Screening and monitoring of stress using biofeedback equipment

by

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Submitted in fulfilment of the requirements for the degree MSc (Community Health)

in the Health Sciences Faculty

University of Pretoria

Pretoria

(June 2012)

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Acknowledgements

- Professor Margaretha Viljoen for insight, mentorship and guidance
- Doctor Nicolaas Claassen for mentorship and technical support in the analysis of HRV
- Mitzi Claassen, Donna Moser and Frank DeGregorio, for providing information, training and technical support with regards to biofeedback and biofeedback equipment
- Mike Purday from CamNtech for the loan of the Actiheart device
- All the participants who volunteered their time
- My parents, Riaan and Willemien Coetzee
- My husband, Trevor Maré

Summary

Title: Screening and monitoring of stress using biofeedback equipment
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Department: School of Health Systems and Public Health
Degree: MSc (Community Health)

Biofeedback equipment is intended to train conscious regulation of normally sub-conscious processes like autonomic nervous system activities. The manufacturers claim that measurements made with the equipment are accurate enough for research purposes, but these claims have not been vigorously tested. The subconscious processes recorded with biofeedback equipment are often disturbed by stress, and the aim of this study was to determine if the markers of stress could be accurately determined with biofeedback equipment. The physiological processes that were screened were:

- Time and frequency domain heart rate variability (HRV) determined from blood-volume-pulse (BVP)
- Time and frequency domain HRV determined from electrocardiogram (ECG)
- The amplitude of the BVP
- Electromyographic (EMG) activity
- The pulse transit time
- Respiration rate and depth
- Skin conductivity
- Fingertip temperature
- Quantitative electroencephalographic (QEEG) activity

The accuracy of the HRV measurements were tested by comparing them to readings made simultaneously with a gold-standard device (Actiheart), and the main findings were:

- The hardware capabilities of the two systems are comparable when it comes to registering heartbeats and calculating heart rate

- The frequency domain biofeedback HRV variables had relatively good correlations to the Actiheart results, but improvements are necessary
- Frequency domain HRV variables differ when calculated with fast Fourier transform or with autoregression
- The BVP signal is prone to movement artifact and other forms of interference

The HRV measurements of both the biofeedback and Actiheart device were correlated to psychometric evaluations of anxiety and burnout, two conditions closely related to the concept of stress. The main findings were:

- Worry and anxiety can have a cardiac accelerating effect, largely mediated by vagal withdrawal
- A decrease in resting autonomic variability associated with anxiety
- Significant autonomic nervous system inflexibility occurs in the face of a cognitive stressor with increased anxiety
- An increase in vagal and a decrease in sympathetic cardiac control correlated with increased levels of vital exhaustion
- HRV assessment with specialized software such as Polar Precision Performance Software and the advanced HRV Analysis 1.1 software for windows (Biomedical Signal Analysis Group) were superior to assessments by means of the Biograph Infinity program

Next it was investigated whether any association existed between levels of anxiety, burnout and that of Biograph-derived physiological indicators such as BVP amplitude, BVP HRV, ECG HRV, pulse transit time, EMG, fingertip temperature, respiration rate and amplitude, skin conductivity and QEEG levels. The overriding observations with increases in the levels of stress-related emotional conditions such as anxiety were that of a decrease in variability in almost all physiological functions assessed by Biograph.

In conclusion, relatively good associations were found between certain, but not all, Biofeedback monitor results and that of other assessments of stress. The potential exists to develop a program which would accurately reflect stress levels.

Keywords: Biofeedback, stress, Actiheart, autonomic nervous system, HRV, QEEG, burnout, anxiety

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Faculty of Health Sciences Research Ethics Committee

27/05/2010

Number :	**S56/2010**
Title :	The use and biofeedback equipment in the screening and monitoring of stress
Investigator :	Irma Mare', School of Health Systems and Public Health, University of Pretoria (SUPERVISORS: PROF M VILJOEN / DR N CLAASSEN)
Sponsor :	**None**
Study Degree:	**MSc (Department of Public Health)**

This Student Protocol was approved by the Faculty of Health Sciences Research Ethics Committee, University of Pretoria on 25/05/2010. The approval is valid for a period of 3 years.

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1 Introduction and Background

1.1. Introduction and Rationale

The term ‘stress’ is commonly used to describe the package of mental, emotional and physical conditions that modern day living exacts, as well as the act of agonizing about the perceived ability to meet these demands.

