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Fundamentals of Heart Rate Variability and applications in sports science

The aim of this paper is to provide fundamental information about the measurement and interpretation of heart rate variability (HRV). Fundamental physiological principles related with HRV are described and relevant applications for the field of sports science are given.
Tables 1 and 2 shown below describe the most common parameters used in the analysis of HRV, both in time and frequency domain. Fundamentals and principles of frequency domain analysis in general are presented and discussed (e.g. fast fourier transform, auto and cross correlation analysis), as well as state-of-the-art HRV related methods. Finally, problems concerning normalisation and standardisation procedures of HRV-maesurments in sports are emphasized and possible solutions are proposed and discussed.

Table 1: Parameters of HRV in the time domain

Parameter	Common synonyms	Unit	Description
RR	avgRR, RR_{MW}	ms	Mean Duration of all R-R-Intervals
RRSD	SD, $SD_{RR,}$	ms	Standarddeviation of all R-R-Intervals (=Total Variability) (used as a long-term parameter SDNN)
RMSSD	r-MSSD	ms	Root mean square of all R-R-Intervals
SDSD	ΔRRSD	ms	Standarddeviation of all differences between all R-R-Intervals
pNN50 (NN50)		%	Ratio of the number of differences of consecutive R-R-Intervals larger than 50ms and total number of differences of consecutive R-R-Intervals
D_L		ms	Length of the horizontal axis of the 95%-confidence ellipse
D_Q	D_W	ms	Length of the vertical axis of the 95%-confidence ellipse
SD1	stdb, $SO_{Q,}$ SD-quer	ms	Standarddeviation of the orthogonal distance of the RR_i / RR_{i+1}-plots in relation to the horizontal axis of the ellipse
SD2	stda, $SO_{L,}$ SD-längs	ms	Standarddeviation of the orthogonal distance of the RR_i / RR_{i+1}-plots in relation to the vertical axis of the ellipse

Table 2: Common parameters of HRV in the frequency domain

Parameter	Common synonyms	Unit	Description
TP	Total power	ms²	Total Power Density Spectra (Variance of all R-R-Intervals ≤ 0,4 Hz)
VLF	Very low frequency	ms² %	Power density spectra between 0,00 Hz to 0,04 Hz Ratio of VLF-spectra and Total Power Density Spectra
LF	Low frequency	ms² %	Power density spectra between 0,04 Hz and 0,15 Hz Ratio of LF-spectra and Total Power Density Spectra
HF	High frequency	ms² %	Power density spectra between 0,15 Hz and 0,4 Hz Ratio of HF-spectra and Total Power Density Spectra
LF/HF		%	Ratio of LF- and HF-Spectra

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Performance diagnostical value of heart rate variability in cycling ergometry

This study investigates into the diagnostic value of heart rate variability (HRV) in standardised cycle ergometry. It mainly focuses on the question of possible relations between HRV and performance diagnostic parameters which are important in training practise, and to what extent HRV can be used to draw conclusions referring individual training ranges.
With increasing physical load HRV is decreasing. This decrease reflects changes in the vegetative heart activity control (vagotonic decrease and sympathicotonic increase).
Under load HRV-parameters of the scatterogram (stda, stdb) as well as of the time domain analysis (SD, RMSSD) and of the frequency domain analysis (TP, LF, HF) show a characteristic course. For the initial phase we found a steep decrease of HRV at the beginning of load, followed by an additional slow decrease in the medium range of intensity. With respect to the short-term variability parameters (stdb, RMSSD, HF) this phase is followed by changes reflecting vagotonic changes - a plateau with a minor increase at the end of the load. We found a continuous decrease in the long-term variability parameters (stda, SD, TP, LF) until the end of loading.
In 46 well trained endurance triathlon and cycling athletes (25 ± 6 years, 74,8 ± 9,0 kg, 183,5 ± 5,4 cm, maximal performance Pmax 4,61 ± 0,45 W/kg, VO_2max 60,1 ± 6,1 ml/kg·min) dynamics of HRV in standardised cycle ergometry (starting with a load of 40 W, duration of one step 5 min, increase by 30 W until fatigue) has been studied in relation to cardiopulmonary (heart rate HR, oxygen uptake VO_2) and metabolic functional parameters (performance at lactate 2 and 4 mmol/l, individual anaerobic threshold IAT). 12 athletes were tested a second time two days later to check the reproducability of the HRV-parameters.
In all athletes we found a significant decrease of HRV. On average the plateau of the short-term parameters started at 1,5 mmol/l lactate (55% Pmax, 70% HRmax, 55% VO_2max). The individual minimum of the short-term variability parameters were defined as HRV-threshold and the minimum was found, on average, at 2,4 mmol/l lactate (67% Pmax, 80% HRmax, 67% VO_2max). Analoguous to the metabolic and respiratory threshold this HRV-threshold is displaced depending on the endurance performance capacity. On average athletes' HRV-threshold was slightly 10 per cent under performance at individual anaerobic threshold. When comparing test and retest values we found a good reproducability of the HRV-parameters ($p<0,001$).
For the subjects of this study we found a good correspondence between HRV-threshold and training relevant load intensities in the aerobic-anaerobic metabolism.

