

# A preliminary attempt to understand compatibility of photoplethysmographic pulse rate variability with electrocardiographic heart rate variability

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**Abstract.** In this study, we investigated the difference between heart rate variability (HRV) derived from electrocardiographic (ECG) signals and pulse rate variability (PRV) derived from photoplethysmographic (PPG) signals. Fourteen healthy subjects conducted the protocol: 10 min physiological signals including distal pulse wave on finger and ear from photoplethysmography (PPG), and heart beat from electrocardiogram (ECG). In this paper, the analytical methods accounting for time and frequency domain, agreement, correlation coefficient and geometrical distribution were utilized to process the finger pulse rate variability (fPRV) and ear pulse rate variability (ePRV). The experimental results express that the parameters of frequency domain are inadequate in the subject group statistics, and fPRV and ePRV are sufficient surrogates for HRV derived from the ECG recording, while the ECG recording is unavailable and inconvenient. Photoplethysmography (PPG) could offer a simple and robust means to fulfill the requirements of rhythmical pulsation assessment.

Keywords: heart rate variability, pulse rate variability, electrocardiogram, photoplethysmography

## 1. Introduction

In recent decades noninvasive techniques based on the electrocardiogram (ECG) have been widely employed as markers of autonomic modulation of the heart, these clinical references include heart rate variability (HRV) (van Ravenswaaij-Arts *et al* 1993, Task Force of the ESC and the NASPE 1996), baroreflex sensitivity (BRS) (La Rovere *et al* 2001), Q-T interval (Yi *et al* 1998) (Yi *et al* 1998), QT dispersion (Spargias *et al* 1999), T-Wave alternans (TWA) (Rosenbaum *et al* 1994) and heart rate turbulence (HRT) (Guzik and Schmidt 2002), etc. Among these techniques, HRV has been recognized as a simple and useful method to assess the regulation of heart rate behavior.

The measurement of typical multiple lead ECG, however, requires multiple electrode attachments and cable connections. The clinical users must either confirm that the leads are correctly placed or optimize the leads position before the recording. The above procedures could preclude frequent assessments of HRV in general populations.

Measurement of pulse wave using photoplethysmography (PPG) is another approach to measure cardiac time intervals. In contrast to ECG, pulse waves, the throbbing of the arteries as an effect of the heart beat, can be traced with a single opto-electronic sensor without any

electrode, and with neither the inconvenience of installation nor the need for subjects to unclothe indeed.

However, some researchers (Constant *et al* 1999) suggested that pulse rate variability (PRV) derived from PPG signals is not a surrogate for heart rate variability (HRV) derived from ECG signals. The study population in their work, children with implanted pace maker triggering a 'constant' heart rate, indicated researchers making further experimental settings in general populations to assess the degree of parameters substitution between HRV and PRV.

In this study, the pulse wave signals were obtained from the finger tip and the ear lobe through PPG. The aim of this study was to determine whether PRV could be compatible with HRV by analyzing and comparing HRV from ECG and PRV from PPG signals of the finger or ear. Moreover, the difference between the finger pulse rate variability (fPRV) and the ear pulse rate variability (ePRV) has been analyzed to learn which PRV, i.e. fPRV or ePRV, could be better to assess rhythmical pulsations of heart.

## **2. Methods**

### *2.1. Subjects*

Fourteen volunteers (7 females and 7 males), aged  $25.8 \pm 4.2$  years (Mean $\pm$ Std) without known history of cardiovascular abnormalities, participated in this study. All subjects gave their informed consent to conduct this study under the obligation to the procedures from the University ethical advisory committee.

### *2.2. Data acquisition*

ECG signals and PPG signals were collected from the subjects by a multi-channel physiological signal recording system (PowerLab/16SP, ADInstruments, Castle Hill, Australia, 2002). The PPG signals were collected from the left ear lobe (ear clip: MLT1020EC, ADInstruments, Australia) and the index finger (finger clip: MTL1020FC, ADInstruments, Australia). The two transducers were connected to the PPG amplifier (ML305, ADInstruments, Australia) through a shielded cable to record the blood volume pulse (BVP) waveform with a gain of 100. The PPG signal was filtered with a 50Hz low pass filter online. Also, the Lead I ECG signal was collected with three electrodes on the right wrist, the left wrist and the right leg of the subjects, separately. The bandwidth of the ECG amplifiers was set from 0.13 to 100 Hz with 50Hz notch. The three signals were logged simultaneously and digitized at a sampling rate of 1 kHz with 16 bit resolution.