The act of ‘stressing’ can be interpreted as a form of anxiety in the mental dimension, whereas the physiological adaptation of the human body to stressors involves, among others, activation of the hypothalamo-pituitary-adrenocortical (HPA) and sympatho-adrenomedullary (SAM) axes in an attempt to attain homeostasis (1-3). Most persons experience anxiety to some extent, and a certain level of anxiety is not unhelpful in motivating and focusing the mind (eustress) (4), but when the adaptations fail to restore homeostasis, or in conditions of chronic stress, the adaptations can become pathological in themselves (1-3). As a consequence, there emerges various stress-related conditions like stress hormone imbalances and hypertrophy of the adrenal gland, disturbed circadian rhythms, atrophy and/or plasticity in certain brain structures, hypertension and cardiovascular disease (1,3,5-7). A typical emotional picture of prolonged stress is seen in the so-called burnout syndrome where the individual becomes vitally exhausted, cynical in an attempt to distance him- or herself from circumstances, and where the individual loses confidence in his or her professional efficacy.

In order to screen for and monitor stress, autonomic nervous system (ANS) imbalance is sometimes used as a marker (1,5). Measures of autonomic imbalance include physical arousal, as measured by heart rate variability (HRV) (3,5,8,9), skin conductivity, respiration rate, as well as changes in blood pressure and regional blood flow. Immune and endocrine markers of stress include cytokine profiles and levels of stress hormones like adrenalin and cortisol, which can be determined by blood tests. Cognitive arousal include disturbances in the pattern of cortical activity, hypervigilance and an inability to regulate levels of arousal, and can be measured using qualitative electroencephalography (QEEG), event-related potentials (ERP) and psychometrics (7,10-18).

Blood tests and measurement of HRV and QEEG is often time consuming, require expensive equipment, specialized laboratories and highly trained operators. Yet portable biofeedback equipment, which is much more affordable, offers the opportunity to measure these variables, as well as training individuals to restore homeostatic balance. It is, however, imperative to determine the efficacy of the portable devices in identifying the markers of stress. The difficulty facing researchers using biofeedback equipment was well illustrated in the 1978 article by Kinsman and Staudenmayer (19), where two almost identical muscle relaxation biofeedback studies had conflicting results because one of the studies did not make sufficient provision for the variation in baseline values, which obscured the response to the treatment. Kinsman *et al* suggested analysis of covariance as a way of correcting data with highly variable baseline measurements (19). Still, the validity of biofeedback equipment as measuring instruments, in addition to their use as training instruments, has not been established.

1.2. Biofeedback

On May 18, 2008, the Association for Applied Psychophysiology and Biofeedback (AAPB), the Biofeedback Certification Institution of America (BCIA) and the International Society for Neurofeedback and Research (ISNR), which represent three of the world's most distinguished organizations in the field of biofeedback, agreed upon a standard definition of the term:
"Biofeedback is a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance. Precise instruments measure physiological activity such as brainwaves, heart function, breathing, muscle activity, and skin temperature. These instruments rapidly and accurately "feed back" information to the user (See Figure 1.1)*. The presentation of this information — often in conjunction with changes in thinking, emotions, and behaviour — supports desired physiological changes. Over time, these changes can endure without continued use of an instrument"* (20).

