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A comparative study of pulse rate variability and heart rate variability in healthy subjects

Jih-Sen Wong · Wan-An Lu · Kung-Tai Wu · Margaret Liu · Gau-Yang Chen · Cheng-Deng Kuo

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Abstract Both heart rate variability (HRV) and pulse rate variability (PRV) are noninvasive means for the assessment of autonomic nervous control of the heart. However, it is not settled whether or not the PRV obtained from either hand can be the surrogate of HRV. The HRV measures obtained from electrocardiographic signals and the PRV measures obtained from the pulse waves recorded from the index fingers of both hands were compared in normal subjects by using linear regression analysis and Bland and Altman method. Highly significant correlations ($P < 0.001$, $0.89 < r < 1.0$) were found between all HRV measures and the corresponding PRV measures of both hands. However, there were insufficient agreements in some measures between pairwise comparisons among HRV, right PRV and left PRV except heart rate and ultra-low frequency power (ULFP). The PRV of either hand is close to, but not the same as the HRV in healthy subjects. The HRV, right PRV and left PRV are not surrogates of one another in normal subjects except heart rate and ULFP. Since HRV is generally accepted as the standard method for the assessment of the autonomic nervous modulation of a subject, the PRV of either hand may not be suitable for the assessment of the cardiac autonomic nervous modulation of the subject.

Keywords Autonomic nervous system · Heart rate variability · Pulse rate variability · Sympathetic · Vagal

1 Introduction

The heart rate variability (HRV) obtained from electrocardiographic (ECG) signals is a useful method for the assessment of cardiac autonomic nervous function [1–3]. HRV measures has been used as indices for sympathovagal interaction in many clinical settings, such as after acute myocardial infarction [4, 5], and the prediction of morbidity and mortality [6]. Depressed sympathetic and sympathovagal modulation may be an early indication of deterioration of septic patients in the intensive care unit [7], and may predict significant morbidity or mortality rates for septic patients in the emergency department [8].

McKinley et al. [9] pointed out that in healthy adults, blood pressure waveforms can produce reliable indexes of heart period variability. Srinivas et al. [10] showed that in all cases monitored, the results of HRV deduced from photoplethysmographic signals are in tune with clinical picture of the subjects. Carrasco et al. [11] also demonstrated that values of heart rate provided by the Finapres are not completely interchangeable with those obtained from the ECG during the studied conditions. Lucena et al. [12] demonstrated that by using statistical methods and nonlinear

Wan-An Lu and Kung-Tai Wu contributed equally with the first author.

J.-S. Wong · W.-A. Lu · K.-T. Wu · M. Liu · C.-D. Kuo (✉)
Laboratory of Biophysics, Department of Research and Education, Taipei Veterans General Hospital, Taipei 112, Taiwan
e-mail: cdkuo23@gmail.com

W.-A. Lu
Institute of Cultural Asset and Reinvention, Fo-Guang University, Yilan, Taiwan

G.-Y. Chen
Institute of Biomedical Engineering, National Yang-Ming University, Taipei, Taiwan

G.-Y. Chen
Department of Internal Medicine, Ten-Chen General Hospital, Yangmei, Tao-Yuan, Taiwan

analysis no difference between heart instantaneous frequency derived from blood pressure and HRV derived from ECG could be observed. Constant and associates [13] performed a study on pulse wave recorded from the 3rd finger of the right hand, and showed that the pulse rate variability (PRV) did not precisely reflect respiratory HRV in standing healthy subjects and in patients with low HRV. Similarly, Chuang SS et al. [14] pointed out that the right and left pulse were not the same in that the total power (TP) of right pulse was higher than that of left pulse in healthy subjects, patients with coronary artery disease (CAD), and CAD patients after coronary artery bypass graft (CABG) surgery, and that the decrease in the right-to-left ratio of total power of both pulses is one of the 3 significant changes in the power spectra of the pulses in CAD patients after CABG. From the results of these studies, it can be seen that whether or not the PRV of either hand can serve as a surrogate of HRV is still controversial. Thus, the aims of this study were: (1) to examine whether the PRV of either hand can be the surrogate of HRV in healthy subjects; (2) to examine whether the PRV of the right hand is equivalent to that of the left hand.

2 Methods

2.1 Study subjects

Thirty-one healthy subjects (19 women and 12 men, aged 59.7 ± 8.9 years) were included in this study. All healthy subjects recruited from the community were requested to refrain from alcoholic or caffeinated beverages for at least 24 h prior to the study. Subject who had major cardiopulmonary disease or was on regular medicine for diabetes mellitus, hypertension, renal or liver disease was excluded from the study. The Institute Review Board of the hospital has approved this study, and signed written informed consent was obtained from every participant before study enrollment.

