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ORIGINAL ARTICLE

Assessing autonomic response to repeated bouts of exercise below and above respiratory threshold: insight from dynamic analysis of RR variability

Daniela Lucini · Chiara Vigo · Fabio Tosi · Gianfranco Toninelli · Fabio Badilini · Massimo Pagani

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Abstract

Purpose The dynamics of vagal withdrawal and reactivation during pulses of exercise are described by indices computed from heart period (RR) variations, which may be sensitive to duration and load. We sought to assess the consistency over time of these indices, which is not well established.

Methods We recorded continuous electrocardiogram during series of five successive bouts (2 min) of submaximal exercise (at 40 and 70 % of VO_{2peak}, different days). Autonomic responsiveness was inferred from quantification of onset and offset of RR dynamics of each individual bout. Consistency of results was assessed with intraclass correlation (ICC).

Results During exercise bouts, indices from tachycardic and bradycardic transients reach lower levels in response to higher exercise loads and progression of exercise. There is a significant effect of load and time (i.e., bout repetition) for all examined variables, with a clear interaction. However, no interaction is observed with the 60 s change in heart rate. ICC analysis demonstrates that various indices are characterized by large differences in stability, which is generally greater within the same day (e.g., tachyspeed ICC at 40 % = 0.751, at 70 % = 0.704, both days = 0.633; bradyspeed, respectively, = 0.545, 0.666, 0.516).

Conclusions Intensity and duration of exercise modulate vagal withdrawal and reactivation. Analysis of RR variations, during successive brief exercise bouts at lower and higher intensity, ensures a consistency similar to that reported for autonomic cardiac regulation at rest and might guide the choice among multiple indices that are obtained from the tachogram.

Keywords Autonomic nervous system · Heart rate dynamics · Cardiovascular regulation · Sympathetic modulation · Vagal reactivation

Abbreviations

DELTAHR60sec	Difference between peak heart rate at end of exercise and heart rate at 60 s into recovery
ECG	Electrocardiogram
GLM	General linear model
HF	High frequency
HR	Heart rate
ICC	Intraclass correlation
LF	Low frequency
RQ	Respiratory quotient
S.A. node	Sinoatrial node

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D. Lucini (✉)
Sezione Medicina dell'Esercizio e Sindromi Funzionali, Dipartimento di Riabilitazione e Recupero Funzionale, IRCCS Istituto Clinico Humanitas, Universita' degli Studi di Milano, Via Alessandro Manzoni, 56, 20089 Rozzano (Milan), Italy
e-mail: daniela.lucini@unimi.it

D. Lucini · C. Vigo · F. Tosi · M. Pagani
Scuola Specializzazione in Medicina dello Sport, Universita' degli Studi, Milan, Italy

G. Toninelli · F. Badilini
AMPS-LL, New York, USA

M. Pagani
Dipartimento Scienze Biomediche e Cliniche, Centro di ricerca Terapia Neurovegetativa e Medicina dell'esercizio, Università degli Studi di Milano, Milan, Italy

M. Pagani
U.O. Telemedicina e Medicina dello Sport, Ospedale "Luigi Sacco", Milan, Italy

TRIMP	Training impulse
VO_2	Oxygen consumption
σ^2	Variance

Introduction

The heart rate response to exercise is governed by dynamical changes in the balance between vagal and sympathetic drive to the sinoatrial node (S.A. node) during onset, steady state and offset. The heart rate response is gradual and consists in an initial rapid tachycardia (Coote 2010), generally accepted as a convenient index of vagal withdrawal (Iellamo 2001; O'Leary et al. 1997) complemented by a subsequent sympathetic activation. These changes recover relatively rapidly after the cessation of each exercise bout, yet they are slower after greater loads or longer episodes (Martinmaki and Rusko 2008; Stuckey et al. 2012; Su et al. 2010). The repetition of exercise bouts over a long time leads to the complex adjustments of training, largely characterized by basal increase in vagal (Mizuno et al. 2011) and reduction of sympathetic mechanisms resulting in the cardinal sign of training bradycardia (Astrand et al. 2003).

Heuristically, the heart rate response to exercise and recovery, beyond its use in the context of physical training for health (Buchheit et al. 2007; Manzi et al. 2009), is of practical importance since it provides predictive information on cardiac morbidity and mortality (Imai et al. 1994; Morise 2004; Leeper et al. 2007; Savonen et al. 2008), for example in the context of sudden death (Jouven et al. 2005).

The majority of clinical investigations on the autonomic effects of exercise employ protocols providing a single bout of exercise, using a treadmill or a bicycle, and measures obtained intermittently. More recently, attention has been focused on the dynamical beat-by-beat profile during onset and more frequently offset of exercise bouts, using mathematical modeling of the continuous tachogram and digital filters to improve the signal-to-noise ratio (Buchheit et al. 2007; Ricardo et al. 2010; Stuckey et al. 2012). In individual studies, the specific exercise modalities vary largely both in duration and intensity, from few seconds and supramaximal (Stuckey et al. 2012; Martinmaki and Rusko 2008) to several minutes and submaximal. Accordingly to compare different studies may be difficult, also because of the diverse mathematical manipulations involved.

