ORIGINAL ARTICLE

Assessment of ventilatory thresholds during graded and maximal exercise test using time varying analysis of respiratory sinus arrhythmia

G Blain, O Meste, T Bouchard, S Berman

Br J Sports Med 2005;39:448–452. doi: 10.1136/bjism.2004.014134

See end of article for authors' affiliations

Correspondence to:
 Gregory Blain, Université
 de Toulon-Var,
 Département Ergonomie
 Sportive et Performances,
 Avenue Valombrose, NICE
 cedex 2 06107, France;
 blain@unice.fr

Accepted
 7 September 2004

Objective: To test whether ventilatory thresholds, measured during an exercise test, could be assessed using time varying analysis of respiratory sinus arrhythmia frequency (f_{RSA}).

Methods: Fourteen sedentary subjects and 12 endurance athletes performed a graded and maximal exercise test on a cycle ergometer: initial load 75 W (sedentary subjects) and 150 W (athletes), increments 37.5 W/2 min. f_{RSA} was extracted from heart period series using an evolutive model. First (T_{V1}) and second (T_{V2}) ventilatory thresholds were determined from the time course curves of ventilation and ventilatory equivalents for O_2 and CO_2 .

Results: f_{RSA} was accurately extracted from all recordings and positively correlated to respiratory frequency ($r=0.96$ (0.03), $p<0.01$). In 21 of the 26 subjects, two successive non-linear increases were determined in f_{RSA} , defining the first (T_{RSA1}) and second (T_{RSA2}) f_{RSA} thresholds. When expressed as a function of power, T_{RSA1} and T_{RSA2} were not significantly different from and closely linked to T_{V1} ($r=0.99$, $p<0.001$) and T_{V2} ($r=0.99$, $p<0.001$), respectively. In the five remaining subjects, only one non-linear increase was observed close to T_{V2} . Significant differences ($p<0.04$) were found between athlete and sedentary groups when T_{RSA1} and T_{RSA2} were expressed in terms of absolute and relative power and percentage of maximal aerobic power. In the sedentary group, T_{RSA1} and T_{RSA2} were 150.3 (18.7) W and 198.3 (28.8) W, respectively, whereas in the athlete group T_{RSA1} and T_{RSA2} were 247.3 (32.8) W and 316.0 (28.8) W, respectively.

Conclusions: Dynamic analysis of f_{RSA} provides a useful tool for identifying ventilatory thresholds during graded and maximal exercise test in sedentary subjects and athletes.

The spectral approach of heart period variability (HPV) has highlighted the fact that respiratory sinus arrhythmia (RSA) during exercise is the main mechanism regulating short term heart period (HP) fluctuations.^{1–3} RSA results from modulation of sinus node activity by breathing. Indeed, strong correlations have been found between the centred frequency of respiratory sinus arrhythmia (f_{RSA}) and respiratory frequency (f_R).^{3–5} Classical spectral analysis requires stationarity of the studied signal. Consequently, studies of HPV and RSA during exercise are scarce. To overcome these limitations, time varying models have been developed which allow us to depict a signal divided into its instantaneous frequency and power components. During pyramidal exercises, the dynamic behaviour of f_{RSA} has been accurately extracted and strong links between f_{RSA} and f_R dynamic behaviours have been pointed out.⁶ This original approach to signal processing may be used in practice. For instance, Anosov *et al*⁶ have found that the dynamic behaviour of f_{RSA} extracted from HP series, recorded during a ramp load protocol, demonstrates significant changes in the region of the anaerobic threshold (AT). Previously, James *et al* showed that during graded exercise, the AT could be detected in healthy adults by f_R analysis. Moreover, ventilation ($\dot{V}_1$) time course analysis reveals two disproportionate increases in $\dot{V}_{O_2}$,⁷ defining the first and second ventilatory thresholds. These disproportionate increases are related to exercise induced acidosis compensation and are mainly linked to f_R increase.^{8–9} Although disagreement exists,^{10–11} ventilatory thresholds are closely related to lactate thresholds^{12–16} and could provide reliable indices of changes in response to endurance training or be useful when prescribing exercise training.^{17–19}

As the two disproportionate increases in $\dot{V}_1$ are explained by f_R disproportionate increases, analysis of f_{RSA} dynamic behaviour

during a graded and maximal exercise test could reveal both the first and second ventilatory thresholds and provide practical applications as previously suggested. Such a method would be non-invasive and less expensive than the ventilatory flow and gas measurements required by ventilatory methods.

