derived) versus average HF (panel A) and LF (panel B) heart rate variability measures calculated by ECG- and pleth-derived interbeat intervals. Dashed lines indicate mean of differences. Dash and dot lines demark boundaries of 95% limits of agreement.

Experimental Tasks

“Vanilla” baseline. The “vanilla” baseline task is a minimally demanding color detection task designed and shown to provide a stable baseline against which changes in response to experimental challenges can be measured (Jennings, Kamarck, Stewart, Eddy, & Johnson, 1992). Using a computer monitor, the task involves the presentation of a 10 × 12 cm rectangle that changes color every 10 s. Six colors are presented randomly and with equal probability over the course of the baseline period. Participants are told beforehand to count the number of times the object changes back to a randomly determined initial color. At the end of the task, participants are asked to report their count.

Stroop Color-Word Test. The Stroop Color-Word Test is a demanding task, designed and shown to induce psychological stress and physiological arousal (Manuck et al., 1996; Muldoon et al., 1992). The computerized version used in this study involves the successive presentation in the middle of the monitor screen of one of four color words (red, blue, green, or yellow) displayed in a color that may or may not match the name of the word (i.e., the word and the color are independently random). At the bottom of the screen all four color words are presented in random order. They also may or may not be shown in colors that match the names of the words. Subjects are told to use a keypad to select the color

word at the bottom of the screen that matches the color of the word presented in the middle of the screen. The speed of the stimulus presentations is adjusted according to each subject’s level of performance, increasing after three consecutive correct responses and decreasing after two consecutive incorrect responses.

Procedure

Participants were seated upright in a comfortable chair positioned in front of an adjustable height table, on which a computer monitor and keyboard were positioned for comfortable viewing and typing. After a brief (10 min) acclimation period, subjects performed the vanilla baseline task for 8 min, immediately followed by the Stroop Color-Word Test, also performed for 8 min.

Data Reduction

Interbeat interval time series were created as in Experiment 1, but using only R-R intervals from the ECG signal and interpeak intervals from the finger-plethysmograph record. Also, only time series derived from the full 991-Hz file were analyzed. High frequency and low frequency heart rate variabilities were calculated using the FFT method described in Experiment 1. The ratio of low frequency to high frequency variabilities was also calculated, which some authors believe to be a more “pure” measure of sympathetic activity or even “sympathovagal balance” (e.g., Pagani et al., 1986), although the logic of this tenet has been questioned (Eckberg, 1997). This ratio was included, however, for the purpose of comparison with many other studies.

Results

As in Experiment 1, both high frequency and low frequency heart rate variability measures recorded under baseline conditions were highly correlated (Figure 4). Also, high frequency and, to lesser extent, low frequency values were again higher for plethysmograph-derived data (Table 3). The mean difference of the natural log of plethysmograph- and ECG-derived HF was 0.39 (*SD* = 0.12), with 95% limits of agreement 0.15–0.63. The 95% confidence intervals for the lower and upper limits of agreement were 0–0.31 and 0.48–0.79, respectively. Differences between the two measures were significantly negatively correlated with HF values, *r* = –.90,

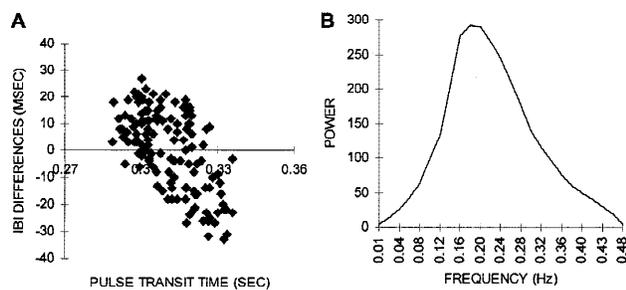


Figure 3. A: Scatterplot of differences between ECG- and plethysmograph-derived interbeat intervals as a function of pulse transit time. B: Smoothed power spectrum of differences between ECG- and plethysmograph-derived interbeat intervals over time.