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Heart rate variability during prolonged exercise of different intensities on a bicycle ergometer

Problem: During stepwise incremental exercise test there is a rapid decline of heart rate (HR) variability (HRV) when starting activity and a further significant decrease during low and moderate intensities (60% VO_2max) followed by an asymptotic expansion up to exhaustion. The decomposition of HRV in the frequency-domain and an analysis of the Pointcaré plots show an individual slight final increase of high-frequency oscillations beginning at about 80% of maximal workload (P). In view of the greater dynamics of HRV measures during light and moderate exercise in comparison to changes of heart rate and lactate the option to control training-load by means of HRV is being discussed. Fundamental knowledge on the dynamics of HRV and the paralleling metabolic changes during incremental exercise as well as on time-related changes during prolonged physical activity is needed. Therefore the aim of the present study was to assess HRV during prolonged exercise of different intensities on a bicycle ergometer in comparison to maximal lactate steady-state (maxLass).

Methods: 11 males (25±5 yrs, 182±5 cm, 82±14 kg) underwent a graded cycle test and after that 11 to 21 30-minute tests of various constant workloads in randomised order (beginning at 30% P_{max} and increasing 10 watt until 1 test was above PmaxLass, i.e. slope of lactate(LA)-increase > 0.05 mmol l^{-1} min^{-1}). Continuously RR-intervals were monitored with Polar Vantage® and blood lactate was determined on 8 occasions. The average and standard deviation of RR-interval-length (RR_{MW} and RR_{SD}) were determined and additionally HRV was assessed by quantitative analysis of Pointcaré plots as plot-dispersion to the principal length- and width-axis (SO_L and SO_W corresponding to Stda and Stdb).

Results: Up to intensities of 60-65% PmaxLass there is an exponential decrease of SO_W , RR_{SD} and SO_L. In contrast to SO_W and RR_{SD} instantaneous HRV (SO_L) increases again at 93% PmaxLass (191±36 watt; 72% Pmax), with significant correlation between individual workload in SO_L-minimum and PmaxLass (206±41 watt, 78% P_{max} , r=0.94). According to this the relation of SO_L and RR_{MW} (SO_L/RR_{MW}) is constant between 50% and 93% PmaxLass and rapidly increases when reaching PmaxLass. There are no statistically relevant time-related effects on SO_W, RR_{SD} and SO_L. In contrast, when reaching PmaxLass, especially SO_L/SO_W and SO_L/RR_{MW} increase due to duration of activity ($p<0,05$).

Conclusion: It is reported that about 35% of recreational runners train with non-recommendable high intensity levels (LA $\geq$ 4 mmol l^{-1}) for purpose of health and basic-endurance training. The present study demonstrates that in addition to pronounced changes during recommended light and moderate intensities the high frequency oscillations of HRV may indicate the transition to partially anaerobic energy expenditure. Reaching PmaxLass, SO_L raises especially when it is expressed in relation to heart rate and points out increasing fatigue due to prolonged exercise. In combination to traditional heart rate monitoring online recorded HRV may offer appropriate detail information for controlling training-load.

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Estimation of individual training zones based on Heart Rate Variability (HRV)

Monitoring and regulation of the individual training intensity are fundamental for all endurance disciplines. Only if an “adequate” individual training intensity is ensured over a certain period of time an athete is able to improve his endurance capacity. Thus an optimal regulation of the individual training load requires a permanent coordination of training intensity and actual performance capacity.
The Goal of the study was to prove whether HRV-related parameters are adequate parameters to determine individual training zones.

Methods
16 endurance athletes aged 27,3 ± 5,2 years performed two different test procedures (steptest I: start 8-10 km/h, increasing 2 km/h every 3 min, 1 min rest; steptest II: start 2 km/h, increasing 2 km/h every 3 min without rest) on a treadmill. The subjects had to walk and run respectively at the given speed, while HRV, heart rate (HR) and oxygen consumption (VO2) were measured. Additionally, the Polar „Own-Zone“ was determined using the Polar „M52“ heart rate monitor.

Results and Discussion
The individual anaerobic threshold (IAS) (basic blood lactate value +1,5 mmol/l, Dickhuth et al. 1989) was reached in steptest I at 3,1 ± 0,5 mmol/l blood lactate, 86,8 ± 2,5 % HRmax and 79,9 ± 7,6% VO_2max. Steptest II showed that in OWN-ZONE-Low the average heart rate was in between 120,1 ± 8,3 and 140,1 ± 8,3 beats/min, corresponding to 62,7 ± 5,0% and 73,5 ± 4,8 % of individual HRmax respectively. The upper limit of OWN-ZONE-High could be set at heart rates of 160,1 ± 8,3 beats/min (83,6 ± 4,9 %HRmax).
HRV in steptest II decreased significantly on the first speed levels until a value of 60% of VO_2max was reached. On the following speed levels HRV was approximately zero. On the other hand the short-term variability parameter „stdb“ (=SD1) significantly decreased on the first speed levels and reached a minimum at 78% of HRmax and 66% of VO_2max respectively. From that minimum on the stdb-values rose again when speed was further increased.

66% of VO_2max correspond to an adequate training intensity under primarily aerobic conditions. Heart rate and VO2 at this value are significantly ($p < 0,01$) below the individual anaerobic threshold. Therefore the stdb-minimum seems to be a relevant parameter to ensure aerobic conditions in endurance training.

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Influence of an endurance training on heart rate variability in sedentary subjects

Problem: A greater heart rate variability (HRV) is accotiated with a decreased cardiovascular mortality. Endurance trained subjects have lower resting heart rate and a higher HRV compared to sdentary controls. Therefore, the aim of th study was to determine the influence of a 12 week endurance program on HRV.