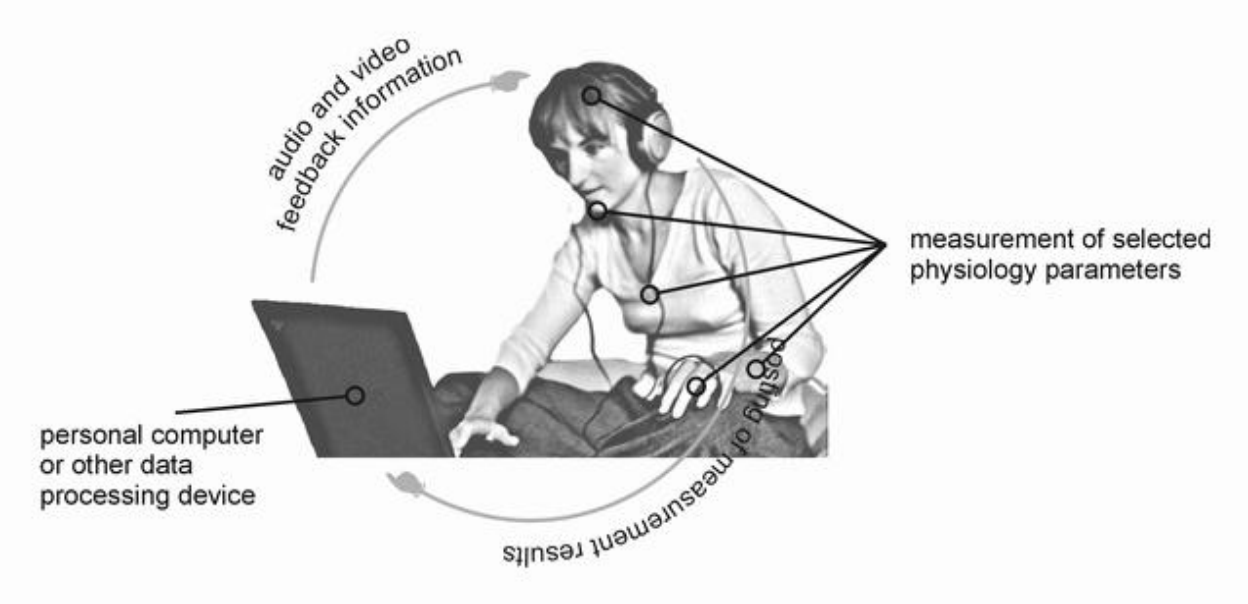

Figure 1.1 Biofeedback system diagram. Author: Marek Jacenko. Source: TheFreeDictionary.com (21). Originally published at www.relaksacja.pl, 14-05-2006. Permission to reprint under the GNU Free Documentation License

Biofeedback has its roots in the 1960's and 1970's, when researchers started toying with the idea that autonomic processes could be consciously regulated by employing operant conditioning. In the last half decade an explosion of rigorous scientific research into the efficacy of different biofeedback applications has illustrated the power of mind-body interactions, and biofeedback has gained a respected and prominent place as a clinical tool in the promotion of well-being and the enhancement of performance (22-24).

Some of the best-studied remedial applications of biofeedback include (22,23):

- urinary and faecal incontinence
- high blood pressure
- migraine and other tension type headaches
- chronic pain disorders and the management of chronic pain
- irritable bowel disorders

Neurofeedback, which is the learned self-regulation of brainwave activity, has shown immense promise in the treatment of, amongst others (11,22,23):

- attention deficit hyperactivity disorder (ADHD)
- post-traumatic stress disorder (PTSD)

- anxiety disorders
- schizophrenia
- autistic spectrum disorders
- traumatic brain injuries
- depression
- seizures

In mental and neurological settings, one of the most attractive features of neurofeedback is that it is often comparable with pharmacological interventions, but with almost no side effects (23).

Besides remedial uses, biofeedback is now often applied to help athletes, dancers, musicians and artists achieve peak performance. In the 2008 Beijing Olympics some of the medal-winning athletes used biofeedback to enhance their performance, and it is becoming more and more popular under company executives and human resource officers to promote productivity in the workplace (22).

Even though manufacturers claim that biofeedback equipment measures physiological functions accurately and sensitively, this has not been thoroughly proven. In this study, variables associated with stress were measured by biofeedback equipment, a benchmark ECG-based heart rate variability assessment device and psychometric questionnaires. The results were compared and correlated to determine the validity of values obtained by the biofeedback equipment. The physiological variables examined include heart rate and heart rate variability (HRV), pulse volume variations, skin conductivity, muscle tension, electro-encephalography (EEG), fingertip temperature and respiration.

1.3. Heart Rate Variability

Heart rate variability (HRV) is a non-invasive technique for the assessment of autonomic balance. HRV refers to the change in the R-R interval of the electrocardiogram (ECG) (5,9). Research suggests that the balance of autonomic control of the heart rate is located in the anterior cingulate cortex, as damage to this area impairs the autonomic arousal reaction to challenging mental and motor tasks (25,26). The effect of stress on the autonomic control of HRV seems to be

specifically associated with the insular cortex, as stimulation of parts of this area can induce severe arrhythmia (26,27). Some research points to a stress induced lateralization of midbrain autonomic control of the heart, linking stressed mental states to high blood pressure (5), cardiac arrhythmia and sudden death (28).

The normal response to stress that one would expect from HRV is illustrated in a study on chess players by Troubat *et al* (29), who found that mental stress was associated with increased heart rate, increased LF/HF ratio and decreased mean HRV, with the changes attributed to increased LF but unchanged HF, pointing to increased sympathetic stimulation and unchanged parasympathetic tone.

High heart rate variability is usually associated with good cardiac health and a well-balanced ANS, whereas a decreased HRV is associated with stress and increased sympathetic stimulation (8,9). Hughes and Stoney (30) found a significant relationship between depressive symptoms and a decreased magnitude of parasympathetic modulation in healthy college students, showing that mood disturbances has an influence on HRV parameters independent of cardiac disease. In chronic stress, the balance between sympathetic and parasympathetic stimulation, as well as the way in which the ANS reacts to acute stressors, can be seriously disturbed (5,9). Some research findings suggest that when chronic stress becomes pathological, the ANS balance becomes less flexible, and autonomic stress responses are repressed (18,31,32).