The first objective of this study was to use the signal processing method we previously developed⁶ to extract f_{RSA} from HP series recorded during graded and maximal exercise tests. Dynamic behaviours of f_{RSA} and ventilatory indices were then compared as regards exercise intensity in sedentary and athlete groups.

METHODS

Subjects

Fourteen sedentary healthy men (mean (SD) age: 24.5 (2.3) years) and 12 endurance athletes (age: 25.7 (2.8) years; >12 h of training/week) (characteristics shown in table 1) participated in the study. All subjects were non-smokers and none was taking medication. Physical activity and consumption of alcohol and caffeinated beverages were prohibited 24 h before the exercise testing session. Written informed consent was obtained prior to participation and ethical approval was granted by the Local Ethics Committee.

Experimental design

Subjects performed a graded and maximal exercise test on a cycle ergometer (Ergomedic 824 E, Monark Exercise, Vansbro, Sweden) in a quiet room at a controlled temperature of 21°C, at least 3 h after the last meal. In the sedentary and the athlete

Abbreviations: AT, anaerobic threshold; HP, heart period; HPV, heart period variability; RSA, respiratory sinus arrhythmia

Table 1 Anthropometric and maximal ergometric characteristics of the subjects

	Sedentary group (n = 14)		Athlete group (n = 12)		p
	Mean	SD	Mean	SD	
Age (years)	24.5	2.3	25.7	2.8	NS
Height (cm)	173.4	9.1	183.8	5.6	**
Weight (kg)	68.3	9.9	81.4	8.5	**
$\dot{V}O_{2\max}$ (ml/min/kg)	44.7	4.6	56.4	9.3	***
$W_{\max}$ (W)	266.6	27.1	383.9	26.6	***
$W_{\max}$ (W/kg)	3.96	0.44	4.78	0.72	**
$HR_{\max}$ (bpm)	197.6	7.8	188.3	5.7	**

HR, heart rate; NS, not significant; $\dot{V}O_{2\max}$, maximal oxygen uptake; $W_{\max}$, maximal aerobic power.

Difference between groups: **p<0.01; ***p<0.001.

groups, the initial load was fixed at 75 and 150 W, respectively, and increased by 37.5 W every 2 min until exhaustion. The pedalling rate was kept constant at 75 rev/min.

Ventilatory indices and gas exchanges were measured using an automatic ergospirometer on a breath by breath basis (Metasys TR-M, Brainware, Toulon, France). Subjects breathed through a silicon facemask connected to a two-way non-rebreathing valve (Hans Rudolph, Kansas City, MO). Inspired and expired O_2 and CO_2 concentrations were measured using paramagnetic and infrared sensors, respectively. Averages every 10 s were then established for $\dot{V}_I$ (l/min), O_2 uptake ($\dot{V}O_2$, l/min), CO_2 production ($\dot{V}CO_2$, l/min), respiratory ratio (R), and ventilatory equivalents for O_2 ($\dot{V}_I/\dot{V}O_2$) and CO_2 ($\dot{V}_I/\dot{V}CO_2$). f_R was calculated on a breath by breath basis. Before each test, the gas analysers were calibrated with gases of known composition and an accurate controlled volume syringe was used to adjust the pneumotachograph. During the exercise tests, a one lead ECG (Cardiicap II, Datex Engstrom, Helsinki, Finland) was recorded and digitised on line by a 12 bit analog-to-digital converter (DAS 1600, Keithley Instruments, Taunton, MA) at a sampling rate of 1000 Hz, on a personal computer. Oxygen uptake was considered maximal ($\dot{V}O_{2\max}$) if three of the following criteria were met: levelling off of $\dot{V}O_2$ despite increasing load, R greater than 1.10, and inability to maintain the fixed pedalling rate. The power corresponding to $\dot{V}O_{2\max}$ defined the maximal aerobic power ($W_{\max}$).

ECG preprocessing

R wave peak occurrence was estimated using a threshold technique applied to the filtered and demodulated ECG signal.