However, these measures may provide stable proxies of vagal control of the S.A. node, which could be easily employed also for brief repeated exercise bouts (Buchheit et al. 2007; Ricardo et al. 2010; Stuckey et al. 2012). The use of indices derived from the continuous tachogram appears also relatively easy to adapt to interval training protocols. This may be clinically important in view of the growing attention to the interval training modality that is thought to guarantee more efficient training programs, both for athletic and clinical applications (Stanley et al. 2013; Buchheit and Laursen 2013). A critical aspect of autonomic assessment relates to the relatively modest stability of direct and indirect measures of neural control of the cardiovascular system (Borne van de et al. 1997), as expressed with intraclass correlation (ICC) analysis. This type of information is not available for autonomic proxies derived from RR dynamics of onset or offset of exercise.

We hypothesize that dynamic indices from automatic analysis of digitally filtered tachogram at onset and offset of exercise bouts may provide a more sensitive window on vagal withdrawal and recovery than simple, frequently employed measures of heart rate.

Materials and methods

Participants

Anagraphic and anthropometric descriptive data about the 29 healthy young subjects, 12 females and 17 males, who participated in this study, are summarized in Table 1. All subjects were free from known cardiac, respiratory or other diseases and were not under any pharmacological treatment. The study conforms to the recommendations of the Declaration of Helsinki (WMA 2013), and participants gave voluntary written consent to participate in this experiment, which was approved by the local ethics committee.

Study protocol

All subjects were studied on three different days. Day 0 provided an initial baseline evaluation. Day 1 and day 2 (random allocation) provided the response to different levels of short repeated bouts of bicycle exercise, at low

Table 1 Summary of anthropometric data and estimated weekly aerobic activity

Variables	Unit	Total Mean ± SE
Subjects	*N*	29
Gender	(M/F)	17/12
Age	(years)	23.55 ± 0.38
Weight	(kg)	68.34 ± 2.03
Height	(cm)	175 ± 1.59
BMI		22.21 ± 0.45
Waist	(cm)	79.14 ± 1.61
METS	(METs min week^{-1})	2,660.7 ± 403.2

BMI body mass index, *METS* metabolic equivalent

Table 2 Summary of cardiopulmonary exercise test data

Variables	Unit	Total ($N = 29$) Mean ± SE
VO_{2peak}	(mL kg min)	41.4 ± 1.5
VO_2 VT	(mL kg min)	24.2 ± 1.4
$Watt_{peak}$	(*W*)	234 ± 8
RQ_{peak}		1.15 ± 0.01
HR ecg	(bpm)	68.9 ± 2.0
HR pre-exercise	(bpm)	88.0 ± 2.7
HR VT	(bpm)	137.1 ± 2.9
HR_{max}	(bpm)	179 ± 2
HR reserve	(bpm)	1,109 ± 3
SAP_{rest}	(mmHg)	113 ± 3
SAP_{peak}	(mmHg)	157 ± 3
DAP_{rest}	(mmHg)	75 ± 2
DAP_{peak}	(mmHg)	74 ± 2

VO_2 oxygen uptake, *VT* ventilatory threshold, *RQ* respiratory quotient, *HR* heart rate, *SAP* systolic blood pressure, *DAP* diastolic blood pressure

intensity (40 % of VO_{2peak}) and at high intensity (70 % of VO_{2peak}). These percentages were, respectively, below and above the observed respiratory threshold (Table 2).

Each day of the study, all subjects arrived at the laboratory ≥2 h after a light breakfast, avoiding caffeinated beverages and heavy physical exercise in the preceding 24 h.

Day 0

At baseline all subjects underwent a standard medical examination with a resting electrocardiogram, standard sphygmomanometric arterial blood pressure, and an assessment of resting autonomic cardiac regulation using spectral analysis of RR variability. In addition, we obtained an assessment of aerobic performance using cardiopulmonary exercise testing.

Peak aerobic capacity for each subject was assessed by a standardized incremental cycle ergometer test with a duration set at about 8–12 min, reaching a peak subjective effort in the absence of electrocardiogram (ECG) irregularities or of a hypertensive response and a respiratory quotient (RQ) >1.1 (Table 2), indicating that a peak effort had been reached (Balady et al. 2010). The protocol is a continuous ramp exercise where the load increases by 20 W/min for females and 25 W/min for males. The subjects maintain a pedaling frequency of 60/70 rev/min. During baseline, exercise and recovery heart rhythm and frequency are monitored from 12 leads ECG. Expired air is collected using a breathing apparatus and analyzed with a metabolic measurement cart (Vmax-Encore, Viasys, Carfusion, SanDiego, CA) to determine ventilatory and gas exchange variables on a breath-by-breath basis.

Days 1 and 2

All subjects participate in two constant-load interval-based exercise sessions on two different (random sequence) days, defining in essence an interval exercise. One of them is dedicated to a session of low-intensity exercise (40 % of the peak power and below the observed ventilatory threshold) and the other to high-intensity exercise (70 % of the peak power and above the observed ventilatory threshold). Each session comprises an initial 2 min pre-exercise rest with subjects sitting still on the bicycle, followed by five bouts of 2 min exercise at the set load, where subjects are asked to reach as soon as possible the predetermined pedaling rate (80/90 rev/min). At the end of each bout, subjects are asked to stop as rapidly as possible and to remain still for 2 min. Accordingly the entire episode lasts 22 min.

During these sessions, the ECG (CM5) and the respiratory signal are recorded in all subjects with a two-way radio telemetry system (Marazza, Monza. IT). Data are acquired with a personal computer using an acquisition rate of 250 samples per channel per second; the accuracy of R peak detection is improved with parabolic interpolation.

