Higuchi Fractal Analysis of Heart Rate Variability is Sensitive during Recovery from Exercise in Physically Active Men

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OBJECTIVE: Nonlinear techniques to assess heart rate variability (HRV) have received much recent attention. We aimed to evaluate nonlinear HRV responses during recovery from exercise through the novel algorithm Higuchi Fractal Dimension.
METHOD: We examined 35 healthy male volunteers aged between 18 and 35 years old. For the training of exercise intensity we used 60% of Vmax determined through a progressive test using the Conconi threshold. HRV was analyzed 10 minutes before and 10 minutes after exercise. We analyzed the geometric indices of HRV (SD1, a measure of short-term HRV and SD2, a measure of long-term HRV) and applied the Higuchi Fractal Dimension to RR intervals.
RESULTS: During recovery from exercise the Poincaré plot indices SD1 and SD1/SD2 decreased while SD2 and SD2/SD1 increased (p<0.0001) compared to control at rest. All parameters of Higuchi Fractal Dimension analysis were lowered after exercise compared to control at rest (p<0.0001).
CONCLUSION: Physical exercise acutely decreased the chaotic behavior of HRV as measured through the Higuchi Fractal Dimension analysis. Physiologically, this indicates that we detected complex changes in HRV immediately after exercise.

KEYWORDS: Cardiovascular system; Autonomic Nervous System; Physical Exercise; Nonlinear Dynamics; Higuchi Fractal Dimension.

■ INTRODUCTION

Physical exercise induces variation in the autonomic nervous system (ANS) sequentially to maintain the physiological homeostasis of the human body. At the begining of exercise the parasympathetic withdrawal induces heart rate increases and immediately after exercise cessation vagal reactivation returns the heart rate to basal levels.[1]

Cardiac autonomic recovery from exercise involves an integrative physiological mechanism. It is a relevant method to investigate cardiac autonomic regulation responsiveness and ANS function. The recovery of heart rate and cardiac autonomic modulation from exercise may expose the magnitude of vagal reactivation.[2]

Heart rate variability (HRV) is a noninvasive method that describes fluctuations in the interval between consecutive heart beats (RR interval). This method presents information regarding cardiac autonomic regulation.[3] Traditional analysis of HRV in the time and frequency domains are mostly applied in the literature in several pathological and physiological situations. Those linear indices analyze the magnitude of HRV and provide limited information.[4]

Recently, description of the nonlinear methods used in the scientific literature were published by the European Society of Cardiology together with the European Heart Rhythm Association and co-endorsed by the Asia Pacific Heart Rhythm Society.[5] The authors verified that after validation of some nonlinear methods to evaluate HRV it may assist to give additional physiological and clinical information.

In this manner, the Higuchi Fractal Dimension (HFD) algorithm was developed and has been applied for determining the fractal dimension of discrete time sequences.[6] It is applied directly to the RR intervals of the time-series. It is not applied to any power spectra as would be the case with chaotic globals.[7]

So, HFD is suggested to estimate chaotic and complex behaviour of heart rate dynamics. However, there is an absence of studies with regard to the interpretation of this algorithm applied in RR intervals to analyse cardiac autonomic regulation. Consequently, we aimed to investigate nonlinear behaviour of HRV during recovery from aerobic exercise through HFD.

■ METHOD

Study Population

The subjects participating in the study were 35 healthy male students who practiced activity at least two hours per week - all non-smokers, aged between 18 and 35 years. All volunteers were informed about the procedures and the 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 (No. 2011-385),[8] and were in accordance with Resolution 196/96 National Health 10/10/1996. Exclusion criteria comprised body mass index (BMI) >35 kg/m^2; systolic blood pressure (SBP) >140 mmHg or diastolic blood pressure (DBP) >90 mmHg (at rest); cardiovascular, respiratory and reported neurological disorders.

Initial Evaluation

Baseline information included: age, gender, mass, height and body mass index (BMI). Mass 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 220 cm of extension. BMI was calculated as mass/height^2, with mass in kilograms and height in meters.

HRV analysis

We enforced a procedure based on Task Force guidelines.[9] Instantaneous RR intervals (RRi) were recorded with a digital telemetry system, which consisted of a transmitter placed on the patients chest and a HR monitor (Polar® RS800CX; Polar Electro Oy, Kempele, Finland). This system detected ventricular depolarization, corresponding to the R wave on the electrocardiogram, at a sampling rate of 1000 Hz and was previously validated.[5] Data was 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, 750 RR intervals were selected for the data analysis. Only series with sinus rhythm greater than 95% were included in the study. HRV was analysed during two time epochs: the period 10 min before the exercise (control); and 10 min after the period of acute exercise (experimental). HRV analysis details were previously reported.[11-14]

HRV geometric indices

We evaluated the Poincaré plot indices (SD1, SD2, SD2/SD1 ratio and SD1/SD2 ratio). In general terms SD1 is the standard deviation measuring the dispersion of points in the plot **across** the identity line. SD2 is the standard deviation measuring the dispersion of points **along** the identity line. SD1 is interpreted as a measure of short-term HRV, whereas SD2 is interpreted as a measure of both short- and long-term HRV.

