Guideline for the application of heart rate and heart rate variability in occupational medicine and occupational science

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1 Preliminary remarks

The present guideline is a result of the consolidation and a thorough revision of two guidelines, „Nutzung der Herzschlagfrequenz bei arbeitswissenschaftlichen Untersuchungen (Application of the heart rate in examinations in the field of occupational science)“ (AWMF 002-012, Authors: Frauendorf H, Pfister EA, Wirth D) [81], latest version updated in 2005, and „Herzrhythmusanalyse in der Arbeitsmedizin (Analysis of heart rate in occupational medicine)“ (AWMF 002-021, Authors: Pfister EA, Böckelmann I, Rüdiger H, Seibt R, Stoll R, Vilbrandt R) [197], latest version updated in 2006. Due to recent advancements of measurement techniques, the determination and analysis of heart rate (HR) and heart rate variability (HRV) an update of the guidelines was necessary. The revision was carried out by the Forum of Occupational Physiology within the German Society for Occupational and Environmental Medicine („Forum Arbeitsphysiologie“ der Deutschen Gesellschaft für Arbeitsmedizin und Umweltmedizin e.V. (DGAUM)) and the Society for Occupational Science (Gesellschaft für Arbeitswissenschaft e.V. (GfA)). Because HR and HRV are correlated and show substantial congruencies regarding physiological determinants, recording techniques as well as fields of application, the two guidlines were merged to the current guideline.

This guideline has been developed for application in clinical practice and research purposes in the fields of occupational medicine and occupational science to complement evaluation procedures with respect to exposure and risk assessment at the workplace by the use of objective physiological workload indicators. It gives an overview of factors influencing the regulation of the heart rate and heart rate variability at rest and during work. It further illustrates methods for measuring and analyzing these parameters under standardized laboratory and real workload conditions, areas of application as well as the quality control procedures to be followed during the recording and evaluation of heart rate and heart rate variability.

2 Introduction

The HR provides information about the strain of the cardiovascular system in response to physical and mental workload. The HRV gives additional information regarding the dynamics and mechanisms of cardiovascular regulation [113]. Both physiological parameters have been established for the use in inpatient and outpatient care (e.g. cardiology, intensive care, endocrinology, neurology, occupational medicine, sports medicine, obstetrics) as well as medicine and scientific research (occupational physiology, exercise physiology, occupational science, sport science, psychology and pharmacology) for many years because of their non-invasive data acquisition and comfortable methods of, analysis.

Along with the technological advancement Holter monitors with tape recordings, which were used till the end of the 20th century, have been replaced by digital data storage systems. These recorders provide high quality recordings of cardiac activity and the evaluation of HRV [146]. Thus, tape devices will not be further mentioned in this paper.

3 Definitions

HR is defined as the number of beats or contractions of the heart per minute. It can also be calculated as a ratio of 60,000 and the average NN interval[1] in milliseconds. The HR is a measure of the individual workload response of the cardiovascular system and is influenced by various factors (see section 7). HR should be differentiated from the *pulse rate*, which is defined as the number of pulsations per minutes palpated at the periphery, e.g. at the wrist or at the neck. A difference between HR and pulse rate may

[1] NN interval = normal-to-normal interval, used synonymously with the terms RR interval, IBI (interbeat interval), cycle length variability, heart period variability

occur in certain types of cardiac arrhythmias where some contractions of the heart do not produce a palpable pulse at the periphery. A difference between the HR and the pulse rate is called *pulse deficit*.

The normal *heart rate at rest* (HR_{Rest}) varies between 60 and 80 beats/min (bpm) in adults. It is usually higher in children i.e. up to 120 bpm. In endurance trained adults, the HR_{Rest} is often below 50 bpm.

The HR reaches a maximum during physical exertion. The maximum value differs between individuals and decreases with age. The most commonly used empirical formula for estimating the *maximum HR* (HR_{max}) is [79]:

$$HR_{max} = 220 - age.$$

However, this formula underestimates the HR_{max} in persons >40 years of age [249]. Based on a meta-analysis and their own examinations, Tanaka et al. [249] calculated a regression formula to estimate age-dependent maximum HR by:

$$HR_{max} = 207 - 0.7 \times age$$

in which sex-related differences have not been considered [96, 249]. The determination of the individual HR_{max} requires maximum physical exertion under conditions of dynamic muscle activity of a larger muscle mass, e.g. a cardiac stress test using treadmill or bicycle ergometry [244]. Depending on the specifity of the subjects, usually other instruments like the arm crank ergometer could be used as well.

In the field of exercise physiology, the HR following a maximal exercise test is frequently taken as an indicator of the fitness level of a subject. The value is measured one minute after the cessation of a maximal exercise test. It reflects the rapid regulative phase of recovery and is called the *recovery heart rate* ($HR_{Recovery}$).

In the fields of occupational medicine and occupational science, the *heart rate during work*[2] (HR_{Work}) is taken into consideration while analysing the respective activity, e.g. evaluation of physical work. The HR_{Work} is defined as the difference between HR_{Rest} and the value measured during physical work [93, 106, 108]. HR_{Work} is also known as *net heart rate* (HR_{net}) [253]. HR_{net} correlates better with the physical exertion than the HR, provided a resting phase without physical or emotional stress of at least five minutes (ideally, fifteen minutes) before starting the work can be maintained to assess a valid baseline HR. This is a necessary requirement while carrying out tests in the laboratory, whereas in cases of measurements at real workplaces, it could be difficult to achieve these conditions before the working shift. Under circumstances of unreliable and not representative HR_{Rest} measurements absolute HR might better reflect the intensity of the workload during physical exertion than HR_{Work}. Alternatively, the *reference heart rate* can also be determined for light dynamic work (see section 5.2).

In addition, the individual physical exertion is also frequently described by calculating the *summated recovery heart rate* as a measure of the fatigue and recovery [185]. For this procedure, all heart beats during the recovery phase are summed until HR reaches the baseline level (e.g. HR_{Rest}).

The term *heart rate variability* (HRV) comprises a number of mathematically calculated parameters, which characterise the variance, rhythm or complexity of a time series of consecutive heart beats – the so-called NN interval. Because of robustness and reliability issues the R-wave is usually used in place of the P-wave as a sign of activity of the sinus node during automatic detection (Fig. 1). A detailed list of the frequently used HRV parameters can be found in section 6.

4 Physiological mechanisms

4.1 Physiological mechanisms of HR

During the resting phase, the frequency of the heartbeat is triggered by the primary impulse generating tissue (pacemaker), the sino-atrial node (SA-node). The rate of the non-innervated SA-node itself is variable and ranges between 60 - 80 bpm, depending on the reference source [198, 266]. It is usually higher in children [101, 128]. The pacemaker tissue also has other subordinate nodes that are capable of spontaneous depolarisation with lower rates (AV-node, Bundle of His, Purkinje fibres). The autonomic modulation of HR by the sympathetic and the parasympathetic (vagus) nervous systems is primarily mediated by the SA-node. This dual control by the autonomic nervous system (ANS) has been shown in various experiments: using sympathetic blockade by propranolol and vagus blockade by atropine [66, 129, 130].