2.2 Equipment

After 5 min rest, the trends of conventional ECG signal and pulse waves of the subject in supine position were picked up by the PowerLab 16sp (ML795 PowerLab/16sp, ADInstruments, Sydney, Australia) for 10 min and transferred to a personal computer for recording. The photoplethysmography (PPG) module in the PowerLab 16sp was used to record the pulsatile volume flow at the fingertips of both hands with the help of infrared light. All analog signals were sampled with a sampling rate of 400 Hz. All recordings were performed in a bright and quiet room with a constant temperature of 24–25°C.

2.3 HRV and PRV

A R-wave detecting software was used to identify the peaks of the R waves in the recorded ECG signals (Fig. 1, the 1st panel) and to measure the consecutive RR intervals (Fig. 1, the 2nd panel). Similarly, a peak detecting software was developed to identify the peaks of the pulse waves in the recorded pulse wave signals of both hands (Fig. 1, the 1st panel) and to measure consecutive pulse-to-pulse (PP) intervals (Fig. 1, the 3rd and 4th panels). The last 512 stationary RR intervals and the corresponding PP intervals of both hands were used for the power spectral analysis of HRV and PRV, respectively. Both atrial and ventricular ectopic beats were eliminated before spectral HRV and

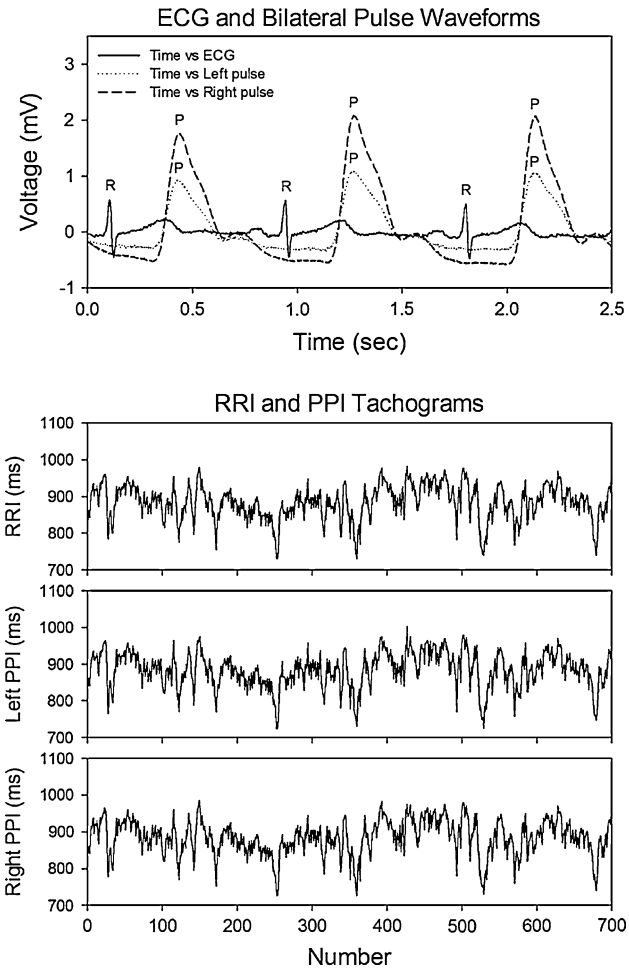

Fig. 1 The 1st *panel* shows the waveforms of ECG and bilateral pulse waves of a representative subject over a short time interval. The symbol 'R' denotes the peaks of the R waves in the ECG tracing; and the symbol '*P*' denotes the peaks of the pulse waves in the tracings of photoplethysmographic signals. The 2nd to 4th *panels* show the tachograms of RRI, left PPI, and right PPI which are obtained from the ECG and bilateral pulse wave tracings by using the peak detecting software. These 3 tachograms are very close to one another with few subtle differences

PRV analyses. If the percentage of ectopic beats were greater than 5%, the subject was excluded from statistical analysis.

The foot point detection method has been employed to determine the pulse intervals by measuring them from foot-to-foot in the pulse wave velocity studies [15, 16]. However, the foot points of pulse waves are not sharp enough to facilitate accurate determination, as measurements are susceptible to tiny noises superimposed upon them. Furthermore, in the HRV analysis the R waves of ECG are always detected by using peak detection method and the RR intervals are measured sequentially from one R peak to the next R peak, rather than from one R foot to the next R foot by using foot point detection method. To comply with the detection of R peaks and the measurement of RR intervals by using peak detection method in HRV analysis, we identified the peaks of the pulse waves by using peak detection method also, and measured the PP intervals of pulse waves for the power spectral analysis of PRV.