In the specific case of this study, SD1 and SD2 were determined as follows: an ellipse was fitted to the points of the chart, with the centre determined by the average RR interval. The SD1 indices were calculated to measure the standard deviation of the distances of the points from the diagonal Y=X; SD2 measures the standard deviation of the distances of points from the line $y = -x + RR_m$, where RR_m is the average RR interval. The SD1 is an index of the instantaneous recording of the variability of beat-to-beat and represents the parasympathetic activity, whereas the SD2 index represents the long-term HRV and reflects the overall variability. The SD1/SD2 shows the ratio between the short-and long-term variation among the RR intervals and the SD2/SD1 ratio indicates the ratio between the long- and short-term variation among the RR intervals, reflecting sympathetic tone on the heart.[15]

The plot was qualitatively analyzed by HRV analysis software based on the figures formed by its attractor. The expected shapes were described by Tulppo *et al.*[16] as:

1) Figures in which an increase in the dispersion of RR intervals is observed with increased intervals, characteristic of a normal plot.

2) Figures with small dispersion of beat-to-beat without increased long-term dispersion of RR intervals, characteristic of a reduced HRV.

For analysis of HRV indices we applied the Kubios HRV® analysis software.[17]

Maximal oxygen consumption (V_{max}) analysis

For the preparation of exercise intensity we applied 60% of V_{max} found in the progressive test through the Conconi threshold, which has been proposed to estimate the anaerobic threshold for identifying the HR deflection point using a progressive test with the use of the D_{max} method.[18]

The volunteers sustained a methodical progressive treadmill test (TPEE; Inbrasport ATL 2000) starting at a speed of 8km/hour which was incremented by 1km/hour each 2 minutes until volitional interruption, exhaustion or onset of clinical changes that prevented the continuity of test, such as dizziness, shortness of breath or intense "air hunger".[19,20] The inclination of the treadmill remained fixed at 1%, since this condition reflects more precisely the energy expenditure of running outside.

During the test we recorded HR at the end of each phase and perceived exertion (PSE) through the Borg Scale.[21] We included volunteers that reached up to 90% of maximal HR.[22]

For the identification of HR deflection point, the matched HR and speed points were plotted. Later the values were adjusted by means of a third-degree polynomial function and a linear equation of the first degree, which are data derived from each individual. Afterwards, the difference of the values of HR obtained through the above mentioned equations were calculated and a curve was designed with these values. We considered the heart rate deflection point (HRDP) as the highest value before a change of direction in curve.[22]

Exercise Protocol

Data collection was performed in the same soundproofed room for all volunteers. The temperature varied between 21 and 25°C and the relative humidity 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.

Volunteers performed a treadmill exercise at 6.0 km/hour + 1% slope in the first five minutes for physically "warming up", followed by 25 minutes with intensity equivalent to 60% of V_{max} according to the Conconi threshold with the same slope. HRV was analyzed in the following periods: control protocol – the 10-minute epoch before the performance of the exercise and the 10-minute epoch after the performance of the exercise.

Statistical analysis of HRV geometric indices

Standard statistical methods were applied for the calculation of means and standard deviations. Normal Gaussian distribution of the data was verified by the Shapiro-Wilk goodness-of-fit test (z value >1.0). For parametric distributions we applied paired Student's t-test while for non-parametric distributions we used the Wilcoxon test. Differences were considered significant when the probability of a Type I error was less than 5% ($p<0.05$). We used the Biostat Professional Software v5.8.4 for Windows.

Higuchi Fractal Dimension (HFD)

The HFD aims to quantify self-similarity and complexity of the signal. It has been applied to brain[23-25] and other biological signals.[26,27] The algorithm is described by Khoa *et al.*[28] (see below). It is based on a measure of length, $L(k)$, of the curve that represents the considered time series while using a segment of k samples as a unit, if $L(k)$ scales such as:

$$L(k) \sim k^{-Df}$$

The curve is believed to show fractal dimension D_f. A simple curve has dimension equal to 1. Nevertheless, a plane has a dimension equal to 2. This value of D_f is always between 1 and 2. D_f measures complexity of the curve and so of the time series this curve is represented on a graph.

From a given time series, $X(1), X(2), ... , X(N)$, the algorithm constructs k new time series:

$$X_{km}: X(m), x(m+k), X(m+2k), ...,$$

$$X\left(m+\mathrm{int}\left(\frac{(N-m)}{k}\right)\cdot k\right) \ for \ m = 1, 2, ...k,$$

where m is initial time, k is interval time, $\mathrm{int}(r)$ is integer part of a real number r.