In 1996, the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology (9) published a set of definitions, standards and guidelines on the measurement and applications of HRV. Many different modalities can be used to analyze HRV (8,9,33), of which three are relevant to this study:

- Time domain analysis – calculated from the R-R interval in a certain period of time. Short term variability (STV) represent fast changes in heart rate and long term variability (LTV) represent slower variations in heart rate. The following indicators related to ANS function are derived with time domain analysis:

- Mean RR (ms) - The mean of the intervals between successive QRS complexes. It is influenced by both vagal (short term) and sympathetic (long term) stimulation.
- SDNN (ms) - Standard deviation of intervals between successive QRS complexes, it is an indicator of vagal (short term), and sympathetic (long term) influence on HRV.
- RMSSD (ms) - Root mean square of the standard deviation between RR intervals, indicator of vagal influence (short term)
- pNN50 (%) - The percentage of successive RR-interval differences larger than 50 ms computed over the entire recording, it is an indicator of only vagal (short term) influence on HRV.

- Frequency domain analysis – by applying the Fast Fourier Transform (FFT) or autoregression to the R-R interval tachogram, a power-spectral plot can be obtained, which is able to discriminate between sympathetic or parasympathetic stimulation. For short term recordings (5 minutes), the following indicators are useful in relation to ANS modulations:
  - VLF (ms^2) – Power in the very low frequency range (≤ 0.04Hz), the physiological process involved in this component are not well defined, and some doubt whether it truly exists.
  - LF (ms^2) – Power in the low frequency range (0.04 to 0.15 Hz). It is an indicator of sympathetic influence, but also includes a parasympathetic component.
  - LF (n.u.) – The LF power in normalized units are calculated as follows: (LF power)/(Total power – VLF) x 100. LF n.u. is considered a better indicator of the sympathetic control than absolute LF power.
  - HF power (ms^2) – Power in the high frequency range (0.15 to 0.4 Hz). It is an indicator of only parasympathetic influence.
  - HF (n.u.) – The HF power in normalized units are calculated as follows: (HF power)/(Total power – VLF) x 100.
  - HF/HF ratio – Calculated by dividing LF power with HF power, this indicator represents autonomic balance between sympathetic and parasympathetic modulation.

- Poincaré plot – A method for determining non-linear properties of HRV, it represents the nature of the R-R interval as compared to the previous R-R interval. Two parameters derived from this method are:
    - SD1 (ms) – An indicator of the standard deviation of the immediate, or short-term R-R variability due to parasympathetic (vagal) influence on the sino-atrial node.
    - SD2 (ms) – An indicator of the standard deviation of the long-term or slow variability of the heart rate. This value is accepted to represent the global variation in HRV, which is modulated by vagal and sympathetic input. It is, however, by some considered as an indication of sympathetic activity – especially in conditions of controlled breathing.

Besides ECG, a photopletysmograph or blood volume pulse (BVP) sensor can also be used to determine the R-R interval (34,35). The BVP sensor uses infrared light reflection to calculate the changes in tissue saturation level associated with each cardiac cycle. Both ECG and BVP were used in this study to calculate inter-beat-interval, heart rate, SDNN and pNN50 in the time domain, and an FFT in the frequency domain. The VLF, LF and HF components are reported as percentage of total power, i.e. (HF power) / (Total power) x 100. This differs from HF n.u., in the sense that the power of the VLF component is not subtracted from the total power before the division.

1.4. Skin Conductivity

Merocrine (eccrine) sweat glands are innervated by the sympathetic nervous system and respond to stimulation by secreting watery sweat over most of the body surface (36), which in turn affects the resistance of the skin to carrying an electrical current. Skin conductivity (SC), or galvanic skin responses (GSR) accurately reflect the emotional autonomic reaction to nociception or pain, and are often used in anesthetised and post-operative patients (37) as the reaction is immediate and independent of hemodynamics (37,38). As demonstrated by Jacobs *et al* (38) skin conductivity levels rise in response to mental stress, and the effect is not influenced by β-blocking medication, making it clinically very useful to study autonomic arousal in cardiovascular patients (38). Similar to HRV, the anterior cingulated cortex seems to be involved in autonomic regulation of skin conductivity, as well as the putamen

and somatosensory cortex (26). Research by Kilpatrick in the 1970's (39) indicated that changes in skin conductivity could fall into phasic and tonic classes; with phasic changes being a more sensitive indicator of the psychophysiological reaction to stress. Tonic fluctuations certainly also reflect emotional arousal, but appears to be mediated through increased cognitive and perceptual processes that accompany an emotional stress response (39). The study into PTSD biomarkers by Falconer *et al* (17) found a decreased slope of tonic arousal changes, meaning that at rest the autonomic arousal as measured by skin conductivity showed less decrease than expected.

It is also possible for some individuals to have repressed or low skin conductivity in response to a stressor, as seen in work done by White *et al* (18), who attributes it to the autonomic suppression seen in some patients with Generalized Anxiety Disorder (31,32).

1.5. Muscle Tone

Nilsen *et al* (40) measured muscle tension in trapezius and frontalis muscles, and found that muscle activity increased in both muscles in response to a stressful task. The muscular activity could be correlated with the heart rate response measured simultaneously. While generalized anxiety disorder is associated with increased muscle tension (41,42), there are indications that striate muscle activity also exhibits reduced variability, just like the decreased flexibility of other autonomic indices in generalized anxiety disorder (32,41).