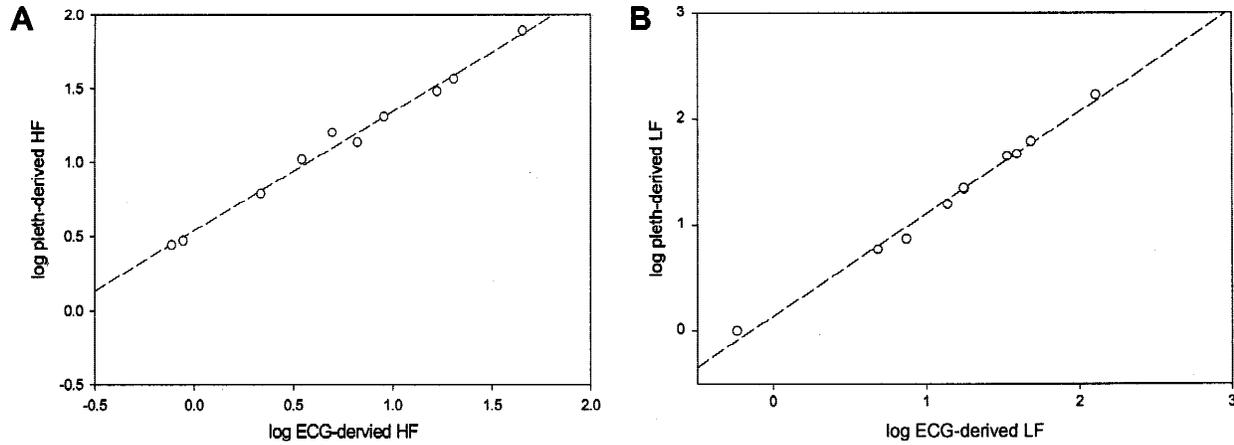


Figure 4. Experiment 2, rest period. Scatterplots of high frequency (0.15–0.40 Hz; panel A) and low frequency (0.07–0.15 Hz; panel B) heart rate variability calculated from ECG- versus finger plethysmograph (interpeak interval)-derived interbeat interval time series.

$p < .001$. Again, discrepancies between the two measures increased as HF values decreased. For low frequency heart rate variability during rest, the mean difference between the natural log of plethysmograph- and ECG-derived values was 0.10 ($SD = 0.06$), with 95% limits of agreement $-0.02-0.22$. The 95% confidence intervals for the lower and upper limits of agreement were $-0.10-0.06$ and $0.14-0.30$, respectively. Differences between the two measures were nonsignificantly negatively correlated with LF values, $r = -.32$, $p = .38$. Differences between ECG- and pleth-derived values versus averages of the two methods are shown in Figure 5.

During the Stroop task, correlations between measures were lower, especially for high frequency heart rate variability (Figure 6). Once again mean values for high frequency and, to a lesser extent, low frequency variabilities were significantly higher for

plethysmograph-derived values (Table 3). The mean difference of the natural log of plethysmograph- and ECG-derived HF was 0.74 ($SD = 0.26$), with 95% limits of agreement $0.23-1.24$. The 95% confidence intervals for the lower and upper limits of agreement were $-0.10-0.56$ and $0.92-1.57$, respectively. Finally, differences between the two measures were nonsignificantly negatively correlated with HF values, $r = -.28$, $p = .43$. For low frequency heart rate variability during rest, the mean difference of the natural log of plethysmograph- and ECG-derived was 0.15 ($SD = 0.08$), with 95% limits of agreement $-0.01-0.31$. The 95% confidence intervals for the lower and upper limits of agreement were $-0.03-0.09$ and $0.21-0.41$, respectively. Differences between the two measures were uncorrelated with LF values, $r = .08$, $p = .83$. Differences between ECG- and pleth-derived values versus averages of the two methods are shown in Figure 7.

Table 3. Mean Values and Correlations Between ECG- and Plethysmograph-Derived Heart Rate Variability in Experiment 2.

Condition	Mean (bpm ² /Hz)	SD	r	t	p
Rest					
High frequency (0.15–0.40 Hz)					
ECG	2.42	1.37			
Plethysmograph	3.41	1.57	.99	12.23	<.001
Low frequency (0.07–0.15 Hz)					
ECG	3.83	2.07			
Plethysmograph	4.22	2.36	.99	4.02	.003
LF/HF					
ECG	1.93	1.32			
Plethysmograph	1.37	0.84	.99	3.56	.006
Stroop					
High frequency (0.15–0.40 Hz)					
ECG	1.46	0.58			
Plethysmograph	2.99	0.82	.71	8.34	<.001
Low frequency (0.07–0.15 Hz)					
ECG	2.73	1.03			
Plethysmograph	3.15	1.06	.97	4.99	.001
LF/HF					
ECG	1.98	0.73			
Plethysmograph	1.07	0.30	.73	5.19	.001