The "length" $L_m(k)$ of each curve X_{km} is then calculated as:

$$L_m = \frac{1}{k}\left[\left(\sum_{i=1}^{\mathrm{int}((N-m)/k)} \left| \begin{matrix} X(m+i\cdot k)- \\ X(m+(i+1)\cdot k) \end{matrix} \right| \right)\right] \times \frac{N-1}{\mathrm{int}\left(\frac{(N-m)}{k}\right)\cdot k}$$

Where N is total number of samples. $L_m(k)$ is not "length" in the Euclidean sense: it represents the normalized sum of absolute values of differences in ordinates of pairs of points distant k (with initial point m). The "length" of curve for the time interval k, $L(k)$, is calculated as the mean of the k values $L_m(k)$ for $m= 1, 2, ... , k$:

$$L(k) = \frac{1}{k}\sum_{m=1}^{k} L_m(k)$$

The value of fractal dimension, D_f is calculated by a least-squares linear best-fitting procedure as the angular coefficient of the linear regression of the log-log graph.

So, when $L(k)$ is plotted against $1/k$ on a double logarithmic scale, with $k = 1,2,...,k_{max}$, the data should fall on a

straight line, with a slope equal to the Fractal Dimension of X. Thus, Higuchi Fractal Dimension is defined as the slope of the line that fits the pairs $\{\ln[L(k)], \ln(1/k)\}$ in a least-squares sense. In order to choose an appropriate value for the parameter k_{max}, Higuchi Fractal Dimension values were plotted against a range of k_{max}. The point at which the Fractal Dimension plateaus is considered a saturation point and that k_{max} value should be selected.

With $a = D_f$, according to the following formulae:
$y=ax+b$

where, yk=ln L(k), x(k)=ln(1/k) and k $k=k_1, ... , k_{max}$, and n denotes the number of k values for which the linear

$$D_f = \frac{n \sum (x_k \cdot y_k) - \sum x_k \sum y_k}{n \sum x_k^2 - \left(\sum x_k\right)^2}$$

regression is calculated where;
    ($2 \leq n \leq k_{max}$).

■ RESULTS

Figure 1 illustrates quantitative analysis of the Poincaré plot. We detect that immediately after exercise SD1 and SD1/SD2 ratio decreased compared to before exercise. Conversely, SD2 and SD2/SD1 increased after aerobic exercise.

Figure 2 presents an exemplar of the Poincaré plot of one volunteer before and immediately after exercise.

In Table 1 we present descriptive data regarding HFD analysis before exercise, while in Table 2 we show results for HFD analysis after exercise.

There was significant reduction after exercise in all parameters of the HFD analysis (Figure 3).

■ DISCUSSION

The intention of this research was to investigate the complex behavior of heart rate dynamics after exercise through an algorithm poorly explored in previous HRV studies. HFD analysis indicated reduced chaotic responses of cardiac autonomic modulation after aerobic exercise, followed by a decline in Poincaré plot indices; thus supporting HFD as a nonlinear method able to provide chaotic analysis of HRV during physiological conditions.

According to our data, SD1 index and SD1/SD2 ratio significantly decreased after exercise compared to rest control. The SD1 index corresponds to the transverse axis of the Poincaré plot, it conveyed that the standard deviation of the instantaneous variability of the beat-to-beat HR, representing the parasympathetic influence on the heart.[3] The SD1/SD2 is related to sympatho-vagal balance and its decrease indicates reduced parasympathetic cardiac modulation after exercise.

Previous studies reported reduced SD1 values in pathological situations such as obesity[29] and chronic obstructive pulmonary disease.[30] Raimundo *et al.*[31] supported SD1 changes during physiological situations, since SD1 was reduced after a single bout of aerobic exercise in stroke patients.