1.6. Quantitative Electro-Encephalography

Electroencephalography (EEG) is a technique used to measure the electrical activity of the brain. The synchronized depolarization of neurons result in a measurable electrical fluctuation, and electrodes placed on specific sites on the scalp are able to pick up the changes in potential difference between each electrode and the reference electrode on the earlobe of a person. Classically, visual inspection of raw EEG traces revealed five intrinsic rhythmic components that are distinguishable by their frequency, amplitude and waveform morphology. In general, these rhythms are indicative of the age and level of arousal of an individual, but they are also more

prevalent in some cortical areas than others, and can be correlated to underlying neural processes (42,43) (Table 1.1).

Table 1.1. Classic interpretation of the main rhythmic components of the analogue EEG trace. From (43) and (44).

Designation	Frequency Range	Main Features & Functional Correlates
α (Alpha)	8 to 13 Hz	Highly rhythmic, sine-shaped waveform generated by pacemaker cells in the thalamus. Dominant rhythm in normal, wakeful adults with eyes closed. Mainly found over posterior parts of the cortex and parietal lobes, diminishes anteriorly, rarely found prefrontally. Abolished by concentration or imagery, or by opening the eyes.
θ (Theta)	4 to 7.5 Hz	Prominent in sleep and drowsy recordings, and in children. Limited in the wakeful adult EEG trace to sporadic bursts over the frontal-temporal areas
δ (Delta)	≤3.5 Hz	While normal in infants and adults in deep sleep, finding slow, high amplitude Delta waves in the wakeful adult EEG is strongly indicative of pathology.
β (Beta)	13 to 30 Hz	Low amplitude, asymmetric waves common to wakeful, eyes-open adult EEG traces, especially in frontal-central regions. The frequency of Beta activity appears to be related to the level of arousal.
γ (Gamma)	>30 Hz	The appearance of high frequency activity has been experimentally correlated to visual binding and integrative cortical processing.

A further advancement in the EEG technique is the quantitative EEG (QEEG). QEEG and event related potentials (ERP) represent electrophysiological processes of the cerebral cortex, and indirectly, underlying structures (10,13). The power of QEEG and ERP, as opposed to EEG, lie in the ability to quantify findings and compare them to extensive normative databases (11,43,45). Digital spectral analysis techniques allow resolution of frequency bands 0.5 to 1 Hz in width, and combined with temporal resolution and topographical mapping, it has opened the door to a complex symphony of electrocortical activity. The power spectrum of a normal, healthy brain appears to be very stable across individuals with diverse backgrounds, and patterns of deviation from the norm exist that can be associated with mental and psychiatric disorders, but the exact functional correlates of all the electrophysiological features now available for investigation is still a work in progress (43,46). One of the advantages of using digital analysis of EEG is the ability to identify synchronous or coherent activity that functionally unites cortical areas, providing insight into difficult-to-study neural assemblies (46).

The classification of rhythmic EEG components is undergoing much change, but for convenience some frequencies are still clustered together in bands that resemble the classic Delta, Theta, Alpha, Beta and Gamma rhythms. Where increased resolution is necessary, the rhythms are sometimes divided into ‘high’ and ‘low’ sub-components. A type of low-beta activity prominent over the somatosensory cortex has been dubbed the sensorimotor rhythm (SMR), and is associated with movement inhibition. Beginning with the work of Sterman, the relative ease of learning to manipulate SMR through operant conditioning was first illustrated in cats (47,48). In neurofeedback, training a person to produce more SMR reduces restlessness and fidgeting (49).

The QEEG profiles of depressed patients show that they often exhibit an asymmetry in alpha activity in their frontal cortex, and that they have decreased left frontal activation (13-16). In an experiment on stressor controllability, depressed patients showed a prefrontal increased post-imperative negative variation (PINV) of their event-related potentials (ERP), relating to a subsequent bias in information processing even when controllability was objectively restored (50).

QEEG abnormalities in patients with anxiety disorders are present but not well defined (13,51,52). Psychiatric reference literature describes patterns of reduced alpha power and increased beta power that are consistently seen in EEG recordings during fear and anxiety (42). Hemispheric asymmetry can be interpreted in different ways; in one view left hemisphere activation is associated with approach behaviour and right hemisphere activation with withdrawal behaviour, a different view suggests left hemisphere activation could be associated with rumination and worry, anxious processes with a strong verbal component, and right hemisphere activation with behavioural arousal (42).

