

Autonomic response to exercise as measured by cardiovascular variability

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Abstract

Motivation. There is growing interest in the use of cardiovascular variability indicators as measures of autonomic activity, even though reported results are not always comparable or as expected. This review aims to determine the consistency of results reported on the autonomic response to physical exercise as measured by heart rate variability, blood pressure variability and baroreceptor sensitivity.

Method. An Ovid MEDLINE Database search for the period 1950 - March 2008 produced 46 articles for review. The published articles that evaluate the effect of exercise on the autonomic nervous system (ANS) are summarised in three categories: the response of the ANS during a bout of exercise, directly after exercise (recovery measurements), and after a long-term exercise programme.

Results. Articles on the effect of training on the ANS as measured by cardiovascular variability indicators show increased variability, decreased variability, and no change in variability.

Conclusion. Findings in this review emphasise that standardisation and refinement of these measuring tools are essential to produce results that can be repeated and used as reference. Standardisation is essential as these measurements are increasingly employed in studies regarding investigations of central autonomic regulation, those exploring the link between psychological processes and physiological functioning, and those indicating ANS activity in response to exercise, training and overtraining. This review shows that important aspects are inter-individual differences, duration and intensity of the exercise programme, and choice and specific implementation of variability analysis techniques.

Introduction

Heart rate variability (HRV), blood pressure variability (BPV) and baroreceptor sensitivity (BRS) are often used as measures of autonomic activity, even though reported results are not always comparable or as expected. It is known that endurance athletes have lower average resting heart rates than non-exercising individuals.^{33, 50} However, other exercise-induced autonomic influences on cardiac control are far more controversial.

Autonomic control via sympathetic and parasympathetic modulation of the heart has been assessed by power spectral analysis of HRV^{1,7,33,41,46,48,50} and BPV.^{44,52} Different frequency peaks reflect specific physiological stimuli and it is possible to estimate the involvement of the autonomic nervous system (ANS) influence and balance in heart rate (HR) regulation.^{1,2,6} With power spectral analysis of HR, two characteristic peaks between 0.04 Hz and 0.15 Hz (A) and between 0.15 Hz and 0.5 Hz (B) are used to quantify the autonomic balance in terms of the low-frequency (LF)/high-frequency (HF) ratio.^{1,6,48} Peak A is found in the region of Mayer waves (0.1 Hz) and is situated in the so-called LF area. It appears to be linked to the combined activities of the sympathetic and parasympathetic branches of the ANS. Peak B is synchronous with respiration, reflects vagal activity, is situated in the so-called HF area

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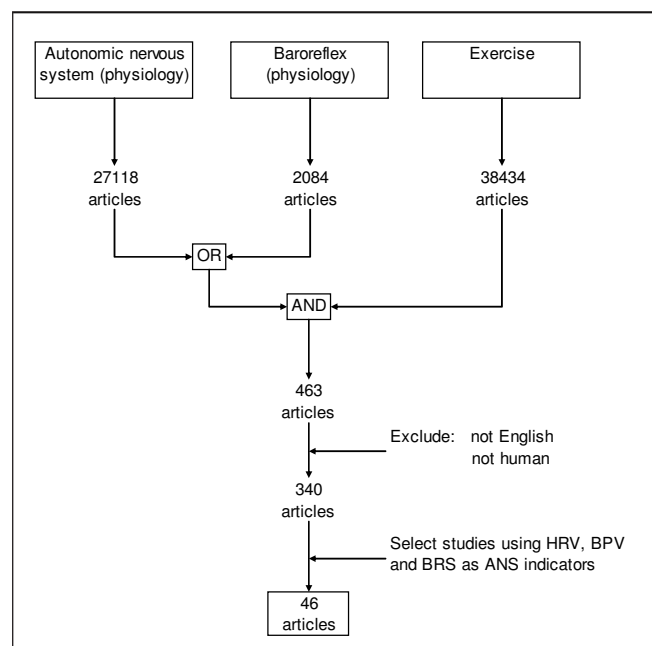


Fig. 1. Summary of the Ovid MEDLINE Database search.