Autonomic assessment

The traditional approach to autonomic assessment with autoregressive spectral and symbolic algorithms (Casadei et al. 1995; Guzzetti et al. 2005; Malliani et al. 1991), although feasible, is critical in the conditions of repeated bouts of exercise. Accordingly, using a dedicated software tool (HeartScope) (Badilini et al. 2005), we performed this type of analysis of the tachogram solely at baseline and pre-exercise rest to assess a potential autonomic arousal in this latter case.

The quantification of the onset and offset of RR dynamics of each individual bout was performed with an ad hoc software (DynaScope) (Toninelli et al. 2012) (see Figs. 1, 2).

This software tool automatically detects the onset and offset of each individual exercise bout. The selection is optimized by operator adjustment of episode boundaries. Each detected episode is filtered (Fig. 1C) using a 15-beat median filter, then the average linear slopes for the tachycardia and bradycardia transients are computed, and the HR at 60 s into recovery assessed. The running RR 15-beat variance provides peaks both during the onset and offset transients (Fig. 1D, E), and the peak of the derivative filtered tachogram is detected during both the onset and offset transients. RR variance is important as it represents the square of standard deviation of RR, which is among the established time domain indices of RR variability.

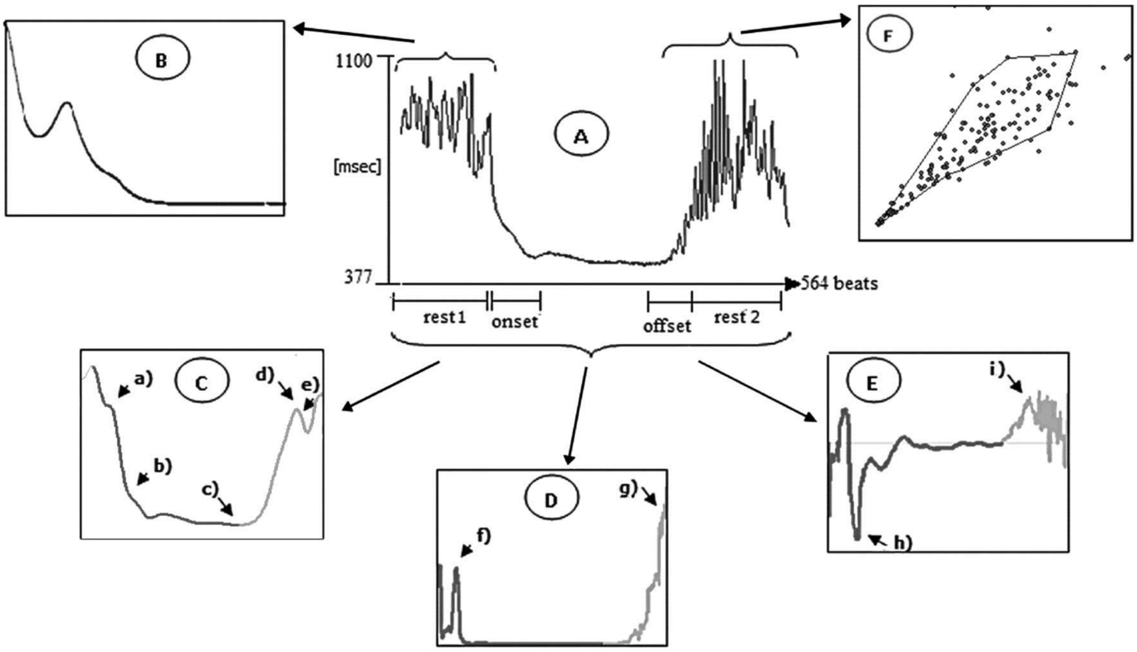


Fig. 1 Schema of analysis performed on the continuous tachogram (**A**). This explanatory illustration is limited to the first low-intensity (40 % of VO_{2peak}) bout of a series of five in a subject, and the various panels depict the different steps of analysis: **B** The autospectrum of RR interval during the rest preceding exercise onset; **C** the filtered tachogram, depicting in *dark gray* the onset (from *a* to *b*) and *light gray* the offset (*c*–*d*) segments (the *same gray* scale applies to the following panels), the HEARTRATE60sec is *e*; **D** the instantaneous variance (peak values are at *f* and *g*); **E** the instantaneous derivative of the tachogram (peak values are at *h* and *i*); **F** a Poincare' plot of the rest period following exercise offset. See also Fig. 3 for the series of five subsequent bouts at 40 and 70 %

This approach therefore extracts the totality of dynamical information embedded in the tachogram and provides several related indices from onset and offset transients.

Finally, a Poincaré plot is produced for each of the five after-bout rest periods (see Figs. 1, 2), and the areas (absolute and normalized as percent of baseline) are computed using the median of pertinent values, which may better account for the geometric asymmetries of the plot, as compared to the more commonly used ellipse-based model (Piskorski and Guzik 2007).