Post-traumatic stress disorder, rightly or wrongly, is one of the most popular conditions used in studying the effect of chronic stress on the body. Neurological studies on the neurohormonal stress axes of PTSD patients point to a general hyperarousal of the brain as a result of thalamic sensitization by circulating cortisol, but eventually the compensatory measures taken by the body to try and restore homeostasis leads to a blunted autonomic reaction to an emotional stressor (7). An integrative study into PTSD biomarkers found a decreased slope of tonic arousal changes (measured by GSR), reduced P3 ERP amplitudes in auditory oddball, increased duration of attention switching, increased reaction time and increased false negatives during working memory or vigilance tasks (17). Research has also found correlations between emotional stress, P50 suppression and a depressed skin conductivity response, once again illustrating the blunted autonomic reaction to acute emotional stressors seen in clinical populations (18).

Another study reported decreased cortical alpha and an increased theta/alpha ratio, with P3 ERP amplitude abnormalities related to medication used by the PTSD patients (53).

Female rape victims and male combat veterans with PTSD would appear to have a depressed P1 potential in their auditory ERPs, reflecting an impaired sensory gating mechanism (54).

A biophysical study found, in addition to cortical over activation, a significant reduction in mean axonal range of pyramidal cells, which is supported by findings of hippocampal cell death due to neurotoxicity in prolonged stress induced high cortisol

levels. They also found that the tonic signal propagation time in thalamocortical-corticothalamic loops were slower at Fz and Cz of the EEG, but faster at Pz (55).

A study looking at resting EEG asymmetries found no difference between PTSD patients and controls, but a distinction could be induced by displaying images related to trauma. The author suggests a state rather than trait disturbance in PTSD (56), but it could also be true that the cortisol-mediated hyperarousal is merely less prominent under baseline conditions, when sensory stimulation is usually kept to a minimum.

Investigators found a relative right hemisphere parietal over-activation in patients with spider phobia, which correlated to self-reported levels of phobia, while also finding a correlation that approaches significance between right frontal over-activation and avoidance behaviour, as measured in alpha band (12).

The literature suggests that an underlying QEEG signature for high stress levels do exist, but it is certainly not clearly defined yet. Much of the conflicting findings could be due to persons caught in different stages of the chronic stress burnout pathway. The three features that are most commonly agreed upon are:

1. A generalized hyperarousal, which could present as more power in the high beta bandwidth and/or a higher peak frequency (7,11,12,57) or as less alpha or “idling” activity (42);
2. An asymmetry between the left and right hemisphere activity, where increased right hemisphere activity is associated with a negative emotional bias and avoidance behaviour (12-16,42,58);
3. A blunted response to acute stressors, as seen in ERP suppression and less reactivity in the high beta range. It is even possible that an acute stressor disturbs the ruminative processing and results in a decrease of high beta activity (17-18).

1.7. Vasomotor Responses: Fingertip Temperature and BVP Amplitude

One of the mechanisms of temperature regulation by the hypothalamus is to control the flow of blood to superficial vessels in the skin. Sympathetic stimulation generally leads to increased peripheral vascular resistance, and subsequently a decrease in blood flow to the skin surface. Some of the ways the vasomotor response can be

non-invasively registered include measuring the temperature fluctuations of the skin surface or by using a photoplethysmograph (or BVP sensor) to measure the waveform of blood pulses permeating the vascular bed of the skin (35,59,60). Fingertip temperature is affected by multiple factors besides tissue perfusion, like muscle tone, evaporation and environmental temperature, and as such do not represent purely autonomic vasomotion (35), but the variability of the temperature has been shown to be a sensitive indicator of vasomotor responses to stress (35) (60). Fingertip temperature is sometimes used to investigate sleep disorders, and as a biofeedback protocol for the treatment of sleep disorders, as progressive relaxation is characterized by an increase in fingertip temperature (61).
BVP is a non-invasive method for HRV analysis, with the added benefit of reflecting vasomotor activity, but it is also very sensitive to movement artefact, somewhat reducing its reliability in monitoring autonomic responses (34,35,59).

1.8. Respiration

Respiration rate and volume is an autonomic function driven by a pacemaker complex in the brainstem and modulated by various chemical and mechanical feedback systems (62). It is well known that pain or strong emotions like fear or anger can affect the respiration rhythm generated in the brainstem (42,62,63), and also that conscious modification of respiratory pattern can conversely influence mental state (64) as well as indices of autonomic arousal like HRV (65). Troubat *et al* (29) investigated stress in 20 male chess players, and found that even though respiration rate increased only slightly at the start of a chess game, the respiratory exchange ratio decreased during the game, indicating a switchover from mainly carbohydrate oxidation to lipid oxidation. The author warns that expectation could have caused a transient increase in carbohydrate metabolism before the chess game, meaning that the observed change would be a return to baseline oxidation processes (29).