HP series were visually inspected to ensure the absence of artefacts. In case of artefacts arising from a spurious R wave detection, the HP was restored by summing the two or more spuriously short periods. In cases of undetected R wave, the erroneous HP was replaced by using the two adjacent HP values. Artefacts did not exceed 1% of the total HP series. The first 20 s of exercise, which correspond to a marked HP decrease, were removed to limit sources of non-stationarity. In addition, the local mean HP was also removed using a polynomial approximation $po(k)$ (order equal to 20) and a 100th order high pass finite impulse response filter was applied to the detrended HP series.

Since the stationarity conditions are not fulfilled under dynamic exercise, classical spectral analysis methods were replaced by a previously described method.^{6,20} Using this method, the dynamic behaviour of f_{RSA} was extracted.

ECG preprocessing was performed using Matlab software 6.0 R12 (MathWorks, Natick, MA).

Determination of ventilatory and RSA thresholds

Ventilatory thresholds were determined from the time course curves of $\dot{V}_I$, $\dot{V}_I/\dot{V}O_2$, and $\dot{V}_I/\dot{V}CO_2$ by a first independent operator. T_{V1} corresponded to the last point before a first non-linear increase in both $\dot{V}_I$ and $\dot{V}_I/\dot{V}O_2$. T_{V2} corresponded to the last point before a second non-linear increase in both $\dot{V}_I$ and $\dot{V}_I/\dot{V}O_2$, accompanied by a non-linear increase in $\dot{V}_I/\dot{V}CO_2$.⁷ The f_{RSA} thresholds were determined from the time course curve of f_{RSA} by a second independent operator. The first f_{RSA} threshold (T_{RSA1}) corresponded to the last point before a first non-linear increase in f_{RSA} . The second f_{RSA} threshold (T_{RSA2}) corresponded to a second non-linear increase in f_{RSA} .

Thresholds were expressed in terms of absolute (W) and relative (W/kg) power and percentage of $W_{\max}$.

Statistical analysis

Differences between the sedentary and athlete groups were tested using unpaired Student's *t* test. Comparison and relationship between ventilatory and f_{RSA} thresholds were tested using paired Student's *t* test and a linear regression analysis, respectively. Individual relationships between f_{RSA} and f_R were tested by calculating Pearson's *r* correlation coefficients. The mean (SD) of all individual correlation coefficients was then calculated. Statistical significance was set at p<0.05. Results are means (SD). Statistical analysis was performed using Statistica software 5.5 (StatSoft, Tulsa, OK).

RESULTS

Athletes showed significantly higher values of $\dot{V}O_2$ and $W_{\max}$ when compared to sedentary subjects (see table 1).

Table 2 First and second thresholds obtained from f_{RSA} and ventilatory indices, in sedentary and athlete groups

		Sedentary group (n = 12)		Athlete group (n = 9)		p
		Mean	SD	Mean	SD	
Absolute power (W)	T_{RSA1}	150.3	18.7	247.3	32.8	***
	T_{V1}	151.0	19.5	247.0	33.6	***
	T_{RSA2}	198.3	28.8	316.0	28.8	***
	T_{V2}	200.3	29.4	310.9	26.7	***
Relative power (W/kg)	T_{RSA1}	2.21	0.33	3.09	0.64	***
	T_{V1}	2.22	0.34	3.09	0.65	***
	T_{RSA2}	2.94	0.39	3.96	0.67	***
	T_{V2}	2.97	0.38	3.90	0.66	***
% $W_{\max}$	T_{RSA1}	56.5	6.0	62.5	6.6	*
	T_{V1}	56.8	6.7	62.3	5.7	*
	T_{RSA2}	74.4	7.5	82.3	4.9	**
	T_{V2}	75.1	7.6	81.0	4.9	*

% $W_{\max}$, percentage of maximal aerobic power; T_{RSA1} , first respiratory sinus arrhythmia frequency (f_{RSA}) threshold; T_{RSA2} , second f_{RSA} threshold; T_{V1} , first ventilatory threshold; T_{V2} , second ventilatory threshold.