Other parameters obtained by the program are the HR reserve and a simple heart rate-based training impulse

$$\mathrm{TRIMP} = (\text{exercise duration (min)}) \times (\mathrm{HR_{exercise}} - \mathrm{HR_{rest}})/(\mathrm{HR_{max}} - \mathrm{HR_{rest}}) \times 0.64 \times e^{[1.92 \times (\mathrm{HR_{exercise}} - \mathrm{HR_{rest}})(\mathrm{HR_{max}} - \mathrm{HR_{rest}})]}$$

where e = Naperian logarithm having a value of 2.712, which integrates both intensity and volume of exercise into a single term (Banister and Calvert 1980; Manzi et al. 2009); however, it does not consider the metabolic elements.

To compute these measurements, the nominal maximum HR is taken as the peak HR at the exercise stress test and the minimum HR from the resting baseline electrocardiogram (day 0).

Statistical analysis

Descriptive data are presented as mean ± SEM. The normality of distribution of data was assessed with Kolmogorov–Smirnov test. The significance of effects was estimated with repeated measures general linear model procedure, considering time and load and their interaction. Since not all variables appeared normally distributed in this observational design, we performed also the analysis on rank transformed data (Conover and Iman 1976). Simple correlation (Pearson) and the ICC technique (McGrow and Wong 1966; van de Borne et al. 1997) were employed to assess, respectively, the strength of the relative links and the stability of the indices derived from the continuous tachogram. Data were treated as independent observations. From van de Borne study it may be deduced that the long-term reliability of variables follows two thresholds: a higher one at about 0.70 for direct variables such as respiratory rate, and a lower one beyond 0.34 for indirect autonomic variables. All computations were performed using a commercial statistical package (SPSS version 19).

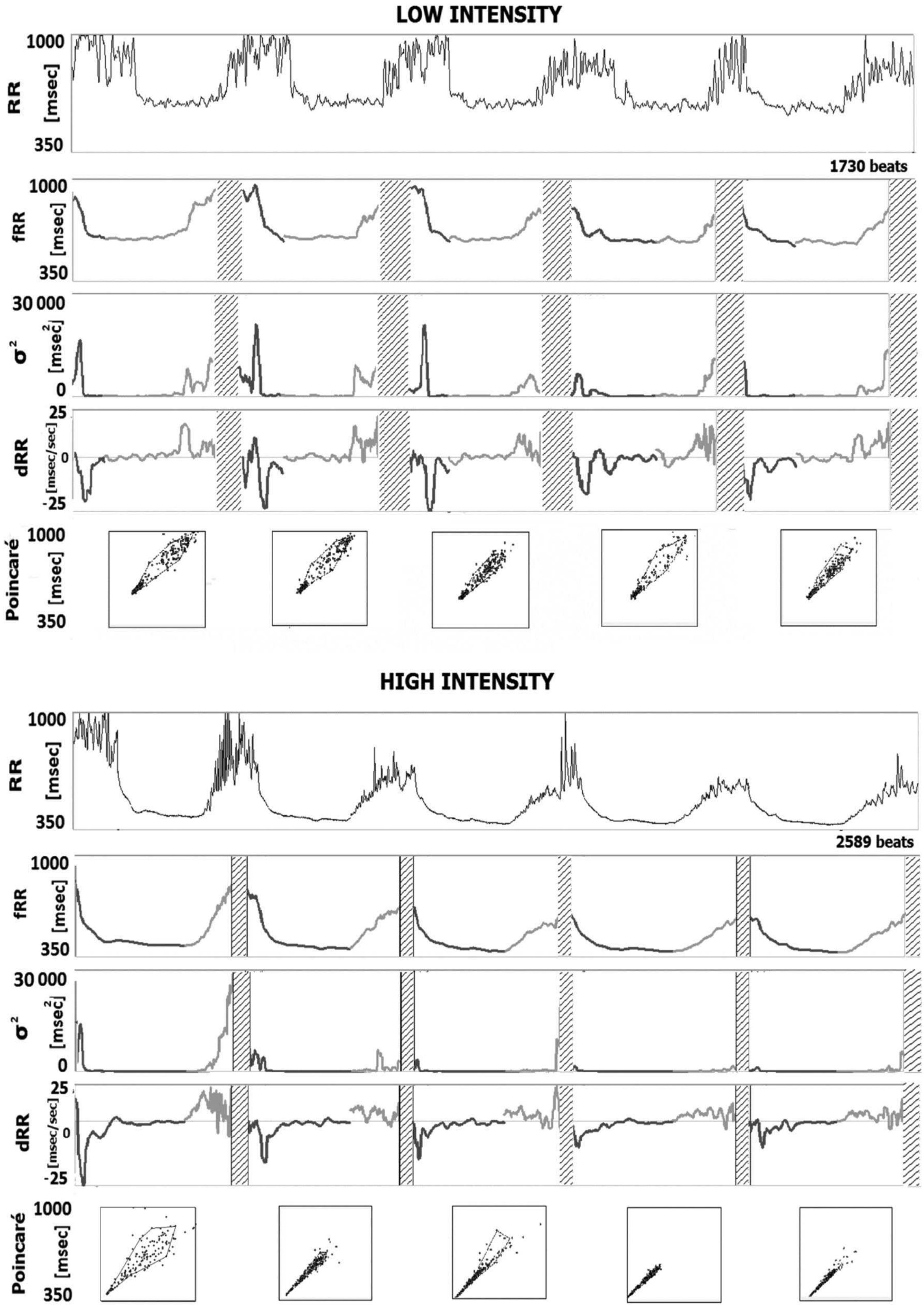


Fig. 2 Example of the continuous tachogram (*top panel*, RR) and derived onset and offset indices at low intensity (corresponding to 40 % of VO_{2peak}) and high intensity (corresponding to 70 % of VO_{2peak}) of successive exercise bouts in a typical subject. The *additional panels* represent indices extracted from the subsequent, automatically chosen segments of tachogram. Notice that the automatic procedure clips the inter-bouts tachogram (*shadowed fields*). *Variables* represented in the series of panels are as follows: *fRR* filtered RR, $\sigma^2 =$ RR variance, *dRR* first derivative representing speed of RR change, *Poincare*' plot (*x* axis scale is equal to *y* scale) of the recovery phase of each bout

Results

Cardiopulmonary exercise test

Table 2 reports the summary data from the cardiopulmonary exercise test, indicating that the population of examined subjects shows a normal aerobic fitness profile.

