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Heart Rate Variability: Rescaling and Normalization

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Abstract**: *Heart rate variability (HRV) is a useful measure to evaluate activity of the autonomic nervous system (ANS) and monitor both pathological and psychological conditions. However, HRV analysis still has difficulties with changes in HRV parameters due to an increase or decrease in the average heart rate. At present, the interpretation of the average changes in HRV datasets and their HRV parameters is not fully understood. Therefore, this study aimed to analyze how much deviation in HRV parameters occurs from rescaling tachograms and normalizing HRV datasets. Four rescaled tachograms and their corresponding normalized HRV datasets were created by increasing the average heartbeat from 50 to 110 bpm in 20 bpm steps. The difference in low frequency powers (Ln LFs) calculated between two successive rescaled groups was 0.89, 1.03, and 1.04, as the average heartbeat increased from slow to fast, while the difference in high frequency powers (Ln HFs) was 1.06, 1.53, and 1.37. However, in the four normalized HRV datasets, the difference in Ln LFs and Ln HFs between two successive normalized groups was -0.28 and -0.12, 0.31 and 0.27, and 0.31 and 0.37, respectively. The results suggest that the normalized HRV datasets are more valuable than the individual rescaled-tachogram HRV dataset for obtaining measurements using frequency-domain HRV parameters for HRV analysis in clinical applications.***

Keywords**: *Heart rate variability, frequency power, rescaling, autonomic nervous system, normalization, tachogram.***

I. INTRODUCTION

Heart rate variability (HRV) analysis is widely used in clinical applications to monitor the balance between the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) and changes in autonomic nervous system (ANS) activity. HRV data consist of the set of all individual heartbeats measured between two successive normal-to-normal (NN) intervals in the time series in milliseconds. The patterns and fluctuations in HRV datasets are classified in terms of all HRV parameters in frequency, time, and geometric domains, leading to the extraction of important cardiovascular information [1, 2, 3, 4]. Among the frequency-domain HRV parameters that have mainly been considered are the low frequency power (Ln LF) and the high frequency power (Ln HF), which represent a mix of SNS and PNS activities and the majority of PNS activities, respectively [5, 6, 7]. For the geometric-domain parameters, Poincare plot analysis has frequently been performed for discriminating a young or healthy person from a person with any disease symptoms [8, 9, 10].

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The coefficient of variation for the NN intervals (CVAA) has been used as an HRV index for investigating cardiac automatic activity and ANS activities among different workers in an industrial environment [11, 12, 13]. However, one unresolved problem in HRV analysis arises from changes in HRV parameters as a result of a nonlinear relationship between NN intervals in milliseconds and their corresponding heart rate in beats per minute (bpm). Fig. 1 demonstrates that a gradual increase in the average heart rate from 50 to 110 bpm in 20 bpm steps, which correspond to step1 to step4 in the graph, produces an exponential decrease in the NN interval. Even though HRV datasets contain the same frequency components, frequency-domain HRV parameters can change according to the magnitude of the mean heart rate. At present, it is difficult to make detailed interpretations between HRV datasets in terms of heart rate in bpm and the NN interval in milliseconds. Therefore, the purpose of this study is to analyze a degree to which four different HRV datasets (step1 to step4) are different from each other in terms of HRV parameters and propose a normalization technique for overcoming these shortcomings. The four corresponding tachograms were rescaled to have a range of 20 bpm between the maximum and minimum values, and the average heart rate was increased by 20 bpm four times. It was found that the Ln LF/Ln HF ratio, which corresponds sympathovagal balance, increases with an increase in the mean heart rate of the tachogram-rescaled HRV datasets, while the Ln LF/Ln HF ratio remained relatively stable for the normalized HRV datasets. The results suggest that for a patient with a heart rate higher than the average of 80 bpm, frequency-domain HRV parameters should be compensated in order to avoid a false conclusion in evaluating ANS balance.

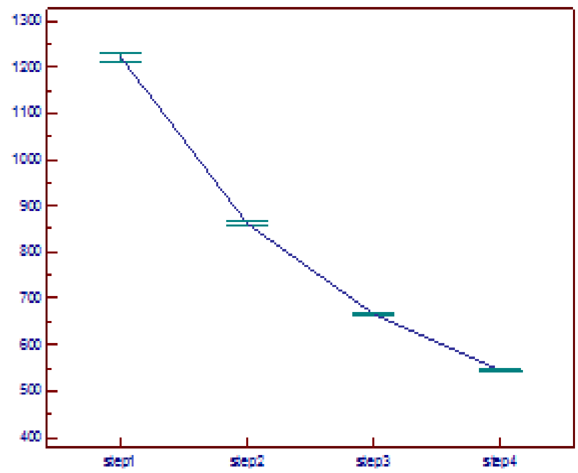

Fig. 1. Nonlinear relationship between average heart rate and NN interval in milliseconds.