4.2 Physiological mechanisms of HRV

Even under constant physical exertion, HR shows a physiological variability, which predominantly reflect the interplay between the sympathetic (SNS) and the parasympathetic nervous systems (PNS). In additionother regulatory factors can affect HRV. The sympathetic part of the ANS typically decreases the absolute HRV by shortening the NN-intervals. The transmitter of the SNS at the SA-Node is noradrenaline. In contrast, the

[2]Older scientific papers use the term working pulse, instead of working heart rate

PNS typically increases absolute HRV. The transmitter of the PNS is acetylcholine [62].

At rest and during mild exertion, the parasympathetic (vagal) control outweighs the sympathetic effect on the HR. This leads to an increased variability of the heartbeats: the difference in the gap between two consecutive heartbeats increases.

The HRV analysis is used particularly for the differential evaluation of the interplay between the sympathetic and the parasympathetic nervous systems under various conditions. Therefore, the quantification of the autonomic activity is carried out by analysing the rhythmic fluctuations of the heartbeat. Rapid changes in the HR with a cycle length of about 2-7 seconds are closely associated with breathing (Respiratory Sinus Arrhythmia [RSA]). These high-frequency fluctuations are modulated almost exclusively by the parasympathetic branch of the ANS (vagus nerve); whereas the slow fluctuations (cycle length of about 10 seconds) are modulated by the efferents of both parts of the ANS [16]. However, for the interpretation of HR and HRV, it must be taken into consideration that both parameters reflect the net effect of autonomic cardiac efferent activity but also other modulating factors like mechanical influences during physical exertion, heat and other environmental factors.

A high aerobic fitness of a person typically results in a higher resting vagal tone. Thus, endurance athletes normally show a low HR_{Rest} and a high HRV.

5 Determination of the NN intervals for the calculation of HR and HRV

5.1 Technical Possibilities and requirements

Several methods are available to record the interbeat intervals: stationary ECG instrument – which is more suitable for laboratory studies or intensive care units – and mobile measurement techniques that can be used in field studies. The mobile measurement systems include 24-hour Holter-ECG and chest belts providing internal data storage or data transmission to and storage on an external data module (e. g. in a separate wristwatch).

For the analysis of HRV, a so-called “beat-to-beat recording“ is necessary. In addition the raw ECG should be sampled at a high rate (ideally 1,000 Hz) so that the NN intervals can be measured with high temporal accuracy..

In addition, the instruments should fulfill the following requirements:

- non-invasive,
- mechanically robust (for examinations at workplaces which involve heavy physical work or difficult environmental factors like heat, cold and wet conditions) and
- non-interfering (the method itself should not influence the results in any way).

The advantages and disadvantages of the different measurement systems are given in Table 1.

5.2 Electrodes

The following should be done to avoid errors during measurement:

- adhesive electrodes should be used so that they do not lose contact with the skin even after longer periods of recording (e.g. 24 hours) and in cases of sweating,
- the electrodes on the chest belt (contact points) should be moistened,
- the chest belt should fit firmly and
- a textile strap should be preferred, because it can adapt itself optimally to the individual‘s upper body.

5.3 Preparation of the skin

The skin should be prepared carefully in order to obtain optimal results of measurements, especially iflong-term recordings (24 hours) are carried out. In cases of skin-electrode contact with high impedance, the quality of the recording decreases and the probability of the appearance of artifacts are high.

The main objective of preparing the skin is to remove the natural oily film of the skin. This reduces the contact resistance between the skin and electrodes and enables a better adherence of the electrodes. The contact points on the skin for the electrodes are first wiped with a dermatologically safe, lipid-dissolving solution (e.g. alcohol solution). However, any damage or injury to the skin has to be avoided. In case, hair over the contact points should be carefully removed before placing the electrodes. An additional fixing of the electrodes and the cables can be useful for long-term recordings or other conditions.

5.4 Lead choice and electrode positioning

The ECG leads must be chosen based on the largest amplitude of the R-wave of the QRS complex (see Fig. 1). In principle, recordings from a single lead are sufficient. However, multiple leads should be used to enable a reliable correction of artifacts.

During the automatic determination of the NN interval, it should be ensured that R-wave detection is consistently based on the same lead. Changing the lead during the same recording can lead to an artificially generated increase in the HRV. While the point of time at which the QRS complex begins is almost identical in most of the leads, the fiducial point (R-wave), which serves as the basis for determining the NN interval, can significantly vary between the different leads [88, 267].

The positioning of the electrodes influences the quality of the recordings. If electrodes are not positioned appropriately, recording quality might suffer, resulting in an accumulation of artifacts. The intercostal spaces are suitable areas for positioning the electrodes. Within these spaces, flat and even areas of the skin should be selected (e.g. positioning above dermal naevi should be avoided).

5.5 Quality assurance while determining the HR

The following aspects should be taken into consideration for the purpose of quality assurance:

- the determination of HR_{Rest}[3] before the beginning of the exertion as physiological baseline for the evaluation (see section 8.2),
- checking for artifacts and, if possible, removal of artifacts (e.g. by visually checking the data during analysis, automatic methods for correcting artifacts),
- a high sampling rate (a measuring instrument with a sampling rate of ideally 1,000 Hz or more should be selected, i.e. accurate sampling of the ECG signal up to the millisecond),
- the possible influencing factors depending on the case (see Table 3) and
- the circadian rhythm should be kept in mind for comparable examinations.

5.6 Quality assurance while determining the HRV

The following aspects should be taken into consideration for the purpose of quality assurance:

- a resting ECG should be recorded before the HRV is analysed in order to rule out cardiac arrhythmias (e.g. atrial fibrillation),
- recordings with more than 1% of ventricular or supraventricular extrasystoles should be evaluated critically because of the apparent increase in the HRV [214],
- checking for artifacts and, if possible, removal of artifacts (e.g. by visually checking the data during analysis, automatic methods for correcting artifacts),
- the analytical method of choice (e.g. Fast Fourier Transformation, Autoregressive Model, Trigonometric Regressive Spectral Analysis) to enable comparable interpretations (see section 6),
- the selected duration of recording (subsequent length of the sequence of analysis) or the underlying amount of data depending on the analytical method selected and the research question (see Table 2),
- a high sampling rate (a measuring instrument with a sampling rate of ideally 1,000 Hz or more should be selected, i.e. accurate sampling of the ECG signal up to the millisecond),
- the possible influencing factors depending on the analytical method selected and the research question (see Table 3) and
- the circadian rhythm should be considered as a possible confounder if comparing repeated measurements examinations.

In the case of short-term recordings (less than 1 hour), the selection of a suitable, representative area of the NN intervals is an important quality criterium for HRV analysis. For this, the non-steady setting phase at the beginning of the examination and the recordings with artifacts should not be used for the analysis as far as possible (Fig. 2).