The elevated RQ supports in addition that a maximal peak effort has been reached. There was also a physiological HR and blood pressure response as expected from this group of healthy volunteers.

Exercise onset and offset transients

The comparison of baseline data with pre-exercise rest indicates that in this latter condition there is a marked (expectation) tachycardia (HR baseline 65.9 ± 2.1 bpm, pre-exercise rest 78.8 ± 2.2 bpm, $p < 0.001$) accompanied by an increase of indirect indices of sympathetic and reduction of parasympathetic modulation (spectral power LF_{RR} and HF_{RR} in normalized units, respectively, baseline 41.9 ± 4.8 and 52.3 ± 4.7, pre-exercise rest 79.4 ± 2.8 and 16.0 ± 2.5, both $p < 0.001$) as compared to baseline condition, suggesting autonomic arousal (other data not presented for simplicity).

Figure 2 provides an example of a complete test on a single subject, considering both low (i.e., 40 % of VO_{2peak}) and high (i.e., 70 % of VO_{2peak}) exercise intensities (see panels A, low intensity, and B, high intensity). It is clear that the RR dynamics are well captured by the automatic software, providing a series of indices that describe the variation in RR interval, in its dynamic variance and time derivative.

Regarding the entire group, a repeated measure GLM procedure shows a significant effect of load and time (i.e., bout repetition) for all examined variables, with a clear interaction (Fig. 3). However, no load × time interaction is observed with the 60 s change in heart rate.

Also the Poincare' analysis showed a significant effect for load and time as well as interaction (data not shown for simplicity).

Relationship between transient derived indices

Table 3 provides a summary view of the overall relationship between individual indices, separately for low and high loads. This table shows overall a strong link among transient derived variables, at both levels of exercise, as well as with a simple HR derived variable, but less so with Npoincare'.

ICC analysis demonstrates (Fig. 4) that various indices are characterized by large differences in stability, which is generally greater within the same day. ICC values computed across the entire series (2 days) of measurements are generally lower. Indices from time domain analysis (TRIMP, HR_{min}, HR_{max}) together with σ^2 are consistently highest, nearing (both days) or overcoming (single day) the 0.7 threshold. ICC of DELTAHR60secs remains always below this value.

Indices from onset and offset dynamics (TachySpeed, BradySpeed, TachyVar, BradyVar, Npoincare') are slightly lower, yet always above the 0.34 threshold, with the exception of tachyslope that is above it only for the lower intensity load.

