BEHAVIOUR OF GLOBALLY CHAOTIC PARAMETERS OF HEART RATE VARIABILITY FOLLOWING A PROTOCOL OF EXERCISE WITH FLEXIBLE POLE

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Aim. The aim of this study was to evaluate the effect of flexible pole exercise on cardiac autonomic modulation. This was investigated while at rest before and, then in the recovery phase from the flexible pole exercise.

Material and methods. Thirty-two female subjects were allocated to equal groups. The analysis of cardiac autonomic modulation was through the recording of temporal separations of interpeak RR intervals taken from the heart rate monitor. The analysis was performed by chaotic global measures of heart rate variability (HRV). Two parameters were proposed based on the greater resolution of multi-taper method (MTM) power spectra. They were high spectral entropy (*hs*Entropy) and high spectral detrended fluctuation analysis (*hsDFA*) and were applied owing to the greater parametric response in short data series. After applying Anderson-Darling and Lilliefors tests for confirmation of high non-normality; Kruskal-Wallis test of significance was used for the statistical analysis, with the level of significance moderately set at (p<0.15).

Results. On recovery from flexible pole exercise there was a significant decrease in three of the combinations of CFP. The algorithm which applied all three chaotic global parameters was the optimum statistically measured by Kruskal-Wallis and standard deviation. It was also the most influential by principal component analysis (PCA) with almost all variation covered by the first two components.

Conclusion. Flexible pole exercise leads to a further significant decrease in chaosity measured by the combination of chaotic globals.

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Key words: cardiovascular system, autonomic nervous system, flexible pole exercise, chaotic globals.

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HRV — heart rate variability, IPAQ — International Physical Activity Questionnaire, MTM — multi-taper method, ANS — autonomic nervous system, sDFA — Detrended Fluctuation Analysis, DPSS — discrete prolate spheroidal sequences, CFP — Chaotic Forward Parameter, PCA — Principal Component Analysis.

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ПОВЕДЕНИЕ ГЛОБАЛЬНО ХАОТИЧЕСКИХ ПАРАМЕТРОВ ВАРИАБЕЛЬНОСТИ СЕРДЕЧНОГО РИТМА ПОСЛЕ ПРОТОКОЛА ТРЕНИРОВКИ С ГИБКИМ ШЕСТОМ

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Цель. Целью данного исследования явилась оценка влияния упражнения с гибким шестом на кардиальную вегетативную модуляцию. Исследование было проведено в состоянии покоя до и, затем в фазе восстановления после выполнения упражнения с гибким шестом.

Материал и методы. Тридцать две женщины были разделены на две равные группы. Анализ кардиальной вегетативной модуляции проводился путем регистрации временных разделений interpeak RR интервалов, полученных при мониторировании сердечного ритма. Анализ проводился хаотическими глобальными измерениями вариабельности сердечного ритма (ВСР). Предполагалось, что два параметра были основными в большем разрешение мульти-конического метода (МТМ) спектра мощности. Это были методы высокой спектральной энтропии (hsEntropy) и анализа высокого спектрального колебания с исключенным трендом (hsDFA) и были применены как обладающие большим параметрическим ответом при исследованиях коротких периодов данных. После применения тестов Андерсона-Дарлинга и Lilliefors для подтверждения высокой аномальности, тест значимости Крускала-Уоллиса был использован для статистического анализа, среднем при уровне значимости (p<0,15).

Результаты. При восстановлении после тренировки с гибким шестом наблюдалось значительное снижение трех комбинаций из CFP. Алгоритм, который применяется во всех трех хаотических глобальных параметрах, статистически оптимально измеряется Крускала-Уоллиса и стандартным отклонением. Он также является самым влиятельным методом главного компонентного анализа с большинством вариаций, которые охватывают первые два компонента.

Заключение. Упражнение с гибким шестом приводит к дальнейшему значительному снижению chaosity и измеряется сочетанием хаотических глобальных измерений.

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Ключевые слова: сердечно-сосудистая система, вегетативная нервная система, упражнения с гибким шестом, хаотические глобальные измерения.

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During the aerobic exercise the increased parasympathetic withdrawal and sympathetic activity elicit heart rate increase and reduce heart rate variability (HRV). Immediately after exercise the parasympathetic reactivation is responsible for heart rate recovery and HRV increase [1]. The flexible pole is an instrument with mass 0,8 kg and around 150 cm in length. This tool provides oscillation caused by periodic movements of the upper limbs. The frequency of the flexible pole provides resistance during exercises. Exercise protocols using the flexible pole were shown to present positive results in shoulder muscle function training [2]. However, it is not clear the quantitative level or direction of cardiac autonomic response after a standardized protocol of exercise with this instrument. Thus, this study aimed to investigate the acute effects of an exercise protocol with flexible pole on the globally chaotic parameters of HRV.