We established increased SD2 and SD2/SD1 values after exercise. The SD2 index represents the standard deviation of the long-term variability of the heart rate.[3] The SD2 index provides information related to the global variability of heart rate. It is unable to detect if the parasympathetic or sympathetic component is implicated.
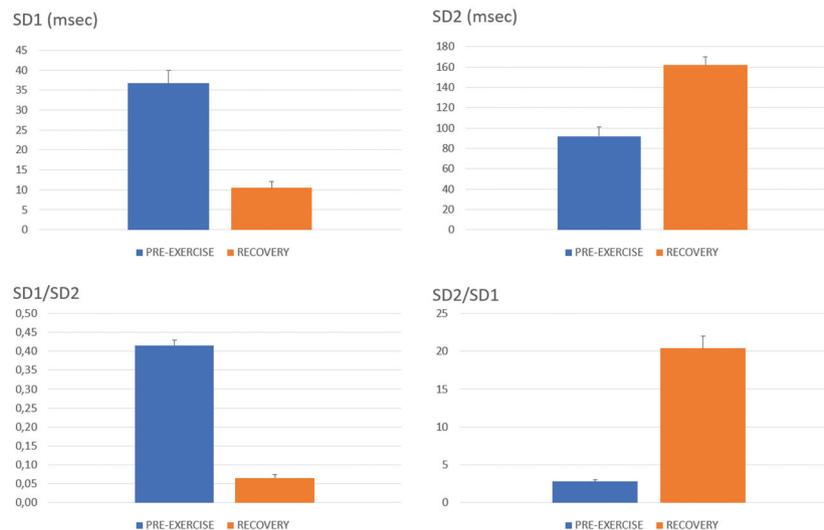
Figure 1. SD1, SD2, SD2/SD1 ratio and SD1/SD2 ratio before (Pre) and after exercise (Recovery). SD1, standard deviation of the instantaneous variability of the beat-to-beat heart rate; SD2, standard deviation of long-term continuous RR interval variability; SD1/SD2 ratio, ratio between the short- and long-term variation of the RR intervals; SD2/SD1 ratio, ratio between the long- and short-term variation of the RR intervals; ms: milliseconds.
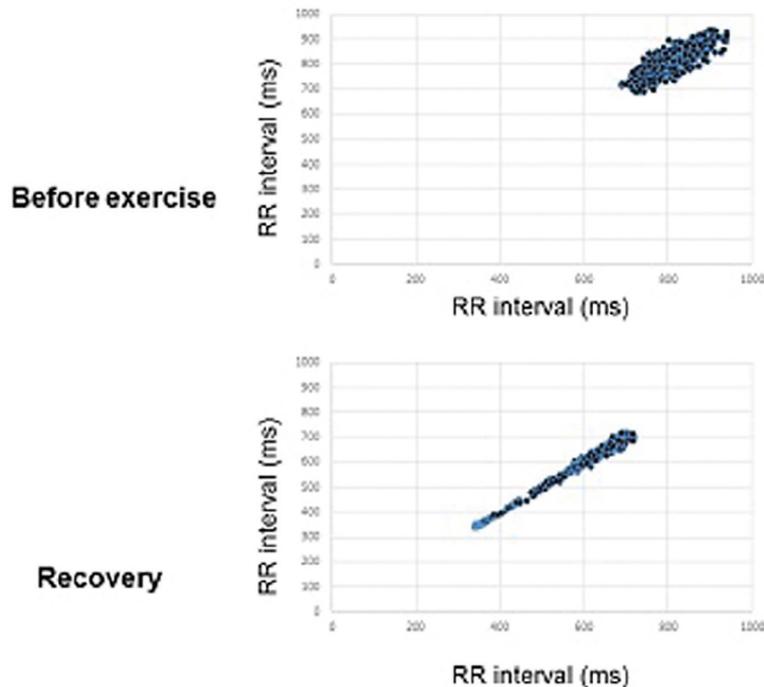
Figure 2. Visual pattern of the Poincaré plot observed in one subject before and after exercise.

Table 1. The mean, standard error of the mean, standard deviation, lower quartile (Q1), median and upper quartile (Q3) for the Higuchi Fractal Dimension (HFD) at varying levels of K_{max} between 10 and 150 at equidistant intervals of 10 before exercises. The number of RR-intervals is 750 and there were 35 subjects. When comparing means for HFD control with HFD experimental, all ANOVA1 and Kruskal-Wallis are $p<0.0001$ or $<0.1\%$

| Kmax	Mean	SE Mean	SD	Q1 (25%)	Median	Q3 (75%)
10	1.8234	0.01730	0.1021	1.7645	1.8146	1.8814
20	1.8597	0.01190	0.0705	1.8139	1.8542	1.9101
30	1.8751	0.01070	0.0631	1.8390	1.8774	1.9305
40	1.8851	0.00993	0.0588	1.8524	1.8855	1.9398
50	1.8906	0.00971	0.0575	1.8554	1.8921	1.9453
60	1.8968	0.00935	0.0553	1.8622	1.8971	1.9508
70	1.9032	0.00884	0.0523	1.8701	1.9027	1.9501
80	1.9093	0.00834	0.0493	1.8744	1.9075	1.9530
90	1.9150	0.00788	0.0466	1.8801	1.9176	1.9567
100	1.9193	0.00744	0.0440	1.8866	1.9195	1.9557
110	1.9228	0.00698	0.0413	1.8920	1.9206	1.9551
120	1.9255	0.00670	0.0396	1.8974	1.9214	1.9589
130	1.9283	0.00644	0.0381	1.8993	1.9260	1.9581
140	1.9309	0.00607	0.0359	1.9052	1.9302	1.9598
150	1.9333	0.00575	0.0340	1.9089	1.9331	1.9642

The SD2/SD1 ratio isolates the sympathetic cardiac component, indicating increased sympathetic cardiac regulation after exercise.

Based on our results, the HFD analysis presented a highly significant discrimination between at rest and after periods of exercise. There was reduction in all HFD parameters after exercise, indicating lowered chaotic behavior of heart rate dynamics; which is in accordance with the Poincaré plot analysis.

The nonlinear behavior of HRV during recovery from exercise was explored in previous studies.[11-15] Mendonça *et al.*[32] analyzed nonlinear behavior of HRV during recovery from a supramaximal exercise period. The study established: (a) a significant increase in alpha-1 scaling component of detrended fluctuation analysis (DFA) after exercise in healthy men and women and (b) a positive correlation with LF/HF ratio, indicating decreased chaotic behavior of HRV associated with elevated sympathetic cardiac modulation after exercise, which uphold our analysis here.