Methods: 16 subjects (7m/7f; 40±12 years; 171±8 cm; 74±15 kg) (TR) performed a 12 week endurance running program (2-3 times a week, 40-60 min each training session). Before and after the training program a graded exercise test was performed on a treadmill. Heart rate was measured beat-to-beat with the Polar Vantage® heart rate monitor. Measured HRV parameters: standard deviation of RR intervals (RR_{SD}); quantitative evaluation of the pointcaré plots (SO_L: standard deviation of the orthogonal distances to the length diameter of the 95% confidence ellipse; SO_W: standard deviation of the orthogonal distances to the width diameter of the 95% confidence ellipse). A control group (CO) (8m/8f; 37±12 years; 172±10 cm; 74±16 kg) carried out the same testing procedures with the exception of the endurance training.

Results: The results of the treadmill test (velocity at 4 mmol/l lactate) and the beat-to-beat analysis of resting heart rate are as follows:

		v_4 (m/s)		HR (1/min)		SO_W (ms)		SO_L (ms)	
		before	after	before	after	before	after	before	after
TR	mean	2,5	2,9	68	61	64	91	36	45
	SD	0,6	0,6	12	8	37	39	30	28
n=14	p<	0,01		0,01		0,05		0,05	
CO	mean	2,3	2,5	63	64	66	65	36	33
	SD	0,6	0,6	8	8	30	25	27	22
n=16	p<	0,01		n.s.		n.s.		n.s.	

The increase of SO_W (□SO_W) correlates with the changing ọfv_4 ($p<0,05$). There are no significant correlations between □SO_L and □v_4.

Conclusion: The increase of v_4 in CO can be explained by a familiarisation to treadmill running. The increase of HRV by endurance training may be influenced by metabolic adaptions in the trained skeletal muscle.

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Autonomic cardiovascular control and Heart Rate Variabiliy in Endurance Trained Athletes, strength athletics and Healthy Sedentaries

Problem: Endurance training leads to adaptations in the cardiovascular system, which improve physical performance. On the other hand, cardiovascular diseases can reduce the function of this system. Aside from morphological changes which can be identified with diagnostic imaging techniques, adaptations in autonomic cardiac control are observed. Heart Rate Variability (HRV) is a new, non invasive method to monitor the influence of the autonomic nervous system on cardiac function. The present study aims at describing differences in HRV between endurance trained, strength athletes and non-trained, to detect indices and influents on the autonomic cardiac control in these groups.
Methods: We analysed 3 age-matched groups (Endurance trained athletes, N=76, therefrom cycling n=19, cycling offroad n=4, Triathlon n=18, athletic sports n=1, soccer n=3, Biathlon n=31; strength athletics N=10, therefrom weightlifting n=3, wrestling n=7; normal sedentaries, N=30;) with automatic HRV measurement (time- and frequency domain) during a standardised tilt-test. A questionnaire evaluated possible vegetative disturbances on the measured variables. Average values and group differences were calculated.
Results: Trained persons showed a significantly higher vagal activity compared to sedentaries (time-domain: MeanNN, SDNN, CVNN, pNN50, $p < 0,01$) and a faster regulation of autonomic cardiac control after tilt-testing. Sympathovagal balance (frequency-domain: Ln LF/HF) in rest recumbency shows also significant difference between the examined groups. The heart rate in rest was not significant. Between the groups of endurance athlets and strength athlets a significant difference in time domain meanRR was observed ($p=0,02$), which is also be seen in the heart rate. In comparison of the different kind of sports significant differences in time domain particularly between Biathletics and weight lifters were noticeable. Even between the endurance sports Biathlon and Cycling sporadic differences in time domain were noted.
Conclusion: Trained persons show significant differences in the adaptational capacity of their autonomic cardiac control system compared to non-trained persons. While there is a distinct difference between endurance trained athlets and healthy sedentaries with also significant differences to the strength athlets in the time domain , these discrepancies between strength athlets and healthy sedentaries are not given in such a degree. This could be a indication, on the basis of the different kind of stress, that stength sports come along with a higher sympatical activity and that the vagal, parasympatic regulation in endurance sport has a greater influence.

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Effects of a 10-week endurance training program on heart rate variability in untrained runners

Heart rate variability (HRV) is a field of increasing importance not only in clinical cardiology but also in sports medicine, especially in high performance sports.
The aim of the present study was to investigate the changes in the autonomic regulation of heart rate documented by HRV indexes in untrained subjects of middle age during a 10-week endurance training program of moderate intensity.
7 healthy untrained subjects (6 female, 1 male, age 39.9±4.9 years, height 169.9±10.6 cm, weight 72.3±18.8 kg) participated in a 10-week endurance training program for beginners. The program consisted of two one-hour sessions a week. Each session included a combination of running and walking phases. The proportion of running segments was raised continuously leading to a mere running time of 60 minutes at the end of the program.
Heart rate was measured every two weeks by means of the Polar® Vantage NV system in beat-to-beat-mode before, during, 5 min after and 15 min after exercise. The original data were analyzed by a computer-based program which, after elimination of artefacts and linear trends, computed the common used time domain HRV indexes within an analysis range of 256 beats.
Significant differences could be found for the indexes RR, ΔRR, RRSD, RMSSD, D_L, D_Q, SO_L and SO_Q, whereas there were no significant differences for ΔRRSD, SArel, pNN50 and pNN6.25.
Our results indicate that in untrained persons an endurance training within short time can lead to significant changes of HRV.

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Does "Stretching" Beneficially Improve Heart Rate Variability ?