The mean (Mn), heart rate (HR), standard deviation (SD_{RR}), coefficient of variation (CV_{RR}), and root mean square of successive differences (RMSSD) in 512 stationary RR intervals and corresponding PP intervals were calculated using standard formulae for each subject. The power spectra of RR intervals from ECG and PP intervals from pulse waves of both hands were obtained by means of fast Fourier transformation (Mathcad 11, Mathsoft Inc., Cambridge, MA, USA). Direct current component was excluded before the calculation of the powers. The definitions of the HRV measures for short term recordings by the Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology [17] were adopted with slight modifications. The area-under-the-curve of the spectral peaks within the range of 0.01–0.4 Hz, 0–0.01 Hz, 0.01–0.04 Hz, 0.04–0.15 Hz, 0.15–0.40 Hz was defined by total power (TP), ultralow-frequency power (ULFP), very low-frequency power (VLFP), low-frequency power (LFP), and high-frequency power (HFP), respectively. The normalized high-frequency power (nHFP = HFP/TP) was used as the index of vagal modulation, the normalized low-frequency power (nLFP = LFP/TP) as the index of sympathetic and vagal modulations, the low-/high-frequency power ratio (LHR = LFP/HFP) as the index of sympathovagal balance [18], and the normalized very low frequency power (nVLFP = VLFP/TP) as the index of renin-angiotensin-aldosterone system and vagal withdrawal [19, 20].

2.4 Statistical analysis

Data are presented as mean ± SD or median and interquartile range (25–75th percentiles) values, depending on the normality of the data, which was determined by the Kolmogorov–Smirnov test. The variance among different methods was compared using Friedman repeated measures ANOVA on ranks. The correlation coefficient was calculated by using linear regression analysis for data with normal distribution or by Spearman rank order correlation for distribution free data. A $P < 0.05$ was considered statistically significant. All statistical analyses were performed using the SigmaStat 3.0 software (SPSS Inc., Chicago, IL, USA).

The agreement between two different methods of measurement was analyzed by using the Bland and Altman method [21–23]. In addition, the ratio of half the range of limits of agreement (LA) and the mean of the pairwise measurement means (MPM) was computed. A ratio that was smaller than 0.1 was defined as good agreement, a ratio between 0.1 and 0.2 was defined as moderate, and a ratio higher than 0.2 was defined as insufficient [22, 23]. Both time and frequency domain measures of HRV and PRV were compared [24, 25].

3 Results

The general data of these subjects are shown in Table 1. Table 2 tabulates the results of comparisons among the measures of HRV, left PRV, and right PRV. It was found that the CV, RMSSD, TP, LFP, HFP, and nHFP of left PRV were significantly higher than those of HRV, whereas the VLFP and nVLFP of left PRV were significantly lower than those of HRV (Table 2). It was also found that the SD, CV, RMSSD, TP, VLFP, LFP, HFP, and nHFP of right PRV were significantly higher than those of HRV, whereas the nVLFP, nLFP, and LHR of right PRV were significantly lower than those of HRV. Similarly, it was found that the HFP and nHFP of right PRV were significantly higher than those of left PRV, whereas the nLFP and LHR of right PRV were significantly lower than those of left PRV (Table 2).

Linear regression analysis showed significant and positive linear relationship in all measures between HRV and left PRV, between right PRV and left PRV, and between right PRV and HRV (Table 3). However, the Bland–Altman analysis showed that between HRV and left PRV there were good agreements (ratio < 0.1) in Mn, HR, SD, CV, ULFP,

Table 1 Subjects characteristics

Gender (M/F)	12/19
Age (year)	59.7 ± 8.9
Height (cm)	162 ± 7
Weight (kg)	61.9 ± 8.9
Body mass index (kg/m^2)	23.5 ± 2.2