TABLE I. Articles on the response of the ANS measured during a bout of exercise

Reference number	Author/s	Title	Cardiovascular variability indicator
43	Sandercock <i>et al.</i>	The use of HRV measures to assess autonomic control during exercise	Results from spectral analysis of HRV not as expected; more research needed: word of caution
5	Banach <i>et al.</i>	HRV during incremental cycling exercise in healthy, untrained young men	Spectral and time domain analysis of HRV ↓SDNN, RMSSD ↓LF, HF; LF/HF ↓Ptot
16	Freeman <i>et al.</i>	ANS interaction with the CV system during exercise	Encourage the use of HRV at rest and during exercise
14	Eryonucu <i>et al.</i>	The effect of ANS activity on exaggerated blood pressure response to exercise: evaluation by HRV	Used spectral analysis of HRV in a comparative study
29	Lucini <i>et al.</i>	Analysis of initial autonomic adjustments to moderate exercise in humans	Spectral analysis of HRV ↑LF suggest ↑SNS ↓HF suggest ↓PNS ↔ and ↑LF of BPV
42	Saito and Nakamura	Cardiac autonomic control and muscle sympathetic nerve activity during dynamic exercise	Spectral analysis of HRV ↓LF power, ↓ HF power, ↔total power ↑LF/HF: SNS↑ ↓HF/Ptot : PNS↓
26	Kamath <i>et al.</i>	Effects of steady-state exercise on the power spectrum of HRV	Spectral analysis of HRV ↓LF, ↓HF, SNS↓, PNS↓
3	Arai <i>et al.</i>	Modulation of cardiac autonomic activity during and immediately after exercise	Spectral analysis of HRV ↓HF ↓LF
51	Yamamoto <i>et al.</i>	Autonomic control of HR during exercise studied by HRV spectral analysis	Spectral analysis of HRV ↓HF: PNS↓ ↑and↔LF/HF:↑ and ↔SNS
37	Perini and Veicsteinas	HRV and autonomic activity at rest and during exercise in various physiological conditions	Spectral analysis of HRV No change in HF and LF power during increased loads ↔HF, ↔LF

LF = low frequency; HFR = high frequency; SDN = standard deviation of all intervals; Ptot = total frequency power; pNN50 = percentage of successive interval differences greater than 50ms; SNS = sympathetic nervous system; PNS = parasympathetic nervous system; SAP = systolic arterial pressure.

and also gives an indication of respiratory sinus arrhythmia (RSA).^{1,48} During measurement of systolic BPV the LF peak corresponds with sympathetic activity while the HF peak is determined by mechanical effects of respiration on intrathoracic pressure and cardiac filling.^{44,52} The variability in blood pressure and identification of the corresponding physiological stimuli are difficult to identify. Indications are that the very low frequencies (≤ 0.04 Hz) are influenced by vascular tone, endothelium factors and thermoregulation, and the LF peak (0.07 - 0.15 Hz) relates to sympathetic activity and represents vasomotor tone.² BRS reflects mainly vagal modulation of the HR by the arterial baroreceptors and the magnitude of response in heart beat interval to a change in blood pressure (ms/mmHg).⁶

Physical exercise requires rapid and complex physiological adaptation, particularly by the ANS. Exercise programmes require changes in the neural cardiovascular and ANS control that are unique to the person and his/her surroundings. This review aims to determine the consistency of results reported on the autonomic response to physical exercise as measured by HRV, BPV and BRS.

Method

An Ovid MEDLINE Database search was conducted for the period 1950 - March 2008 (Fig. 1). The term 'ANS (physiology)' produced 27 118 articles, and 'baroreflex (physiology)' 2 084 articles. When link-

ing the results with the term 'exercise' (38 434 articles) and then limiting the results to 'humans and English', 340 references were found. Only articles that used HRV (determined by time-domain analysis, Poincaré analysis and/or frequency-domain analysis), non-invasive BPV and BRS as indicators of autonomic function were selected, yielding 46 articles.