Table 2 - The mean, standard error of the mean, standard deviation, lower quartile (Q1), median and upper quartile (Q3) for the Higuchi Fractal Dimension (HFD) at varying levels of K_{max} between 10 and 150 at equidistant intervals of 10 after exercise. The number of RR-intervals is 750 and number of subjects is 35. As stated previously when comparing means for HFD control with HFD experimental, all ANOVA1 and Kruskal-Wallis are p<0.0001

Kmax	Mean	SE Mean	StDev	Q1 (25%)	Median	Q3 (75%)
10	1.5486	0.0211	0.1247	1.4504	1.5237	1.6402
20	1.6194	0.0168	0.0991	1.5470	1.6219	1.6570
30	1.6329	0.0158	0.0935	1.5652	1.6334	1.6725
40	1.6344	0.0160	0.0947	1.5536	1.6367	1.6864
50	1.6302	0.0163	0.0963	1.5464	1.6379	1.6960
60	1.6252	0.0166	0.0981	1.5541	1.6320	1.6921
70	1.6175	0.0168	0.0996	1.5407	1.6216	1.6924
80	1.6083	0.0172	0.1016	1.5230	1.6098	1.6843
90	1.5992	0.0175	0.1038	1.5194	1.5988	1.6739
100	1.5898	0.0178	0.1054	1.5141	1.5870	1.6637
110	1.5807	0.0181	0.1072	1.5039	1.5746	1.6526
120	1.5714	0.0184	0.1089	1.4912	1.5614	1.6442
130	1.5620	0.0186	0.1102	1.4804	1.5480	1.6353
140	1.5523	0.0189	0.1116	1.4687	1.5346	1.6264
150	1.5428	0.0190	0.1127	1.4577	1.5305	1.6164
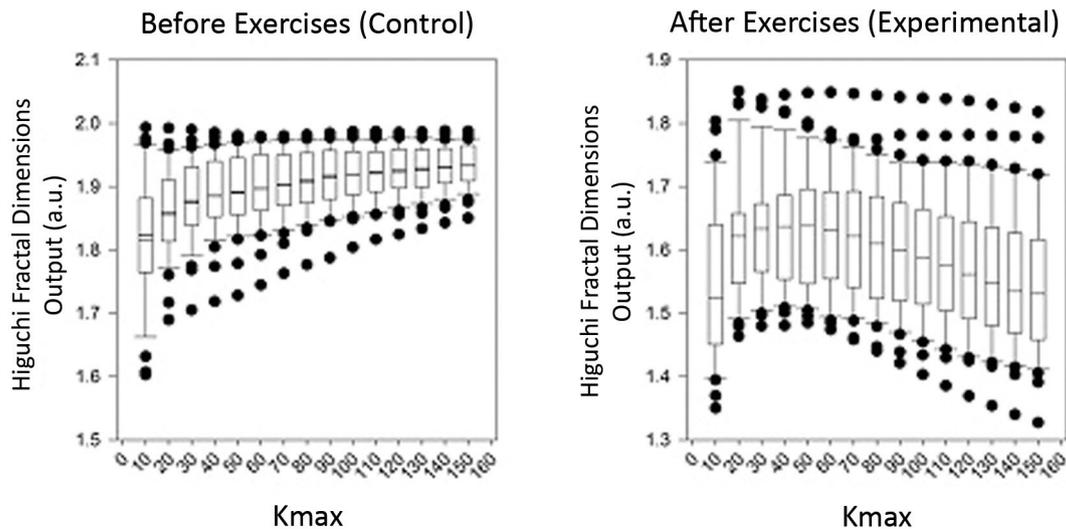
Figure 3. The boxplots demonstrate Higuchi Fractal Dimension (HFD) of RR–intervals; before exercises (control) subjects (left) and after exercises (Experimental) subjects (right); calculated multiple times between 10 and 150; equidistantly for different levels of K_{max}. The number of RR-intervals is 750 and number of subjects for both is 35. The output is measured in arbitrary units (a.u.). The point closest to the zero is the minimum and that farthest away the maximum. The second closest to the zero is the 5th percentile and second farthest away the 95th percentile. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median (not the mean), and the boundary of the box farthest from zero indicates the 75th percentile. The difference between these points is the inter-quartile range (IQR). Whiskers (or error bars) above and below the box indicate the 90th and 10th percentiles.

Alternatively, Francica *et al.*[33] reported a deficiency of HRV changes in healthy subjects during recovery from exercise by applying nonlinear methods.[33] They undertook a symbolic analysis of HRV, previously validated by Porta *et al.*[34], in stroke patients and gender and age-matched subjects after a single bout of aerobic exercise. Yet, there are discrepancies between the population analyzed in their study and in our research. The cited study[33] investigated older (50 to 70 years old) and inactive women, while in our study the population was composed by healthy young men (18 to 35 years old).