Introduction: Patients with coronary heart disease or other cardiac risk factors (e.g. diabetic neuropathy) and concomitant signs of reduced heart rate variability (HRV) have increased risk to suffer cardiac death. ECG of those patients is characterized by nearly equidistant R-R, indicating reduced vagal and/or increased sympathetic tone. In contrast, in large populations normal or increased HRV seems to indicate good health. In addition, some drugs (e.g. -blocker), relaxation techniques (e.g. autogenously training) or regular sport activities – reducing sympathetic and/or increasing vagal tone – may have beneficial effects on health protection and HRV. Stretching is a popular, easy to learn and everywhere to perform technique. So far, little is known about its effects on neurocardiac control.

Subjects and Methods: To further elucidate the role of stretching on HRV we conducted a study in 15 healthy male athletes normally training force for at least 2 hours a day on 5 days per week in the last 1 year (age range: 22-44 years; BMI range: 23-28). All volunteers enrolled in this study had to practice an additional standardized (about 20 min) stretching program (of bigger muscle groups) for 28 days. At days 0 (before start of stretching program) and 28 statistical measures of HRV were performed and muscular flexibility of 7 joints was investigated. Mean heart rate (HR), the root mean square of successive differences (RMSSD), and the number of pairs of adjacent RR intervals differing by more than 50 ms in the entire recording divided by the total number of all RR intervals (pNN50) were calculated for the whole observation period of 3 min resting in sitting position, ca. 20 min stretching activities, 3 min rest in recumbent position, and 2 min while standing (testing orthostatic load).

Results: HRV parameters increased significantly (*** p<0,001) from day 0 to day 28, indicating increase of vagal outflow. A summarized (7 joints) increase of flexibility of 44,7+/-19,3 cm demonstrates good motility profit.

Mean (SD)	***HR [bpm]***	***RMSSD [ms]***	***PNN50 [%]***
Day 0	94,0 (13,7)	21,0 (7,1)	1,8 (1,3)
Day 28	80,5 (14,5) ***	38,9 (15,9) ***	6,6 (3,6) ***

Conclusion: While in "normal populations" higher age or low fitness states are accompanied by reduced HRV and increased cardiac risk, stretching has been found as an effective stimulator of HRV. This beneficial phenomenon may putatively be caused by muscular-brain-interactions (e.g. muscular relaxation induces psycho-physiological relaxation, vascular (e.g. "endothelial massage") or neurohumoral (e.g. decrease of plasma levels of norepinephrine and cortisol) effects. Regarding to the wide spread suggestion that HRV is an indicator of cardiac risk one can speculate on cardio-protective effects of stretching. If further studies will confirm our data, stretching techniques should enrolled in health care programs for the prevention and therapy of cardiovascular diseases.

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Influence of a specific relaxation and concentration technique (Freeze-Frame®) on parameters of Heart Rate Variability (HRV)

The Institute of Heart Math (California, US) developed a relaxation and concentration technique called Freeze-Frame®, which is based on 5 different steps and is primarily used in stress management (Childre 1994, 27). The application of the Freeze-Frame® technique causes visible changes in the R-R-Interval-time histories resulting in a sinusidal curve. 3 subjects (single case studies) experienced in Freeze-Frame® technique voluntarily participated in a study to verify the influences of this technique on parameters of HRV. Therefore for all 3 subjects HRV was assessed (Polar Vantage NV) over a period of 10 minutes when they were sitting in upright position on a chair. The relaxation and concentration technique was performed after the first 5 minutes of data storage. Using Polar Precision Performance 2.0 software the data was seperated into the first and last 5 minute periods and were analysed seperately. (Table 1). In total 60 measurements were taken, while for each subject 10 of them were assessed after a rest period in sitting position and 10 of them after 30 minutes of endurance activity.
The most obvious changes could be detected in the frequency domain as the percentage of the LF-components (0,04-0,15 Hz) increased substantially (Table 1).

Table 1: Changes in the LF-components of the frequency domain before and during a phase of concentration (ConPh) and before and after a period of endurance activity

Proband	LF-Component (%±SD)	Before ConPh	During ConPh	t-test (p-value)
A.B.	Before endurance activity	22,8 ± 4,5	59,4 ± 13,1	<0,01
	After endurance activity	27,7 ± 5,7	70,6 ± 9,9	<0,01
t-test (p-value)		<0,05	<0,01	
J.H.	Before endurance activity	14,7 ± 7,2	66,0 ± 12,4	<0,01
	After endurance activity	26,9 ± 10,2	73,3 ± 11,7	<0,01
t-test (p-value)		<0,05	=0,094	
K.V.	Before endurance activity	23,9 ± 8,1	85,6 ± 5,3	<0,01
	After endurance activity	23,5 ± 4,9	83,9 ± 2,4	<0,01
t-test (p-value)		=0,45	=0,19	

The results show that the Freeze-Frame® technique causes substantial changes in HRV at the same heart rate. Thus the assessment of HRV can be seen as a biofeedback system to support subjects learning the relaxation and concentration technique.

References:
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Measurement of Relaxation Effects using Heart Rate Variability

During different techniques of relaxation (autogenic training (AT), massage with rollers (RM)) the decrease in tension was measured among 207 subjects aged between 30 and 50 years. The heart rate (HR), the heart rate variability (HRV) and the rate of relaxation (RLX) were measured with Polar Vantage NV. Additionally the subjective feeling of relaxation was determined.

In effect of the relaxation exercises the HR decreased on an average from 73 bpm to 64 bpm (AT) and 63 bpm (RM). The RLX rose on an average from 18 ms to 28 ms (AT) and 36 ms (RM). Concerning HR there were no significant differences between the different relaxation techniques, regarding HRV a higher decrease in tension could be identified with the RM. Subjects, who had a low basic heart rate at the beginning of the relaxation exercise, had a less significant decrease in heart rate in progress. For these subjects the heart rate is a less appropriate measuring instrument.