Results

Published articles on the effect of exercise on the ANS as measured by HRV and BPV are summarised in three categories: the response of the ANS measured during a bout of exercise,^{3,5,14,16,26,29,37,42,43,51} and directly after a bout of exercise (recovery measurements),^{3,9,22-24,28,40,49} and the long-term effect of regular exercise on the ANS.^{4,8,10-13,15,17,18,19-21,25,27,30-32,34-36,38,39,45,47}

The results of 10 articles on ANS response measured during exercise are shown in Table I. Some authors expressed concern about the measurement of spectral analysis of HRV during exercise, while others reported increases (↑), decreases (↓) and no changes in variability indicators (↔) of sympathetic (SNS) and parasympathetic (PNS) influence.

Table II shows results of 10 articles on the response of the ANS measured after a bout of exercise (recovery measurements). Comments found were based on time domain, spectral and coarse-

TABLE II. Articles on the response of the ANS measured directly after a bout of exercise (recovery measurements)

Reference number	Author/s	Title	Cardiovascular variability indicator
24	Heffernan <i>et al.</i>	Cardiac autonomic modulation during recovery from acute endurance v. resistance exercise	Spectral analysis of HRV After endurance: ↔total power, ↑LF/HF, After resistance: ↓total power of HRV, ↑LF/HF
49	Terziotti <i>et al.</i>	Post-exercise recovery of autonomic cardiovascular control: a study by spectrum and cross-spectrum analysis in humans	Spectral analysis of HRV and BPV ↑LF of systolic blood pressure ↓HF activity of heart rate ↓decreased BRS
22	Hayashi <i>et al.</i>	Cardiac autonomic regulation after moderate and exhaustive exercises	Coarse-graining spectral analysis of HRV ↓HF ↑LF/HF
40	Raczak <i>et al.</i>	Cardiovagal response to acute mild exercise in young healthy subjects	Time domain and spectral analysis of HRV and BRS ↑SDNN ↔LF and HF ↓BRS
26	Kamath <i>et al.</i>	Effects of steady state exercise on the power spectrum of HRV	Spectral analysis of HRV ↑LF activity
23	Heffernan	Arterial stiffness and baroreflex sensitivity following bouts of aerobic and resistance exercise	BRS via the sequence technique ↓BRS after resistance and aerobic exercise. Greater reduction after resistance
9	Brown and Brown	Resting and post-exercise cardiac autonomic control in trained master athletes	Time domain and spectral analysis of HRV ↓SDRR, ↓total power, ↓HF. ↔LF
28	Lucini <i>et al.</i>	Selective reductions of cardiac autonomic responses to light bicycle exercise with aging in healthy humans	Spectral analysis of HRV and BPV HRV decreases with age BRS via sequence technique
15	Figuroa <i>et al.</i>	Endurance training improves post-exercise cardiac autonomic modulation in obese women with and without type 2 diabetes	Spectral analysis of HRV BRS via sequence technique ↑HF, LF, BRS
3	Arai <i>et al.</i>	Modulation of cardiac autonomic activity during and immediately after exercise	Spectral analysis of HRV ↓HF, ↓LF

LF = low frequency; HFR = high frequency; SDN = standard deviation of all intervals; Ptot = total frequency power; pNN50 = percentage of successive interval differences greater than 50ms; SNS = sympathetic nervous system; PNS = parasympathetic nervous system; SAP = systolic arterial pressure.

graining analysis of HRV and BRS via the sequence technique and spectral analysis of BPV.

Table III summarises findings on the long-term effect of regular exercise on the ANS. Some of the different techniques used to estimate cardiovascular variability were time domain and spectral analysis of HRV, BRS via sequence technique and the alpha index, spectral analysis of BRS and also BRS via the slope of the baroreflex sequences and transfer function gain.

Discussion

Articles published on cardiovascular variability measured during exercise concluded that the interpretation of variability measurements is difficult because indicators reflecting sympathovagal interactions at rest do not behave as expected during exercise and that the increased respiratory effort had a confounding effect on HF bands.⁴³ It is also suggested that the presence of cross-sectional differences between HRV in athletes and non-athletes should be noted and that one should not use HRV data to determine autonomic control during exercise. Doubt was expressed on the applicability of the HRV power-spectrum analysis, with its present interpretation, to assess the sympathovagal interaction during exercise.⁵ However, other authors encouraged the use of HRV components at rest and during exercise