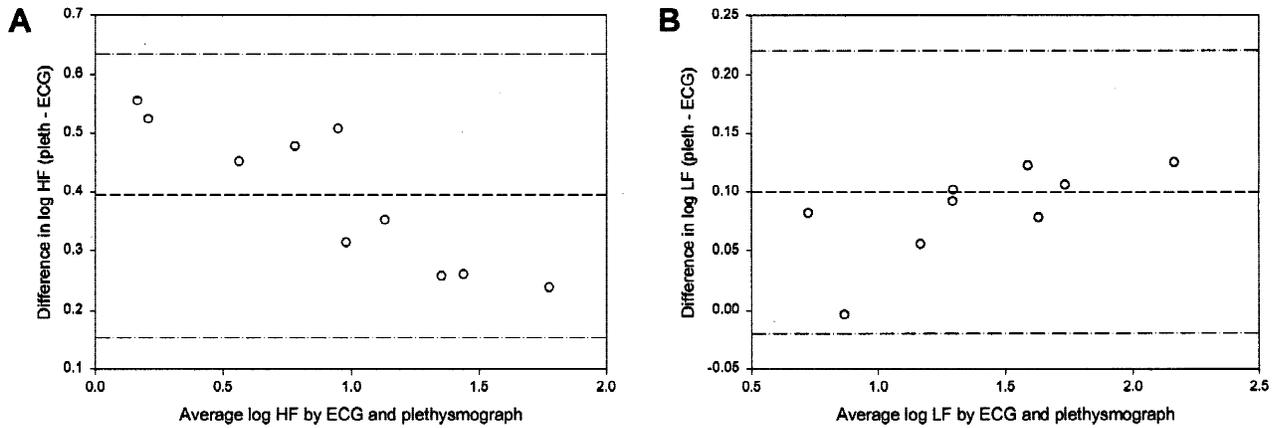


Figure 5. Experiment 2, rest period. Difference (pleth-derived – ECG-derived) versus average HF (panel A) and LF (panel B) heart rate variability measures calculated by ECG- and pleth-derived interbeat intervals. Dashed lines indicate mean of differences. Dash and dot lines demark boundaries of

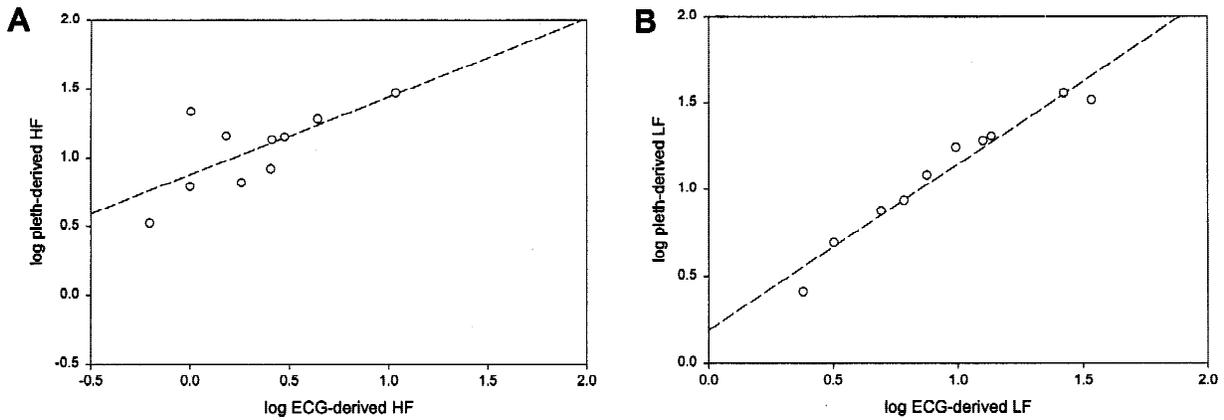


Figure 6. Experiment 2, Stroop Task. Scatterplots of high frequency (0.15–0.40 Hz; panel A) and low frequency (0.07–0.15 Hz; panel B) heart rate variability calculated from ECG- versus finger plethysmograph (interpeak interval)-derived interbeat interval time series.