### *2.3. Protocol*

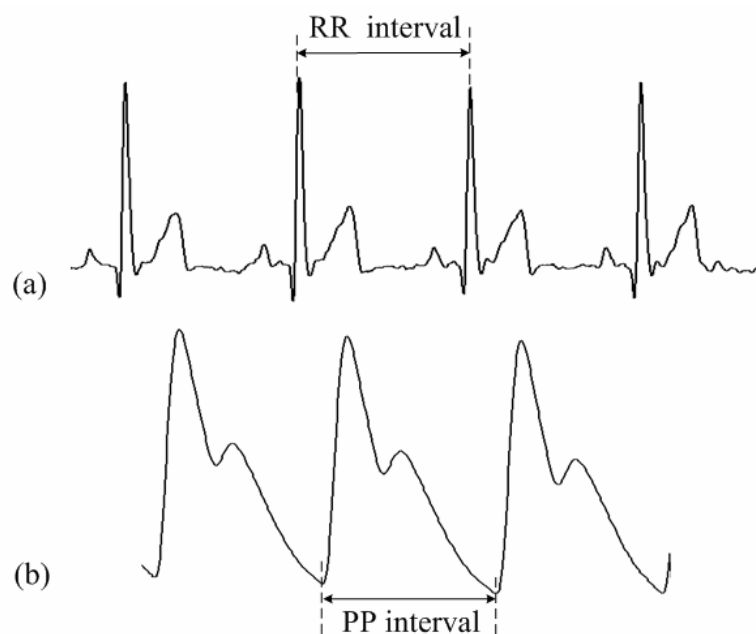
All subjects were asked to avoid strenuous exercise, consuming hot drinks or those containing caffeine or eating a substantial meal in one hour prior to the test. All measurements were taken in a temperature-controlled room ( $25 \pm 1^\circ\text{C}$ ). Subjects were requested to remove their earrings, if any, prior to the measurements so that the pulse probes could be applied easily to the ear lobes. The measurements were performed whilst subjects lay with supine posture breathing spontaneously. All the ECG and PPG signals were collected continuously and simultaneously for 10 min.

### *2.4. Pulse-to-pulse intervals (PPI) and R-wave-to-R-wave interval(RRI)*

The PPG signal oscillates with the heart cycle period, due to the systolic increase in the tissue

blood volume, resulting in a lower transmission of light (Nitzan *et al* 1998). PPI was defined as the time interval between two successive pulse troughs at the finger and the toe. The successive pulse trough points on the peripheral pulse, the pulse trough (end-systolic minimum) and the pulse peak (end-diastolic) (Nitzan *et al* 1998), could be applied to measure PPI. In this study, PPI is calculated by neighborhood of the PPG minimum, i.e. the trough of the pulse as opposed to the peak of the pulse, where the PPG signal is flat and the little disturbance could cause erroneous determination at the pulse peak.

Figure 1 demonstrates that the RRI is the time period between two successive R-wave peaks of ECG. According to the general consensus (Task Force of the ESC and the NASPE 1996), artifacts, premature beats and non-sinus tachycardia episodes should be edited out of the data prior running the analyses. All time domain measurements are very sensitive to such artifacts and episodes.



**Figure1.** Definition of RRI derived from ECG (a) and PPI derived from PPG (b).

### 2.5. Statistics

Simple time domain variables include the mean NN interval (normal-to-normal RR interval), the mean heart rate and the range of NN interval (the difference between the longest and shortest NN interval). The most commonly used measures derived from interval differences comprise SDNN (the standard deviation of the NN interval), SDSD (the standard deviation of the differences between adjacent NN intervals), RMSSD (the square root of the mean squared differences of successive NN intervals), NN50 (the number of interval differences of successive NN intervals greater than 50 ms), and pNN50 (the proportion derived by dividing NN50 by the total number of NN intervals).

Also, LF (0.04–0.15 Hz) and HF (0.15–0.4 Hz) power components are employed to analyze the results in this study. LF and HF are measured in normalized units (n.u.) [(absolute power)  $\times$  100/(total power – VLF power)] representing the relative value of each power component in proportion to the total power minus the VLF component (Pagani *et al* 1986; Task Force of the ESC and the NASPE 1996). Moreover, the normalization tends to minimize

the effect on the values of LF and HF components of the changes in total power (Task Force of the ESC and the NASPE 1996). Hence, the normalized values are more suitable for evaluations among different measurement positions than the absolute values.