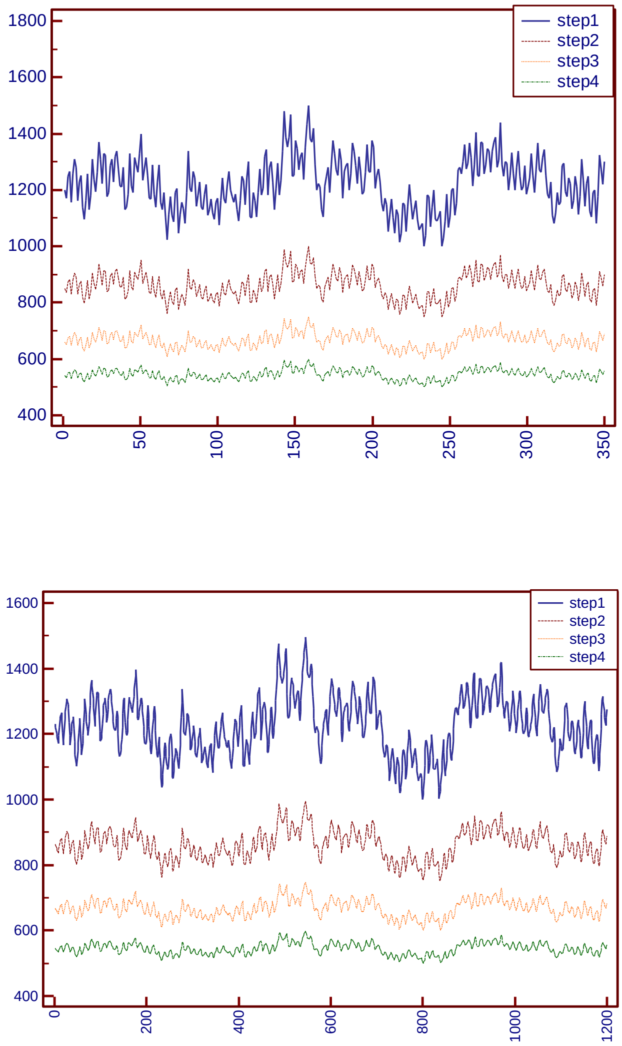

Fig. 2. Four rescaled-tachogram HRV datasets; (top) original datasets and (bottom) resampled datasets including linear interpolation.

II. RESCALING THE HRV TACHOGRAMS

The HRV datasets were grouped into four categories according to the overall average heart rates of the original tachograms obtained over a 5 min period; 50, 70, 90, and 110 bpm, whose groups were named step1, step2, step3, and step4, respectively. The range of the heart rate depends on the nature of the data. In this study, the ranges of step1, step2, step3, and step4 were between 40 and 60 bpm, 60 and 80, 80 and 100, and 100 and 120 bpm, respectively. Five-minute HRV datasets were obtained from the index finger using a photoplethysmogram (PPG)-based HRV analyzer (TAS9VIEW/Canopy9 RSA, IEMBIO Ltd., Chuncheon, Gangwon-do, South Korea). The rescaling algorithm is a recently developed method that rescales a range of heart rates between an arbitrary set of heart rate values between [a, b], where a and b indicate the minimum and maximum heart rates in bpm, respectively. The formula is as follows:

$$NN[x] = a + \frac{(NN[x]-minNN[x]))(b-a)}{maxNN[x]-minNN[x]} \quad (1)$$

The rescaled-tachogram HRV datasets, NN[x], are prepared for power spectral estimates after resampling NN[x] in the time domain. The resampling process is essential for analyzing frequency-domain HRV parameters. Upsampling among resampling algorithms was introduced to generate an exact 1024 data points from a range of approximately 350 data points because the number of raw data points over a 5 min period depends on both the measurement period and the heart rate itself. After resampling, a linear interpolation algorithm was applied to increase the frequency resolution. Linear interpolation draws straight lines between two data points. For a value x in the interval (x0, x1), the value y = NN[x] along a straight line is obtained from the following equations:

$$\frac{y-yo}{x-xo} = \frac{y1-yo}{x1-xo} \quad (2)$$

$$y = yo\left(1 - \frac{x-xo}{x1-xo}\right) + y1(1 - \frac{x1-x}{x1-xo}) \quad (3)$$

Fig. 2 plots the original raw data with 350 data points (top) and the resampled data with 1024 data points (bottom) after the linear interpolation. The interpolated HRV data are transferred to a power spectral analysis module that includes a fast Fourier transform (FFT).