1.9. Aims of the study

The aims of this study were to:

1. Develop a stress evaluation program (including HRV, SC, QEEG, BVP, EMG temperature and respiration) by using biofeedback equipment and software;

2. Test the accuracy of the HRV results obtained with biofeedback equipment by comparing it to that obtained by a benchmark ECG device specifically developed for HRV determinations;
3. Test the validity of results obtained with biofeedback equipment by comparing the results to psychometric questionnaire scores.

1.10. Overview of chapters to follow

- Chapter 2 describes the biofeedback equipment, software and the development of the testing protocols of this study
- Chapter 3 deals with the technical problems experienced during the pilot study, and the steps taken to resolve them
- Chapter 4 compares the performance of the biofeedback system in measuring HRV to that of the gold standard device
- Chapter 5 describes the Biograph Infinity Biofeedback equipment and the Biograph Infinity software in a clinical application. This is done by using HRV data obtained by Actiheart to study the relationship between autonomic function, anxiety and burnout and then to compare these findings to that obtained when HRV values are obtained by Biograph Biofeedback equipment. Levels of anxiety and burnout in a group of normal, apparently healthy, professionals are compared to their baseline autonomic nervous system status and to their autonomic response to a moderate mental challenge
- Chapter 6 deals with the correlations between the Spielberger State/Trait Anxiety Scale and the Maslach Burnout Inventory values on the one hand, and the HRV, EEG, EMG, BVP, skin conductivity, respiration and temperature variables recorded with the biofeedback system, on the other
- Chapter 7 presents a summary of the dissertation and the final conclusions

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2 Materials and Methods

Ethical clearance for the study was obtained from the University of Pretoria's Research Ethics Committee (reference number S56/2010), and all participants signed informed consent documents. The subject numbers differ for each part of the study, and are described in the relevant chapters.

2.1 Biofeedback Equipment

The biofeedback equipment used in this study was from Thought Technology, and included the Procomp Infinity encoder unit and Biograph Infinity version five software package (Thought Technology, Montreal West, Quebec, Canada). Also from Thought Technology were the electrodes and sensor devices. During a recording session, electrodes were placed on the skin, or in the case of respiration, an elastic band was worn around the thorax over clothing. The physiological variables were measured by electrodes and sensors; generally they fall into one of the following classes (1):

- EEG electrodes for neurofeedback are placed on the surface of the scalp and a ground electrode is placed on the earlobe (Figure 2.1).They are held in place with conductive paste. The electrodes record brainwaves and also register muscle tension in the scalp, which is helpful to eliminate electronic artifact of non-cerebral origin

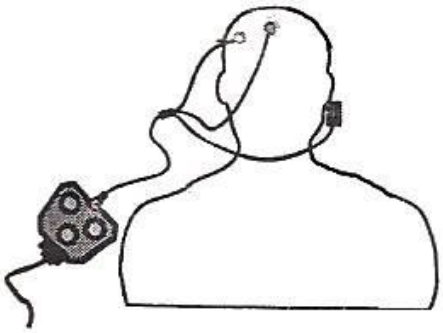

Figure 2.1. EEG electrodes. From (1)

- Disposable self-adhesive ECG electrodes can be placed on the chest or on the arms and legs (Figure 2.2). The electrodes are connected to the sensor via extender cables. They record the electrical activity of the heart and can be used for HRV feedback and the control of anxiety, blood pressure and pain.

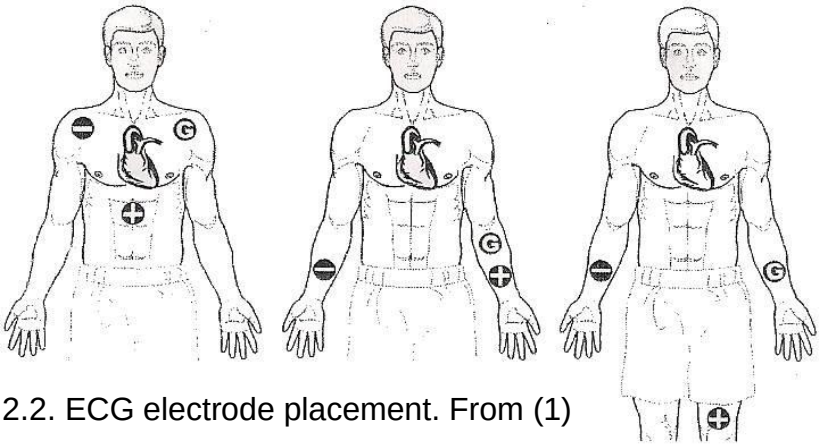

Figure 2.2. ECG electrode placement. From (1)

- Temperature sensors are held to the tip of a finger with a band (Figure 2.3) and record the temperature fluctuations of the skin caused by variations in cutaneous blood flow.

