



Heart rate variability metrics for fine-grained stress level assessment



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ABSTRACT

Background and Objectives: In spite of the existence of a multitude of techniques that allow the estimation of stress from physiological indexes, its fine-grained assessment is still a challenge for biomedical engineering. The short-term assessment of stress condition overcomes the limits to stress characterization with long blocks of time and allows to evaluate the behaviour change in real-world settings and also the stress level dynamics. The aim of the present study was to evaluate time and frequency domain and nonlinear heart rate variability (HRV) metrics for stress level assessment using a short-time window. **Methods:** The electrocardiogram (ECG) signal from 14 volunteers was monitored using the Vital Jacket™ while they performed the Trier Social Stress Test (TSST) which is a standardized stress-inducing protocol. Window lengths from 220 s to 50 s for HRV analysis were tested in order to evaluate which metrics could be used to monitor stress levels in an almost continuous way. **Results:** A sub-set of HRV metrics (AVNN, rMSSD, SDNN and pNN20) showed consistent differences between stress and non-stress phases, and showed to be reliable parameters for the assessment of stress levels in short-term analysis. **Conclusions:** The AVNN metric, using 50 s of window length analysis, showed that it is the most reliable metric to recognize stress level across the four phases of TSST and allows a fine-grained analysis of stress effect as an index of psychological stress and provides an insight into the reaction of the autonomic nervous system to stress.

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1. Introduction

The impact of the mental stress in the health condition is currently well recognized [1–3]. The effect of the stress on the human body capability to regulate inflammation can promote the development and progression of diseases. Stress was identified as a risk factor in the heart diseases, diabetes, asthma, upper respiratory infections and depression [1,2,4,5]. For these reasons, it is extremely important to have instrumental solutions that allow the stressful events assessment and monitoring in order to measure, quantify and correlate with health impact [4,6–8].

In the last two decades several efforts have been made to apply sensors and novel technologies for stress detection and assessment [9–11]. Conventionally, stress levels were estimated by assessing hormonal responses and using questionnaires [12]. However, these methods are not useful in a real-world context, also referred to as ecological settings [13]. A method for stress assessment in real context should be minimally obtrusive in order to allow the sub-

jects to perform their tasks with complete freedom, and it should allow to monitor stress levels in an almost continuous way [4].

Several non-invasive measurements have been considered in the literature for ecological studies. These include the electrocardiogram (ECG), electroencephalogram (EEG), body temperature, electromyogram, galvanic skin response and blood volume pulse [10]. The metrics from ECG have been used as a marker of the autonomic modulation of the heart, and recent developments in wearable technology made it possible to monitor this physiological signal in non-invasive and non-obtrusive ways. Heart rate variability is an established, non-invasive and quantitative method of assessing cardiac autonomic activity [7,8,14].

Although HRV was firstly used in recordings from 5 min to several hours in length (long-term recordings), currently it is recognized that HRV from records of less than 2 min duration (short-term recordings) can be used to accurately assess cardiac autonomic activity [14]. The use of long or short-term recordings depends on the study goal [15,16]. The short-term (≤ 5 min) analysis represents an advantage for stress studies due to the rapid physiological response time. Table 1 summarizes recent works that evaluated the differences in HRV under stress vs baseline using short time windows. The first studies that used short window length

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Table 1
Summary of HRV studies using short-time windows for stress assessment.

Subjects (n) [Reference]	Age (years)	Procedure	HRV	Windows length
738 [17]	–	3 stressors (virtual reality car driving - video game challenge - social competence interview)	rMSSD and HF	30 s
19 [18]	17–27	Stressor (flight simulator)	mid- and high- frequency bands	30 s
24 [19]	26 ± 4.6	Rest and Stressor (stroop test)	AVNN, rMSSD, pNN50, HF, LF/HF, LFnu and HFnu	50 s
48 health 48 major depression (MD) [8]	Health: 21 ± 2; MD: 23 ± 2	Neutral and emotionally audiovisual stimuli	LF, HF, LF/HF, ApEn, SampEn	90 s
25 [21]	21.36 ± 2.97	Baseline and Stressor (TSST)	HR, SDNN, rMSSD, pNN50, LF, LFnu, HF, LF/HF	3–5 min
92 [22]	20–25	Baseline and Stressor (university examination)	AVNN, SDNN, rMSSD, pNN50, Mo, AMo, LF, HF, LF/HF	5 min
42 [23]	–	Baseline and Stressor (university examination)	SD1, SD2, En, D_2 , α_1 , α_2 , REC, DET, ShEn	5 min
18 [24]	18.7 ± 0.69	Baseline and Stressor (university examination)	HR, SDNN, pNN50, RMSSD, VLF; LF, HF, LFnu, HFnu and LF/HF	5 min

