HEART RATE VARIABILITY ANALYSIS IN SPORT

UTILITY, PRACTICAL IMPLEMENTATION AND FUTURE PERSPECTIVES

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Heart rate variability (HRV) represents variations between consecutive heart beats (beat to beat or R-R interval) over time (Figure 1). This beat to beat variation in heart rhythm is considered normal and even desirable. Disappearance of variations between consecutive heart beats is a result of autonomic dysfunction which can be associated with neurological, cardiovascular and psychiatric disease states[1]. There is a large body of evidence reporting that higher variability of heart rhythm is associated with reduced mortality[2,3], improved quality of life[4] and better physical fitness[5]. The most common use of HRV analysis is in risk prediction and prevention of heart failure[6,7]. Interestingly, in ancient China, HRV was known to physician Shu-he Wang (265 to 317 AD) who described heart rhythm as an indicator of disease: "if the pattern of the heart beat becomes as regular as the tapping of a woodpecker or the dripping of rain from the roof, the patient will be dead in 4 days"[8].

The physiological background of HRV is complex and affected by circulating hormones, baroreceptors, chemoreceptors and muscle afferents. An important factor which influences HRV is respiratory sinus arrhythmia – the natural variation in heart rate (HR) that occurs during breathing[5]. During inspiration, HR increases whereas expiration is characterised by a decrease in HR. The autonomic nervous system (ANS) through sympathetic (SNS) and parasympathetic (PNS) pathways regulates the function of internal organs and the cardiovascular system[1,5]. Sympathetic activity increases cardiac contractility and HR, whereas parasympathetic (vagal) stimulation reduces HR[5,9]. Any source of stress (psychological, physical or illness) will provoke disturbance in the ANS and consequently in HRV. The long-term presence of imbalance between sympathetic and parasympathetic tone can impair the performance of athletes.

The analysis of HRV in sport has become established and recognised in the past 2 decades as a non-invasive method

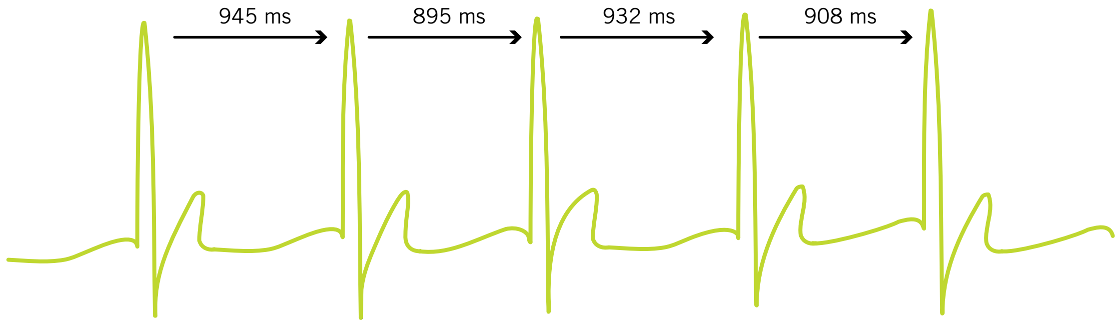


Figure 1: Beat to beat (R-R) variations in heart rate. R-R interval represents the time difference between consecutive R waves derived from electrocardiography (ECG) recording.

Table 1

Variable	Unit	Description	Frequency range	Relation
Time domain measures of HRV				
Variable	*Unit*	*Description*		*Relation*
SDNN	*ms*	*Standard deviation of all NN intervals*		*Total variability*
RMSSD	*ms*	*The square root of the mean of the sum of the squares of differences between adjacent NN intervals*		*Parasympathetic*
NN50	*count*	*The number of pairs of adjacent normal R–R intervals that differ by more than 50ms*		*Parasympathetic*
pNN50	*%*	*NN50 count divided by the total number of all NN intervals*		*Parasympathetic*
Frequency domain measures of HRV				
Variable	*Unit*	*Description*	*Frequency range*	*Relation*
Total	*ms²*	*Entire power spectral area*	*< 0.40 Hz*	*Total variability*
VLF	*ms²*	*Very low frequency*	*0.003 – 0.04 Hz*	
LF	*ms²*	*Low frequency*	*0.04 – 0.15 Hz*	*Sympathetic - Parasympathetic*
HF	*ms²*	*High frequency*	*0.15 – 0.4 Hz*	*Parasympathetic*
LF/HF		*Ratio of the low-to high frequency power*		*Sympathovagal balance*
Scattergram (Poincare plot)				
Variable	*Unit*	*Description*		*Relation*
SD1	*ms*	*Represents the short-term beat-to-beat variability*		*Parasympathetic*
SD2	*ms*	*Represents the long-term beat-to-beat variability*		*Sympathetic - Parasympathetic*