as prognostic indicators, but called for the refinement of exercise measurements.¹⁶ Eryonucu *et al.* used HRV as an indicator of ANS activity before, during and after exercise in a comparative study.¹⁴ Two other studies reported increased sympathetic influence (measured by LF and LF/HF) on autonomic cardiac control during graded exercise,^{29,42} including increased, peripheral, vascular sympathetic activation at 30% of maximum exercise in the study by Saito and Nakamura.⁴² These results were in direct conflict with studies indicating significant suppression of both SNS and PNS autonomic cardiac control during graded exercise measured by the LF and HF of the power spectrum of HRV.^{3,26} In 1991 Yamamoto *et al.*⁵¹ reported decreased PNS activity (HF) and unchanged SNS activity (LF/HF) up to 100% of the predetermined ventilatory threshold (T_{vent}), with an abrupt increase in SNS activity (LF/HF) only at 100% T_{vent} . Perini and Veicsteinas³⁷ concluded that changes in HF and LF power and in LF/HF observed during exercise do not reflect the decrease in vagal activity and the activation of the SNS at increasing loads; neither did fitness level, age and hypoxia have any influence. However, exercising at medium-high intensities in the supine position did produce measurable increased power in LF.

Cardiovascular variability measured during recovery from a single bout of endurance exercise indicated that the total power of HRV

TABLE III. Articles on the long-term autonomic effects of regular exercise

Reference number	Author/s	Name	Cardiovascular variability indicator
15	Figueroa <i>et al.</i>	Endurance training improves post-exercise cardiac autonomic modulation in obese women with and without type 2 diabetes	Spectral analysis of HRV BRS via sequence technique ↔HRV and BRS: no baseline changes
47	Spierer <i>et al.</i>	Exercise training improves cardiovascular and autonomic profiles in HIV	Spectral analysis of HRV BRS via alpha index ↑BRS increased ↑HF ↓LF/HF
4	Aubert <i>et al.</i>	Low-dose exercise does not influence cardiac autonomic control in healthy sedentary men aged 55 - 75 years	Spectral analysis of HRV ↔LF, HF, LF/HF
31	Martinelli <i>et al.</i>	HRV in athletes and non-athletes at rest and during head-up tilt	Spectral analysis of HRV ↑SDNN ↔LF, HF: SNS/PNS↔
45	Sharma <i>et al.</i>	Short term physical training alters cardiovascular autonomic response amplitude and latencies	Time domain and spectral analysis of HRV ↔HRV indicators
37	Perini and Veicsteinas	HRV and autonomic activity at rest and during exercise in various physiological conditions	Spectral analysis of HRV Fitness level has no influence
10	Buchheit and Gindre	Cardiac parasympathetic regulation: respective associations with cardiorespiratory fitness and training load	Time domain and spectral analysis of HRV ↑HF, RMSSD, PNN ₅₀
39	Raczak <i>et al.</i>	Long-term exercise training improves ANS profile in professional runners	Time domain and spectral analysis of HRV, spectral analysis of BRS ↑SDNN, pNN ₅₀ , RMSSD, ↑Total power and LF ↑BRS
36	Okazaki <i>et al.</i>	Dose-response relationship of endurance training for autonomic circulatory control in healthy seniors	Spectral analysis of HRV BRS via transfer function gain ↑SDRR, LF, HF ↑BRS
32	Melo <i>et al.</i>	Effects of age and physical activity on the autonomic control of heart rate in healthy men	Time domain and spectral analysis of HRV ↑RMSSD ↓HR
19	Goldsmith <i>et al.</i>	Exercise and autonomic function	Review ↑SNS activity ↓PNS activity
17	Goldsmith <i>et al.</i>	Physical fitness as a determinant of vagal modulation	Spectral analysis of HRV ↑HF
27	Kiviniemi <i>et al.</i>	Cardiac vagal outflow after aerobic training by analysis of high-frequency oscillation of the R-R interval	Spectral analysis of HRV ↑HF
12	Cooke <i>et al.</i>	Effects of training on CV and sympathetic responses to Valsalva's maneuver	Time domain analysis of HRV, BRS ↑SDRR ↑BRS
13	Costes <i>et al.</i>	Influence of exercise training on cardiac BRS in patients with COPD	BRS via the slope of the baroreflex sequences between systolic blood pressure changes ↑BRS
34	Monahan <i>et al.</i>	Regular aerobic exercise modulates age-associated declines in cardiovagal baroreflex sensitivity in healthy men	BRS via linear regression between BP en RR intervals during a Valsalva maneuver ↑BRS
11	Carter <i>et al.</i>	Effect of endurance training on autonomic control of heart rate – review	Review ↓SNS activity ↓PNS activity
25	Iellamo <i>et al.</i>	Conversion from vagal to sympathetic predominance with strenuous training in high-performance athletes	Spectral analysis of HRV BRS via the sequences method 100% training load reverse effects: ↑LF, ↓HF, BRS↓
8	Bowman <i>et al.</i>	Effects of aerobic exercise training and yoga on the baroreflex in healthy elderly persons	BRS via the alpha index ↔BRS