5.7 Other sources of interference

When chest belts with wireless data transmission are used in the vicinity of electromagnetic fields from power poles or power supply lines [113] or used in vehicles and their vicinity [215, 216], interferences can occur. Artifacts due to body movements and due to electrical activity of other muscles can occur during physical activity. In the case of an ECG recording, these artefacts should be detected and manually removed at the end of the recording, whereas in cases of gathering data without ECG recording (like in most cases of chest belts systems), it is not always possible to attribute the artefacts to the movements.

6 Analytical methods and parameters of HRV

HRV is quantified using time and frequency domain methods as well as methods of non-linear analysis (Fig. 3).

Time domain methods are divided into statistical and geometrical methods. In the case of the statistical methods, the NN intervals are evaluated mathematically with respect to its variance and the measurement of the rhythm is tagged with the time dimension or the percentage values, whereas geometrical methods provide an evaluation of HRV based on geometric forms. For these purpose histograms, HRV triangular index and its modifications, triangular interpolation of the NN interval histogram are used [20].

For frequency domain analysis the following methods are established and have been applied frequently: Fast Fourier Transformation, Autoregression [35], the Zero Crossing Method [9], Wavelet Analysis [9] and

[3] The following procedure is recommended: the recording should be carried out preferably in an upright seated posture after 5 minutes of rest (ideally 15 minutes) and with two consecutive recordings. The minimum duration of recording should be 30 seconds. Smoking, food and caffeine intake and any physical exertion should be avoided at least 30 minutes before the recording.

the Trigonometric Regressive Spectral Analysis (TRS) [212, 213]. The Fast Fourier Transformation and Autoregression are the most widely methods applied. Sepctral analysis decomposes the periodic oscillation of the NN-signal, into different frequencies and amplitudes. Distinct frequency bands are supposed to reflect different physiological processes and regulatory systems [213].

In some cases, the Lomb algorithm is also used to analyse recordings with varying lengths and non-equidistant sampling [168]. The Lomb algorithm is an extremely slow method; but approximation methods have been established to speed up the application of the algorithm [202].

The TRS method by Rüdiger et al. [213] works on the same basic mathematical principle, but is more effective, as only frequency in the periodogram significantly contributing to variance reduction are calculated.

The methods of non-linear dynamics (e.g. Approximate Entropy [ApEn], Sample Entropy [SampEn], Detrended Fluctuation Analysis [DFA]) [175, 241, 264] vary from the traditional time and frequency parameters in that they do not reflect the strength of the HRV, but they rather indicate qualitative aspects of the series of NN intervals [175]. These methods often prove to be suitable for long-term as well as short-term recordings and are considered more robust against artifacts.

One form of visualisation of the time series of NN intervals is offered by the so-called Poincaré Plot[4] (see Fig. 2). From this plot various indices can be determined and interpreted (e.g. length and width of the scatter-plot). Further, the form can also give hints about certain diseases [221].

A detailed listing of the HRV parameters is given in Table 2.

7 Factors influencing the individual HR and HRV

Aside from acute physical exercise/exertion HR and HRV can be affected by several modifiable and non-modifiable factors. The most relevant factors for investigations in the field of occupational medicine and occupational science are described in Table 3. The knowledge of these factors is of importance when HR and HRV are evaluated. In addition, various other factors and conditions (e.g. HRV in patients with sepsis that needs intensive care) have been mentioned in scientific literature. As these cases are normally not relevant in the field of occupational medicine and occupational science they will not be considered any further in the current guideline.

Pharmacological drugs can have significant impact on the autonomic nervous system or the electrical conduction system of the heart and thus should be considered when assessing and evaluating HR and HRV. For example, the group of beta blockers typically lead to a reduction of HR and no long-term effects on HRV, while some ACE inhibitors can cause a reduction of HRV. Antiarrhythmic agents can lead to an increase in HRV and psychotropic drugs to a reduction of HRV [69].

8 Evaluation and interpretation of HR and HRV

For a valid and reliable evaluation and interpretation of HR and HRV adequate study designs, data sampling strategies and analysis methods are necessary prerequisites. HR and HRV parameters mirror the indvidual physiological workload response within a given context of individual, psychophysiological and work-related factors (see Table 3). Thus measurements of HR and HRV should always be combined with complementary data (e.g. questionnaire about the subjective stress, perception of stress and the state of health). If possible, information about the ambient conditions at the workplace, like noise and temperature, should be collected at the same time.

8.1 Heart rate (HR)

Important factors that influence HR are dynamic activity of larger muscles, static muscular load of smaller muscles and thermal stress as well as mental workload [56, 57]. These factors often act together on the cardiovascular system and can induce a corresponding increase of HR during exertion. These effects were studied by e.g. Hettinger et al. [107] in cases of varying workload levels with respect to muscle groups and temperature. A delineation of the individual components is possible under controlled conditions only. E.g. HR during dynamic work of larger muscles can be used for estimating the energy expenditure only if the activity of smaller muscles and the mental workload are negligible and thermal conditions remain neutral [56].

8.2 Heart rate at rest (HR_{Rest})

The HR_{Rest} is the preferred baseline value for an individual evaluation of the HR during physical exertion (see section 5.5). Baseline measurement conditions (e.g. posture of the person, duration of recording) should be standardized to enable within- and between-subject comparisions. Both, an increased or a decreased HR_{Rest} can be associated with an apparent cardiac disease [50, 272]. After considering physiological contributors to HR_{Rest} (see section 7) persons with unexplained higher (tachycardia) or a lower (bradycardia) HR_{Rest} should be subjected to a cardiological examination.

[4] The terms, Lorenz plot or Scatter plot, are used as synonyms

Sometimes the determination of HR_{Rest} is difficult in field studies, due to confounding effects on HR (psychological factors, environmental conditions like noise, ambient temperature etc.). Therefore, Hettinger and Wobbe [107] recommended the determination of a *reference heart rate* ($HR_{Reference}$) during light dynamic work (e.g. 20 Watt on a bicycle ergometer for 10 minutes). Since this workload is typically perceived as a "light exertion", the effect of psycho-emotional stress ("psychological heart rate") is largely eliminated. Compared to the resting value in the supine position the HR increases by an average of 18.5 bpm in men during this procedure; while in women, an average increase of 24.5 bpm with relatively narrow limits of agreement can be expected [107].

8.3 Maximum heart rate (HR_{max})

The HR_{max} serves as a criterium for maximum physical exertion and can be determined during a standardised exhausting exercise protocol [252]. The most widely used methods for this are the treadmill and the bicycle ergometry. An optimal motivation to bring about the maximum performance and the observance of the stop criteria are the main requirements for the determination of the $HR_{max.}$ However, one should keep in mind that apart from factors like age, sex and fitness level [96] and certain bradycardia producing drugs [244], the value of the HR_{max} determined largely depends on the muscle mass that is used.

For an appropriate estimation of cardiac workload the interpretation of the HR response during a given (occupational) physical task should always be refered to the individual HR_{Rest} and HR_{max} (see section 3). Here, a value of the HR during physical exertion (occupational), which lies closer to the HR_{max}, indicates a higher degree of stress on the heart. The (HR) endurance limit can also be referred to for the interpretation (see section 8.5).