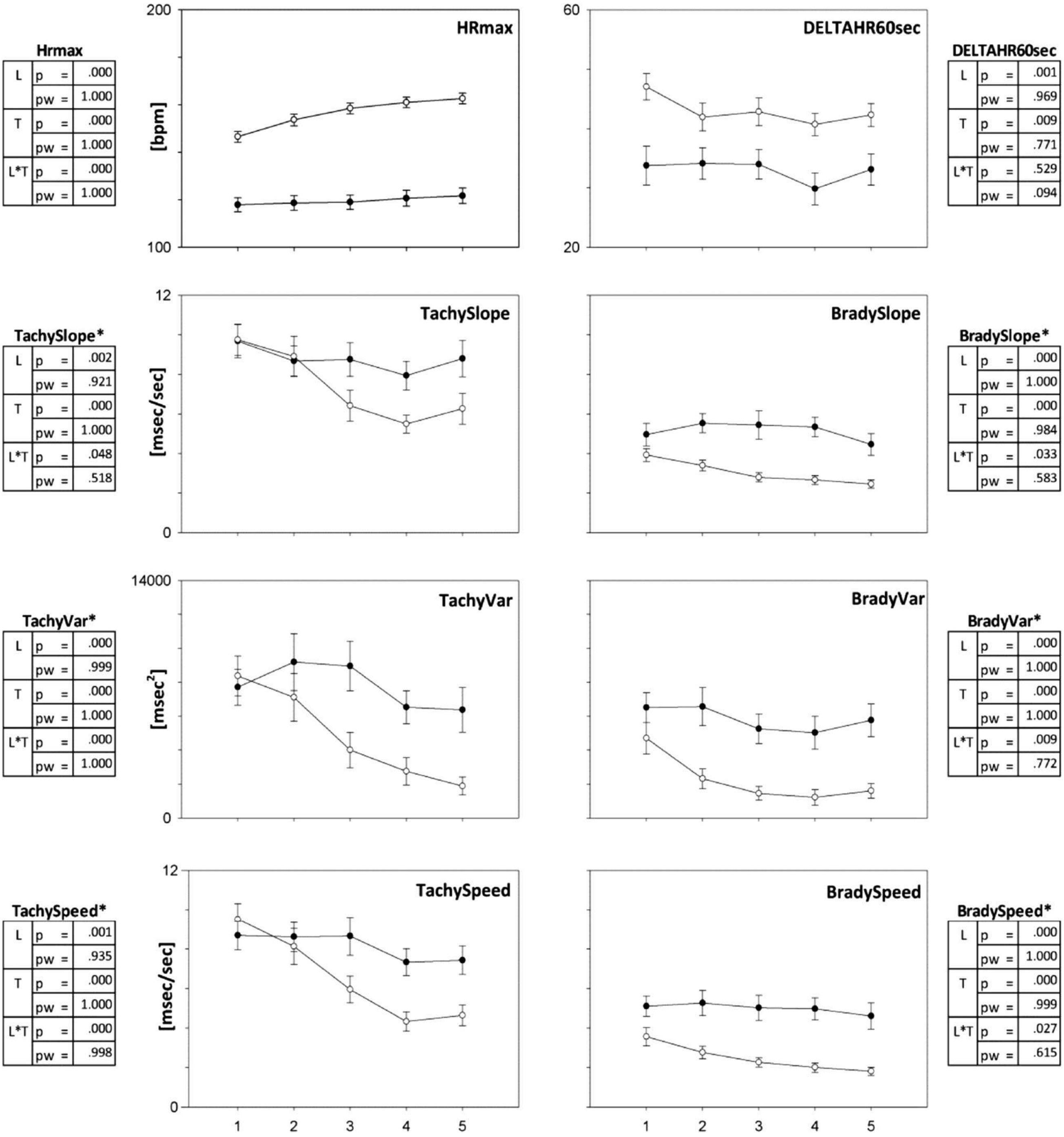
Discussion

In this study employing automatic analysis of the continuous tachogram of a series of exercise bouts (Toninelli et al. 2012) to extract indices of vagal withdrawal and reactivation (Buchheit et al. 2007; Dupuy et al. 2012; Goldberger et al. 2006; Ricardo et al. 2010; Su et al. 2010; Stuckey et al. 2012; Sugawara et al. 2001), we observe that dynamic indices may represent a more sensitive window than simple, frequently employed measures of heart rate. Furthermore, data suggest a significant interaction between load and time.

Exercise bouts

Exercise-induced changes are governed by a complex array of regulatory mechanisms encompassing peripheral and central circuits (Iellamo 2001; Lucini et al. 1995), none of which are addressed directly on the present investigation. We focus instead only what can be measured (Lucini et al. 2011) with a multiplicity of indices, addressing specific windows within the complex phenomenon of RR dynamics during the sequence of short exercise bouts and providing indirect information on autonomic regulation. Maximal heart rate or training impulse (Banister and Calvert 1980; Manzi et al. 2009), the latter integrating volume and intensity into a single value, depicts the progressively greater influence of higher exercise loads on the autonomic response.

Simple, HR-based variables as well as indices obtained from transients furnish information on vagal withdrawal and vagal reactivation, respectively, at the onset and offset of each exercise period (Javorka et al. 2003). It is important to notice that the onset and offset variables are computed automatically by a software tool (Toninelli et al. 2012) that extracts all dynamical information from the entire, digitally filtered, tachogram. Accordingly they might be less affected by random noise than simple indices (like HR and RRi) measured at given intervals. Moreover, they may be more sensitive to subtle variations in the fast dynamics (Mizuno



Hrmax

L	p =	.000
	pw =	1.000
T	p =	.000
	pw =	1.000
L*T	p =	.000
	pw =	1.000

DELTAHR60sec

L	p =	.001
	pw =	.969
T	p =	.009
	pw =	.771
L*T	p =	.529
	pw =	.094

TachySlope*

L	p =	.002
	pw =	.921
T	p =	.000
	pw =	1.000
L*T	p =	.048
	pw =	.518

BradySlope*

L	p =	.000
	pw =	1.000
T	p =	.000
	pw =	.984
L*T	p =	.033
	pw =	.583

TachyVar*

L	p =	.000
	pw =	.999
T	p =	.000
	pw =	1.000
L*T	p =	.000
	pw =	1.000

BradyVar*

L	p =	.000
	pw =	1.000
T	p =	.000
	pw =	1.000
L*T	p =	.009
	pw =	.772

TachySpeed*

L	p =	.001
	pw =	.935
T	p =	.000
	pw =	1.000
L*T	p =	.000
	pw =	.998

BradySpeed*

L	p =	.000
	pw =	1.000
T	p =	.000
	pw =	.999
L*T	p =	.027
	pw =	.615

Fig. 3 Summary plot of onset (*left*) and offset (*right*) indices computed from tachogram obtained at inter-bout intervals (from 1 to 5) for both low (*close circles*) and high (*open circles*) loads. HR_{max} HR_{max} at the end of exercise bout, *DELTAHR60sec* difference between HR_{max} and HR measured at 60 s of recovery, *TachySlope* slope of the initial descent of RR series during exercise, *BradySlope* initial slope of the RR series during recovery, *TachyVar* maximum variance of the RR series during onset of tachycardia for every bout, *BradyVar* maximum variance of the RR series during the after-bout recovery, *TachySpeed* maximum speed of the descent of the RR series during exercise bout, *BradySpeed* maximum speed of the RR series during after-bout recovery. Kolmogorov–Smirnov test: $*p \leq 0.01$; in the lateral tables significance (p) and observed power (pw) are presented for load (L), time (T) and their interaction ($L \times T$)

et al. 2010) of changes in vagal activity, and less affected by the slower changes in sympathetic activity. This might translate into a clearer interaction between load and time, which indeed is not observed with HR-derived variables (see Fig. 3). This potential limitation of HR variables probably does not apply to clinical studies (Jouven et al. 2005),