Fields of application for HRV and RLX are: the determination of the state of the vegetative function, the measurement of relaxation effects, the comparison of different relaxation techniques and the measurement of training effects.

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Intraindividual variation of heart rate variability

Problem: By means of heart rate variability (HRV) the balance of the autonomic nervous system can be determined. Therefore, the parameters of heart rate variability may be interesting for diagnosing insufficient regeneration or overtraining syndrome. In practice, however, informations about the intraindividual variation of HRV parameters without the infuence of training are necessaray. The aim of the present study was to determine the variation of HRV parameters in series and from day-to-day.
Methods: 15 male subjects (28±4 years; 183±7 cm; 81±7 kg) performed a 15 min beat-to-beat heart rate recording (both spontaneous breathing and metronome breathing with a frequency of 6/min) with the Polar Vantage® heart rate monitor at 5 different days. To determine the variation in series the 15 min recording was repeated four times seperated by a pause of 5 min. Measured HRV parameters: standard deviation of RR intervals (RR_{SD}); quantitative evaluation of the pointcaré plots (SO_L: standard deviation of the orthogonal distances to the length diameter of the 95% confidence ellipse; SO_W: standard deviation of the orthogonal distances to the width diameter of the 95% confidence ellipse).
Results: The intraindividual variation of heart rate (HR) and HRV parameters are as follows:

		spontaneous breathing				metronome breathing (6/min)			
		HR (1/min)	RR_{SD} (ms)	SO_W (ms)	SO_L (ms)	HR (1/min)	RR_{SD} (ms)	SO_W (ms)	SO_L (ms)
series	mean	56	84	105	49	58	95	124	50
	VC (%)	**4**	**21**	**22**	**20**	**5**	**15**	**15**	**17**
	min	2	4	5	8	1	4	4	4
	max	12	37	44	45	14	30	30	36
day-to-day	mean	58	75	95	43	60	89	117	47
	VC (%)	**9**	**32**	**34**	**26**	**8**	**20**	**20**	**24**
	min	3	12	11	2	2	7	8	5
	max	14	54	53	66	13	41	34	64

Metronome breathing decreases the variation of RR_{SD} and SO_W significantly.
Conclusion: The intraindividual variation of HRV is remarkably higher than the variation of heart rate. The day-to day variation can be explained mainly by the variation in series. For routine investigation of HRV breathing should be controlled. Because of the great intraindividual variation the usefulness of HRV to determine autonomic function in single case longitudinal studies seems to be questionable.

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Simulation of the effect of heart rate on measures of heart rate variability in the time- and frequency-domain

Problem: Outstanding feature of sports medical research on heart rate variability (HRV) is the excessive spread of monitored heart rate (HR) that occur between rest and physical exhaustion. At rest HRV-powerspectrum shows two characteristic peaks around 0.1 Hz (low-frequency; LF) and 0.3 Hz (high-frequency, HF). Physical stress induces qualitative and quantitative changes in the spectrum, accompanied by a shift of the LF-peak towards lower and of the HF-peak towards higher frequencies. Instead of spectral power estimations the variability of consecutive heart period durations may be assessed more easily by statistical time-domain (TD) measures and quantitative analysis of Pointcaré plots. The qualitative relationship between time- and frequency-domain measures has already been reported. The present study was designed to evaluate how TD-measures quantitatively reflect various spectral patterns regarding the low- and high- frequency power (LFP, HFP) and to what extent an additional mathematic-methodic component independently of the biological one affects HRV measures. In particular the focus was set on the physiological interaction with varying heart rates. To exclude physiological effects on the spectrum artificial RR-series with simulated different heart rates and oscillatory-characteristics were analysed.

Methods: A set of 9 RR-Series (256 RR-intervals) was generated by superposition of 0.1 and 0.3 Hz harmonics each with 3 times varying amplitudes. 3 of such sets were calculated under variation of the baseline RR-interval duration corresponding to HR 60;100;140 min^{-1}. RR_{SD} and parameters of Pointcaré plot as dispersion to length- and width-axis (SO_L; SO_W corresponding to Stda; Stdb) and LFP, HFP and Total power (TP) were computed. The parameters were correlated for each HR.

Results: HR hardly affects the absolute values of LFP and HFP (average VK 1 ± 0.6; $1.6\pm1\%$). In TD RR_{SD} is constant, SO_L decreases with increasing HR but independent of the amplitude-modulation (avg. VK $40\pm1\%$). In contrast to SO_L SO_W increases (avg. VK $11\pm5\%$) and varies the stronger the more HF-power exceeds the LF-power-component. SO_L correlates stable (and independent of HR) almost absolutely with HFP $r\geq0.98$ but to a lesser extent with TP and LFP the faster the HR. RR_{SD} correlates just moderately but stable over HR-changes with both frequency-bands (r=0.69-0.72). The correlation between SO_W and LFP and TP is high when HR is low HR (60 min^{-1}) (r=0.91; 0.92) but an increase in HR (100, 150 min^{-1}) weakens the relationship between SO_W and LFP (r=0.78 and 0.73) and enhances the one with TP (r=0.96; 0.97).

Conclusion: HR affects HRV to a different variable extent and induces qualitative changes in the correlation between frequency-measures and RR_{SD} or SO_W. In contrast, SO_L is a reliable highfrequency-filter. This study showed an increase in SO_L and a decrease in SO_W with faster HR even if spectral characteristics are stable (LFP, HFP constant). This methodogically induced contrary behaviour seems to shift the relation between respiratory- (SO_L) and total variability (SO_W) that should be taken into account if the aim is to asses autonomic tone with different underlying HR.