ApEn, approximate entropy; Mo, mode (geometrical metric); AMo, mode amplitude (geometrical metric); REC, recurrence rate (nonlinear metric); DET, determinism (nonlinear metric); ShEn, Shannon entropy (nonlinear metric).

spurred the exploitation of the idea that HRV provides insight on mental effort intermediate variations, however, only a low number of metrics were tested (rMSSD and HF) [17,18]. The work that tried to evaluate how short ECG recordings could be reliably used for mental stress monitoring concluded that it is possible within 50 s of window length [19]. Nevertheless, the referred work studied a small group of metrics and tested only two situations, the baseline stage and stroop color word test [19]. Time domain metrics showed low repeatability for ten-seconds segment analysis [14], therefore, larger windows should be used. The frequency domain metrics limit the segment length for analysis, for that reason small segments do not allow the determination of lower frequency bands [17,18,20]. The heart rate (HR) series length should be defined by the balance between the time window length that allows a fine-grained analysis of stress level and the resolution of the spectral estimation. The longer the recording time, the better spectral resolution because it would be based on more data points, however, long analysis windows preclude fine-grained stress monitoring.

Several studies have shown an association between HRV and stress, and use HRV as a psychophysiological index of mental stress. A significantly lower mean RR interval (time between R waves in QRS) i.e., higher HR, was measured during a mental task than in a control condition, while pNN50 was significantly higher in the control condition than within a mental task [22,25]. For the SDNN and rMSSD metrics a significant decrease with stress condition was verified [22]. The mean LF during cognitive stress sessions was significantly lower than during the rest sessions [22,26]. The nonlinear metrics were used for stress assessment and showed that they could be effective in stress detection [23].

The Trier Social Stress Test (TSST) is an effective laboratory protocol for inducing mental stress by exposing individuals to situations that constitute social evaluative threat [27]. Heart rate monitoring with a wearable device was used for stress assessment and the obtained HR was compared with cortisol levels during TSST [27]. The study concluded that assessment of the psychobiological stress response during TSST is a better measure as compared to post-TSST values [27]. This important conclusion is a motivation to assess the stress levels with fine-grained analysis that allows stress condition monitoring on an almost continuous way.

Guided by the previous studies and using novel wearable technology, the current work uses the TSST method to examine how four contextual conditions (silent, reading, public presentation and counting arithmetic task) influence the heart rate variability [12]. Since standard laboratory stressors do not always engage subject's affective response, social interaction stressors such as public speak-

ing tasks are applied to provide a more appropriate social context [28]. The TSST tasks involve active cognitive processing and responses, and are generally associated with varied degrees of parasympathetic withdrawal and sympathetic activation [29]. The TSST was applied to 14 volunteer participants who were equipped with the Vital Jacket™, which is a comfortable wearable biomedical equipment that records high quality ECG.

This work represents a global evaluation of HRV metrics on an healthy and young sample in a lab context that emulates the real-world. Time and frequency domain and nonlinear HRV metrics were used to assess the effect of mental stress, analysing which are reliable as stress indicators in a short-term analysis. The main objective of this work was to determine which metrics could be used for a fine-grained stress levels assessment. The changes in HR occur very rapidly and are caused by shifts in autonomic nervous system [30]. The sympathetic nervous system regulation has an initial response delay of up to 5 s, followed by a progressive change and a maximum response after 20 to 30 s [31]. In this work an attempt was made to assess these changes during the TSST proceeding. The window size chosen for the HRV analysis try to approximate time length with the physiological response of mental stress and monitor the changes along the TSST activities. The 50 s window size provides the best approximation of the physiological response, and short-term analysis reflect the dynamic response of the cardiovascular control system to a physiological perturbation induced by the stress and for this reason the HRV metrics were studied for different windows sizes in order to determine which metrics could discriminate between stress levels with small windows of analysis.

2. Materials and methods

The TSST was used to induce stress in a lab context that emulates the real-life condition. The State-Trait Anxiety Inventory (STAI) is a self-reported assessment of stress that was performed at non-stress phase and after the stress period [32]. The ECG signal was recorded with the Vital Jacket™ system in order to extract HRV and to obtain a fine-grained stress assessment.

2.1. Study population

Fourteen participants (five female) aged between 20 to 26 years participated in the study. No participant had an history of cardiac or mental disease. Only one subject was smoker, none of the subjects were regular consumer of alcohol and 4 practiced sport. Participants were volunteers and their physiological signals were

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