Along these lines, we aimed to focus on HFD because the relationship between this algorithm and HRV is poorly scrutinized. After searching on Pubmed/Medline database, we found that this algorithm was applied on RR intervals during meditation[35] and in patients with cardiovascular disorder.[36,37]

Signori *et al.*[37] evaluated nonlinear methods in heart failure patients. Additionally, they analyzed HFD to probe long correlations and self-similarity of data series and proposed that it was effective in separating pathological and physiological circumstances. In addition, Cerutti *et al.*[38] reinforced the role

of HFD as a parameter of clinical significance. It was robustly shown that this technique is efficient at discriminating different datasets, supporting the hypothesis that the HRV signal might be related in the long term.

However, it is unclear in the literature whether HFD analysis applied on RR intervals is effective in short term physiological situations. In this perspective, our data provide additional evidence regarding the role of this nonlinear method in HRV during short periods of exercise.

Nonlinear analysis of HRV offers supplementary information for cardiac autonomic regulation. The traditional indices formulate quantitative analysis of HRV, whereas nonlinear methods are intended to assess the quality and correlation propoerties of the signal.[5] In addition it performs complex analysis of the cardiovascular system,[5] which is suggested to be involved in the generation of heart rate dynamics.[38]

Cardiac autonomic regulation throughout recovery from exercise is an important method to perceive the possibility of cardiovascular events; since attenuated responses of heart rate after exercise were reported as a strong and independent indicator of mortality.[2] In this circumstance, new methods to detect variations of HRV after exercise provide new methods of scientific research which may assist and further balance clinical examinations.

■ CONCLUSION

A single bout of aerobic exercise acutely reduced the complexity of heart rate dynamics through HFD analysis. We reinforced the application of this algorithm to RR intervals under physiological situations. In this sense, we identified nonlinear changes in heart rate dynamics immediately after exercise.

■ CONFLICT OF INTEREST

Authors Declare no conflict of interest relating to this project.

■ AUTHOR CONTRIBUTION

RL Gomes participated in the acquisition of data, conduction of experiments and draft the manuscript. LCM Vanderlei designed the project, performed data analysis and wrote the manuscript. DM Garner performed statistical analysis, draft and reviewed the manuscript. FM Vanderlei designed the experiments and performed manuscript guidelines process submission. VE Valenti supervised the study, wrote the manuscript section and gave final approval for the version submitted for publication. All authors reviewed and approved the manuscript.

ANÁLISE DA VARIABILIDADE DA FREQUÊNCIA CARDÍACA PELO MÉTODO DA DIMENSÃO FRACTAL DE HIGUCHI É SENSÍVEL DURANTE A RECUPERAÇÃO APÓS EXERCÍCIO EM HOMENS FISICAMENTE ATIVOS

OBJETIVO: Métodos não-lineares para avaliar a variabilidade da freqüência cardíaca (VFC) têm recebido muita atenção recente. Nosso objetivo é analisar as respostas não-lineares da VFC durante a recuperação do exercício através do novo algoritmo da análise fractal da dimensão de Higuchi.

MÉTODO: Foram examinados 35 voluntários saudáveis, com idade entre 18 e 35 anos. Para o treinamento de intensidade de exercício utilizamos 60% de Vmax determinado através de um teste progressivo utilizando o limiar de Conconi. A VFC foi analisada 10 minutos antes e 10 minutos após o exercício. Analisamos os índices geométricos de VFC (SD1, uma medida de VFC em curto prazo e SD2, uma medida de VFC em longo prazo) e aplicamos a Dimensão Fractal de Higuchi aos intervalos RR.

RESULTADOS: Durante a recuperação do exercício, os índices de plot de Poincaré SD1 e SD1/SD2 diminuíram, enquanto que SD2 e SD2/SD1 aumentaram (p <0,0001) em relação ao repouso. Todos os parâmetros da análise da Dimensão Fractal de Higuchi foram reduzidos após o exercício em comparação com o controle em repouso (p <0,0001).

CONCLUSÃO: O exercício físico diminuiu agudamente o comportamento complexo da VFC, conforme medido pela análise da Dimensão Fractal de Higuchi. Fisiologicamente, isso indica que detectamos alterações na complexidade da VFC imediatamente após o exercício.

PALAVRAS-CHAVE: Sistema cardiovascular; Sistema nervoso autônomo; Exercício físico; Dinâmica não-linear; Dimensão do Fractal de Higuchi.