TABLE III. Articles on the long-term autonomic effects of regular exercise – continued

35	Nagai <i>et al.</i>	Moderate physical exercise increases cardiac ANS activity in children with low HRV	Spectral analysis of HRV ↑LF, ↓HF
38	Pigozzi <i>et al.</i>	Effects of aerobic exercise training on 24hr profile of HRV in female athletes	Time domain and spectral analysis of HRV ↔Time domain ↔LF, HF (daytime)
20	Gulli <i>et al.</i>	Moderate aerobic training improves autonomic CV control in older women	Spectral analysis of HRV and BPV ↑BRS ↑LF (RR), LF (SAP)
18	Goldsmith <i>et al.</i>	Comparison of 24-hour parasympathetic activity in endurance-trained and untrained young men	Report conflicting results Spectral analysis of HRV ↑HF
21	Hautala <i>et al.</i>	Cardiovascular autonomic function correlates with the response to aerobic training in healthy sedentary subjects	Baseline vagal (HF) influences determines effect of exercise training

LF = low frequency; HFR = high frequency; SDN = standard deviation of all intervals; Ptot = total frequency power; pNN50 = percentage of successive interval differences greater than 50ms; SNS = sympathetic nervous system; PNS = parasympathetic nervous system; SAP = systolic arterial pressure.

TABLE IV. Possible confounding factors

Inter-individual variation
Baseline cardiovascular autonomic function
Age
Gender
Fitness
BMI
Diet
Alcohol consumption
Smoking
Analysis techniques
Time and frequency domain measures do not describe non-linear features in HR behaviour
Use of DA, ApEn
Length of sampling time (tachogram)
Training/exercise
Length of training period
Intensity of training
Type of exercise: resistance or endurance

did not alter compared with significantly reduced total power found after resistance exercise. However, the LF/HF ratio was significantly increased after both resistance and endurance exercise, indicating increased SNS (LF) and/or decreased PNS (HF) influence.²⁴ This corresponds with results published by Terziotti *et al.*, who found a reduced HF (vagal) component of HR and decreased BRS during 15 minutes of recovery.⁴⁹ Another study²² also found suppressed vagal (HF) activities 10 minutes of recovery after 100% of the individual ventilatory threshold compared with baseline values. Raczak *et al.* found no differences in HF and LF activities between pre- and post-exercise measurements, but increased BRS and overall HRV as measured by standard deviation of all intervals (SDNN) after exercise.⁴⁰ However, Kamath *et al.*²⁶ and Figueroa *et al.*¹⁵ reported significant increased LF power during post-exercise recovery. This contrasts with findings by Arai *et al.*, who reported significantly decreased HR power at all frequencies compared with baseline values in normal subjects.³ Decreased BRS and HRV after exercise were also reported in other studies.^{9,23} Lucini *et al.* reported that ageing progressively reduces the cardiac autonomic excitatory response to light exercise.²⁸