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Validation of the Polar® Advantage for Assessment of Heart Rate Variability

Introduction: Parameters of heart rate variability (HRV, e.g. HF/LF-ratio, RMSSD) are indicators for differing autonomic control mechanisms. Therefore, assessment of HRV is a non-invasive and helpful tool for diagnostic of neuropathies or cardiac disease as well as for monitoring autonomic side effects of drugs. In psychosomatic medicine and psychiatry HRV has drawn interest in the last few years. However, most of the commercially available biomonitoring systems are cost-intensive and difficult to handle. Thence, we intended to investigate a easy to handle low cost system for its use in assessing HRV.

Methods: 50 healthy subjects (31 male; mean age: 26.4+/-9.8 years) were examined during resting conditions and whilst metronomic deep respiration (6 cyl./min). A low cost Polar® Advantage (Polar, Finland; costs about 200 $) HR monitor with wireless transmission and bundled software and a conventional ECG with HRV analyses software (PowerLab + Chart, ADI, Australia) were applied to the subjects. A combined sensor/transmitter was placed around the chest with an elastic band (Polar system), for conventional ECG monitoring three electrodes (ECG) were stuck to the chest. HRV standard parameters were calculated with both systems.

Results: Both systems provided comparable results with correlation coefficients between 0.85 and 0.99 ($p<0.001$). Especially time domain parameters (i.e. HR, SD, and RMSSD) showed sufficient agreement for both systems. Due to different algorithms frequency domain parameters (i.e. VLF-, LF-, and HF-frequencies, LF/HF-ratio) and due to calculation variations pNN50% fit not sufficiently.

Conclusion: However, the evaluated Polar® system seems to be applicable in assessment of HRV, especially most time domain parameters agree well with ECG data. In addition, applying this low cost system in long term studies the intra-individual comparability may also be given using the frequency domain parameters of the Polar® system. Especially for screening HRV of plenty of patients, e.g. in field studies, the Polar® system can be preferred due to its low costs and easy handling.

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Monitoring of heart rate variability in load tolerance diagnostics

One presupposition for success in elite sport are reliable and practicable procedures for an optimum training control. While heart rate (HR) has already been applied in controlling training load for a long time, heart rate variability (HRV), reflecting the differentiated changes of the vegetative state, has been applied only to a small extend. As part of a longitudinal study, being designed as a single case study, the applicability of HRV in load tolerance diagnostics has been analysed.

As subject served a top long distance triathlon athlete (age: 40 years, training volume approx. 1000 h/year, IRONMAN® time: 8:58 h). Data were monitored using a Polar Vantage NV with an monitoring rhythm of heart time interval of five minutes in the morning during a total period of four years. A detailed HRV analysis was performed with the Polar Precision Performance software package. Part of the analysis were the parameters of the scatterogram (stda, stdb) as well as of the time domain analysis (SD, RMSSD) and the frequency domain analysis (TP, LF, LF%, HF, HF%, LF/HF%). The evaluation of 1078 single data records resulted in a mean HR of 43,9 $\pm$ 4,2 min^{-1} with the following HRV reference values: stdb 123,9 $\pm$ 28,0 ms, SD 137,0 $\pm$ 24,0 ms, RMSSD 174,6 $\pm$ 71,0 ms, TP 20081 $\pm$ 7149 ms^2, HF 15051 $\pm$ 5451 ms^2, HF% 75 $\pm$ 12, , LF 1124 $\pm$ 1763 ms^2, LF% 6,0 $\pm$ 3,9 and LF/HF% 9,3 $\pm$ 13,1. Comparing with the standard values reported in scientific literature, especially the parameters representing the short-term variability of the vagus (stdb, RMSSD, HF und HF%) are significantly increased in the subject (e.g. RMSSD 175 ms vs. 27 ms). When comparing HRV in situations with different physical and psychic load we found characteristic changes. In case of subjective bad states, disturbed sleep, mental tension, infectious diseases, injury induced stress or high training and competition load the vegetative balance is displaced in direction of an increased sympathicotone functional state. This is connected with a significant HR increase and HRV decrease. Load and environmental influences on the vegetative system can overlap in such situations. In case the individual HRV reference value is not reached for a longer period of time this can be understood as a possible regeneration deficiency or the onset of overtraining. Subsequent to extreme physical load, for example the participation in an IRONMAN® competition, with an HRV control one can draw conclusions regarding the course of recovery.

For daily training control an express information on the actual HRV is of special importance in addition to a computer based analysis. Therefore in another study the diagnostic value of RLX has been studied, which is presented on Polar's Vantage NV display as modified standard deviation and a five seconds interval. We found significant correlations between the RLX-values monitored during five minutes (highest and lowest value) and the short-term variability parameters. The RLX-value turned out to be qualified in daily training control to make statements on the present load tolerance.

Our findings make plain that HRV is a proper parameter in training practise, because it reflects complex inter-relations of vegetative regulation. With regular HR and HRV control functional changes and adaptations as a consequence of positive load processing can be detected as well as vegetative dysbalances caused by a high total load (physical and/or psychic) or by an impaired health.