■ REFERENCES

1. Peçanha T, Silva-Júnior ND, Forjaz CL. Heart rate recovery: autonomic determinants, methods of assessment and association with mortality and cardiovascular diseases. Clin Physiol Funct Imaging. 2014;34(5):327-39. DOI: 10.1111/cpf.12102.
2. Watanabe J, Thamilarasan M, Blackstone EH, Thomas JD, Lauer MS. Heart rate recovery immediately after treadmill exercise and left ventricular systolic dysfunction as predictors of mortality: the case of stress echocardiography. Circulation. 2001;104(16):1911-6.
3. Vanderlei LCM, Pastre CM, Hoshi RA, Carvalho TD, Godoy MF. Basic notions of heart rate variability and its clinical applicability. Rev Bras Cir Cardiovasc. 2009;24(2):205-17. DOI: 10.1590/S0102-76382009000200018.
4. Valenti VE. The recent use of heart rate variability for research. J Hum Growth Dev. 2015;25(2):137-40.

5. Sassi R, Cerutti S, Lombardi F, Malik M, Huikuri HV, Peng CK, et al. Advances in heart rate variability signal analysis: joint position statement by the e-Cardiology and the ESC Working Group and the European Heart Rhythm Association co-endorsed by the Asia Pacific Heart Rhythm Society. Europace. 2015;17(9):1341-53. DOI: 10.1093/europace/euv015.

6. Higuchi T. Approach to an irregular time series on the basis of the fractal theory. Physica D. 1988;31(2):277-83. DOI: 10.1016/0167-2789(88)90081-4.

7. Wajnsztejn R, Carvalho TD, Garner DM, Vanderlei LCM, Godoy MF, Raimundo RD, et al. Heart rate variability analysis by chaotic global techniques in children with attention deficit hyperactivity disorder. Complexity. 2015. 21:412-9. DOI:10.1002/cplx.21700.

8. Harriss DJ, Atkinson G. Ethical Standards in Sport and Exercise Science Research. 2014 Update. Int J Sports Med. 2013;34(12):1025-8. DOI: 10.1055/s-0033-1358756.

9. Camm AJ, Malik M, Bigger JT, Breithardt G, Cerutti S, Cohen RJ. Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation. 1996;93(5):1043-65.

10. Barbosa MPR, Silva NT, Azevedo FM, Pastre CM, Vanderlei LCM. Comparison of Polar® RS800G3™ heart rate monitor with Polar® S810i™ and electrocardiogram to obtain the series of RR intervals and analysis of heart rate variability at rest. Clin Physiol Funct Imaging. 2016;36(2):112-7. DOI: 10.1111/cpf.12203.

11. Abreu LC, Roque AL, Castro BCR, Souza ACA, Vanderlei LCM, Ferreira LL, Raimundo RD, Fonseca FLA, Valenti VE, Cisternas JR. Responses of the geometric indices of heart rate variability to the active orthostatic test in women. MedicalExpress (São Paulo, online). 2014;1(6):351-355. DOI: 10.5935/MedicalExpress.2014.06.11.

12. dos Santos António AM, Cardoso MA, do Amaral JAT, de Abreu LC, Valenti VE. Cardiac autonomic modulation adjustments in isometric exercise. MedicalExpress (São Paulo, online). 2015;2(1):M150102. DOI: 10.5935/MedicalExpress.2015.01.02.

13. Nogueira ML, Garner DM, Osório E, Abreu LC, Valenti VE. Globally chaotic measurements of Heart Rate Variability during acute auditory stimulus by heavy metal music. MedicalExpress (São Paulo, online). 2015;2(5):M150504. DOI: 10.5935/MedicalExpress.2015.05.04.

14. Porto AA, Ferreira C, Abreu LC, Garner DM, Gonzaga L, Valenti VE. Symbolic analysis of heart rate variability and its interaction with p-value of normality tests applied on RR intervals. MedicalExpress (São Paulo, online). 2016;3(2):M160204. DOI: 10.5935/MedicalExpress.2016.02.04.

15. Antonio AMS, Garner DM, Rodrigo D. Raimundo RD, Abreu LC, Navega MT, Valenti VE. Chaotic analysis of heart rate dynamics after an exercise with flexible pole. MedicalExpress (São Paulo, online). 2016;3(5):M160505. DOI: 10.5935/MedicalExpress.2016.05.05.

16. Tulppo MP, Mäkikallio TH, Seppänen T, Laukkanen RT, Huikuri HV. Vagal modulation of heart rate during exercise: effects of age and physical fitness. Am J Physiol. 1998;274:H424-9.

17. Tarvainen MP, Niskanen JP, Lipponen JA, Ranta-Aho PO, Karjalainen PA. Kubios HRV– Heart rate variability analysis software. Comput Meth Prog Bio. 2014;113(1):210-20. DOI: 10.1016/j.cmpb.2013.07.024.

18. Conconi F, Ferrari M, Ziglio PG, Droghetti P, Codeca L. Determination of the anaerobic threshold by a noninvasive field test in runners. J Appl Physiol Respir Environ Exerc Physiol. 1982;52(4):869-73.

19. Banzett RB, Lansing RW, Brown R, Topulos GP, Yager D, Steele SM, et al. 'Air hunger' from increased P_{CO2} persists after complete neuromuscular block in humans. Respir Physiol. 1990;81(1):1-17. DOI: 10.1016/0034-5687(90)90065-7.