All the parameters, i.e. the mean NN interval, the mean heart rate, the range of NN interval, SDNN, SDDSD, RMSSD, pNN50, LF and HF, were calculated based upon HRV from ECG. With similar principle of the pulse to pulse interval, the fPRV and the ePRV were determined from PPG. The results are presented in Median Values (MV), Interquartile Range (IQR) and Distribution Index (DI). IQR is a measure of statistical dispersion, being equal to the difference between the third and the first quartiles. DI is the ratio of IQR to MV; The larger the Ratio, the more dispersive the distribution.

### 2.6. Geometrical expression

The series of NN intervals were converted into a geometric pattern, such as the sample density distribution of NN interval durations, the sample density distribution of differences between the durations of neighboring NN intervals, Poincaré plot of NN or RR intervals, etc (Task Force of the ESC and the NASPE 1996). The contours of frequency histogram of NN intervals or  $\Delta$ NN intervals show the similar characteristic when the signals come from the same source, e.g. the NN intervals of the same person. The Poincaré plot, where each RR interval is plotted against its successor, can indicate the correlation between consecutive intervals in a geometric manner as displayed by the shape of the cloud of points.

Kurtosis and Skewness coefficients are used to assess the probability distributions of the signal series.

The Kurtosis is defined as:

$$kurtosis = \frac{E[(X - \mu)^4]}{\sigma^4} \quad (1)$$

where  $X$  is the data set, i.e. the RRI or PPI series,  $\mu$  is the mean value of the data set, and  $\sigma$  represents the standard deviation of the data set, and  $E(t)$  represents the expected value of the quantity  $t$ . The Kurtosis measures how sharply peaked a distribution is, relative to its width. A Kurtosis being greater than 3 indicates a leptokurtic data set and a value being less than 3 indicates a platykurtic data set.

The Skewness is defined as:

$$skew = \frac{E[(X - \mu)^3]}{\sigma^3} \quad (2)$$

where  $X$  is the data set, i.e. the RRI or PPI series,  $\mu$  is the mean value of the data set,  $\sigma$  represents the standard deviation of the data set, and  $E(t)$  represents the expected value of the quantity  $t$ . The Skewness measures the asymmetry of the tails of a distribution. A positive Skewness indicates that most of the data is located to the left of the mean and a negative value shows that most of the data is on the right side of the mean.

## 3. Results

The RRI series derived from ECG signal were used as reference data and compared to the PPI

time series derived from PPG signal on finger tip and ear lobe. Figure 2, table 1 and table 2 show the time domain variables, the frequency domain variables, the agreement analysis, and the correlation coefficient analysis in the group. The time domain variables, the frequency domain variables and the geometrical methods in individuals are presented in table 3, table 4, table 5, figure 3 and figure 4.