8.4 Recovery heart rate ($HR_{Recovery}$)

The $HR_{Recovery}$ can be used to estimate the recovery capacity of the cardiovascular and the metabolic sytems. It strongly correlates with the function of the parasympathetic branch of the autonomic nervous system [122] and typically decreases exponentially after the end of the exertion. The main factors that influence the temporal course of the recovery of the vagus are intensity, duration and method of the physical exertion, initial performance level and the type of recovery [245-247].

8.5 Endurance limit (w.r.t. the heart rate)

The endurance limit (DLG) of physical exertion characterizes the maximum muscular work that can be maintained over a regular working shift (about 8 hours) without any progressive symptoms of fatigue and where the measurable physiological parameters return to baseline or fall even below basline within 15 minutes after the work cessation [253]. The DLG can be used for the identification of muscular physical exertion without fatigue (below the DLG) and muscular exertion inducing fatigue (above the DLG) with respect to an 8-hour working shift [93, 209, 220]. The value of DLG can be determined using cardiac (e.g. HR) as well as metabolic parameters (e.g. energy turnover, lactate). Spiroergometry can also be used as an alternative for the determination (e.g. 40% of the maximum oxygen intake). HR, as one of the easiest accessable physiological workload indicators, is used to evaluate the cardiopulmonary stress. In the cases of dynamic activity of larger muscle masses, the DLG ranges between 105-110 bpm or alternatively between HR_{Rest} + 30-35 bpm [253]. It should be noted that HR used for the determination of the DLG also underlies a strong individuality due to e.g. age and the level of physical fitness.

Below the DLG, the HR shows a linear increase along with the intensity of workload. In the case of light work with a constant performance over time, the HR reaches an almost constant deflection ("steady state") within a short time (few minutes). Typically, this "steady state" can be maintained over the entire 8-hour working shift (Fig. 4).

Small, short-term overshootings beyond the DLG (e.g. HR of 130-140 bpm) are common during a work shift and do not pose any health risks, while scheduled breaks during constant physical exertions with a HR >130 bpm help to overcome the muscular fatigue.

If the DLG is being continuously exceeded, this kind of work is classified as heavy physical work or hard labour, in terms of energy [28]. It leads to increasing muscle fatigue (along with anaerobic metabolism), which is generally reversible without any effects on health. There is a continuous rise in the HR and and a rise in fatigue as well (see Fig. 4). Heavy physical work is also relevant from the motor and the biomechanical point of view, because the skeletal system (joints, intervertebral discs) might be damaged under relevant conditions [220]. However, these aspects will not be illuminated in this guideline.

Apart from the DLG, the summated recovery heart rate (see Fig. 4) is also considered an indicator of the individual physical exertion [185].

It should be noted that an evaluation of workload based on by the DLG (as described above) is only valid, if larger muscle masses (> 1/6 of the total muscle mass) are dynamically active. If smaller muscles masses are used for dynamic tasks, the DLG has to be adjusted (e.g. decreased) in proportion to the muscle mass used. Typically HR, HR_{Work} and oxygen are lower compared to whole body exertion, despite similar or even shorter time until exhaustion. Sometimes, e.g. in cases of work done by the arm or hand, the DLG is not valid for estimating time to fatigue or exhaustion [80]. In cases of isometric muscular work or with an increasing portion of isometric muscle activity during dynamic tasks, an evaluation of the workload

intensity with respect to the DLG is not valid.

With respect to work structuring, the occupational tasks that are seen as being responsible for an increase in DLG should be considered in detail.

8.6 Heart rate variability (HRV)

Several methods are available for the analysis of HRV. In principle, the time domain parameters of HRV can be calculated using mathematical functions in established spreadsheet programmes. In addition, many manufacturers of mobile ECG instruments also provide software programmes that enable the calculation of the time domain and the frequency domain parameters of HRV and also a non-linear analysis of the NN interval series. Freely available software packets with good documentation can also be found.

To interprete the response of HRV in terms of ANS activity, several indices (see Table 2) and recording durations are recommended. (see sections 9.1 and 9.2). While doing this, it is important to see which of the effects are to be measured – those of the SNS or the PNS.

While assumptions based on specific HRV parameters require long-term recordings (see Table 2), HRV parameters that are suitable for short-term measurements are primarily used for the evaluation of physical stress at work with rapidly changing requirements. While the observation of transient effects might be of interest under circumstances, the first minute after a workload change should be excluded from the data analysis, because transient effects of the ANS dominate this phase and HRV values might not be representative for the workload response of interest (Figure 2).

Due to the high inter-individual variability and numerous exogenous and endogenous factors affecting the NN interval, HRV analysis should be used only in combination with a baseline assessment or with repeated measurements during work under the comparable conditions.

Currently, the evaluation of individual HRV values is limited because of missing reference values with respect to age and sex. The reference values published in 1995 in the guideline of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [69] are of limited use only, as in the meanwhile techniques for recording and analysis have been advanced. Nunan et al. [190] have published specified average values independent of age for 5-minute short-term recordings of the known HRV parameters in a systematic review (based on 44 studies published to date) (Table 4). The average values cited in this review are lower than those published in the 1995 guideline [69]. However, even the values published by Nunan et al. [190] are of limited use due to the missing age references.

It can be concluded that generally applicable cut-off values are currently not available for HRV parameters. It is also presently not possible to make any conclusive HRV-based statements neither with respect to health and nor for psychosocial stress. Therefore, an interpretation of HRV parameters based on a single measurement is not possible. Standardised serial measurements (individual longitudinal studies) of HRV in combination with the history, clinical examination and other methods (e.g. questionnaires) can be valuable in explaining the individual heath risks and help to evaluate the effectiveness of medical preventive measures.

9 Application in the fields of occupational medicine and occupational science

The methods used for the recording and evaluation of HR and HRV can be used to gain an objective view of the activity of the autonomic nervous system. The applications in the fields of occupational medicine and occupational science are:

- complementary examinations for the risk analysis and risk assessment to identify the core areas of work-related stress,
- analysis of the individual physical and mental workload and a process-integrated measurement for an objective view of the workload response over the course of the working day,
- determination of a health status indicator,
- derivation of actions to be recommended for each individual e.g. workplace design,
- determination of the fatigue and recovery behaviour and
- evaluation of interventions in medicine and occupational medicine.

9.1 Application to assess of physical exertion

The evaluation of physical exertion using the HR especially during dynamic muscle work has been known for a long time. The knowledge gained through HRV in such cases and under standardised conditions are: a proven correlation between HRV parameters and the metabolic and respiratory stress indicators, the multi-phase course during progressively increasing exertion and the recovery behaviour after varying degrees of exertion [51, 132]. This enable an accurate evaluation of the physical exertion without the use of a time-consuming, cost-intensive recording method that is also partly unavailable in the ambulatory and reactive forms. Among the HRV parameters, the RMSSD, LF power and HF power and the non-linear indices are suitable for the determination of the acute physical exertion in addition to the parameters of total variability like SDNN or Total Power.