Articles on the effect of an endurance training programme over a period of time also showed a wide range of results. One study¹⁵ reported no change in baseline BRS and HRV values after a 16-week fitness programme, while another found increased BRS

when comparing fitness levels.⁴⁷ Aubert *et al.* also found no evidence of significant changes in resting autonomic modulation of the sinus node after a low-volume, moderate-intensity 1-year exercise programme.⁴ Comparing 11 young sedentary participants and 10 endurance-trained cyclists Martinelli *et al.* found no difference in power-spectral components of HRV at rest.³¹ However, a lower HR and higher values for time domain HRV indicators were reported during rest and head-up tilt, concluding that resting bradycardia seems to be more related to changes in intrinsic mechanisms than to ANS control modifications. Sharma *et al.* found no statistically significant changes in autonomic cardiovascular control measured by HRV after a physical training programme of 15 days.⁴⁵ Perini and Veicsteinas³⁷ reported no influence of factors such as age and fitness level, while Bucheit and Gindre¹⁰ showed that modifications in autonomic activities induced by training are visible in HRV power spectra at rest. Rackzak *et al.*³⁹ reported PNS dominance by measuring HRV and increased BRS after long-term exercise training. Another study³⁶ reported increased HRV and BRS in Masters Athletes compared with decreased values for sedentary seniors. Several other studies also concluded that regular physical activity increases vagal influence on the HR and BRS, while the sympathetic tone may be decreased.^{8,11-13,17,19,25,27,32,34} However, Iellamo *et al.*²⁵ found a reversal of these effects after a period of training at 100% training load. Very intensive training shifted the CV autonomic modulation from PNS toward SNS predominance. Increases were reported in all components of HRV after a 1-year exercise training programme in children who initially had low HRV.³⁵ In 2001 Pigozzi *et al.*³⁸ found that a 5-week exercise training period in female athletes increased the SNS cardiac modulation, which may coexist with relatively reduced or unaffected vagal modulation. Gulli *et al.*²⁰ reported increased LF reactivity (SNS) and BRS after a moderate aerobic training programme in older women.

In 1992 Goldsmith *et al.*¹⁸ noted that, although exercise training may increase PNS activity, studies report conflicting results. As seen from the above summary, nearly two decades later conflicting results persist when the effects of exercise training on the ANS is measured during exercise, directly after exercise and after a long-term exercise programme. Possible confounding factors mentioned and identified are listed in Table IV.

A possible explanation for conflicting results is that the individual's response is greatly influenced by the baseline cardiovascular autonomic function, thus producing large inter-subject variation in the

conventional non-spectral and spectral measures of cardiovascular variability. Hautala *et al.*²¹ suggested that high vagal activity at baseline is associated with improvement in aerobic power caused by aerobic exercise training. We also observed that some studies used non-homogeneous participant groups with regard to age, gender and BMI, while others did not include these in the participant description. Factors often not taken into consideration are baseline blood pressure, blood cholesterol and diet. The effect of duration and intensity of the training programme as well as the type of exercise (endurance or resistance) may have been underestimated in studies on the ANS and exercise.²⁴ In this review training periods from 15 days to 1 year were studied and the different degrees of exercise intensity used were not even mentioned in many articles.²² The choice and specific analysis techniques implemented may also play a role in the observed conflicting results. The recommended sampling time (tachogram) for HRV analysis is 5 minutes,⁴⁸ but different time windows were selected by different authors – 5 minutes, 10 minutes, 15 minutes and 24 hours. The articles studied used mostly traditional measures of variability, such as time and frequency. However, it is known that non-linear phenomena are involved in cardiovascular control. Therefore, the use of analysis techniques that acknowledge this fact should be co-implemented and reported with traditional measures. Examples include the measurement of fractal scaling exponents (describes the fractal-like correlation properties of R-R interval data) and ApEn (quantifies the amount of complexity in the time series data).³⁰

Conclusions

This review demonstrates the wide variety of results published during the past decades on the effect of training on the ANS as measured by cardiovascular variability indicators. It is clear from the results that standardisation and refinement of these measuring tools are essential to produce repeatable results that can be used as references in other studies. This is necessary as these measurements are increasingly employed in studies ranging from investigations of central autonomic regulation; to studies exploring the link between psychological processes and physiological functioning; to the indication of ANS activity in response to exercise, training and overtraining. Important aspects to consider when developing standardised procedures are inter-individual differences, duration and intensity of the exercise programme, and the choice and implementation of a specific variability analysis technique. Much more research needs to be done to fully describe and accurately quantify the effect of exercise on the ANS.

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