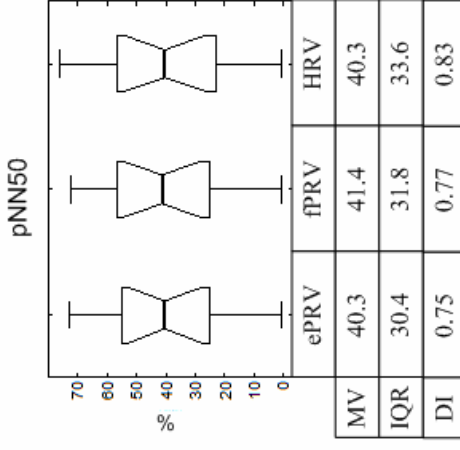
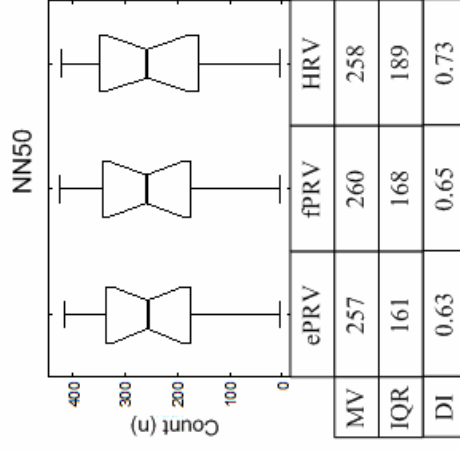
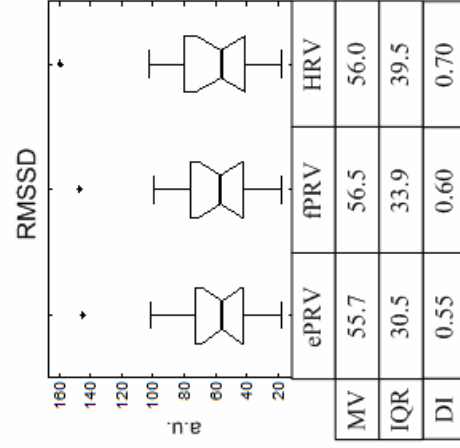
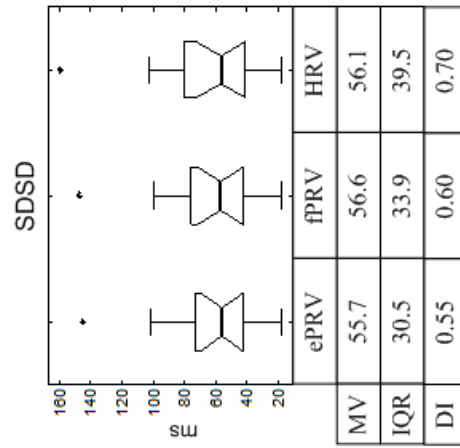
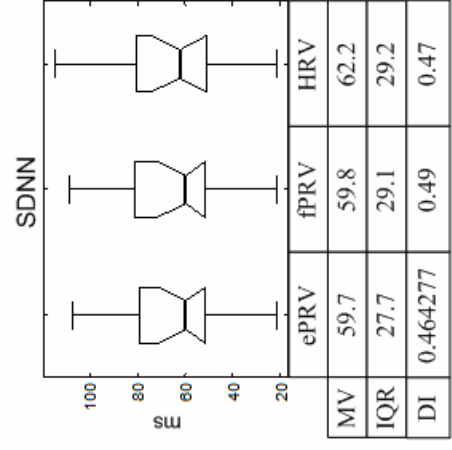
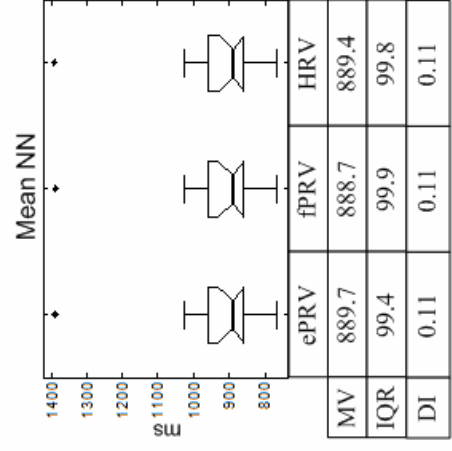
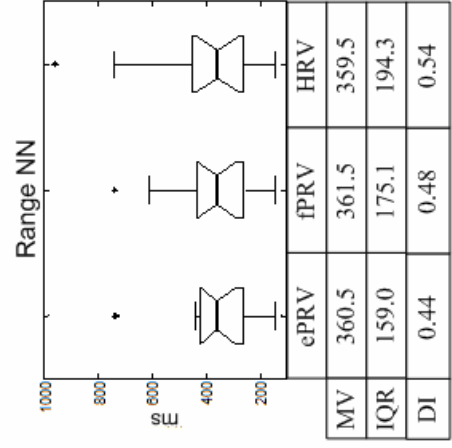
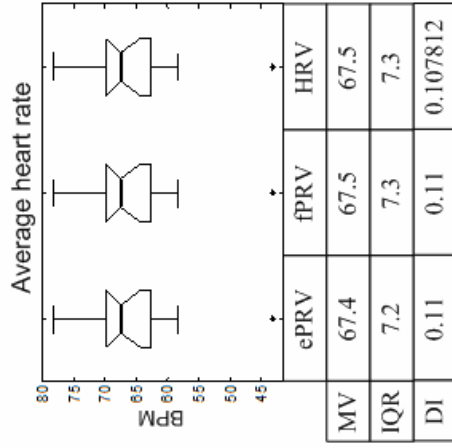
The PRV features derived from the PPG signals are very similar to the HRV derived from the ECG signals. This similarity can be clearly observed in figure 2 where the parameters of the time domain and the frequency domain are used to compare HRV and PRV. The frequency domain parameters from these fourteen subjects depict a decentralized distribution as shown in figure 2.