Table 3 Correlation of matrix of transient derived indices

Low intensity								
DELTAHR60sec	1.000							
TachySlope	0.231	1.000						
	0.247							
BradySlope	0.536	0.593	1.000					
	0.004	0.001						
TachyVar	0.120	0.710	0.659	1.000				
	0.552	0.000	0.000					
BradyVar	0.166	0.663	0.789	0.807	1.000			
	0.408	0.000	0.000	0.000				
TachySpeed	0.416	0.811	0.800	0.841	0.726	1.000		
	0.031	0.000	0.000	0.000	0.000			
BradySpeed	0.434	0.681	0.943	0.765	0.786	0.916	1.000	
	0.024	0.000	0.000	0.000	0.000	0.000		
Npoincaré	−0.055	0.070	0.287	−0.063	0.318	0.108	0.283	1.000
	0.784	0.727	0.147	0.756	0.106	0.591	0.152	
High intensity								
DELTAHR60sec	1.000							
TachySlope	0.694	1.000						
	0.000							
BradySlope	0.800	0.742	1.000					
	0.000	0.000						
TachyVar	0.733	0.773	0.846	1.000				
	0.000	0.000	0.000					
BradyVar	0.705	0.697	0.873	0.897	1.000			
	0.000	0.000	0.000	0.000				
TachySpeed	0.818	0.837	0.888	0.891	0.826	1.000		
	0.000	0.000	0.000	0.000	0.000			
BradySpeed	0.773	0.759	0.984	0.866	0.890	0.911	1.000	
	0.000	0.000	0.000	0.000	0.000	0.000		
Npoincaré	0.479	0.429	0.591	0.445	0.511	0.528	0.573	1.000
	0.012	0.026	0.001	0.020	0.006	0.005	0.002	
	DELTAHR60sec	TachySlope	BradySlope	TachyVar	BradyVar	TachySpeed	BradySpeed	Npoincaré

Number of cases 29; for each cell, the top value is the correlation coefficient, bottom value is the two-tailed significance; each value is the average of indices from five successive bouts

using conventional longer protocols, such as with treadmill stress test and single-point assessment of HR recovery. The potential role of long-term training (Sugawara et al. 2001), disease conditions (Imai et al. 1994) or molecular mechanisms (Hautala et al. 2006) was however not addressed by our present investigation.

Regarding the performance of other commonly employed indices, we report that Poincare plots demonstrate also a significant effect of load, time and interaction.

Stability of autonomic proxies

An additional novel part of our study was the assessment of the stability of various indices extracted from the tachogram over short and, relatively longer, periods as represented by a single or by both experimental days. The ICC analysis quantifies consistency across repetitions, providing a value from 0 to 1, where this latter indicates perfect reproducibility (McGrow and Wong 1966). Previous studies reported its convenient use for assessing the reliability of successive measures of autonomic cardiac regulation (van de Borne et al. 1997) and indicated for longer periods of observations the existence of essentially two thresholds: one above 0.7 that characterizes direct variables (such as respiration rate or HR), and a lower threshold (above 0.34) characterizing indirect measures of autonomic regulation (such as spectral indices of RR variability). These data identify therefore two