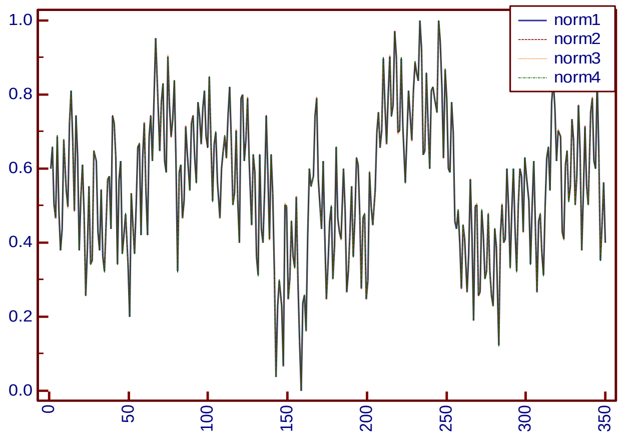

Fig. 3. Normalized HRV datasets with a range of [0, 1].

III. MIN-MAX NORMALIZATION OF THE HRV

Min-max normalization is the simplest method to rescale the full range of heartbeats to a range of [0, 1]. The HRV datasets were grouped into four categories, that correspond to the step1, step2, step3, and step4 rescaled HRV groups: norm1, norm2, norm3, and norm4. The purpose of normalization is to obtain the purely oscillating components of HRV by completely removing the DC components. Normalization to a range between 0 and 1 for HRV datasets could lead to more accurate frequency-domain HRV parameters regardless of changes in the average heart rate. The general formula for obtaining a min-max normalization between [0, 1] is as follows:

$$NN[x] = \frac{NN[x]-minNN[x]}{maxNN[x]-minNN[x]} \quad (4)$$

Fig. 3 shows the four HRV datasets normalized to a range of [0, 1]. Despite the different average heartbeats, data of the four normalized groups are perfectly aligned.

The normalized HRV datasets, NN[x], can then be subjected to the FFT algorithm after resampling in the time domain and linear interpolation.

IV. HRV PARAMETERS

Table- I shows all HRV parameters obtained from frequency, time, and geometric domains. The standard deviation (SD) of NN intervals (SDNN), RMSSD, and pNN50 are in time domains, with SDSD, CVAA, TINN, ApEn, SD1, SD2, and SD2/SD1 ratio in geometric domain. The remaining HRV parameters are in frequency domain. The value of Diff Ln LF or Diff Ln HF indicates the difference between in-groups, such as the four rescaled categories (steps) and their corresponding normalized categories (norms).

Table- I HRV parameters

TP	ms^2	Area under the entire power spectral curve, VLF+LF+HF
Ln VLF	ms^2	Natural logarithmic value of very low frequency power, bands of 0.0033-0.04 Hz
Ln LF	ms^2	Natural logarithmic value of low frequency power, bands of 0.04-0.15 Hz
Diff Ln LF	ms^2	Difference of Ln LFs between two successive HRV groups
Ln HF	ms^2	Natural logarithmic value of high frequency power, bands of 0.15-0.40 Hz
Diff Ln HF	ms^2	Difference of Ln HFs between two successive HRV groups
LF norm	nu	Normalized low frequency power
HF norm	nu	Normalized high frequency power
Ln LF/Ln HF		Ratio of the low to high frequency power
SDNN	ms	The standard deviation of all NN intervals
RMSSD	ms	The square root of the mean of the sum of the squares of differences between adjacent NN intervals
SDSD	ms	The standard deviation of the differences between adjacent NN intervals
CVAA	%	Coefficient of variation of the a-a intervals
TINN	ms	Baseline width of the minimum square difference triangular interpolation of the highest peak on the NN interval histogram
ApEn		Approximate entropy
SD1	ms	One standard deviation of the length of the transverse line on the Poincare plot
SD2	ms	Two standard deviation of the length of the longitudinal line on the Poincare plot
SD2/SD1		Ratio of SD1 to SD2
pNN50	%	Ratio of the count that change between two successive NN intervals exceeds 50 ms to the total beat count.