Table 1: Time domain, frequency domain and non-linear (Poincaré plot) indices of HRV. NN=normal to normal intervals.

for evaluation of the body's reaction to training loads, recovery methods and overtraining syndrome (OTS). In the last 5 years, innovations in wireless technology have significantly increased the number of devices on the market which are using HRV indices to control and manage the training processes of athletes.

INDICES (PARAMETERS) OF HRV

The most common methods for analysis of HRV are time domain, frequency domain (power spectral) and Poincaré plot (scatter gram) analysis. The simplest method to analyse HRV is time domain analysis, which represents basic mathematical and statistical measures such as root mean square of the differences and standard deviation of adjacent NN (normal to normal) intervals (Table 1). NN intervals generally represent adjacent beat to beat intervals that differ more than 50ms. They originate from sinus node depolarisation[10]. Power spectral analysis represents distribution of variation in HR as a function of frequency[11]

(Table 1). The common frequencies of HRV encompass very low (VLF), low (LF) and high frequency (HF) components (Figure 2). Poincaré analysis plots each R-R interval against previous one in a graphical representation of ANS activity (Figure 2).

All aforementioned analysis methods consist of parameters which provide information about sympathetic and parasympathetic modulation i.e. the balance between them (Table 1).

HRV DURING AND AFTER EXERCISE (INDICATORS OF STRESS/TRAINING LOAD)

During exercise HRV is reduced (shorter R-R intervals) and HR is increased as a result of augmented SNS and attenuated PNS activity. Not only are the intervals between R-R peaks shorter, they become more uniform (reduced R-R variability). The relationship between sympathetic and parasympathetic activity during exercise depends directly on training intensity. During physical activity, sympathetic nerves can increase cardiac output to 2 to 3 times the resting value[12]. One of the often researched topics in terms of HRV during exercise is analysis of anaerobic (lactate or ventilatory) threshold during incremental test to exhaustion[13-15]. It looks promising that in the future a non-invasive method, such as HRV analysis, could eventually replace lactate analysis and therefore decrease the cost and time of anaerobic threshold testing.

Caution should be taken when interpreting HRV analysis during exercise. The HF component (PNS activity) of spectral analysis is highly influenced by respiration dynamics. Due to this fact, at high exercise intensities (>90% VO_2 max) increased breathing frequency will cause an increase in vagal contribution (higher PNS activity) caused purely by the mechanical properties of the heart and not neural contribution of the ANS[16,17]. This means that actual SNS activity at higher exercise intensities will be masked by PNS activity as a result of a higher frequency of respiration. Therefore, during an incremental test to exhaustion, the subject has to be instructed to maintain a stable respiration rate as much as possible.

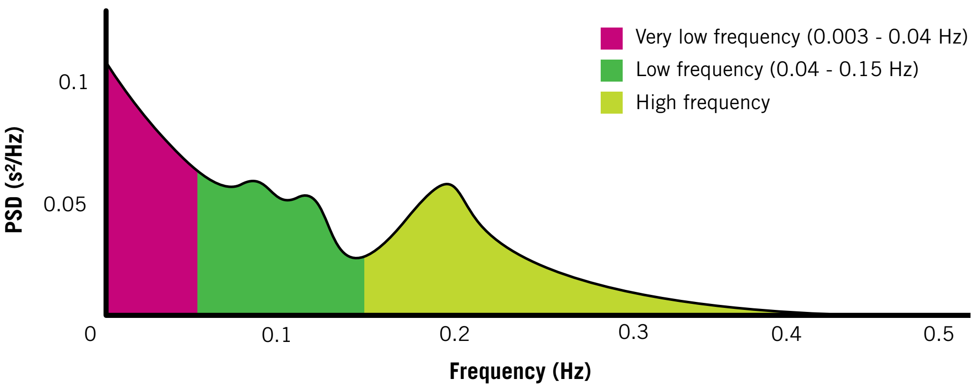
Training load

Distribution of training loads is a fundamental component of periodisation. The elements which comprise training load are training volume and intensity. Interplay between these two elements will define the total training load. Higher training loads will cause a greater degree of ANS disturbance and sympathovagal imbalance[12,18]. Post-exercise HRV analysis appears to be a valuable indicator to evaluate variations in performance level and can indirectly reflect training loads[18-20]. There is evidence that HRV parameters are highly correlated with intensity and volume of exercise and are inversely related to the level of training load[21].