Difference between groups: *p<0.05; **p<0.01; ***p<0.001.

f_{RSA} extraction

A conspicuous high frequency oscillation synchronous with f_R was found in all ECG recordings, clearly indicating the persistence of RSA over the entire graded and maximal exercise protocol. The dynamic evolution of f_{RSA} was accurately extracted from the HP series and f_{RSA} positively correlated ($r = 0.96$ (0.03), $p < 0.01$) with f_R (fig 1).

f_{RSA} dynamic behaviour

Two non-linear increases were observed in f_{RSA} in 21 of the 26 subjects. These non-linear increases coincided with T_{V1} and T_{V2} , respectively (see fig 2) and no statistical difference was observed between T_{RSA1} and T_{V1} (absolute power: $p = 0.98$; relative power: $p = 0.90$; percentage of W_{max} : $p = 0.91$) and T_{RSA2} and T_{V2} (absolute power: $p = 0.57$; relative power: $p = 0.79$; percentage of W_{max} : $p = 0.78$). Power values and percentages of W_{max} at T_{RSA1} , T_{RSA2} , T_{V1} , and T_{V2} are presented in table 2. When expressed as absolute or relative power and percentage of W_{max} , T_{RSA1} , T_{RSA2} , T_{V1} , and T_{V2} were significantly higher in athletes than in their sedentary peers. Linear regression analysis showed high correlation between T_{RSA1} and T_{V1} (absolute power: $r = 0.99$, $p < 0.001$ (fig 3); relative power: $r = 0.99$, $p < 0.001$; percentage of W_{max} : $r = 0.95$, $p < 0.001$) and T_{RSA2} and T_{V2} (absolute power: $r = 0.99$, $p < 0.001$ (fig 3); relative power: $r = 0.99$, $p < 0.001$; percentage of W_{max} : $r = 0.96$, $p < 0.001$).

In the five remaining subjects (three athletes and two sedentary subjects) only one non-linear increase was clearly identifiable and occurred close to T_{V2} (fig 4).

DISCUSSION

To assess HPV and RSA during non-stationary exercise conditions, we developed and validated an original method.⁶ In the present study, this method was used to process the cardiac electrical signal during a maximal and graded exercise test.

Using our original approach, the dynamic pattern of f_{RSA} was accurately extracted from R-R interval series; RSA and breathing have been shown to develop dynamically at the same frequency. This result confirms previous findings³⁻⁵ which showed that during exercise, heart rate is modulated by breathing at the f_R . When f_{RSA} was considered, we were able to point out two successive non-linear increases in 81% of our population. First, we observed that T_{RSA1} was closely related to T_{V1} . This finding is consistent with those of Anosov *et al*⁴ who reported that significant changes in the behaviour of f_{RSA} occurred in the region of the AT. As the f_{RSA} pattern is

Figure 1 Representation of the dynamic behaviour of RSA frequency (f_{RSA} , solid line) and respiratory frequency (f_R , dashed line) recorded in one subject during graded and maximal exercise test.

Figure 2 Example of threshold determination using f_{RSA} (A) and ventilatory (B) methods. f_{RSA} , respiratory sinus arrhythmia frequency; T_{RSA1} , first f_{RSA} threshold; T_{RSA2} , second f_{RSA} threshold; T_{V1} , first ventilatory threshold; T_{V2} , second ventilatory threshold; $\dot{V}_I$, ventilation; $\dot{V}_I/\dot{V}_{O_2}$, ventilatory equivalents for O_2 ; $\dot{V}_I/\dot{V}_{CO_2}$, ventilatory equivalents for CO_2 .

closely linked to f_R , we could state that the first disproportionate increase in $\dot{V}_I$ observed at T_{V1} is mainly induced by an increase in f_R . This is confirmed by the study of James *et al*⁸ who concluded that the first ventilatory threshold (referred as the AT in their study) could be detected by f_R analysis.