9.2 Application to assess mental workload

The deflections that are seen in HR and HRV in cases of mental exertion can be taken as indicators of mental stress. Since the construct of mental workload is difficult to measure, HR and HRV are taken as parameters of general activation and can be used to describe the vegetative balance of the organism. In this way, one can derive conclusions about the given mental exertion through these stress parameters [1, 10, 67, 68, 123, 127, 133, 171, 177, 184, 192, 193, 258, 262]. In addition, HRV can also be used as an indicator of both - the psychophysical condition of the organism and the restriction in the adaptibility for biopsychosocial problems. The HRV parameters, RMSSD, LF, HF or LFnu and HFnu, LF/HF as well as DQ and SD1 are considered mental workload indicators. However, ULF and VLF are not suitable. The resting HRV cannot be not considered as a predictor for the cognitive capacity in cross-sectional studies [268].

9.3 Application for risk stratification of cardiovascular diseases

HR and HRV are well suited for the risk stratification of cardiovascular diseases [37, 38, 92, 200, 254, 259]. Low values of HRV parameters (e.g. reduced SDNN) show significant correlation with mortality in patients with prior myocardial infarction in large cohort studies [34, 46, 120], bypass surgeries [155] or an existing cardiac insufficiency [217]. Conclusions regarding mortality risk in healthy individuals based on reduced HRV parameters is not recommended because of the currently missing normal values and strong interindividual variability in the healthy population. The HRV parameters determined might rather be used in addition to the etablished methods of diagnosis and to monitor individual changes of autonomic heart rate control in the mid-and long-term.

9.4 Application to evaluate preventive measures

HRV has been established particularly as a useful parameter for the evaluation of preventive measures like stress reduction courses, dietary changes, judicious use of stimulants, changes in eating behaviour, sport activities including the preventive monitoring of overtraining syndromes [111] and measures to reduce weight in order to evaluate the success of the corresponding preventive or interventional measures in longitudinal comparisons [250]. For example, a change in the sympathetic-parasympathetic balance and a higher parasympathetic baseline activity (e.g. raised SDNN or RMSSD, reduced LF/HF ratio) indicate positive effects of the preventive measures.

9.5 Application in biofeedback

HR and HRV have been used for biofeedback in cases of stress recovery and recently also in the treatment of posttraumatic stress disorder e.g. for an objective view of the effects of stress relaxation [55, 90, 160-162, 196]. However until now, only short-term effects of such interventions have been observed. It has not yet been possible to demonstrate a long-term effect [90, 196]. With reference to the determination and the evaluation of HRV, it is inevitable that the biofeedback methods, which determine the HRV with the help of pulsoximeter or respiratory activity, cannot be seen as valid measurement methods to measure HRV and therefore cannot be recommended for HRV-based biofeedback.

10 Conclusions

The practicability of the HR and HRV analysis on a daily basis for field studies at workplaces has been proven. These analytical methods can be used with a goal-oriented approach for various problems when the methodological requirements are met. Under these conditions, HR and HRV can be recommended for the use not only in research institutes, but also for practising occupational physicians and company doctors. This might help to improve diagnostic efficiency and and to elucidate heart- and health related mechanisms in the field of modern occupational medicine facing an ever-changing working environment and a demographic change in Germany.

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The present guideline is a result of the consolidation and a thorough revision of two guidelines, „Nutzung der Herzschlagfrequenz bei arbeitswissenschaftlichen Untersuchungen (Application of the heart rate in examinations in the field of occupational science)“ (AWMF 002-012, Authors: Frauendorf H, Pfister EA, Wirth D) [81] that was last updated in 2005 and „Herzrhythmusanalyse in der Arbeitsmedizin (Analysis of heart rate in occupational medicine)“ (AWMF 002-021, Authors: Pfister EA, Böckelmann I, Rüdiger H, Seibt R, Stoll R, Vilbrandt R) [197] that was last updated in 2006.

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Fig. 1: The principle of determining NN intervals using the ECG as the interval between two R-waves.

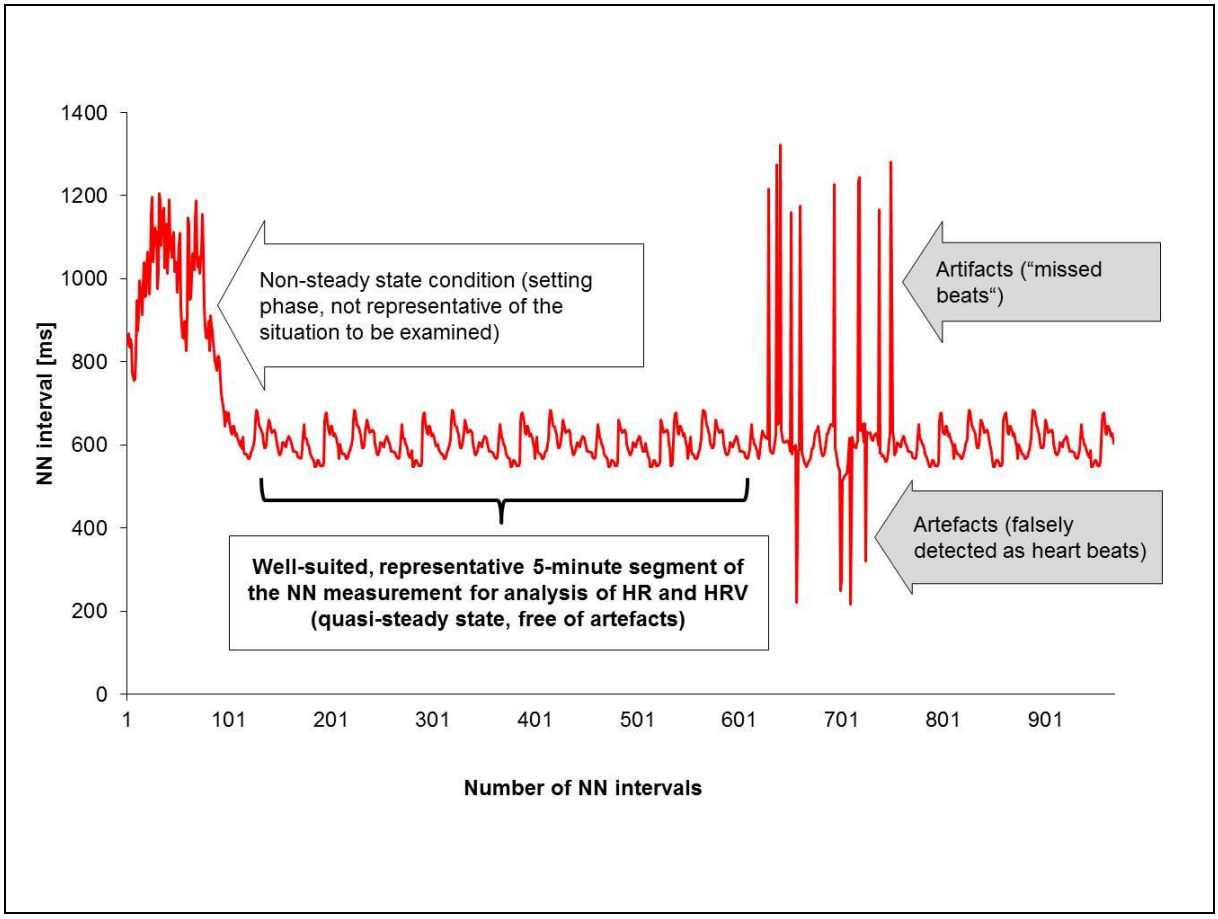

Fig. 2: The principle of selecting a representative 5-minute segment of the NN measurement from a recording exhibiting several artifacts and a previous non-steady phase