HRV AND RECOVERY

On the assumption that physical activity causes stress (a stimulus), the body will respond with a stress reaction on different physiological levels. In addition to a stress reaction, adaptation processes occur during the recovery period. If the magnitude of the stress stimulus (e.g. training load) is high enough (overload principle) to evoke a reaction of the body, then the response will be proportional to the stress level and, as a result, greater training effects will be accomplished (adaptation).

In order to reach higher performance levels, it is essential to understand that well-designed and integrated rest periods are of great importance. Recovery after



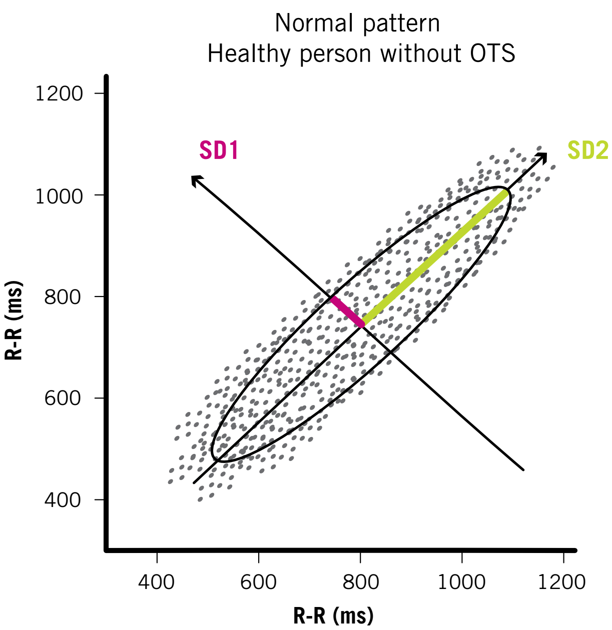


Figure 2: Power spectrum analysis and Poincaré plot. OTS=overtraining syndrome.

> *Every training session can be considered as stress to the body, which in turn causes disturbance of homeostasis and ANS modulation. These changes in ANS activity are manifested by increased sympathetic and/or decreased parasympathetic activity of the ANS and are reflected by HRV parameters*

training is considered an integral part of training methodology. There is no improvement in performance if there is a lack of optimal recovery. Problems occur when the demands are so frequent that the body is not able to adapt[12]. This means that the body will continuously be under sympathetic domination during rest as well as during activity. Every training session can be considered as stress to the body, which in turn causes disturbance of homeostasis and ANS modulation. These changes in ANS activity are manifested by increased sympathetic or/and decreased parasympathetic activity of the ANS and are reflected by HRV parameters[12].

One crucial aspect of recovery is sleep, during which parasympathetic activity should dominate, however, an optimal recovery state is generally characterised by parasympathetic (vagal) predominance of ANS regardless of time of the day[12]. There are a variety of parameters which can be used to measure post-exercise recovery (VO_2 max, creatine kinase, C-reactive protein, plasma cortisol, blood leukocyte, myeloperoxidase protein level and glutathione status), but these methods are mostly invasive, time consuming and expensive for everyday use[22-25]. Accordingly, the importance of a non-invasive, easy and affordable method to evaluate recovery is obvious. Thus, HRV technology is being increasingly used to evaluate the status and level of recovery.

Long-term high-intensity training sessions gradually decrease the parasympathetic component of HRV (root mean square of the differences, HF, one standard deviation parameters), which increases during the rest period[26]. The sympathetic component demonstrates the opposite tendency (LF and two standard deviation parameters). The reactivation of parasympathetic activity of HRV to pre-exercise levels as quickly as possible significantly improves the recovery process of athletes. Inability to return HRV parameters to pre-exercise or optimal levels in a reasonable time is considered a chronic disturbance in ANS activity, which can lead to overtraining. Today, HRV-based devices and software assist in recovery analysis of athletes, providing easily interpretable data to trainers and athletes. The most common procedure used to evaluate recovery level involves overnight measurement (nocturnal) of HRV, although systems which can assess a quick recovery index (5 minute measurement) are available as well.