Bland Altman statistics (Bland and Altman 1986) was used to examine the agreement between HRV and PRVs from the ear and the finger as presented in table 1. The *ratio* of the half range of agreement limits (LA) to the mean of the pairwise means (MPM) was computed and listed in table 1. As indicated in table 1, all *ratios* are below 0.1 except the NN Range, where the *ratios* have a 0.181 of ePRV and 0.157 of fPRV, respectively, The correlation coefficients presented in table 2 are used to compare ePRV and fPRV with corresponding HRV. Except the range NN, where the correlation coefficients are 0.92 and 0.85, respectively, coefficients deviate only 2% or 1%.

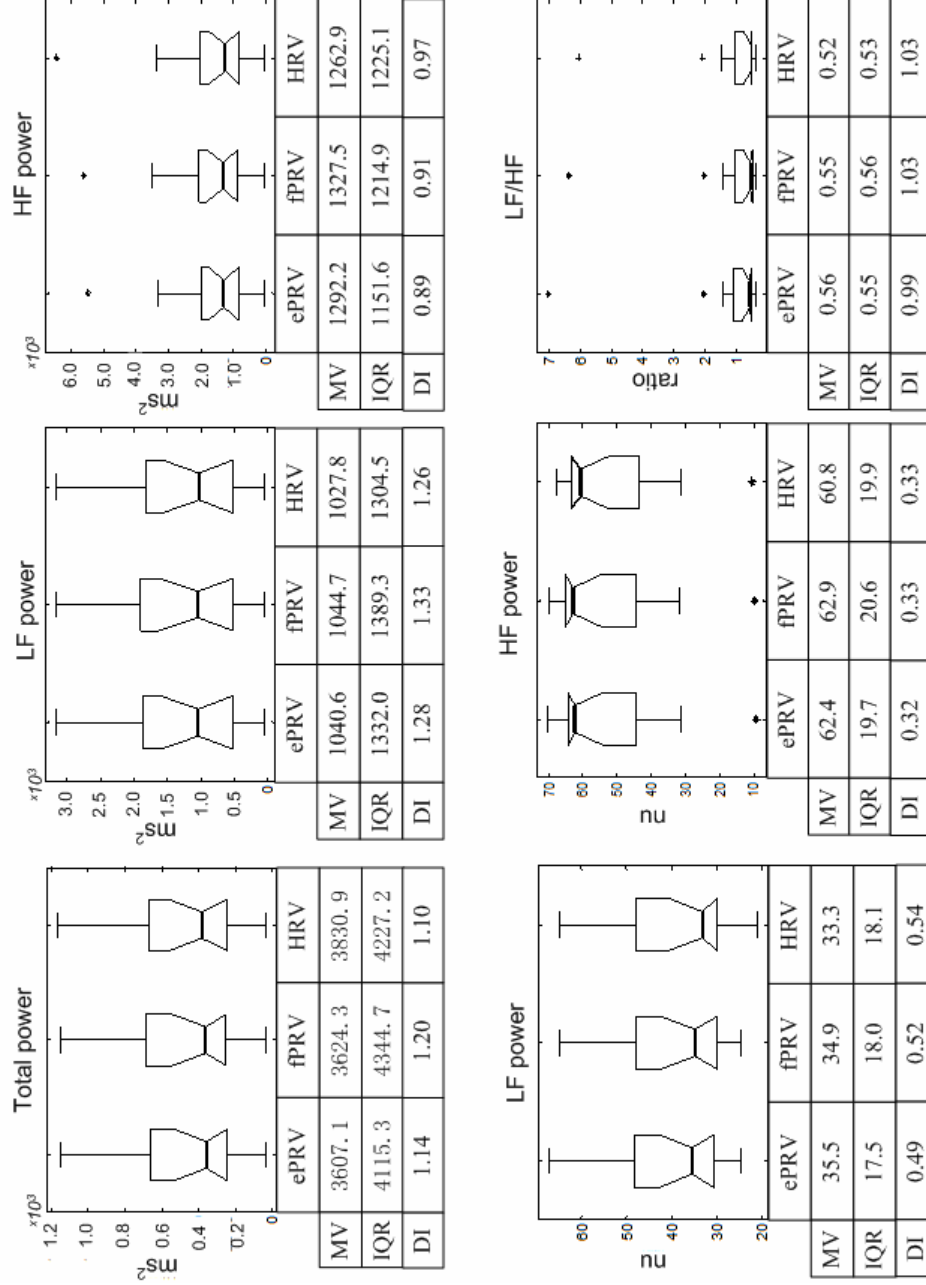
Table 3, table 4, table 5, figure 3 and figure 4 exhibit the agreement between PRV and HRV in individuals. Based upon the principles of Kurtosis and Skewness coefficients, the RRI and PPI variation were listed in the table 3. Table 4 and table 5 list the results of ePRV, fPRV and HRV with the time and the frequency domain for two subjects, differing from those fourteen subjects. The parameters, i.e. the mean NN interval, the mean heart rate, the range of NN interval, SDNN, SDSD, RMSSD, pNN50, LF and HF, are within a receivable range although these parameters are obviously different either in time domain or frequency domain.