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Morgendliche Herzfrequenzvariabilität von Triathleten im Jahresverlauf

Fragestellung: Parameter der Herzfrequenzvariabilität können möglicherweise im Hochleistungstraining zur Beurteilung des vegetativen Funktionszustandes in Training und Regeneration und somit zur Verhinderung trainingsbedingter Überlastungsreaktionen beitragen. Hierzu ist die Kenntnis von Langzeitverläufen der Herzfrequenzvariabilität in der Saison erforderlich. Derartige Daten liegen jedoch nach Kenntnis der Autor/innen derzeit nicht vor. In der vorliegenden Studie wurden die Herzfrequenzvariabilität von 3 Triathleten im Verlauf einer ganzen Saison dokumentiert und mögliche Zusammenhänge mit dem Training analysiert.

Methodik: 3 Triathleten (P1, P2, P3: 28, 28, 34 Jahre, Trainingsalter 7, 6, 7 Jahre, p4: 4.2, 4.0, 3.2 Watt/kg) nahmen an der Untersuchung teil. Zwischen Dez. 1996 und Okt. 1997 wurden von den Probanden morgens vor dem Aufstehen über mindestens 10 min Herzfrequenz-Tachogramme mit dem Polar Herzfrequenzmessgerät Vantage NV im Beat-to-Beat Modus in Körperruhe in Rückenlage aufgezeichnet. Die Athleten wurden gebeten, möglichst mehrmals wöchentlich Messungen durchzuführen. Die Hard- und Software von Polar wurde ebenfalls zur Erhebung und Dokumentation der Trainingsdaten im gesamten Untersuchungszeitraum eingesetzt. Erhoben wurden hierbei die gesamte Trainingsdauer (TRD) unabhängig von den einzelnen Disziplinen und die Trainingsintensität (TRI) als Prozentsatz der jeweiligen Trainingsherzfrequenz von der maximalen Herzfrequenz (niedrig: 55-75%, mittel: 75-90%, hoch: 90-95% und sehr hoch: 95-100% der Hf_{max}). Dauer (D) der Erhebungsphase, Anzahl der Aufzeichnungen (n) und Anzahl (n-ausw) und Prozentsatz (%) der tatsächlich auswertbaren Tachogramme sind in der nebenstehenden Tabelle dargestellt. Die Auswertung der Herzfrequenzvariabilität erfolgte nach optischer Kontrolle der Tachogramme im Zeitbereich als Analyse des RR-Abstandes (RR in ms) und im Frequenzbereich mittels der Spektralanalyse. Ausgewertet wurden hierbei die jeweiligen exakten Positionen des Low- (LF, 0.04 – 0.15 Hz) und Highfrequency-Bereichs (HF, 0.15 – 0.4 Hz) sowie die zugehörigen maximalen Werte der Spektraldichten (SDmax in ms^2/hz). Die LF wird hierbei vor allem mit dem Sympathicotonus, die HF mit dem Parasympathicotonus in Zusammenhang gebracht.

	D (Tage)	n	n-ausw / %
P1	330	210	139 / 66
P2	310	139	107 / 76
P3	220	74	54 / 72

Ergebnisse: Trotz hoher Compliance waren nur etwa 2/3 bis 3/4 der aufgezeichneten Tachogramme auswertbar. Die Messungen sind also sehr sorgfältig durchzuführen und jedes Tachogramm ist individuell auf Artefakte zu prüfen und zu beurteilen. Jeder der 3 Probanden wies eine individuelle Charakteristik in der Funktion der Spektralanalyse auf. Die exakten LF- und HF-Positionen variierten bei allen 3 Athleten deutlich um bis zu 100 % im Saisonverlauf. Ebenfalls wiesen die maximalen Spektraldichten im LF- und HF-Bereich erhebliche Schwankungen über den Zeitverlauf auf. Gleiches gilt für die RR-Intervalle resp. die morgendlichen Ruhe-Herzfrequenzen. Die Trainingsaufzeichnungen waren nahezu komplett. Die Trainingsdauer variierte zwischen 0 und 560 min/d, verteilt auf alle Intensitätsbereiche. Die Betrachtung ausgewählter, offensichtlich in der Spektralanalyse auffälliger Untersuchungstage ließ folgende allerdings nicht immer einheitlichen Tendenzen in Zusammenhang mit dem durchgeführten Training erkennen: Hohe Trainingsbelastungen (Umfänge und/oder Intensitäten) führten tendenziell zu einer Zunahme der LF-Power, regenerative Belastungen zu einer Zunahme der HF-Power. Die Effekte waren zwischen 1-3 Tagen nach der Trainingsbelastung in den Tachogrammen sichtbar. Ähnliche tendenzielle Zusammenhänge zum durchgeführten Training waren bei den RR-Intervallen resp. der Ruheherzfrequenz nicht zu erkennen.

Schlussfolgerung: Die Beurteilung der Parameter der Herzfrequenzvariabilität muss individuell erfolgen. Bei insgesamt sehr hoher inter- und intra-individueller Variation scheinen sich Trainingsmaßnahmen teilweise in den LF- und HF-Spektraldichten, bei der hier durchgeführten Untersuchung nicht jedoch in ähnlicher Weise in den Ruheherzfrequenzen abzubilden. Eine Nutzung der individuellen Herzfrequenzvariabilität in der Trainingssteuerung ist denkbar, jedoch sind noch viele Zusammenhänge unklar. Die Studie wurde gefördert mit Mittels des BISP (VF 0408/01/03 A/97/98/99)

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Nächtliche Herzfrequenz im Jahresverlauf bei Ausdauerathleten und deren Beziehung zum absolvierten Training

Fragestellung: In der bisherigen Sportpraxis basiert die Steuerung des Regenerationsprozesses im wesentlichen auf der subjektiven Einschätzung von Sportler/innen und Trainer/innen. Es ist jedoch wünschenswert, den Regenerationsprozess anhand von objektiven Indikatoren qualitativ und quantitativ beurteilen und somit optimieren zu können. In der vorliegenden Untersuchung wurde versucht, mittels mathematischer Methoden mögliche Interdependenzen recht einfach zu erhebender Parameter des nächtlichen Herzfrequenzverhaltens mit detaillierten Trainingsaufzeichnungen im Rahmen von Einzelfallanalysen im Längsschnittverlauf aufzudecken.