Second, we observed that T_{RSA2} was closely related to T_{V2} , suggesting that the second disproportionate increase in $\dot{V}_I$ is again related to f_R increase. It has been reported that T_{V2} determines the workload before a marked fall in capillary pH.⁷ This exercise induced metabolic acidosis then causes ventilation increase through an increase in f_R .⁹

The concept of ventilatory thresholds is closely linked in the literature to the concept of AT. AT is defined as the intensity of exercise, involving a large muscle mass, above which the oxidative metabolism cannot account for all the required energy and the anaerobic contribution to energy demand increases.²¹ Numerous studies have been conducted to detect one or two thresholds in metabolic (lactate for instance) or ventilatory indices time course curves. This diversity in methods of detection as well as lack of consensus on the theoretical basis have led to confusion and misinterpretation (see Bosquet *et al*¹⁹ and Svedahl and MacIntosh²¹ for reviews). Using blood lactate concentration is probably the most direct and reliable method to detect the AT.¹⁹ However, this method is invasive and requires

Figure 3 Relationships between absolute power measured at T_{RSA1} and T_{V1} (A) and T_{RSA2} and T_{V2} (B). Solid lines represent the regression lines. ● Athlete group; ▲ sedentary group. T_{RSA1} , first respiratory sinus arrhythmia frequency (f_{RSA}) threshold; T_{RSA2} , second f_{RSA} threshold; T_{V1} , first ventilatory threshold; T_{V2} , second ventilatory threshold.

frequent blood sampling which is uncomfortable during continuous exercise. The indirect technique using ventilatory indices could be thus preferable. Indeed, although disagreement exists,^{10–11} ventilatory thresholds are known to be closely related to lactate thresholds.^{12–16} Ventilatory threshold detection is

usually based on assessment of successive disproportionate increases in $\dot{V}_I$, and f_R is known to play a major role in these increases.^{8–9} It is also known that heart activity is modulated by breathing at the f_R and this modulation represents the RSA which is vagally mediated at rest.^{22–24} Although cardiac vagal tone is totally abolished over $\pm 60\%$ of $\dot{V}_{O2max}$ ²⁵ to adapt heart activity to cell metabolic demand,^{26–27} RSA was retrieved over our entire exercise test. This finding confirms that RSA persistence at intense exercise could be related to enhancement of a non-neural mechanism in response to $\dot{V}_I$ increase. Indeed, changes in thoracic pressure induced by breathing influence filling of the right ventricle.²⁹ Increased right ventricle filling during inspiration consequently increases transmural pressure and stretches the sinus node, thus activating positive chronotropic response via mechanosensitive Cl^- channels.^{30–31}

Thus, using f_{RSA} to detect ventilatory thresholds has the advantages of being non-invasive and cheap and may have field application in ambulatory heart rate monitors. Moreover, this technique appears to be reliable in most athletes and sedentary subjects. f_{RSA} thresholds of athletes were detected at higher values than those of their sedentary peers, whatever the mode of expression, confirming that the AT is significantly improved with endurance training.^{32–33} Thus, this f_{RSA} method could be used for the determination of human ventilatory thresholds over a broad range of physical abilities. However, in 19% of our population only one increase close to T_{V2} was clearly identifiable in f_{RSA} , whereas two ventilatory thresholds were detected. As $\dot{V}_I$ is the product of f_R and $\dot{V}_T$, it could be expected that the first non-linear increases in $\dot{V}_I$ and $\dot{V}_I/\dot{V}_{O2}$ were mainly related to $\dot{V}_T$ increase. Indeed, as shown in fig 4, no clear change in f_R was observed around absolute power corresponding to T_{V1} .

Visual detection of both ventilatory and f_{RSA} thresholds can lead to subjective results and may represent a methodological limitation of our study design. Indeed, it has been shown that different evaluators can choose different ventilatory thresholds from the same data.³⁴ However, reliability of the ventilatory method is known to be enhanced when test conditions are kept constant and evaluators are experienced,²¹ which was the case in our study. Detection of ventilatory threshold is known to be dependant both on stage duration and load increase in graded exercise.³⁵ As no exercise protocol test seems consensual, the standard protocol test used in our laboratory was thus preferred.

Figure 4 Example of lack of clear change in f_{RSA} (A) and f_R (B) in the region of T_{V1} . f_R , respiratory frequency; f_{RSA} , respiratory sinus arrhythmia frequency; T_{RSA2} , second f_{RSA} threshold; T_{V1} , first ventilatory threshold.

What is already known on this topic

Respiratory sinus arrhythmia results from modulation of sinus node activity by breathing and during exercise is the main mechanism regulating short term heart period fluctuations. Strong correlations have been found between the centred frequency of respiratory sinus arrhythmia and respiratory frequency.