Values are presented as mean ± SD

Table 2 The HRV measures and right and left PRV

	HRV	Left PRV	Right PRV
Mn (ms)	831.9 (765.1–898.5)	831.9 (765.1–898.5)	831.8 (765.1–898.4)
HR (bpm)	72.1 (66.8–78.4)	72.1 (66.8–78.4)	72.1 (66.8–78.4)
SD (ms)	27.1 (22.0–31.2)	27.9 (23.0–32.1)*	28.1 (23.0–32.2)*
CV (%)	3.38 (2.66–3.82)	3.51 (2.77–3.90)*	3.59 (2.76–3.87)*
RMSSD (ms)	21.5 (16.3–25.4)	22.4 (17.7–27.0)*	23.1 (17.9–32.2)*
TP (ms^2)	248.9 (165.5–350.6)	273.1 (186.5–363.3)*	260.5 (215.2–366.1)*
ULFP (ms^2)	83.6 (41.1–190.4)	83.2 (41.4–190.6)	83.3 (41.1–190.4)
VLFP (ms^2)	85.7 (47.7–127.3)	83.6 (47.7–129.4)*	86.0 (47.8–130.0)*
LFP (ms^2)	73.0 (43.7–112.1)	76.2 (45.7–114.9)*	76.4 (50.6–115.8)*
HFP (ms^2)	91.0 (56.0–132.4)	106.2 (69.7–146.7)*	106.2 (71.7–162.0)*,#
nVLFP (nu)	32.2 (22.3–42.7)	30.8 (22.9–40.2)*	29.9 (19.2–38.0)*
nLFP (nu)	26.0 (19.8–37.3)	25.0 (20.7–34.6)*	24.4 (19.4–35.5)*,#
nHFP (nu)	33.9 (23.0–52.9)	40.9 (26.7–53.8)*	41.8 (30.9–56.1)*,#
LHR	0.82 (0.43–1.32)	0.65 (0.41–1.08)*	0.61 (0.35–1.02)*,#

Values are presented as mean ± SD for normally distributed data or median (IQR, 25–75%) for distribution free data. *Mn* mean RR interval or PP interval, *HR* heart rate, *bpm* beats per minute, *SD* standard deviation of RR intervals or PP intervals, *CV* coefficient of variation of RR intervals or PP intervals, *RMSSD* root mean square of successive difference, *TP* total power; *ULFP* ultralow frequency power, *VLFP* very low-frequency power, *LFP* low-frequency power, *HFP* high-frequency power, *nVLFP* normalized VLFP = VLFP/TP, *nLFP* normalized LFP = LFP/TP, *nHFP* normalized HFP = HFP/TP, *LHR* low-/high- frequency power ratio.* $P < 0.05$ versus HRV; #$P < 0.05$ versus left PRV

Table 3 Linear regression analysis of Mn, SD, CV, RMSSD, TP, nLFP, nHFP and LHR in the pairwise regression of HRV versus left PRV, right PRV versus left PRV, and right PRV versus HRV. n = 31

	HRV (y) versus Left PRV (x)	Right PRV (y) versus Left PRV (x)	Right PRV (y) versus HRV (x)
Mn	y = 2.64 + x	y = 0.08 + 0.99x	y = 0.08 + 0.99x
	$r = 1$	$r = 1$	$r = 1$
	$P < 0.001$	$P < 0.001$	$P < 0.001$
SD	y = −0.86 + x	y = −0.36 + 1.02x	y = 0.50 + 1.02x
	$r = 0.994$	$r = 0.977$	$r = 0.979$
	$P < 0.001$	$P < 0.001$	$P < 0.001$
CV	y = −0.11 + x	y = −0.05 + 1.03x	y = 0.06 + 1.02x
	$r = 0.992$	$r = 0.983$	$r = 0.979$
	$P < 0.001$	$P < 0.001$	$P < 0.001$
RMSSD	y = −2.81 + x	y = 0.44 + 1.04x	y = 3.48 + 0.99 x
	$r = 0.967$	$r = 0.901$	$r = 0.89$
	$P < 0.001$	$P < 0.001$	$P < 0.001$
TP	y = −3.19 + 0.96x,	y = 14.68 + 0.99x,	y = 17.01 + 1.04x,
	$r = 0.995$	$r = 0.988$	$r = 0.989$
	$P < 0.001$	$P < 0.001$	$P < 0.001$
nLFP	y = −1.31 + 1.02x	y = −5.02 + x	y = −2.99 + 0.97x
	$r = 0.994$	$r = 0.966$	$r = 0.972$,
	$P < 0.001$	$P < 0.01$	$P < 0.001$
nHFP	y = −0.04 + 1.05x,	y = 0.01 + 0.99x,	y = −0.06 + 0.93x,
	$r = 0.985$	$r = 0.944$	$r = 0.934$
	$P < 0.001$	$P < 0.01$	$P < 0.001$
LHR	y = −0.04 + 1.24x	y = 3.06 + 0.97 x	y = 0.07 + 0.76 x
	$r = 0.984$	$r = 0.951$	$r = 0.937$
	$P < 0.001$	$P < 0.001$	$P < 0.001$