Material and methods

Study Population. The subjects were 32 healthy female students, all nonsmokers, aged between 18 and 25 years. All volunteers were informed about the procedures and objectives of the study and gave written informed consent. All study procedures were approved by the Ethics Committee in Research of the Faculty of Sciences of the Universidade Estadual Paulista, Campus of Marilia (No. 0554-2012), and were in accordance with Resolution 196/96 National Health 10/10/1996.

We did not include subjects that reported the following conditions: cardiopulmonary, psychological, neurological related disorders and other impairments that prevent the subject known to perform procedures, and treatment with drugs that influence cardiac autonomic regulation. Volunteers were not evaluated on 10-15 days and 20-25 days after the first day of the menstrual cycle [3]. We also excluded physically active subjects according to the International Physical Activity Questionnaire (IPAQ) [4].

Initial Evaluation. Baseline information collected included: age, gender, weight, height and body mass index (BMI). Weight was determined using a digital scale (W 200/5, Welmy, Brazil) with a precision of 0.1 kg. Height was determined using a stadiometer (ES 2020, Sanny, Brazil) with a precision of 0.1 cm and 2.20 m of extension. BMI was calculated with weight in kilograms and height in meters.

Exercise with flexible pole. The exercises with the flexible pole were conducted with volunteers at standing position with feet apart (wide base) and shoulder flexion as the proposed position. To maintain the proper shoulder flexion in each upper limb it was used as a target visual feedback. All exercises were performed for 15 seconds with 50-60 seconds of rest between each exercise. Three repetitions were performed for each exercise. HRV was analyzed during 10 min at control rest and during 10 min during recovery from the exercise protocol. (Figure 1)

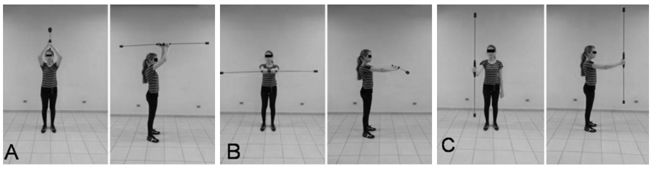

Figure 1. The exercise protocol was composed by the following exercise with both arms on three positions: i) with shoulders at approximately 180° of flexion with the flexible pole on the frontal plane, parallel to the ground (Figure 1A), ii) with the shoulders on 90° of flexion with the flexible pole on the transverse plane (Figure 1B), and iii) one shoulder at 90° of flexion with the flexible pole on the sagittal plane, perpendicular to the ground (Figure 1C).

HRV analysis. The RR intervals recorded by the portable HR monitor (with a sampling rate of 1000 Hz) were downloaded to the Polar Precision Performance program (v.3.0, Polar Electro, Finland). The software enabled the visualization of HR and the extraction of a cardiac period (RR interval) file in "txt" format. Following digital filtering complemented with manual filtering for the elimination of premature ectopic beats and artefacts, 500 RR intervals were used for the data analysis. Only series with sinus rhythm greater than 95% were included in the study.

Protocol. Data collection was undertaken in the same soundproof room for all volunteers; the temperature was between 21°C and 25°C and the relative humidity was between 50 and 60%. Volunteers were instructed not to drink alcohol, caffeine or other autonomic nervous system (ANS) stimulants for 24 hours before the evaluation. Data were collected on an individual basis, always between 18:00 and 21:00 to avoid circadian influences. All procedures necessary for the data collection were explained to each subject separately, and the subjects were instructed to remain at rest and avoid talking during the collection. HRV was analysed in the following periods: control protocol — the 10-minute periods before the performance of the task and the 5-minute periods during the performance of the test.

Chaotic Assessment

Multi-Taper Method: Power Spectrum. A potential criticism in previous studies on diabetes [5] and childhood obesity [6] with respect to chaotic global parameters is that the spectral entropy [7] and spectral Detrended Fluctuation Analysis (sDFA) [8] analysis may be more sensitive if we applied the Shannon entropy [9, 10] and DFA [11, 12] algorithms to the multi-taper spectrum [13] rather than the Welch power spectrum [14]. Thus the spectra applied in all three chaotic global parameters would match. This is pertinent here since the number of RR interval is low at 500. Typically we have examined double this amount when applying Welch power spectrum [14] for spectral entropy and sDFA.