HRV AND OVERTRAINING

Sometimes the line between optimal performance level and overtraining is very thin. Overtraining syndrome is the result of long-term imbalance between stress (internal and/or external) and recovery periods. There is a large body of evidence implying that significant cardiac autonomic imbalance between the two ANS pathways (sympathetic and parasympathetic) occurs due to overtraining syndrome[5,27]. In the literature there are conflicting results about ANS modulation in overtrained athletes, with some studies reporting a

Table 2

Sympathetic tone	*Parasympathetic tone*
Insomnia	*Fatigue*
Irritability	*Depression*
Agitation	*Bradycardia*
Tachycardia	*Loss of motivation*
Hypertension	
Restlessness	

Table 2: Sympathetic and parasympathetic characteristics of overtraining.

predominance of sympathetic[27,28] and some of parasympathetic autonomic tone[29,30] during an overtrained period. These disputed results might be explained by the description of different types of overtraining. Two types of OTS have been reported: sympathetic and parasympathetic overtraining, with each having specific physiological characteristics (Table 2)[29,31]. Early stages of performance impairment are characterised by sympathetic domination of ANS at rest which is often referred to as an 'overreaching state' or 'short-term overtraining'[32], meaning that the disturbance of homeostasis was not high and/or long enough to provoke a chronic overtraining state and therefore the time needed for full recovery of all physiological systems typically encompasses a few days to several weeks[33]. Increased sympathetic tone is generally observed in sports where higher intensity of exercise dominates[34].

If the overreaching state (sympathetic autonomic tone domination) continues over a longer period of time, OTS and domination of parasympathetic autonomic tone will develop[33]. Parasympathetic OTS dominates in sports which are characterised by high training volume[34]. HRV parameters such as root mean square of the differences and HF reflect parasympathetic activity of ANS whereas standard deviation and LF can be partially used as markers of sympathetic autonomic tone. LF/HF ratio, which represents sympathetic to parasympathetic balance, is markedly increased during the overreaching state ,implying that sympathetic autonomic tone is augmented. The reverse effect occurs during the late phase of overreaching where LF/HF ratio decreases (sympathetic activity (LF) decreases and parasympathetic activity (HF) increases). Scattergram (Poincaré plot) analysis provides a clear visual representation of the autonomic imbalance during OTS. OTS will cause the concentration of points in the graph take a more narrow pattern (Figure 3). Today HRV systems are a common part of professional sport organisations due to fact that they reflect the sensitivity of the ANS which can occur during overreaching and overtraining states.

LIMITATIONS, IMPROVEMENTS AND FUTURE PERSPECTIVES OF HRV ANALYSIS IN SPORT

HRV analysis has become a widely accepted method for non-invasive evaluation of ANS modulation during and after exercise. Nevertheless, the majority of physiological signals are non-stationary and non-linear in nature. The same is true for ANS-regulated HR. Thus, in order to overcome the aforementioned disadvantages, the signal of recording must contain a minimum of 5 minutes of HRV fluctuation in order to get reliable results from power spectral analysis and scattergram.

Moreover, new non-linear HRV analysis techniques are continuously being developed and improved. Recent mathematical algorithm advancements have great potential to enhance the accuracy of HRV analysis.

In the last 5 years the number of devices and software programmes/apps using HRV technology has increased exponentially. The current trend in