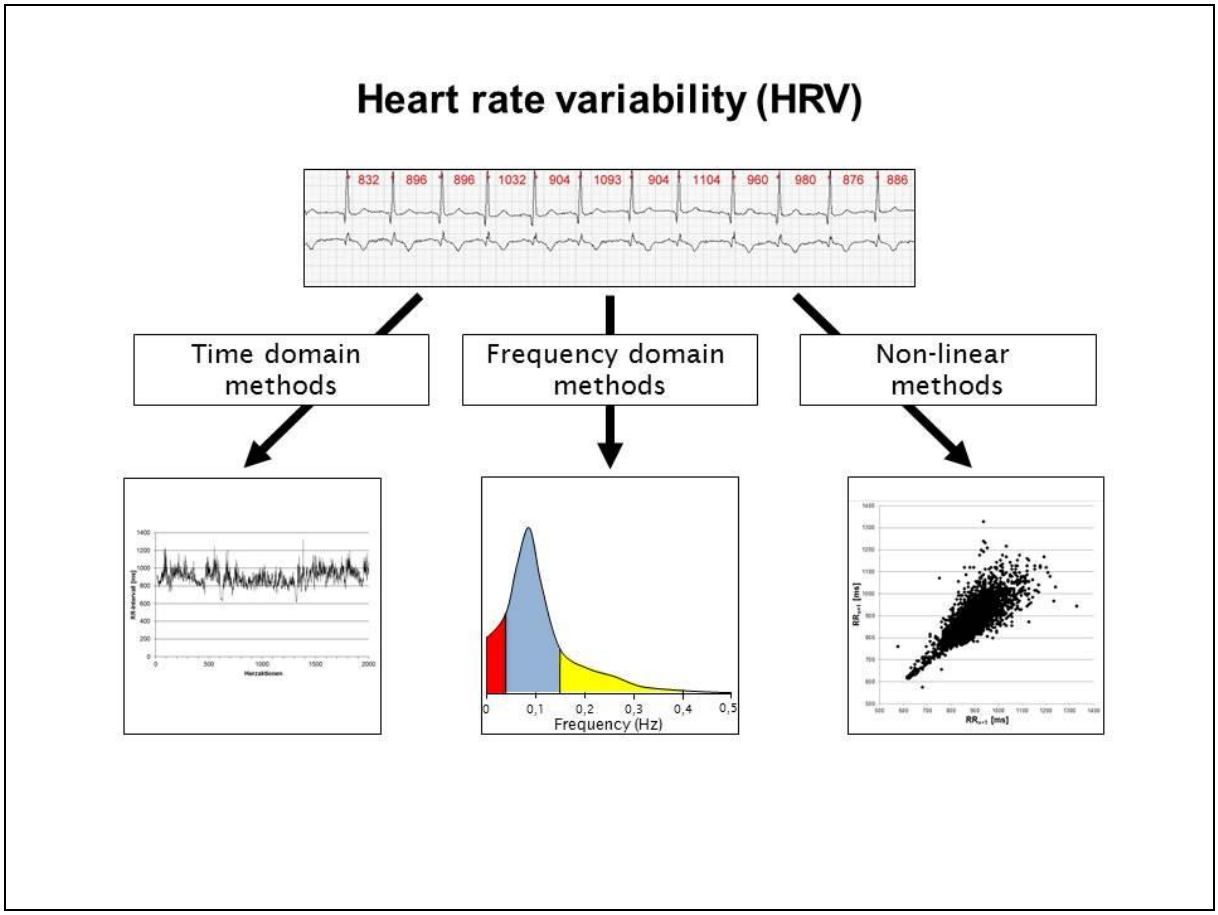

Fig. 3: Overview of the methods of HRV analysis with examples of possible graphical representations

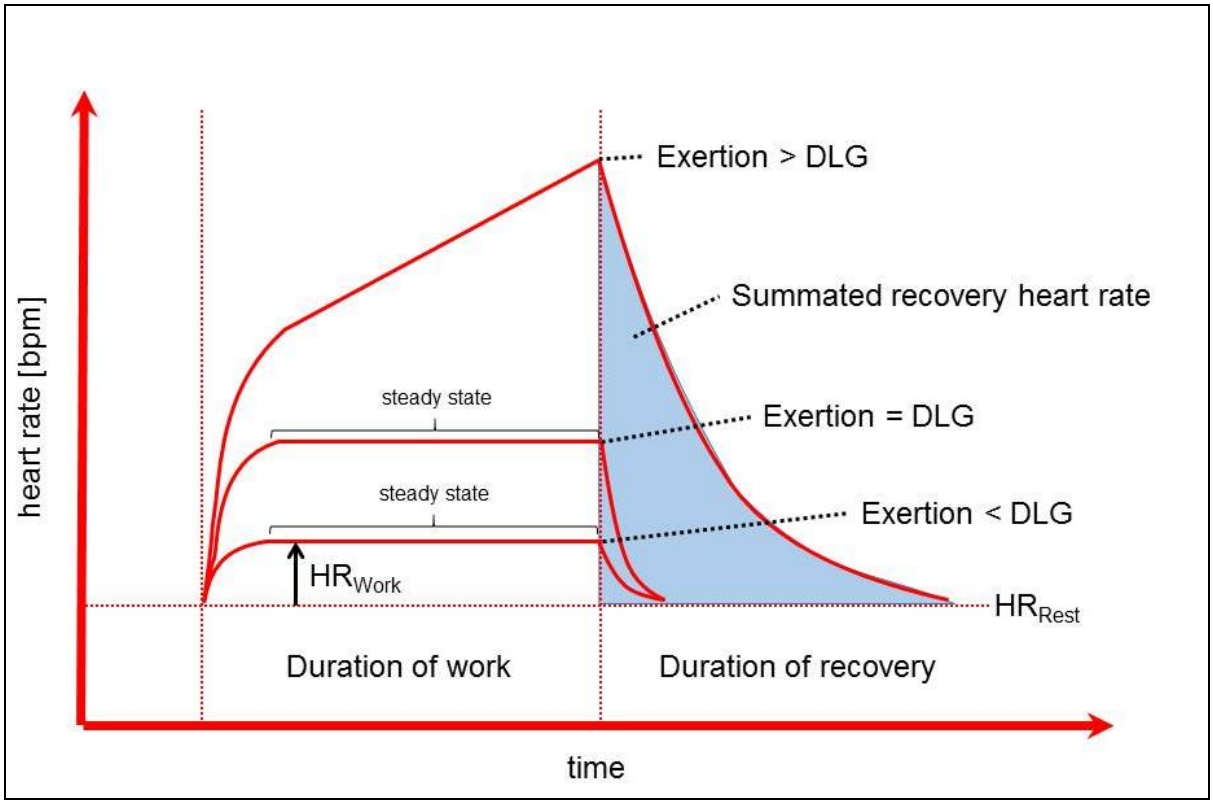

Fig. 4: HR curves in for different workload intensities (below, at or above the DLG) with the respective recovery period, schematic representation, modified according to Mueller [0], DLG = endurance limit