HRV heart rate variability, *Left PRV* pulse rate variability of left hand, *Right PRV* pulse rate variability of right hand, *Mn* mean RR interval or PP interval, *SD* standard deviation of RR intervals or PP intervals, *CV* coefficient of variation of RR intervals or PP intervals, *RMSSD* root mean square of successive difference, *TP* total power, *nVLFP* normalized very low-frequency power, *nLFP* normalized low-frequency power, *nHFP* normalized high-frequency power, *LHR* low-/high- frequency power ratio, *r* Pearson correlation coefficient, *P* *P* value

VLFP, nVLFP, and nLFP, but moderate agreements ($0.1 < \text{ratio} < 0.2$) in RMSSD, TP, LFP, and nHFP, and insufficient agreement (ratio > 0.2) between HFP and LHR (Table 4). For the comparison between HRV and right PRV, there were good agreements in Mn, HR, ULFP, and VLFP, but moderate agreements in SD, CV, LFP, nVLFP, and nLFP, and insufficient agreements in RMSSD, TP, HFP, nHFP, and LHR (Table 5). As for the comparison between left PRV and right PRV, there were good agreements in Mn, HR, ULFP, and VLFP, moderate agreements in SD, CV, LFP, nVLFP, and nLFP, but insufficient agreements in RMSSD, TP, HFP, nHFP, and LHR (Table 6). Note that

Table 4 Bland-Altman analysis of time and frequency domain measures of HRV and left PRV

	HRV	Left PRV	LA	MPM	Ratio
Mn (ms)	831.9 (765.1–898.5)	831.9 (765.1–898.5)	−0.065–0.058	831.9 (762.8–899.3)	7.44×10^{-5}
HR (1/min)	72.1 (66.8–78.4)	72.1 (66.8–78.4)	−0.008–0.008	72.1 (66.7–78.7)	1.13×10^{-4}
SD (ms)	27.1 (22.0–31.2)	27.9 (22.9–32.1)	−0.9–2.4	27.5 (22.3–31.9)	0.0546
CV (%)	3.4 (2.7–3.8)	3.5 (2.8–3.9)	−0.09–0.27	3.4 (2.8–3.9)	0.0530
RMSSD (ms)	21.5 (16.3–25.4)	22.4 (17.7–27.0)	−2.9–6.5	21.6 (17.4–26.9)	0.1935
TP (ms^2)	248.9 (165.5–350.6)	273.1 (186.5–363.3)	−26.7–61.6	263.1 (177.5–364.5)	0.1293
ULFP (ms^2)	83.6 (41.1–190.4)	83.2 (41.4–190.6)	−1.02–1.53	83.4 (39.4–197.3)	0.0089
VLFP (ms^2)	85.7 (47.7–127.3)	83.6 (47.7–129.5)	−3.5–6.2	84.6 (47.6–129.4)	0.0490
LFP (ms^2)	72.9 (43.7–112.1)	76.2 (45.7–114.9)	−14.1–23.6	74.1 (44.5–114.1)	0.1675
HFP (ms^2)	90.9 (56.0–132.4)	106.2 (69.7–146.7)	−20.8–43.7	103.1 (68.1–145.4)	0.2472
nVLFP (nu)	32.2 (22.3–42.7)	30.8 (22.9–40.2)	−1.4–4.6	30.9 (22.3–40.5)	0.0925
nLFP (nu)	25.9 (19.8–37.3)	24.9 (20.7–34.6)	−3.4–1.8	25.7 (20.5–37.1)	0.0901
nHFP (nu)	33.9 (23.0–52.9)	40.9 (26.7–53.8)	−2.8–7.6	38.4 (25.5–53.6)	0.1379
LHR	0.7 (0.5–2.6)	0.8 (0.5–2.1)	−0.95–0.53	0.7 (0.4–1.1)	0.6658

Values are presented as mean ± SD for normally distributed data or median (IQR, 25–75%) for distribution free data. *Mn* mean RR interval or PP interval, *HR* heart rate, *SD* standard deviation of normal interbeat intervals, *CV* coefficient of variation of RR intervals or PP intervals; *RMSSD* root mean square of successive difference, *TP* total power, *ULFP* ultralow frequency power, *VLFP* very low-frequency power, *LFP* low-frequency power, *HFP* high-frequency power, *nVLFP* normalized VLFP = VLFP/TP, *nLFP* normalized *LFP* LFP/TP, *nHFP* normalized HFP = HFP/TP, *LHR* low-/high- frequency power ratio, *LA* limits of agreement (95% confidence interval), *MPM* mean of pairwise means. Ratio = 0.5 × (range of LA)/MPM

Table 5 Bland-Altman analysis of time and frequency domain measures of HRV and right PRV