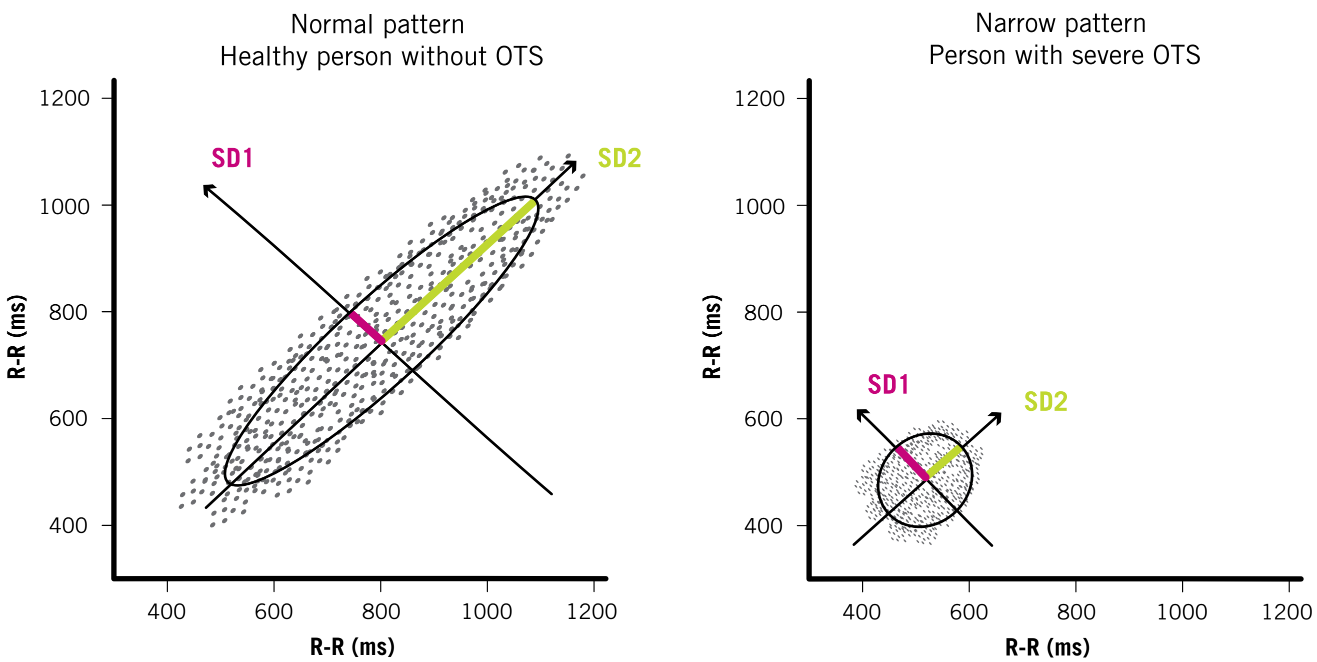


Figure 3: Scattergram (Poincaré plot) analysis. Normal healthy state without OTS has elliptical wide form of scattergram whereas OTS is characterised with narrow shape of scatter gram. OTS=overtraining syndrome.

Practical application

1. *Wrist watch monitor (computer), heart rate belts (Bluetooth or ANT+ wireless technology), smartphones or other commercial HRV systems are required for HRV recording.*
2. *Assessment of recovery and overtraining should be conducted in a quiet and isolated place with optimal ambient temperature.*
3. *All measurements considering recovery and overtraining have to be performed in comfortable supine position with the hands next to the body.*
4. *Subjects must refrain from caffeine, alcohol and exercise for 24 hours and to fast for 2 to 4 hours before measurement (recovery/overtraining).*
5. *Sometimes, a tilt test is recommended for overtraining assessment[27].*
6. *Before measurement starts, the subject has to rest for 5 minutes .*
7. *Subjects have to be advised to maintain a natural pattern of breathing (frequency of breathing should be constant. A metronome can be used).*
8. *HRV is recorded between 5 and 10 minutes (individually).*
9. *R-R data can be transferred to a personal computer and analysed. Some devices can analyse R-R data immediately after recording (HRV portable systems, smartphones app).*

software engineering is to make all wireless sensors for capturing and transmitting of HRV data compatible with smartphones. Hardware and software engineers are continuously improving the accuracy of sensors which record and receive HRV signals (heart rate belts, wireless technologies and protocols), as well as HRV analysis techniques (software, mathematical models). This provides the trainer and athletes quick and easy analysis of HRV data during and after a training workout (training load, recovery and overtraining). In addition, a multidisciplinary approach is required to better understand fluctuations in HR. The true potential of HRV analysis in sport can be only achieved with teams consisting of sport scientists, cardiologists and sport physiologists working together in order to better understand ANS modulation during and after exercise.

SUMMARY

Today, HRV can be easily assessed in athletes with the help of portable HRV systems. Those systems include wrist watch monitors, HR belts and smartphones with software to measure R-R intervals. With improved analysis techniques, for optimal and reliable results, a minimum duration of recording of 5 to 10 minutes is recommended. However, if the purpose of measurement is to assess distribution of stress and recovery in the course of the day, longer measurements are required (overnight recovery measurement, daily stress management). In addition, one of the biggest advantages of HRV analysis is that the day-to-day variability of bodily responses to continuous training processes can be assessed with minimum time and effort. No expensive equipment and skilled lab specialists are required.

References

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