V. STATISTICAL ANALYSIS

Statistical analyses were performed using a statistics software program (MedCalc, Ostend, Belgium) to compare the HRV parameters between rescaled and normalized HRV dataset groups.

One sample t-tests were performed to determine the statistical significance between in-groups for each frequency-domain HRV parameter. Neither an upper-tailed nor a lower-tailed hypothesis was used because the direction of the difference between the sample mean and the comparison value was not under consideration.

The relative standard deviation (RSD) and the standard error of the mean (SEM) were calculated for the rescaled HRV groups, because they are useful for indicating the spread between in-groups.

In addition, it was not important in this study to check the participant's health status because the purpose of the study was to investigate a degree which to the average heart rate affects the HRV parameters.

Table- II. Statistical analysis of the four different rescaled tachograms; 40-60 bpm (step1), 60-80 bpm (step2), 80-100 bpm (step3), and 100-120 bpm (step4).

	step1	step2	step3	step4
n	333	333	333	333
Mean	1221	860	666	544
95% CI	1211-1231	855-865	663-669	542-546
Variance	8507.09	2127.36	766.15	340.01
RSD	0.07549	0.05358	0.04153	0.03387
SEM	5.0544	2.5275	1.5168	1.0105
Minimum	1000	750	600	500
Maximum	1500	1000	750	600
Normal Distribution	0.3322	0.3291	0.3365	0.3165

VI. RESULTS AND DISCUSSION

All HRV parameters, including those in frequency, time, and geometric domains were calculated for the four rescaled-tachogram HRV datasets (step1 to step4) and their four corresponding normalized datasets (norm1 to norm4). The ratio of SD2 to SD1 among the Poincare indices remained unchanged across the four different categories of tachograms, while the frequency-domain HRV parameters, such as Ln LF and Ln HF, did change, as shown in Table- III. The value of the SD2/SD1 ratio can be used to identify how similar the patterns of the HRV datasets are regardless of the increase or decrease in the average heart rate. In some studies, a significant correlation between the SD2/SD1 ratio, LF, and HF powers was reported during changes in subjects' position that caused an increase in the heart rate [14].