	HRV	Right PRV	LA	MPM	Ratio
Mn (ms)	831.9 (765.1–898.5)	831.8 (765.1–898.4)	−0.068–0.087	831.9 (762.8–899.3)	9.37×10^{-5}
HR (1/min)	72.1 (66.8–78.4)	72.1 (66.8–78.4)	−0.01–0.01	72.1 (66.7–78.7)	1.34×10^{-4}
SD (ms)	27.1 (22.0–31.2)	28.1 (22.9–32.2)	−5.1–2.5	27.5 (22.3–31.8)	0.1277
CV (%)	3.4 (2.7–3.8)	3.6 (2.8–3.9)	−0.59–0.28	3.5 (2.7–3.9)	0.1242
RMSSD (ms)	21.5 (16.3–25.4)	23.1 (17.9–32.2)	−15.6–9.0	21.7 (17.4–27.5)	0.4926
TP (ms^2)	248.9 (165.5–350.6)	260.5 (215.2–366.1)	−106.7–47.7	258.9 (200.1–364.5)	0.2220
ULFP (ms^2)	83.6 (41.1–190.4)	83.3 (41.1–190.4)	−1.48–0.96	83.4 (39.1–197.1)	0.0084
VLFP (ms^2)	85.7 (47.7–127.3)	85.9 (47.8–129.9)	−4.0–1.4	85.8 (47.6–129.4)	0.0275
LFP (ms^2)	72.9 (43.7–112.1)	76.4 (50.6–115.8)	−22.0–12.5	74.1 (45.7–112.6)	0.1528
HFP (ms^2)	90.9 (56.0–132.4)	106.2 (71.7–161.9)	−96.6–49.7	102.6 (68.1–149.5)	0.5370
nVLFP (nu)	32.2 (22.3–42.7)	29.9 (19.2–38.0)	−4.0–8.8	30.7 (21.5–40.3)	0.1999
nLFP (nu)	25.9 (19.8–37.3)	24.4 (19.4–35.5)	−3.9–6.4	25.1 (19.6–37.1)	0.1815
nHFP (nu)	33.9 (23.0–52.9)	41.8 (30.9–56.2)	−14.7–7.4	39.7 (26.8–53.8)	0.2878
LHR	0.7 (0.5–2.6)	0.6 (0.3–1.0)	−0.59–1.05	0.7 (0.4–1.1)	0.7470

Values are presented as median (interquartile range, IQR). *Mn* mean RR interval or PP interval, *HR* heart rate, *SD* standard deviation of normal RR intervals or PP intervals, *CV* coefficient of variation of RR intervals or PP intervals, *RMSSD* root mean square of successive difference, *TP* total power; *ULFP* ultralow frequency power, *VLFP* very low-frequency power, *LFP* low-frequency power, *HFP* high-frequency power, *nVLFP* normalized VLFP = VLFP/TP, *nLFP* normalized *LFP* LFP/TP, *nHFP* normalized HFP = HFP/TP, *LHR* low-/high- frequency power ratio; *LA* limits of agreement; 95% = confidence interval; *MPM* mean of pairwise means. Ratio = 0.5 × (range of LA)/MPM

Table 6 Bland-Altman analysis of time and frequency domain measures of right and left PRV

	Right PRV	Left PRV	LA	MPM	Ratio
Mn (ms)	831.9 (765.1–898.5)	831.8 (765.1–898.4)	−0.08–0.093	831.9 (762.8–899.3)	1.05×10^{-4}
HR (1/min)	72.1 (66.8–78.4)	72.1 (66.8–78.4)	−0.007–0.007	72.1 (66.7–78.7)	1.02×10^{-4}
SD (ms)	27.9 (22.9–32.1)	28.1 (22.9–32.2)	−4.8–3.7	27.9 (22.9–32.1)	0.1404
CV (%)	3.5 (2.8–3.9)	3.6 (2.8–3.9)	−0.53–0.41	3.5 (2.8–3.9)	0.134
RMSSD (ms)	22.4 (17.7–27.0)	23.1 (17.9–32.2)	−14.3–11.2	22.9 (17.6–28.8)	0.4942
TP (ms^2)	273.1 (186.5–363.3)	260.5 (215.2–366.1)	−107.1–83.0	266.8 (213.6–376.1)	0.2668
ULFP (ms^2)	83.2 (41.4–190.6)	83.3 (41.1–190.4)	−1.60–1.59	83.2 (39.4–197.1)	0.0111
VLFP (ms^2)	83.6 (47.7–129.5)	85.9 (47.8–129.9)	−4.0–4.0	84.8 (47.3–131.5)	0.0404
LFP (ms^2)	76.2 (45.7–114.9)	76.4 (50.6–115.8)	−15.2–15.1	76.3 (48.7–115.2)	0.1315
HFP (ms^2)	106 (69.7–146.7)	106.2 (71.7–161.9)	−98.3–74.3	106.2 (70.2–149.5)	0.6087
nVLFP (nu)	29.9 (19.2–38.0)	30.8 (22.9–40.2)	−4.9–6.6	30.3 (21.5–39.3)	0.1842
nLFP (nu)	24.9 (20.7–34.6)	24.4 (19.4–35.5)	−4.4–5.4	24.4 (19.7–35.1)	0.1748
nHFP (nu)	40.9 (26.7–53.8)	41.8 (30.9–56.2)	−11.6–9.0	41.1 (30.2–54.4)	0.2613
LHR	0.7 (0.4–1.1)	0.6 (0.3–1.0)	−0.44–0.49	0.6 (0.4–1.1)	0.4666