We have shown that, in most of our subjects, two successive non-linear increases are observed in f_{RSA} . These thresholds are closely related to the first and second ventilatory thresholds, respectively. Thus, the method we developed provides a useful tool for identifying the ventilatory thresholds during graded and maximal exercise test in athletes and sedentary subjects as well as for assessing endurance levels. The next step could be to process HP series recorded during an adapted field test using modern heart rate monitors and time varying modelling.

ACKNOWLEDGEMENTS

We thank the Brainware Company for their technical support.

Authors' affiliations

G Blain, S Bermon, Département Ergonomie Sportive et Performances, Université de Toulon-Var, Nice, France

O Meste, Laboratoire I3S, Université de Nice Sophia-Antipolis, Nice, France

T Bouchard, Université de Nice Sophia-Antipolis, Nice, France

Competing interests: none declared

REFERENCES

- Perini R, Orizio C, Baselli G, et al. The influence of exercise intensity on the power spectrum of heart rate variability. *Eur J Appl Physiol Occup Physiol* 1990;**61**:143–8.
- Perini R, Milesi S, Fisher NM, et al. Heart rate variability during dynamic exercise in elderly males and females. *Eur J Appl Physiol* 2000;**82**:8–15.
- Bernardi L, Keller F, Sanders M, et al. Respiratory sinus arrhythmia in the denervated human heart. *J Appl Physiol* 1989;**67**:1447–55.
- Anosov O, Patzak A, Kononovich Y, et al. High-frequency oscillations of the heart rate during ramp load reflect the human anaerobic threshold. *Eur J Appl Physiol* 2000;**83**:388–94.
- Casadei B, Moon J, Johnston J, et al. Is respiratory sinus arrhythmia a good index of cardiac vagal tone in exercise? *J Appl Physiol* 1996;**81**:556–64.
- Meste O, Blain G, Bermon S. Analysis of the respiratory and cardiac systems coupling in pyramidal exercise using a time-varying model. In: *Computers in cardiology*. Memphis, TN: IEEE Computer Press, 2002:429–32.
- Reinhard U, Müller PH, Schmulling RM. Determination of anaerobic threshold by the ventilation equivalent in normal individuals. *Respiration* 1979;**38**:36–42.
- James NW, Adams GM, Wilson AF. Determination of anaerobic threshold by ventilatory frequency. *Int J Sports Med* 1989;**10**:192–6.
- Wasserman K. Breathing during exercise. *N Engl J Med* 1978;**298**:780–5.
- Hughes EF, Turner SC, Brooks GA. Effects of glycogen depletion and pedaling speed on "anaerobic threshold". *J Appl Physiol* 1982;**52**:1598–607.
- Green HJ, Hughson RL, Orr GW, et al. Anaerobic threshold, blood lactate, and muscle metabolites in progressive exercise. *J Appl Physiol* 1983;**54**:1032–8.
- Aunola S, Rusko H. Aerobic and anaerobic thresholds determined from venous lactate or from ventilation and gas exchange in relation to muscle fiber composition. *Int J Sports Med* 1986;**7**:161–6.
- Davis JA, Vodak P, Wilmore JH, et al. Anaerobic threshold and maximal aerobic power for three modes of exercise. *J Appl Physiol* 1976;**41**:544–50.
- Yoshida T, Nagata A, Muro M, et al. The validity of anaerobic threshold determination by a Douglas bag method compared with arterial blood lactate concentration. *Eur J Appl Physiol Occup Physiol* 1981;**46**:423–30.
- Caiozzo VJ, Davis JA, Ellis JF, et al. A comparison of gas exchange indices used to detect the anaerobic threshold. *J Appl Physiol* 1982;**53**:1184–9.
- Burke J, Thayer R, Belcamino M. Comparison of effects of two interval-training programmes on lactate and ventilatory thresholds. *Br J Sports Med* 1994;**28**:18–21.
- Kindermann W, Simon G, Keul J. The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. *Eur J Appl Physiol Occup Physiol* 1979;**42**:25–34.
- Farrell PA, Wilmore JH, Coyle EF, et al. Plasma lactate accumulation and distance running performance. *Med Sci Sports* 1979;**11**:338–44.