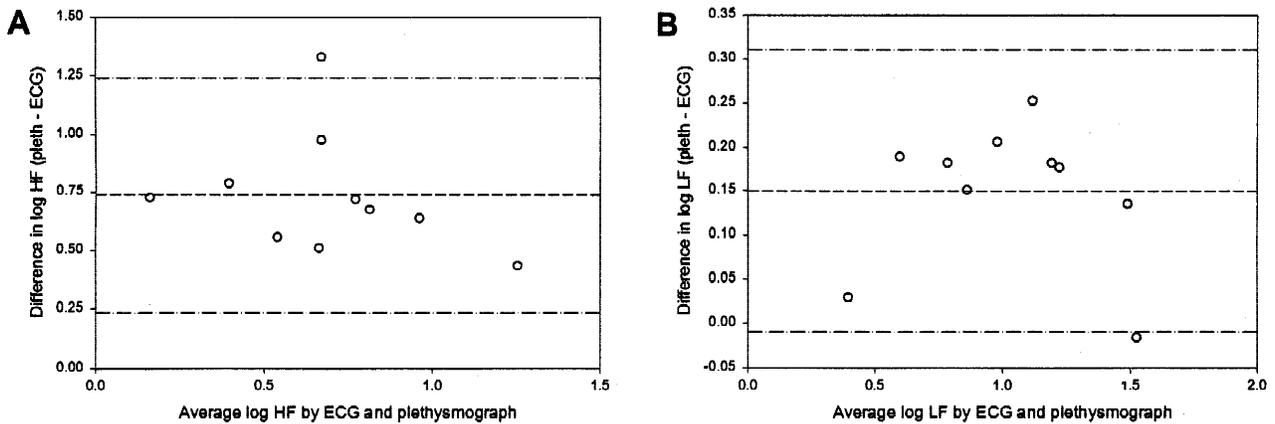


Figure 7. Experiment 2, Stroop Task. Difference (pleth-derived – ECG-derived) versus average HF (panel A) and LF (panel B) heart rate variability measures calculated by ECG- and pleth-derived interbeat intervals. Dashed lines indicate mean of differences. Dash and dot lines demark boundaries of 95% limits of agreement.

Conclusion

Results from Experiment 2 replicated and extended those reported in Experiment 1. While highly correlated, heart rate variability measures obtained from finger plethysmograph-determined time series were significantly greater than those calculated from the ECG signal. This was especially true for high frequency variability. Under conditions of experimental challenge, discrepancies between the two data collection methods increased. Correlation between ECG and plethysmograph-derived heart rate variability obtained during performance of the Stroop Color-Word Test were greatly decreased, especially for the high frequency range. Also high frequency values from the plethysmograph record continued to be significantly greater, on average more the twice as high as those calculated from the ECG. Low frequency values from the plethysmograph data again were also slightly, but significantly, higher than ECG-derived measurements. As would be expected from the greater increase in high frequency values relative to low frequency, the LF/HF ratio was significantly lower in plethysmograph-derived records.

Discrepancies between ECG- and plethysmograph-derived HF measures were also inversely correlated with mean HF values. That is, differences between the two measures increased as HF values decreased. These associations were strong and statistically significant during periods of rest, but weaker and nonsignificant during the Stroop task. No strong or statistically significant relationship between differences between measurement method and average values was found for LF values. Finally, although differences between measurement methods fell within 95% limits of agreement in almost all cases, the absolute differences between HF values were experimentally significant, given that the mean differences between ECG- and plethysmograph-derived HF values were greater than the average change in HF from rest to Stroop task (0.99 vs. 0.73). Discrepancies between measures in the LF were more within acceptable limits, with the average discrepancy between measures of 0.39 the mean change from rest to Stroop task 1.15.

General Discussion

Our pair of experiments were conducted to address the need for a formal comparison between the ECG and distal blood pressure pulse as a reliable signal for the accurate detection of cardiac interbeat intervals for use in the calculation of heart rate variability measures commonly used in psychophysiological research. To that end, we have examined high frequency and low frequency heart rate variability measures calculated from cardiac interbeat interval

time series estimated from simultaneously recorded signals from each source.

Under baseline conditions, variability measures obtained from each data source were highly correlated; however, high frequency and, to a lesser extent, low frequency heart rate variability was significantly higher in the plethysmograph-derived record. Under conditions of experimental challenge, correlations between heart rate variability measures from the two sources were decreased and mean values continued to be inflated for plethysmograph-derived measures. Also, for HF variability, the average discrepancy between the two measurement methods was greater than the mean experimental effect. Thus, it appears that distal pulse is a less reliable source of accurate cardiac interbeat intervals for use in the calculation of frequency-dependent heart rate variability measures, especially under conditions of experimental challenge. Nonetheless, tests of reliability of each data source (i.e., ECG and plethysmograph) with repeated measurements is necessary to fully evaluate the acceptability of finger plethysmograph relative to ECG in the measurement of HRV.

In an effort to explain higher heart rate variability measures from the distal pulse signal, we examined the relationship between pulse transit time and the discrepancies in interbeat intervals from ECG- and plethysmograph-derived time series. Differences in cardiac intervals estimated from the two signals were strongly and negatively correlated with pulse transit time. More interestingly, these differences varied periodically within the frequency range of the heart rate variability measures. One possible explanation for the finding of increased high frequency heart rate variability from the plethysmograph record, thus, may be that respiratory-induced changes in blood pressure, which would be in-phase with the influence of other respiratory rhythms on heart rate, may summate to augment high frequency variability in the distal pulse. Vasomotor rhythms known to occur below typical respiratory frequencies (e.g., 0.10 Hz) may similarly magnify low frequency heart rate variability.

In conclusion, although distal pulse pressure is adequate for determining heart rate variability under resting conditions, our results provide grounds for some caution in the use of finger plethysmograph for this purpose in experimental studies, where manipulations may alter the relationship between cardiac chronotropic control and distal blood pressure changes in unpredictable ways and may distort experimental effects. Therefore, the use of an ECG signal for the measurement of heart rate variability is still recommended. However, further studies that include test-retest reliability assessment of both data collection techniques are warranted before a more certain determination can be made.

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