Values are represented as median (interquartile range, IQR). *Mn*, mean RR interval or PP interval, *HR* heart rate, *SD* standard deviation of normal RR intervals or PP intervals, *CV* coefficient of variation of RR intervals or PP intervals, *RMSSD* root mean square of successive difference, *TP* total power; *ULFP* ultralow frequency power, *VLFP* very low-frequency power, *LFP* low-frequency power, *HFP* high-frequency power, *nVLFP* normalized VLFP = VLFP/TP, *nLFP* normalized LFP = LFP/TP, *nHFP* normalized HFP = HFP/TP, *LHR* low-/high- frequency power ratio, *LA* limits of agreement; 95% = confidence interval; *MPM* mean of pairwise means; Ratio = 0.5 × (range of LA)/MPM

good agreement was a constant occurrence in Mn, HR, ULFP, and VLFP between pairwise comparisons amongst HRV, left PRV and right PRV; whereas insufficient agreement was more common in HFP and LHR between pairwise comparisons amongst HRV, left PRV and right PRV.

4 Discussion

In clinical practice, nurses often obtain the pulse rate of the patient by palpating and counting the number of arrivals of systolic peaks of arterial pulse waves at the radial artery of either hand, and use it as the surrogate of heart rate. Since pulse rate is equivalent to heart rate and is more easily obtained than the heart rate, it is natural to ask whether the pulse rate variability (PRV) obtained from arterial pulse wave can be used as a surrogate of HRV obtained from ECG signals. Furthermore, when the ECG signals from the chest leads are about to be recorded, the application of electrodes onto the chest wall and beneath the breasts is generally inconvenient for subjects and is almost always embarrassing for females, as clothes are to be removed or lifted temporarily. If the PRV from either hand can act as the surrogate of HRV, just a single probe fixed to the subject's finger is needed without having to undress or lift the clothes of a subject. This is certainly a convenience for both the subject and the examiner. Thus, though it is a standard practice to acquire HRV from the R–R intervals of the ECG signals, there have been attempts to use peripheral pulse wave signal for the assessment of autonomic nervous modulation.

In this study, we investigated whether or not the PRV of either hand can be used as the surrogate of HRV, and examined whether the PRV of the right hand is equivalent to that of the left hand in healthy subjects. We found that good agreement was a constant finding for Mn, HR, ULFP, and VLFP, while insufficient agreement was a common finding for HFP and LHR, in the pairwise comparisons of HRV versus left PRV, HRV versus right PRV, and left PRV versus right PRV.

Thus, nurses can use the pulse rate obtained from either hand as a surrogate of HR without appreciable error. It is noteworthy that the ULFP was the only frequency domain measure that was not significantly different and had good agreement amongst HRV, right PRV and left PRV. Our finding suggested that the ULFP obtained from PRV of either hand can be the surrogate of the corresponding ULFP of HRV. Unfortunately, few studies have explored the physiological significance and clinical use of ULFP. Alekseeva et al. [26] have shown that the ULFP of HRV was decreased in patients with arterial hypertension treated with a beta-blocking agent. The ULFP as well as other HRV indices were also shown to be severely decreased in patients with ventricular arrhythmia [27]. Thus, the ULFP may be used in the evaluation of the patients' heart condition, and it will be more convenient to use the ULFP obtained from PRV than to use that obtained from HRV.