Multi-Taper Method (MTM) [13] is useful for spectral estimation and signal reconstruction, of a time series of a spectrum that may contain broadband and line compo-

Table 1

The table below shows the Kruskal-Wallis test of signficance by p-value of [CFP 1-7] for 500 RR intervals from control rest to recovering from the exercise protocol with flexible pole

Combination of Chaotic Globals [CFP1-7]	Kruskal Wallis (p-value)
CFP1	0,1397
CFP2	0,7935
CFP3	0,0469
CFP4	0,2482
CFP5	0,4809
CFP6	0,1379
CFP7	0,5063

nents. MTM is non-parametric since it does not apply an *a priori*, parameter dependent model of the process that generated the time series under analysis. MTM reduces the variances of spectral estimates by using a small set of tapers. Data is pre-multiplied by orthogonal tapers created to minimize the spectral leakage owing to the finite length of the time series. A set of independent approximations of the power spectrum is calculated. Functions identified as discrete prolate spheroidal sequences (DPSS) [15] optimize the tapers. They are defined as eigenvectors of a Rayleigh-Ritz minimization problem [16].

Chaotic Globals. *High spectral* entropy (*hs*Entropy) is a function of the irregularity of amplitude and frequency of the power spectrums peaks. It is derived by applying Shannon entropy to the MTM power spectrum. The parameters for MTM are: (i) sampling frequency of 1Hz; (ii) time bandwidth for the DPSS is 3; (iii) FFT length of 256; (iv) Thomson's adaptive nonlinear combination method to combine individual spectral estimates. This output is then normalized so that the sum of the magnitude is equal to unity; giving a normalized power spectrum. We then calculate an intermediate parameter which is the median Shannon entropy of the value obtained from three different power spectra using the MTM power spectra under three test conditions: a perfect sine wave, uniformly distributed random variables, and finally the experimental oscillating signal. These values are then again normalized mathematically so that the sine wave gives a value of zero, uniformly random variables give unity, and the experimental signal between zero and unity. It is this final value that corresponds to *hs*Entropy.

To obtain *high spectral* Detrended Fluctuation Analysis (*hs*DFA) we calculate the spectral adaptation in exactly the same way as for *hs*Entropy using a MTM power spectrum with the same settings; but DFA rather than Shannon entropy is the algorithm applied.

Spectral Multi-Taper Method (sMTM) [8] is founded on the increased intensity of broadband noise in power spectra generated by irregular and chaotic signals. sMTM is the area between the MTM power spectrum and the baseline.

Chaotic Forward Parameter. The parameter [CFP 1-7] is referred to as Chaotic Forward Parameter for the functions 1 to 7 below where it is applied to at rest and recovery from flexible pole datasets. Since *hs*DFA responds to chaos in the opposite way to the others we subtract its value from unity when applying here. All three chaotic global values have equal weightings. In Figures 2 and 3 for the vertical axis: CFP1 applies all three chaotic global parameters (*hs*Entropy)(1-*hs*DFA)(sMTM); CFP2 includes (*hs*Entropy) (1-*hs*DFA); CFP3 (*hs*Entropy)(sMTM); CFP4 (1-*hs*DFA) (sMTM); CFP5 (1-*hs*DFA); CFP6 (sMTM); CFP7 (*hs*Entropy). These are illustrated in the equations below.

$$[CFP\ 1]=\left[\left\{\left[\frac{hsEntropy}{\max(hsEntropy)}\right]\right\}^2+\left\{\left[\frac{sMTM}{\max(sMTM)}\right]\right\}^2+\left\{1-\left[\frac{hsDFA}{\max(hsDFA)}\right]\right\}^2\right]^{\frac{1}{2}}$$

$$[CFP\ 2]=\left[\left\{\left[\frac{hsEntropy}{\max(hsEntropy)}\right]\right\}^2+\left\{1-\left[\frac{hsDFA}{\max(hsDFA)}\right]\right\}^2\right]^{\frac{1}{2}}$$

$$[CFP\ 3]=\left[\left\{\left[\frac{hsEntropy}{\max(hsEntropy)}\right]\right\}^2+\left\{\left[\frac{sMTM}{\max(sMTM)}\right]\right\}^2\right]^{\frac{1}{2}}$$