Postural change, of course, would have reflected an abrupt change in the heart rate generated by changes in the activities of the ANS and a variety of physiological conditions. However, our results suggest that the SD2/SD1 ratio could serve as a new biomarker when investigating the influence of larger changes in the heart rate than in the patterns of the heartbeats on the HRV parameters. The largest change among the HRV parameters was pNN50%, with 61.86 for step1, 20.42 for step2, 0.90 for step3, and 0.00 for step4. Because pNN50% is defined as dividing NN50, the number of successive NN intervals that exceeds 50 ms, by the total beat count, the value of pNN50% decreases with increasing overall average heart rates. A pNN20% threshold as low as 20 ms has been proposed for distinguishing physiological and pathological groups [15]. However, although pNN50%, is a widely used measure of HRV, whether the best thresholds greater or less than 50 ms has not yet been described. Regarding HRV analysis using pNN50%, more studies are required to establish a relationship between pNN50% and ANS balance. ApEn changed slightly across the different rescaled-tachogram HRVs, with values of 1.0835 for step1, 1.1841 for step2, 1.1652 for step3, and 1.1278 for step4. The difference between the maximum and minimum values of ApEn was only 3.93%, indicating that neither increasing nor decreasing the average heart rate would have a significant impact on this HRV parameter, while the patterns of the heart rate representing the frequency components were maintained. In the frequency domain, the Ln HF value dropped faster than the Ln LF value as the average heart rate increased in 20 bpm steps from step1 to step4. The difference in the Ln LFs obtained between two successive step groups was 0.89 between step1 and step2, 1.03 between step2 and step3, and 1.04 between step3 and step4, while the changes in the Ln HF values were 1.06, 1.53, and 1.37, respectively. Likewise, the differences in the Ln LFs and Ln HFs between two successive norm groups were -0.28 and -0.12, 0.31 and 0.27, and 0.31 and 0.37, respectively, as seen in Table- IV. The Ln LF/Ln HF ratio was 1.05 for step1, 1.07 for step2, 1.22 for step3, and 1.48 for step4. This means that even though the HRV datasets have the same patterns, the frequency-domain HRV parameters could be largely affected by a slight increase or decrease in the average heart rate. Each time the average heart rate increased by 20 bpm, the percentage changes in downward speed for Ln LF (Ln HF) were 16.8% (19.3%), 21.5% (39.0%), and 27.7% (53.8%) between each successive step group. The values of the HRV index and SDSD decreased from step1 to step2 in the same trend as those of Ln LF and Ln HF. The Ln LF/Ln HF ratio has been considered an important measure that indicates sympathetic to parasympathetic autonomic balance in many studies. However, the Ln LF/Ln HF ratio has been criticized for failing to represent sympathovagal balance [16]. The reason for obscuring the interpretation of the Ln LF/Ln HF ratio among the frequency-domain HRV parameters has been reported to be the significant changes caused by increases or decreases in the averaged heart rate. This criticism is acceptable considering the results obtained in this study. To overcome the problems of the rescaled-tachogram HRV datasets, normalization methodology was introduced. Min-max normalization was applied before the HRV parameters were calculated. All HRV parameters in the frequency domain were stabilized compared to those obtained with the rescaled-tachogram methodology. The values of Ln LF and Ln HF across the four normalization categories of norm1 to norm4 that correspond to the changes in the average heart rate from step1 to step4 were 7.31 and 6.74 for norm1, 7.39 and 6.86 for norm2, 7.08 and 6.59 for norm3, and 6.77 and 6.22 for norm4, respectively, as shown in Table- IV. The SDs of Ln LF and Ln HF were 0.2692 and 0.2779, respectively, compared to 1.3144 and 1.7354 for the rescaled-tachogram groups. The SDs for the min-max normalization were much lower than those for the rescaled-tachogram. The RSD and SEM for Ln LF (Ln HF) for the min-max normalization were 0.03776 (0.04209) and 0.1346 (0.1389), respectively, while the RSD and SEM for Ln LF (Ln HF) for the rescaled-tachogram were 0.2480 (0.3767) and 0.6572 (0.8677), respectively. The Ln LF/Ln HF ratio after min-max normalization, regardless of the changes in the average heart rate, was 1.08 for norm1, norm2, and norm3 and 1.09 for norm4. The SD, RSD and SEM of the Ln LF/Ln HF ratio between two successive groups were 0.005, 0.004619, and 0.0025, respectively, while those for the rescaling methodology were 0.1984, 0.1647, and 0.09921. The values of the t statistic for Ln LF, Ln HF, and Ln LF/Ln HF ratio were 52.97249 ($p<0.0001$), 47.51814 ($p<0.0001$), and 433.00000 ($p<0.0001$), respectively, after normalization, as seen in Table- V; all three values indicated statistical significance. All frequency-domain parameters were obtained to a sufficiently stable degree to induce a useful interpretation of the HRV. Fig. 4 and Fig. 5 show ANS charts representing changes in the balance between parasympathetic and sympathetic activities by plotting Ln LF on the x-axis and Ln HF on the y-axis after applying the normalization and rescaling methods.

Table- III All HRV parameters obtained from the rescaled HRV datasets.

	step1	step2	step3	step4
Mean NN	1221	860	666	544
Mean HR	49	69	89	110
SDNN	92.10	46.05	27.64	18.41
RMSSD	77.40	38.68	23.23	15.50
HRV index	17.53	12.33	7.57	6.17
pNN50 %	61.86	20.42	0.90	0.00
ApEn	1.0835	1.1841	1.1652	1.1278
SD1	54.81	27.39	16.45	10.98
SD2	118.50	59.26	35.56	23.68
SD2/SD1	2.16	2.16	2.16	2.16
Ln sArea	9.92	8.54	7.52	6.71
SDSD	77.28	38.62	23.20	15.48
TINN	453.00	230.00	136.00	93.00
CVAA %	7.54	5.35	4.15	3.38
Ln TP	8.45	7.42	6.50	5.80
Ln VLF	8.01	7.00	6.20	5.61
Ln LF	6.81	5.83	4.80	3.76
Diff Ln LF	0	0.89	1.03	1.04
Ln HF	6.51	5.45	3.92	2.55
Diff Ln HF	0	1.06	1.53	1.37
Ln LF/Ln HF	1.05	1.07	1.22	1.48
LF norm	57.47	59.54	70.71	77.11
HF norm	42.53	40.46	29.29	22.89
LF/HF norm	1.35	1.47	2.41	3.37

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Table- IV Frequency-domain HRV parameters obtained from the normalized datasets.