We showed in this study that either right or left PRV cannot be used as the surrogate of HRV in normal subjects except heart rate and ULFP. Our result is in accordance with that of Carrasco et al. [11], and Constant et al. [13],

but is not in accordance with that of McKinley et al. [9], Srinivas et al. [10], and Lucena et al. [12]. Several factors might contribute to the significant difference between HRV and PRV from either hand. Firstly, the ECG signals measured at lead II are the electric waves originating from the heart, while the pulse waves measured at the fingertip are the mechanical waves which go from the heart to the fingertip. These two kinds of waves are different by physical nature. Secondly, there is a momentary delay between the R wave on the ECG and the peak of the pulse wave. After a discharge of electric current from SA node to the ventricles, the transfer of the mechanical force of cardiac contraction from left ventricle to the fingertips undergoes significant damping and modification in the arterial system by many factors such as the caliber and structure of the blood vessels, the viscosity and osmolarity of the blood, the autonomic nervous modulation and the body frame of the subjects, etc. These factors may have substantial effects on the blood flow and pulse waveform, resulting in an appreciable difference between the HRV and PRV of either hand.

We also found in this study that there were insufficient agreements in many variability measures between the right PRV and left PRV. That is, the right PRV is not the same as left PRV. This result is in accordance with our previous report that there is a right-to-left asymmetry in the total power of pulse in normal subjects [14]. Khandoker et al. [28] concluded that the PRV provides accurate inter-pulse variability to measure HRV under normal breathing in sleep but does not precisely reflect HRV in sleep disordered breathing. Their result is similar to, but slightly different from ours because we found that the PRV of either hand is not accurate enough to be the surrogate of HRV even under normal breathing in awake state. Our result is comprehensible because the carotid arterial system is not symmetric in the human body. Several factors may explain why the left PRV is not equivalent to the right PRV. For instance, the orientation of the heart axis within the mediastinum is oblique rather than vertical, the apex of the heart is deviated to the left, and the branching of the aorta within the thorax is left–right asymmetric, etc.

Since the PRV from either hand and HRV were not equivalent to one another, and since there were appreciable amount of moderate agreements and insufficient agreements in the comparisons between HRV and PRV measures, the PRV from either hand may not be used in the analysis of autonomic nervous modulation of the subjects despite the fact that there were significant and positive correlations in almost all variability measures between HRV and PRV of either hand (Table 3).

The Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [17] has recommended the use of ULFP (range: ≤ 0.003 Hz) in long-term recordings such as 24 h duration, but has not recommended it in short-term recordings such as 5 min duration. In this study, we recorded the ECG and pulse wave signals for 10 min which should belong to the category of short-term recordings. Therefore, it may not be necessary to calculate the ULFP of the signals in this study. However, if the ULFP is present in a long-term recording, it should also be detectable in a short-term recording so long as an appropriate frequency range can be set for its calculation. Therefore, we set 0.01 Hz as the upper limit of the ULFP, and calculated it within the frequency range of $\leq$0.01 Hz. Though the 0.01 Hz upper limit of the ULFP in a recording of 10 min duration in this study is only about 3 times larger than the 0.003 Hz upper limit of the ULFP as recommended by the Task Force for a recording of 24 h duration, it is sufficient for the calculation of the ULFP for statistical comparisons.

In this study, the TP, ULFP, VLFP, LFP, and HFP were calculated by using the frequency ranges of 0.01–0.4 Hz, 0–0.01 Hz, 0.01–0.04 Hz, 0.04–0.15 Hz, and 0.15–0.40 Hz, respectively. Our frequency ranges for the computation of VLFP, LFP and HFP were the same as those suggested by the Task Force [17]. However, our definitions for various HRV measures were slightly different from those defined by the Task Force in the following aspects: (1) A value of 0.01 Hz was set as the lower limit of TP instead of an ambiguous '$\approx$' in the definition of the Task Force; (2) The frequency range of ULFP was defined as 0–0.01 Hz instead of 'not defined' in the definitions of the Task Force; (3) The VLFP was also normalized, instead of 'not normalized' in the definitions of the Task Force; (4) The frequency range of the denominator used for the normalization of VLFP, LFP and HFP covers the frequency range of VLFP + LFP + HFP, or 0.01–0.4 Hz; whereas the frequency range of the denominator used for the normalization of LFP and HFP covers only the frequency range of LFP + HFP, or 0.04–0.4 Hz, in the definition of the Task Force.

In conclusion, the PRV of either hand is close to, but not the same as the heart rate variability in healthy subjects. The HRV, right PRV and left PRV are not surrogates of one another in healthy subjects except heart rate and ULFP. Since HRV is generally accepted as a standard method for the assessment of autonomic nervous modulation of the subject, either right PRV or left PRV cannot be used to assess the autonomic nervous modulation of the subject.

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