Methodik: 2 Triathleten und ein Radfahrer (TR1,2, R: Alter: 24-29 Jahre, p4: 3.8 – 4.7 Watt/kg) nahmen an der Untersuchung teil. Registrierungen der nächtlichen Herzfrequenz (Hf) sollten 2x/Woche in der Zeitspanne zwischen Okt. 1997 und Sep. 1998 (301 – 363 Tage) mit dem Messgerät Vantage NV der Fa. Polar, Finnland, im 60s Aufzeichnungsmodus erfolgen. Probleme ergaben sich teilweise durch Verrutschen des Gurtes. Die auswertbaren Hf-Aufzeichnungen wurden durch Vorgabe einer oberen und unteren Hf-Grenze (90 min^{-1} / 30 min^{-1}) gefiltert. Ermittelt wurden: die mittlere Hf (HfMW), Standardabweichung (HfSD) und der Variationskoeffizient (HfVK). Die Hard- und Software von Polar wurde ebenfalls zur Erhebung und Dokumentation der Trainings- (TR-) Daten im gesamten Untersuchungszeitraum eingesetzt. Erhoben wurden hierbei die Dauer in den Einzeldisziplinen, die gesamte TR-Dauer und für das Radfahren und Laufen ferner die jeweilige TR-Intensität (TRI) als Prozentsatz der TR-Hf von der maximalen Hf (≥40, ≥50, ≥65, ≥75, ≥85, ≥90, ≥95% der Hf_{max}). Es wurde versucht, allgemeine Beziehungen zwischen den Hf-Parametern und den Trainingsdaten sowie exemplarisch zwischen Extremwerten/Ausreißern der Hf-Daten und dem absolvierten Training anhand standardisierter mathematischer Verfahren zu belegen. Um die zeitliche Dynamik des Zusammenwirkens der Messgrößen zu erfassen, wurden die Werte der TR-Variablen zu verschiedenen Zeitpunkten (Lags) bis zu 7 Tagen vor Erhebung der Hf-Variablen berücksichtigt.

		HfMW (min^{-1})	HfSD (min^{-1})	HfVK (%)
TR1	MW	46	5.1	11.1
n=69	Min	39	1.2	2.8
	Max	63	13.0	23.4
	Sd	4.3	1.1	3.5
TR2	MW	53	3.5	6.8
n=55	Min	43	1.9	3.3
	Max	61	7.0	16.3
	Sd	4	0.8	1.8
R	MW	56	4.0	7.0
n=103	Min	44	1.0	2.1
	Max	77	14.1	18.9
	Sd	6.5	1.8	2.6

Ergebnisse: TR-Umfänge, -Inhalte und -Intensitäten variierten erwartungsgemäß deutlich im Jahrestrainingszyklus. Die Gesamtumfänge betrugen im Mittel 108-114 min/Tag bei 190-276 TR-Tagen. Es fanden sich eine Vielzahl von Auto- und Kreuzkorrelationen zwischen den einzelnen Trainingsmaßnahmen. Dies ließ eine differenzierte Analyse der Effekte einzelner Intensitäten auf die Hf-Variablen nicht sinnvoll erscheinen. Die Anzahl der auswertbaren nächtlichen Hf-Messungen sowie die weiteren Kenndaten der Messungen sind der nebenstehenden Tabelle zu entnehmen. Auch hier fanden sich große inter- und intraindividuelle Variationen im Saisonverlauf. Einige Extremwerte/Ausreißer der Hf-Parameter von TR1 und TR2, nicht jedoch von R, ließen sich auf außergewöhnliche vorausgegangene Trainingsbelastungen zurückführen. Unter Einbeziehung der unsummierten, bis zu 7 Tagen voraus gegangenen TR-Umfänge konnten sich für TR1, TR2 und R nur sehr wenige, sowohl positive als auch negative, Zusammenhänge zu den Hf-Parametern nachweisen lassen. Die Einbeziehung der summierten, bis zu 7 Tagen voraus gegangenen TR-Umfänge ergab ebenfalls einige wenige Zusammenhänge zu den Hf-Parametern für TR1 und TR2, nicht jedoch für R.

Schlussfolgerung: Insgesamt lässt sich festhalten, dass zwar einige Extremwerte und Ausreißer auf hohe Trainingsbelastungen folgen, man kann jedoch nicht davon ausgehen, dass ein hoher Trainingsumfang in jedem Fall außergewöhnliche Messwerte der nächtlichen Hf-Variablen nach sich zieht, oder dass umgekehrt alle diese Messwerte durch extreme Trainingsbelastungen verursacht wurden. Anhand der Berechnung von Korrelationskoeffizienten wurden einige wenige Interdependenzen zwischen TR-Daten und Parametern der nächtlichen Hf aufgedeckt. Dies variierte sehr stark von Athlet zu Athlet, so dass für weitere Untersuchungen sowie einen möglichen Einsatz in der TR-Praxis eine individuelle Betrachtung erforderlich erscheint. Die Studie wurde gefördert mit Mittels des BISP (VF 0408/01/03 A/97/98/99