20. Banzett RB, Lansing RW, Reid MB, Adams L, Brown R. 'Air hunger' arising from increased P_{CO2} in mechanically ventilated quadriplegics. Respir Physiol. 1989;76(1):53-67. DOI: 10.1016/0034-5687(89)90017-0.

21. Borg G. Escalas de Borg para a dor e o esforço percebido. Manole; 2000.

22. Cambri LT, Foza V, Nakamura FY, Oliveira FR. Frequência cardíaca e a identificação dos pontos de transição metabólica em esteira rolante. R da Educação Física/UEM. 2006;17(2):131-7.

23. Accardo A, Affinito M, Carrozzi M, Bouquet F. Use of the fractal dimension for the analysis of electroencephalographic time series. Biol Cybern. 1997;77(5):339-50. DOI:10.1007/s004220050394.

24. Ferenets R, Lipping T, Anier A, Jantti V, Melto S, Hovilehto S. Comparison of entropy and complexity measures for the assessment of depth of sedation. IEEE Trans Biomed Eng. 2006;53(6):1067-77. DOI: 10.1109/TBME.2006.873543.

25. Godoy MF, Takakura IT, Correa PR. Relevância da análise do comportamento dinâmico não linear (Teoria do Caos) como elemento prognóstico de morbidade e mortalidade em pacientes submetidos à cirurgia de revascularização miocárdica. Arq Ciênc Saúde. 2005;12(4):167-71.

26. Acharya R, Bhat PS, Kannathal N, Rao A, Lim CM. Analysis of cardiac health using fractal dimension and wavelet transformation. ITBM-RBM. 2005;26(2):133-9. DOI: 10.1016/j.rbmret.2005.02.001.

27. Doyle TLA, Dugan EL, Humphries B, Newton RU. Discriminating between elderly and young using a fractal dimension analysis of centre of pressure. Int J Med Sci. 2014;1(1):11-20. DOI:10.7150/ijms.1.11.

28. Khoa TQD, Ha VQ, Toi VV. Higuchi fractal properties of onset epilepsy electroencephalogram. Comput Math Methods Med. 2012;(2012):461426. DOI: 10.1155/2012/461426.

29. Vanderlei LCM, Pastre CM, Freitas Jr IF, Godoy MF Geometric indexes of heart rate variability in obese and eutrophic children. Arq Bras Cardiol. 2010;95(1):35-40. DOI: 10.1590/S0066-782X2010005000082.

30. Carvalho TD, Pastre CM, Rossi RC, Abreu LC, Valenti VE, Vanderlei LCM. Geometric index of heart rate variability in chronic obstructive pulmonary disease. Rev Port Pneumol. 2011;17(6):260-5. DOI: 10.1016/j.rppnen.2011.10.001.

31. Raimundo RD, Abreu LC, Adami F, Vanderlei FM, Carvalho TD, Moreno IL, et al. Heart rate variability in stroke patients submitted to an acute bout of aerobic exercise. Transl Stroke Res. 2013;4(5):488-99. DOI: 10.1007/s12975-013-0263-4.

32. Mendonca GV, Heffernan KS, Rossow L, Guerra M, Pereira FD, Fernhall B. Sex differences in linear and nonlinear heart rate variability during early recovery from supramaximal exercise. Appl Physiol Nutr Metab. 2010;35(4):439-46. DOI: 10.1139/H10-028.

33. Francica JV, Bigongiari A, Mochizuki L, Scapini KB, Moraes AO, Mostarda C, et al. Cardiac autonomic dysfunction in chronic stroke women is attenuated after submaximal exercise test, as evaluated by linear and nonlinear analysis. BMC Cardiovasc Disord. 2015;15:105. DOI: 10.1186/s12872-015-0099-9.

34. Porta A, Gnecchi-Ruscone T, Tobaldini E, Guzzetti S, Furlan R, Malliani A, et al. Symbolic analysis of short-term heart period variability during graded head-up tilt. Comput Cardiol. 2006;33:109-12.

35. Kamath C. Analysis of heart rate variability signal during meditation using deterministic-chaotic quantifiers. J Med Eng Technol. 2013;37(7):436-48. DOI: 10.3109/03091902.2013.828106.

36. Cerutti S, Esposti F, Ferrario M. Long-term invariant parameters obtained from 24-h Holter recordings: a comparison between different analysis techniques. Chaos. 2007;17:015108. DOI: 10.1063/1.2437155.

37. Signorini MG, Ferrario M, Marchetti M, Marseglia A. Nonlinear analysis of heart rate variability signal for the characterization of cardiac heart failure patients. Conf Proc IEEE Eng Med Biol Soc. 2006;1:3431-4. DOI: 10.1109/IEMBS.2006.259744

38. Krstacic G, Martinis M, Vargovic E, Knezevic A, Krstacic A, Smalceli A, et al. Non-linear dynamics in patients with stable angina pectoris. Comput Cardiol IEEE. 2001;28:45-8. DOI: 10.1109/CIC.2001.977587.