$$[CFP\ 4]=\left[\left\{\left[\frac{sMTM}{\max(sMTM)}\right]\right\}^2+\left\{1-\left[\frac{hsDFA}{\max(hsDFA)}\right]\right\}^2\right]^{\frac{1}{2}}$$

$$[CFP\ 5]=\left[\left\{1-\left[\frac{hsDFA}{\max(hsDFA)}\right]\right\}^2\right]^{\frac{1}{2}}$$

$$[CFP\ 6]=\left[\left\{\left[\frac{sMTM}{\max(sMTM)}\right]\right\}^2\right]^{\frac{1}{2}}$$

$$[CFP\ 7]=\left[\left\{\left[\frac{hsEntropy}{\max(hsEntropy)}\right]\right\}^2\right]^{\frac{1}{2}}$$

Statistical Analysis. Parametric statistics assume the data are normally distributed, using the mean as a measure of central tendancy. If we cannot normalize the data we should not compare means. To test our assumptions of normality we apply the Anderson-Darling [17] test and the Lilliefors [18] test. Here in most cases the p<0,01; for both, therefore we have a probability plot of highly non-normal data and so we must apply the non-parametric Kruskal-Wallis test of signficance. The Kruskal-Wallis algorithm computes a significant statistical result for three of the seven combinations (p<0,15). These are combinations [CFP 1, 3 & 6].

Results

Principal Component Analysis (PCA) [19] is the multivariate technique applied. We have seven values of Chaotic Forward Parameter. Therefore, seven groups of thirty-two subjects for the *difference* between at control rest; to those recovering from exercise with flexible pole. Hence, CFP recovery from exercise subtracted from CFP at rest prior to exercise. A grid of 7 by 32 to be assessed. The First Principal Component (PC1) has a variance (eigenvalue) of 5,5253 and accounts for 78,9% of the total variance. The Second Principal Component (PC2) has an eigenvalue of 1,4662 accounting for 99,9% of cumulative total variance. PC2 accounting for 20,9% of its proportion of the variance. Therefore we can assume that most variance is acheived in the first two components.

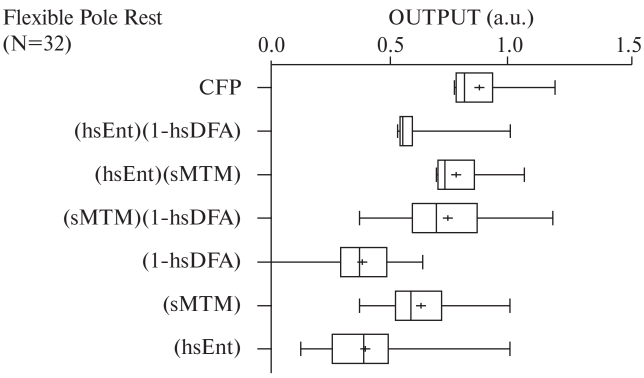

Figure 2. The boxplots illustrate the mean values and standard deviation of [CFP 1-7] for the RR intervals of subjects at control rest. Mean values are indicated by the (+) symbol. The number of RR intervals is 500 and number of subjects is 32.

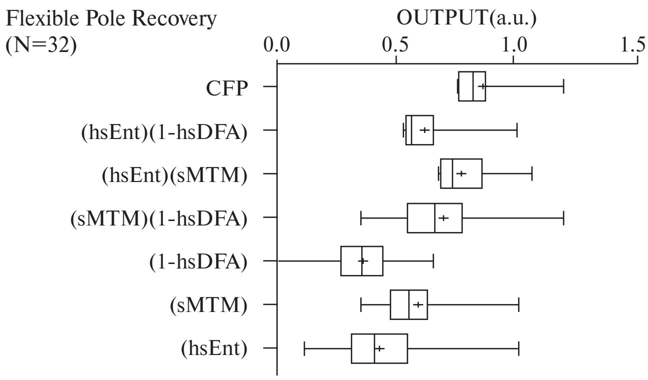

Figure 3. The boxplots illustrate the mean values and standard deviation of [CFP 1-7] for the RR intervals of subjects recovering from flexible pole exercise. The number of subjects is 32 and number of RR intervals is 500. Mean values are indicated by the (+) symbol.