The geometrical methods present the shape characteristic of the HRV or PRV, which visually inspect the ECG or PPG signals, e.g. disease detection (Woo *et al* 1994), assessment of nonlinear characteristics of HRV (Brennan *et al* 2001, Qiu *et al* 2005) and evaluation of paced breathing (Guzik *et al* 2007). Herein, figure 3 and figure 4 presents the likeness of the characteristics of HRV and PRV in the geometrical shape in individual subjects. Figure 4 shows that the NN interval from ePRV and fPRV have a more decentralized distribution. The Poincaré plot illustrates the distribution of the NN intervals of fourteen subjects.

(a) Time Domain Variables



(b) Frequency Domain Variables



**Figure 2.** Box-and-whisker plot for (a) time domain variables and (b) frequency domain variables from ePRV, fPRV and HRV. The points beyond the whiskers are displayed with  $*$ . The means and deviations are presented under each figure. MV: Median Values, IQR: Interquartile Range of a sample, IQR presents the range of the majority dates. DI: Distribution Index. DI is the ratio of IQR to MV, the larger the Ratio, the dispersive the distribution.

**Table 1.** Comparisons between ePRV or fPRV of PPG and HRV of ECG.

	Average HR		Range NN		Mean NN		SDNN		SDSD		RMSSD	
	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV
Limits of agreement(LA) 95%-CI	-0.0147 to 0.016	-0.0295 to 0.0192	-108 to 29.2	-101.1 to 16.6	-0.259 to 0.180	-0.236 to 0.438	-2.63 to 0.41	-2.11 to 0.94	-6.94 to 0.43	-5.83 to 1.41	-6.94 to 0.43	-5.82 to 1.41
Range LA	$3.07 \times 10^{-2}$	$4.87 \times 10^{-2}$	137	118	0.439	0.674	3.04	3.04	7.38	7.24	7.37	7.23
Mean of pairwise means[MPPM]	65.6	65.6	379	376	932	932	62.5	63.1	62.7	63.8	62.7	63.7
Std MPPM	5.8	5.9	123.9	111.7	105.1	105.3	17.8	18.0	23.73	24.0	23.7	24.0
Ratio: 0.5*range(LA)/MPPM	$2.34 \times 10^{-4}$	$3.71 \times 10^{-4}$	0.181	0.157	$2.35 \times 10^{-4}$	$3.61 \times 10^{-4}$	0.024	0.024	0.059	0.057	0.059	0.057

	NN50		pNN50		Total power		NN50		pNN50		Total power	
	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV	ePRV	fPRV
Limits of agreement(LA) 95%-CI	-12.9 to 0.43	-9.64 to 2.36	-1.65 to 0.28	-1.06 to 0.62	-338 to 52.43	-259 to 117	-12.9 to 0.43	-9.64 to 2.36	-1.65 to 0.28	-1.06 to 0.62	-338 to 52.43	-259 to 117
Range LA	13.3	12.0	1.94	1.68	390	376	13.3	12.0	1.94	1.68	390	376
Mean of pairwise means[MPPM]	233.7	236.3	37.2	37.6	0.004	0.005	233.7	236.3	37.2	37.6	0.004	0.005
Std MPPM	91.5	93.2	15.6566	15.8	0.002	0.002	91.5	93.2	15.6566	15.8	0.002	0.002
Ratio: 0.5*range(LA)/MPPM	0.0284	0.0254	0.0260	0.0223	0.0437	0.0414	0.0284	0.0254	0.0260	0.0223	0.0437	0.0414

LF(ms)