Table 1: Advantages and disadvantages of the different measurement systems

	Advantages	Disadvantages
Stationary (24-hour) ECG	• ECG recording • non-invasive • visual monitoring of R-wave detection	• not portable, suitable only for laboratory examinations and intensive care units • bothersome cable
Portable (24-hour) ECG	• portable, small machine • suitable for laboratory and field studies • ECG recording • non-invasive • visual monitoring of R-wave detection	• bothersome cable
Chest belt with saving of data on heart rate monitor	• portable, small machine • high degree of freedom from interactions • non-invasive	• no ECG recording • disturbances in data transmission (power supply lines, vehicles etc.) • not a medical product as per the Medizinproduktegesetz (MPG)* (German medical devices act)
Chest belt with direct saving of data in the belt itself	• portable, small machine • high degree of freedom from interactions • non-invasive	• at least no ECG recording • not a medical product as per the MPG

*as per the MPG, instruments are specified by the manufacturer for use in humans and are meant especially for diagnostic or therapeutic purposes

Table 2: Parameters of HRV

Method	Measure of variability	Other names	Unit of measurement	Definition and explanation	Indicator of …	Activity as part of the autonomic nervous system	Recommendation for evaluation time
Time domain methods							
Statistical	SDNN	RRSD, SD, SDRR	ms	Standard deviation of NN intervals within the measurement area	Total variability	No clear assignment	
	SDANN		ms	Standard deviation of the average of all consecutive 5-minute NN intervals for estimation of HRV for long-term measurements	Short-term and Long-term variability	No clear assignment	Long-term recording, ideally 24 hours
	RMSSD	R-MSSD, rMSSD	ms	Root Mean Square of successive differences of NN intervals	Short-term variability	Parasympathetic	
	SDNN index		ms	Standard deviation of the average of all normal NN intervals of 5-min segments from the 24-hour ECG	Long-term variability	No clear assignment	Long-term recording, ideally 24 hours
	NN 50		n.o.	The number of pairs of neighbouring NN intervals that deviate from one another by more than 50 ms	Spontaneous variability	Parasympathetic	
	pNN 50		%	Percentage of consecutive NN intervals that deviate from one another by more than 50 ms	Spontaneous variability	Parasympathetic	
Geometric	HRV triangular index		n.o	The integral of the density distribution (number of all NN intervals divided by the maximum (height) of the density distribution) or ratio of the absolute number of all NN intervals to the number of all modal NN intervals	Total variability	No clear assignment	At least 20 minutes
	TINN		ms	Triangular interpolation of NN interval histogram: is the baseline width of the minimum square difference of the triangular interpolation for the highest value of the histogram of all the NN intervals	No clear assignment	No clear assignment	At least 20 minutes
Frequency domain methods							
FFT (Fast Fourier Transformation) and Autoregressive Model (AR)	TP		ms^2	Total power: total performance or total spectrum; corresponds to energy density between 0.00001 to 0.4 Hz	Total variability	No clear assignment	
	ULF		ms^2	Ultra very low frequency: power density spectrum below 0.003 Hz	No clear assignment	No clear assignment	
	ULF%		%	Percentage of ULF in the total spectrum	No clear assignment	No clear assignment	
	VLF		ms^2	Very low frequency power: power density spectrum in the frequency range of 0.003 to 0.04 Hz	No clear assignment	Sympathetic	
	VLF%		%	Percentage of VLF in the total spectrum	No clear assignment	Sympathetic	
	LF	B Band	ms^2	Low frequency power: power density spectrum in the frequency range of 0.04 to 0.15 Hz	No clear assignment	Sympathetic and parasympathetic, but predominantly sympathetic	At least 5 minutes
	LF%	B Band	%	Percentage of LF in the total spectrum	No clear assignment	Sympathetic and parasympathetic, but predominantly sympathetic	
	HF	C Band, respiratory sinus arrhythmia, Respiratory	ms^2	High frequency power: power density spectrum in the frequency range of 0.15 to 0.40 Hz	No clear assignment	Parasympathetic	At least 5 minutes

	HF%	C Band, respiratory sinus arrhythmia, Respiratory band	%	Percentage of HF in the total spectrum	No clear assignment	Parasympathetic	
	LF nu	LF n.U.	Nu	Low frequency normalised unit: corresponds with LF/(TP-VLF) x 100	No clear assignment	Sympathetic and parasympathetic, but predominantly sympathetic	
	HF nu	HF n.U.	Nu	High frequency normalised unit: corresponds with HF/(Total Power – VLF) x 100	No clear assignment	Parasympathetic	
	LF/HF	LF/HF Ratio	n.o.	Ratio of the sympathovagal balance; as a value of the interplay between the parasympathetic (HF) and sympathetic (LF)	No clear assignment	Sympathetic and parasympathetic	At least 5 minutes
	VLF Peak		Hz	Very low frequency peak: frequency peak in the VLF band; thermoregulation peak	No clear assignment	No clear assignment	
	LF Peak		Hz	Low frequency peak: frequency peak in the LF band; baroreflex peak	No clear assignment	No clear assignment	
	HF Peak		Hz	High frequency peak: frequency peak HF band; respiratory peak	No clear assignment	No clear assignment	At least 5 minutes
Non-linear methods							
Poincaré Plot	DL	DL, Lorenz length	ms	Length of the major axis of the ellipse (95% confidence region)	Long-term variability	No clear assignment	
	DQ	Dq, DW, Lorenz width	ms	Length of the minor axis of the ellipse (95% confidence region)	Short-term variability	No clear assignment	
	SD1	SDQ, SDw, stdb, SOQ, SD-horizontal, SOW	ms	Standard deviation of the distances of the points from the minor axis	Short-term variability	Parasympathetic	
	SD2	SDL, SD-vertical, stda, SOL	ms	Standard deviation of the distances of the points from the major axis	Long-term variability	Sympathetic and parasympathetic	
Detrended fluctuation analysis (DFA)	DFA1	alpha 1	n.o.	The degree of coincidence /correlation; ranges from 0.5 (coincidental) to 1.5 (correlated) with normal value of 1.0; is often used as a non-linear parameter for short NN interval data	No clear assignment	No clear assignment	
	DFA2	alpha 2	n.o.	Is often used as a non-linear parameter for RR intervals of longer durations of recording, reduced values are associated with a bad prognosis	No clear assignment	No clear assignment	