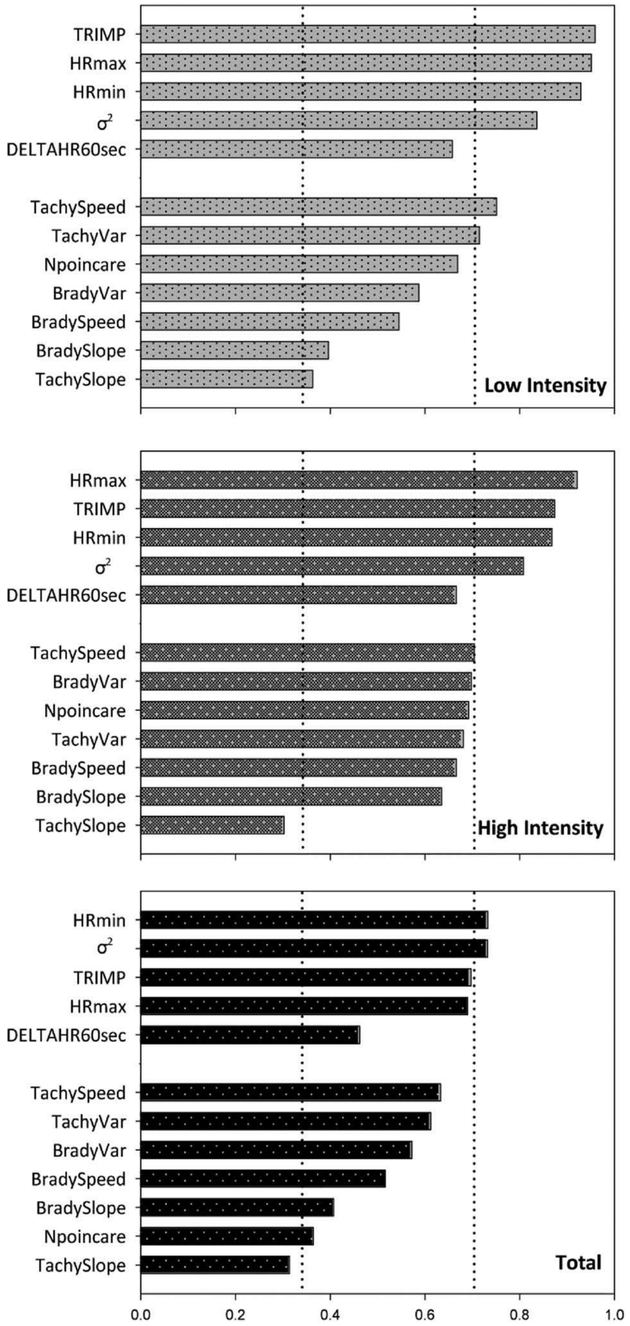


Fig. 4 Intraclass correlation (ICC) between direct parameters derived from continuous tachogram (HR_{min}, HR_{max}, TRIMP, σ^2 and DELTAHR60sec) and autonomic proxies derived from continuous tachogram during onset and offset of repeated bouts of exercise (TachySpeed, BradySpeed, TachyVar, BradyVar, TachySlope, BradySlope, Npoincare'). In the *top panel* ICC for low intensity load; in the *middle panel* ICC for high intensity load; in the *bottom panel* ICC for both low and high loads. The relevant thresholds (0.70 and 0.34) are indicated by a *dotted line* (Abbreviations as in Fig. 3)

ICC thresholds, at 0.7 and 0.34, which could be used as a convenient benchmark to assess reliability of indirect autonomic proxies.

In line with this, the present data identify large differences in stability of various indices and highlight their clear division into two main groups. Indices of ICC from the time domain analysis (TRIMP, HR_{min}, HR_{max}) and σ^2 are consistently highest and above (or very close to) the 0.7 threshold. DELTAHR60sec shows an inferior performance. Indices from onset and offset dynamics (TachySpeed, BradySpeed, TachyVar, BradyVar, TachySlope, BradySlope, Npoincare') are lower; however they fall within the threshold range 0.34 and 0.7. Indices from rest period are not addressed in this study. Among ICC indices from transients, only tachyslope falls below the 0.34 threshold. We conclude that autonomic adaptations to dynamical changes to exercise are well represented by indices of vagal withdrawal and reactivation, from exercise transients. The choice of specific indicators in a practical context, such as in assessing quality of training, may thus reflect also the level of their consistency. These findings might complement recent studies indicating that in addition to daily training logs, data on cardiac parasympathetic activity are useful for individualized training programs, monitoring recovery. Adequate (24–72 h post-exercise) or intermediate (1–48 h post-exercise) parasympathetic activity can be inferred by simple time domain analysis or by frequency domain measures. One potential problem with these analyses is the confounding of factors such as changes in plasma volume (Stanley et al. 2013) or the simultaneous influence of changing sympathetic activity over the hours-long recovery period. However the very fast nature of vagally mediated changes in RR (Mizuno et al. 2010), as occurs at onset and offset of exercise (Coote 2010), suggests a specific advantage of the presented automatic approach, which indeed extracts clinically useful parasympathetic indices from the early onset–offset dynamics of the digital tachogram.

Study limitations

It is important to clarify that although in this study we address the autonomic mechanisms underlying onset and offset heart rate transients during successive bouts of exercise, we do not provide measures of either vagal or sympathetic cardiac activity. These measures are, at the moment, impossible to obtain in humans, and only surrogate indices can be employed (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996).

In our investigation we disregard indices from autoregressive spectral analysis (Pagani et al. 1986) because of their limited consistency in conditions of submaximal exercise. We only use short-term RR variability spectra, as well as simple RR, to show a likely state of arousal during the pre-exercise rest. We employ instead multiple indices from transient analysis using a novel automatic software tool (Toninelli et al. 2012) that examines onset and offset of each bout, assuming together with the majority of investigators (Buchheit et al. 2007; Goldberger et al. 2006; Ricardo et al. 2010; Stuckey et al. 2012; Su et al. 2010; Sugawara et al. 2001) that these indices provide acceptable metrics of vagal withdrawal and reactivation. Although our study has also a methodological side, we do not delve into specific aspects of individual markers from transients, and thus do not compare in detail our results with prior investigations using onset or offset indices one by one, but only consider the collective information (Lucini et al. 2011) provided by the ensemble of them all. Regarding measures of exercise load, we did not measure lactic acid production or levels (Manzi et al. 2009); we assessed more simply the HR_{max} or training impulse. Lactate evaluation could provide additional information.

Conclusions

Our data show that an automatic software tool can provide proxies of vagal withdrawal and reactivation from short series of successive bouts of bicycle exercise, showing their exquisite sensitivity to time and load and to their interaction. The greater the exercise burden, the larger are the changes. In a modern, multidisciplinary, training perspective, combining training logs with parasympathetic assessment, the information on stability of autonomic proxies might be useful to plan training or rehabilitation routines.

The finding of different levels of strength of information and stability of data in simple heart rate changes or transient derived variables suggests the possibility of preferring the latter indices in managing training or rehabilitation procedures.

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Conflict of interest None.

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