Table 2

The table below shows the minimum, maximum, median and the 25th (Q1) and 75th (Q3) percentile of [CFP 1-7] for 500 RR intervals from before the exercise protocol with flexible pole

Combination of Chaotic Globals [CFP1-7]	Before Exercise Minimum	Before Exercise Q1	Before Exercise Median	Before Exercise Q3	Before Exercise Maximum
CFP1	0,7725	0,7826	0,8086	0,9271	1,1898
CFP2	0,5311	0,5365	0,5489	0,5952	1,0000
CFP3	0,6993	0,7020	0,7246	0,8492	1,0657
CFP4	0,3683	0,5965	0,6921	0,8639	1,1829
CFP5	0,0000	0,2922	0,3705	0,4849	0,6319
CFP6	0,3683	0,5200	0,5845	0,7150	1,0000
CFP7	0,1275	0,2548	0,3860	0,4908	1,0000

Table 3

The table below shows the minimum, maximum, median and the 25th (Q1) and 75th (Q3) percentile of [CFP 1-7] for 500 RR intervals for after exercise protocol with flexible pole

Combination of Chaotic Globals [CFP1-7]	After Exercise Minimum	After Exercise Q1	After Exercise Median	After Exercise Q3	After Exercise Maximum
CFP1	0,7544	0,7629	0,7952	0,8659	1,1978
CFP2	0,5292	0,5350	0,5571	0,6467	1,0000
CFP3	0,6766	0,6800	0,7048	0,8568	1,0597
CFP4	0,3507	0,5392	0,6539	0,7667	1,1923
CFP5	0,0000	0,2582	0,3586	0,4404	0,6493
CFP6	0,3507	0,4733	0,5468	0,6276	1,0000
CFP7	0,1151	0,3010	0,3990	0,5382	1,0000

[CFP 1] has the First Principal Component (0.154) and the Second Principal Component (-0,769). While, [CFP 3] has the First Principal Component (0.372) and the Second Principal Component (-0,398). Only the first two components need be considered due to the steep scree plot. [CFP 1, 3 & 6] only need to be considered on the basis of the Kruskal-Wallis test of significance at level $p<0,15$; 15% (Table 1). However since [CFP 6] only represents the increased intensity of broadband noise in the MTM power spectrum we do not consider it further. Consequently, [CFP 1] which applies all three chaotic globals techniques is the best overall combination with regards to influencing the correct outcome. This is on the basis of all three statistical tests — Kruskal-Wallis, Standard Deviation and PCA.

The results illustrate that there is a wide variation in both the mean values and standard deviation for both at control rest, and those with flexible pole during recovery stage (See Figures 2 and 3). In all these cases there is a *decrease* in chaotic response when going from at rest to recovery stage subjects. Tables 2 and 3 below show the minimum, maximum, median and the 25th (First Quartile, Q1) and 75th (Third Quartile, Q3) percentile of [CFP

1-7] for 500 RR intervals for before and after exercise protocol with flexible pole, respectively.

Discussion

Our study aimed to evaluate the cardiac autonomic responses through global chaotic parameters of HRV induced by a standardized protocol of exercise with flexible pole. We reported that this standardized exercise protocol was able to reduced HRV.

[CFP 1 & 3] are the main functions suitable as deduced by the three assessments (Kruskal-Wallis, Standard Deviation and PCA). There is evidence to apply [CFP 1] as the most robust function as with the optimization study by Garner and Ling [8]. This in addition to forward problems in youth and childhood obesity [6], diabetes mellitus [5] and COPD [20].

With regards to PCA applied to the seven different arrangements of chaotic globals subjects for the difference in at control rest to those recovering from exercise with flexible pole. 99.9% of influence is achieved by the first two principal components. The combination with all three chaotic globals applied testing as most influencial algorithm. Second best, and still significant across all three conditions by Kruskal-Wallis is the third algorithm which lacks the (1-*hs*DFA) parameter. It is important to recognize that in most cases the chaosity of the data *decreases* from subjects for those at control rest to those recovering from exercise with flexible pole. Applying the *hs*Entropy and *hs*DFA would seem to be advantageous with regards to the statistical tests here; compared to those standard techniques using Welch power spectra — spectral entropy and sDFA.

So, we have developed two robust functions which can take short time-series of HRV and discriminate between the control and experimental groups. There is a moderate level of significance for both these algorithms ($p<0.15$). By applying either of these novel functions to the shorter time-series via spectrally determined parameters it should be possible to determine which are at rest and those in recovery. This achieved more rapidly and efficiently with regards to time, data length and cohort group size. There has been a decrease in chaotic response of HRV following flexible pole exercise. The relationship between this form of exercise and complexity measures is useful in the risk assessment of dynamical diseases [21]. It identifies severity of the situation from a cheap and reliable method of monitoring the ANS. This is useful in treatments, assisting the determination of the level of physical and pharmacological intervention especially in related dynamical diseases.