	Norm1	norm2	norm3	norm4
Ln TP	8.76	8.74	8.59	8.44
Ln VLF	8.30	8.21	8.16	8.08
Ln LF	7.31	7.39	7.08	6.77
Diff Ln LF	0	-0.28	0.31	0.31
Ln HF	6.74	6.86	6.59	6.22
Diff Ln HF	0	-0.12	0.27	0.37
Ln LF/Ln HF	1.08	1.08	1.08	1.09
LF norm	63.88	62.86	62.15	63.26
HF norm	36.12	37.14	37.85	36.74
LF/HF norm	1.77	1.69	1.64	1.72

Table- V Statistical analysis of one sample t-tests for the rescaled-tachogram and normalized HRV datasets.

		t statistic	*p*	95% CI
step (rescaling)	Ln LF	5.30000	0.0040	3.2086-7.3914
	Ln HF	5.30989	0.0130	1.8460-7.3690
	Ln LF/Ln HF	12.14654	0.0012	0.8893-1.5207
norm (normalization)	Ln LF	52.97249	<0.0001	6.7016-7.5584
	Ln HF	47.51814	<0.0001	6.1603-7.0447
	Ln LF/Ln HF	433.0000	<0.0001	1.0745-1.0905

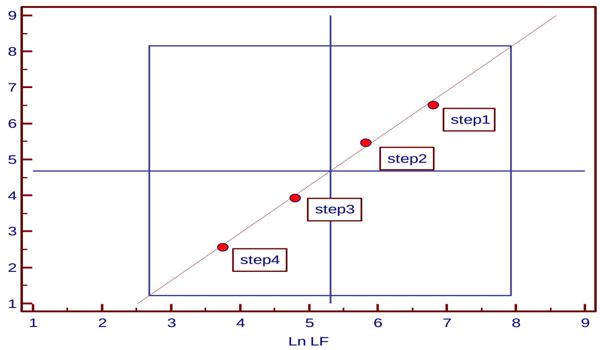

Fig. 4. ANS balance chart for the four different rescaled-tachogram HRV datasets.

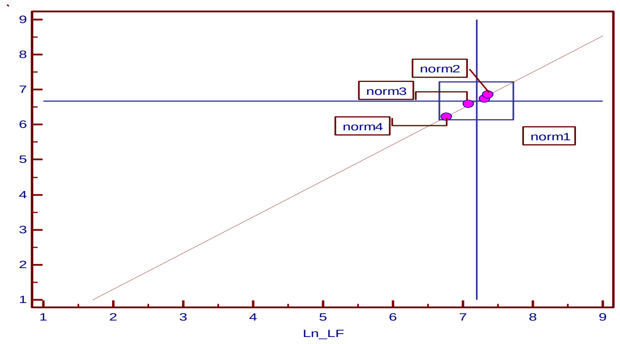

Fig. 5. ANS balance chart for the four normalized HRV datasets.

VII. CONCLUSION

The variability in the heartbeats remained unchanged by the rescaling tachogram algorithm, with the average beats per minute being increased from approximately 50 to 110 bpm in 20 bpm steps. All HRV parameters for the four rescaled-tachogram HRV datasets were independently obtained, including those in the frequency, time, and geometric domains. The results demonstrated that the various HRV measurements could be confusing if different average heart rates were presented despite the same patterns in the heart beats. An adequate rescaling algorithm suitable for a range of average heart rates prior to HRV analysis was needed. The values of Ln LF and Ln HF differed by over 15% between two successive rescaled-tachogram HRV datasets. Meanwhile, when each of the four rescaled-tachogram HRV datasets was normalized with the min-max normalization technique, there were no significant differences between each of the values of Ln LF and Ln HF. Therefore, the normalization method is recommended for obtaining stable measurements for HRV analysis when information about the magnitude of the average heart rate is not important. Consequently, frequency-domain HRV parameters that have been widely used for evaluating ANS balance were acceptable in the normalized HRV datasets. In conclusion, except for the importance of the average heart rates, normalized HRV datasets are more valuable than rescaled-tachograms for utilizing HRV parameters in clinical applications.

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