Note: n.o. = no unit assigned

Table 3: Factors influencing HR and HRV

Influencing factor	Effect on HR_{Rest}	Effect on HRV
Alcohol		Moderate consumption of alcohol generally does not lead to long-term changes in HRV [32, 33, 47, 95, 210], however, short-term changes have been observed [147, 269]. Chronic alcohol abuse can lead to a reduction in the HRV [104, 183].
Breathing	A temporary increase in HR occurs during inspiration and a temporary decrease during expiration [0, 0].	The effects of respiration on HRV is reflected in the form of respiratory sinus arrhythmia (RSA) and is seen in the HF band. On the whole, the HRV parameter, RMSSD, does not seem to be affected by respiration [109]. For the rest of the parameters, the present state of knowledge is not conclusive [124, 135, 219].
Fitness activities , performance capacity, sports	Endurance training often leads to a training-induced bradycardia [167, 180, 226, 233]. Initially, there is a rise in the resting HR due to the increased physical activity; however, regular execrcise without symptoms of overtraining leads to a decrease in the HR due to an increase in the parasympathetic activity and an optimisation of the cardiac output [110].	Endurance training normally increases the HRV [9, 63, 86, 105, 189, 203, 207, 211, 228, 233, 234], highly intensive training sessions and competitions can bring about a reduction in the HRV [9, 112]. Initially, there is a fall in the HRV due to increased activity of the sympathetic system as a result of the physical activity [15], but regular physical activity leads to an increase in the parasympathetic activity which in turn causes a rise in HRV [15, 30, 75, 112, 207]. These effects can be also seen in patients with myocardial infarction and patients with cardiac insufficiency [211].
Sex	The HR is normally higher in women than in men [172].	Most of the studies showed a higher parasympathetic activity in women as compared to men [2, 3, 12, 125, 232, 236, 254], which however showed a narrower difference after the age of 50 [70, 72, 153]. Some of the studies showed a higher baseline sympathetic activity in women [75, 117, 204, 256].
Cardiovascular diseases	**Cardiac insufficiency** leads to a raised HR [29] and unrestricted maximum HR.	**Cardiac insufficiency** generally leads to a reduction in the HRV [23, 53, 97, 156, 218]. A large number of studies have shown an association of prehypertensive and raised blood pressure values (**hypertension**) with reduced HRV [4, 61, 71, 84, 121, 139, 181, 194, 223, 230, 261].
	In patients with previous **myocardial infarction**, the activation of the sympathetic nervous system often leads to an increase in the HR, which is important for the prognosis [18, 78, 99, 145, 149, 169].	Patients with previous **myocardial infarction** often show reduced HRV with increased sympathetic activity [17, 40, 118, 151, 164, 174, 237, 254], this is also true for patients with **angina pectoris** and **coronary heart disease** [116, 173, 270, 271].
Heat, high temperatures	High environmental temperatures lead to an increase in the HR [253].	High environmental temperatures lead to an increase in the sympathetic activity and a reduced HRV [206, 274].
Cold, low temperatures	Low environmental temperatures lead to an increase in the HR [253].	Only few studies about the effects of low temperatures on HRV are currently available: a reduction in the sympathetic activity and thus a raised HRV has been observed [115], however, no influence has been observed in long-term occupational exposure to cold [25] or in the winter months [206]. Some other studies have again shown an increased sympathetic activity with reduced HRV and an adaptation only after 60 days of working in cold environments [102].
Body fat/body weight	Increased body weight (BMI) generally leads to a raised HR [54].	Increased body weight (BMI) and increased mass of body fat often cause a fall in the HRV [21, 70, 74, 75, 208, 275].
Noise	Noise often causes a rise in the HR [107].	Only few studies that give information about the effects of noise on HRV are available; HRV appears to fall in the presence of noise [150, 158, 222].
Age	HR_{Rest} and HR_{Max} normally decrease with increase in age [244].	The HRV rises at first; it is at its highest at younger ages and then shows a non-linear fall with increase in age [2, 6, 12, 33, 60, 70, 72, 75, 77, 85, 95, 100, 153, 227, 239, 263, 276].
Psychiatric disorders	Patients with **anxiety disorders** and **panic attacks** usually have an increased HR [199].	Patients with **anxiety disorders** [83, 140, 143, 199] and **panic attacks** [43, 82, 199] usually show a reduction in the HRV. **Posttraumatic stress disorder** often leads to a reduced HRV [49, 91, 103, 134, 141, 154, 157, 224, 225, 231, 235, 248, 255, 277].
	A **major depression** often leads to an increase in HR [14, 22, 144].	A **major depression** often leads to a decrease in HRV [14, 22, 39, 44, 52, 136, 142, 144, 238, 242, 243, 251].
Smoking	Active [257] and passive smoking [76] can lead to an increase in HR.	Smoking can lead to a decrease in HRV [5, 36, 58], this effect ist dose dependent [75]. Even in non-smokers, passive smoking e.g. at home or at work leads to a reduction in the HRV [58, 76, 273].
Hazardous		Neurotoxic substances can lead to a reduction in the HRV:

substances		e.g. carbon disulphide [26, 126], however, not in the case of long-term low-dose exposure [205]; for acute diesel and biodiesel inhalation [31]; for chronic lead [24, 187] or mercury exposures [94] and for neurotoxic styrene exposure [186, 188]. The data regarding the effects of chronic solvent exposure is not conclusive, both - a fall in the HRV and no differences - have been described [7, 131, 179].
Shift work including night shift		During shift work with night shifts, the sympathetic nervous system is activated and the parasympathetic activity is reduced, which leads to a reduction of the HRV, however, a correlation between the duration of the working shift in years and the reduction of the HRV does exist [98, 166, 265].
Metabolic disorders	**Diabetes mellitus** is often associated with increased sympathetic acivity and hence a raised HR [73].	The HRV is often reduced in patients with **diabetes mellitus** [137, 138, 152, 191, 229, 254], however, a correlation between the value of the HRV and the duration of the diabetes exists especially in cases of badly controlled diabetes [240]. A **metabolic syndrome** often leads to a reduction of the HRV [8, 45, 89, 104, 148, 159, 165, 182, 201, 233, 240].
Stress/mental tension	Stress (e.g. mental, workplace related) generally leads to an increase in the HR [13, 59, 114, 170].	Stress (e.g. mental, workplace related) generally leads to decreased parasympathetic activity and thus to a reduction in the HRV [41, 42, 48, 59, 163, 170].
Circadian rhythm/time of the day	The HR follows a circadian rhythm, with a fall of HR at night [27].	The HR follows a circadian rhythm, but the HRV is decreased at night due to the predominance of the parasympathetic activity and reduced during the day because of the predominance of the sympathetic activity [19, 87, 119, 176, 178, 260].

Table 4: Mean and Standard deviation (M ± SD) for the known HRV parameters in short-term recordings (5 minutes) according to Nunan et al. 2010 [190], Note: The average values given are based on a varying number of original studies (1- 36 different sources).

HRV Parameters	M ± SD	Mean (Men)	Mean (Women)
RR [ms]	926 ± 90	922	885
SDNN [ms]	50 ± 16	40	36
RMSSD [ms]	42 ± 15	21	19
LF [ms²]	519 ± 291	356	414
LFnu	52 ± 10	53	46
HF [ms²]	657 ± 777	475	516
HFnu	40 ± 10	39	38
LF/HF	2.8 ± 2.6	2.1	1.2