Future development could involve the DPSS of the MTM being adjusted to optimize the final level of significance. In addition the weighting of the three chaotic global parameters could be modified since here they have only equal weightings of unity. It would also be statistically favourable to have larger, but equal datasets for both at rest and recovery subjects. If the time-series were longer this may also enhance statistical significances.

Conclusion

The chaotic response of HRV in subjects following flexible pole exercise is generally reduced and the parameter which applies all three parameters is the most influential and statistically most significant. At rest and during the recovery stage there is generally a decrease in chaosity of HRV. It is also the case that the use of the high spectral chaotic globals in the function achieves greater significance by Kruskal-Wallis, for a fraction of the length of time-series and low number of subjects. It quantifies the effectiveness of flexible pole exercise on cardiac autonomic modulation.

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References

1. Pescatello LS, Guidry MA, Blanchard BE, Kerr A, Taylor AL, Johnson AN, et al. Exercise intensity alters postexercise hypotension. Journal of hypertension 2004;22(10):1881-8.
2. Sugimoto D, Blanpied P. Flexible foil exercise and shoulder internal and external rotation strength. Journal of athletic training 2006;41(3):280.
3. Bai X, Li J, Zhou L, Li X. Influence of the menstrual cycle on nonlinear properties of heart rate variability in young women. American Journal of Physiology-Heart and Circulatory Physiology 2009;297(2):H765-H774.
4. Rzewnicki R, Auweele YV, Bourdeaudhuij ID. Addressing overreporting on the International Physical Activity Questionnaire (IPAQ) telephone survey with a population sample. Public Health Nutrition 2003;6(03):299-305.
5. Souza NM, Vanderlei LC, Garner DM. Risk evaluation of diabetes mellitus by relation of chaotic globals to HRV. Complexity 2014.
6. Vanderlei FM, Vanderlei LC, Garner DM. Chaotic global parameters correlation with heart rate variability in obese children. Journal of Human Growth and Development 2014;24(1):24-30.
7. Johnson R, Shore J. Which is the better entropy expression for speech processing:-S log S or log S? Acoustics, Speech and Signal Processing, IEEE Transactions on 1984;32(1):129-37.
8. Garner DM, Ling BWK. Measuring and locating zones of chaos and irregularity. J Syst Sci Complex 2014;27(3):494-506.
9. Shannon CE. A Mathematical Theory of Communication. The Bell System Technical Journal 1948;27:379-423.
10. Zyczkowski K. Renyi extrapolation of Shannon entropy. Open Systems & Information Dynamics 2003;3(10):297-310.
11. Peng CK, Havlin S, Stanley HE, Goldberger AL. Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos 1995;5(1):82-7.
12. Donaldson GC, Seemungal TA, Hurst JR, Wedzicha JA. Detrended fluctuation analysis of peak expiratory flow and exacerbation frequency in COPD. Eur Respir J 2012 Nov;40(5):1123-9.
13. Percival DB, Walden AT. Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques. New York: Cambridge University Press; 1993.
14. Alkan A, Kiymik MK. Comparison of AR and Welch methods in epileptic seizure detection. J Med Sys 2006;6(30):413-9.
15. Slepian S. Prolate spheroidal wave functions, Fourier analysis and uncertainty, V, The discrete case. Bell Syst Tech J 1978;57:1371-430.
16. Gould SH. Variational methods for eigenvalue problems: an introduction to the methods of Rayleigh, Ritz, Weinstein, and Aronszajn. Courier Dover Publications; 1995.
17. Anderson TW, Darling DA. A test of goodness of fit. Journal of the American Statistical Association 1954;49(268):765-9.
18. Razali NM, Wah YB. Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests. Journal of Statistical Modeling and Analytics 2011;2(1):21-33.
19. Jolliffe I. Principal component analysis. Wiley Online Library; 2005.
20. Bernardo AFB, Vanderlei LCM, Garner DM. HRV Analysis — A clinical and diagnostic tool in Chronic Obstructive Pulmonary Disease. International Scholarly Research Notices 2014.
21. Mackey MC, Milton JG. Dynamical diseases. Annals of the New York Academy of Sciences 1987;504(1):16-32.