- Bosquet L, Leger L, Legros P. Methods to determine aerobic endurance. *Sports Med* 2002;**32**:675–700.
- Meste O, Blain G, Bermon S. Some considerations on the IPFM model for the heart rate variability analysis. In: *Computers in Cardiology*, 2003. Thessaloniki, Greece: IEEE Computer Society Press, 2003:709–12.
- Svedahl K, MacIntosh BR. Anaerobic threshold: the concept and methods of measurement. *Can J Appl Physiol* 2003;**28**:299–323.
- Akselrod S, Gordon D, Ubel FA, et al. Power spectrum analysis of heart rate fluctuation: a quantitative probe of beat-to-beat cardiovascular control. *Science* 1981;**213**:220–2.
- Malliani A, Pagani M, Lombardi F, et al. Cardiovascular neural regulation explored in the frequency domain. *Circulation* 1991;**84**:482–92.
- Pomeranz B, Macaulay RJ, Caudill MA, et al. Assessment of autonomic function in humans by heart rate spectral analysis. *Am J Physiol* 1985;**248**:H151–3.
- Warren JH, Jaffe RS, Wrao CE, et al. Effect of autonomic blockade on power spectrum of heart rate variability during exercise. *Am J Physiol* 1997;**273**:R495–502.
- Eklöm B, Goldbarg AN, Kilbom A, et al. Effects of atropine and propranolol on the oxygen transport system during exercise in man. *Scand J Clin Lab Invest* 1972;**30**:35–42.
- Robinson BF, Epstein SE, Beiser GD, et al. Control of heart rate by the autonomic nervous system. Studies in man on the interrelation between baroreceptor mechanisms and exercise. *Circ Res* 1966;**19**:400–11.
- Blain G, Meste O, Bermon S. Influences of breathing patterns on respiratory sinus arrhythmia in humans during exercise. *Am J Physiol Heart Circ Physiol* 2005;**288**(2):H887–95.
- Courmand A, Motley HL, Werko L, et al. Physiological studies of the effects of intermittent positive pressure breathing on cardiac output in man. *Am J Physiol* 1948;**152**:162–74.
- Arai A, Kodama I, Toyama J. Roles of Cl^- channels and Ca^{2+} mobilization in stretch-induced increase of SA node pacemaker activity. *Am J Physiol* 1996;**270**:H1726–35.
- Hagiwara N, Masuda H, Shoda M, et al. Stretch-activated anion currents of rabbit cardiac myocytes. *J Physiol* 1992;**456**:285–302.
- Rowbottom DG, Keast D, Garcia-Webb P, et al. Training adaptation and biological changes among well-trained male triathletes. *Med Sci Sports Exerc* 1997;**29**:1233–9.
- Foster C, Fitzgerald DJ, Spatz P. Stability of the blood lactate-heart rate relationship in competitive athletes. *Med Sci Sports Exerc* 1999;**31**:578–82.
- Yeh MP, Gardner RM, Adams TD, et al. "Anaerobic threshold": problems of determination and validation. *J Appl Physiol* 1983;**55**:1178–86.
- Kang J, Chaloupka EC, Mastrangelo MA, et al. Physiological comparisons among three maximal treadmill exercise protocols in trained and untrained individuals. *Eur J Appl Physiol* 2001;**84**:291–5.

COMMENTARY

During the past 20 years, very many studies have indicated that parameters measured during submaximal exercise may be better markers of endurance performance than Vo_{2max} , the anaerobic (or ventilatory) and lactate thresholds being useful parameters to evaluate functional capability in various types of endurance performance. Both gas analysis and ventilatory flow measurements, as well as blood lactate determinations, can be used to estimate the anaerobic threshold as a predictor of endurance capacity. A procedure that would be simple, relatively inexpensive, and non-invasive would be welcome. Procedures based on maximal heart rate (or a percentage of it) are simple but not reliable. Thus, the determination of ventilatory thresholds by time varying analysis of respiratory sinus arrhythmia, as proposed in this paper, appears to be quite promising, providing that it can be used with data obtained by ambulatory heart rate monitors.

Ramon Segura

Physiological Sciences II, Universitat de Barcelona, Barcelona, Spain; rasegura@ub.edu