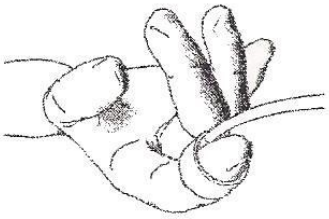

Figure 2.3. Temperature sensor. From (1)

- Blood Volume Pulse (BVP) sensors are held to the fingertip by an elastic band or adhesive tape (Figure 2.4), and register the surges of blood that accompany each heartbeat. They can be used to monitor heart rate, and in combination with ECG electrodes, pulse transit time. Pulse transit time is the time that elapses between the contraction of the heart and the arrival of the pulse of blood at the fingertip.

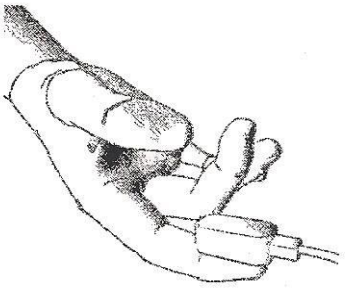

Figure 2.4. BVP sensor. From (1)

- Skin conductivity electrodes strap around two different fingers (Figure 2.5) and measure the galvanic skin reactions. Skin conductivity is a very sensitive indication of autonomic arousal, and it reacts to changes in autonomic tone very quickly.

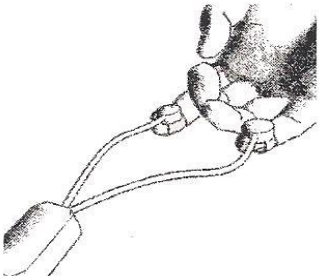

Figure 2.5. Skin Conductivity electrodes.

- Respiration sensors strap around the thorax and can be worn over a shirt or top (Figure 2.6). An elastic segment in the strap records respiration rate as well as amplitude. The training of respiration rate and depth can be applied to pain management, relaxation therapy, blood pressure control, mood disorders and to aid in meditation.

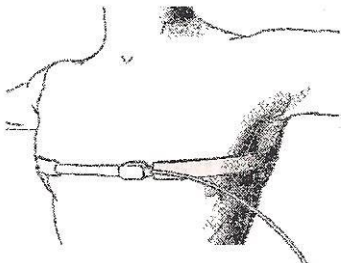

Figure 2.6. Respiration sensor. From (1)

- Electromyography (EMG) sensors clip onto a disposable triode sticker, which is usually placed along the body of the trapezius muscle to record the electrical discharges generated by muscle fiber depolarization (Figure 2.7). The electrical activity is an indicator of the tension in the muscle. EMG feedback can be used to treat tension type headaches as well as anxiety and blood pressure. Even though the electrodes are technically of the surface-electromyography (sEMG) type, in the context of biofeedback they are generally referred to as just “EMG” electrodes.

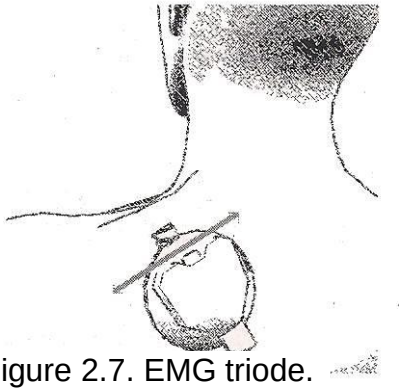

Figure 2.7. EMG triode. From (1)

The EEG, ECG and EMG sensors have built-in pre-amplification capabilities to increase their signal-to-noise ratio. The sensors register their respective physiological variables, and their output can be seen as an analogue signal.

The encoder unit has eight sensor ports, and samples six of them at a rate of 256 Hertz and the remaining two at 2048 Hertz. For each sensor input, it produces a string of measurements, and each string of values from a specific sensor is called a physical channel.

The physical channel data is sent via a fibre-optic and USB cable to a computer. The fibre-optic interface helps to isolate the encoder unit from external electromagnetic interference. The physical channel data can be processed in various ways, from simple algebraic operations to complex Fast Fourier Transformations (FFT), as well as a myriad of user-defined filters and statistical calculations. QEEG measurements can also be compared to a Z score normalised database. The output strings from each calculation is called a virtual channel.

Virtual channel information is displayed by screen instruments, graphs and charts, which can represent real-time feedback or statistical summaries of the information. The output from the virtual channels and the screen instruments can be used to provide biofeedback to a client/patient, or to provide information to a researcher/clinician.

Screens and screen instruments are used in 3 different session types; Open display, script and review sessions. Open display is commonly used for biofeedback, script sessions for assessments/research and review sessions for removing artefact and exporting statistical results (2).

Besides the biofeedback, different testing protocols, participants and additional methods were used in the separate parts of the study, and are detailed in the chapters devoted to each part of the study. Psychometric tests used in this study are also described in the relevant chapters.

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3 Teething Problems in the Assessment of Stress Levels by means of Biofeedback Equipment: Repeatability Pilot Study

3.1. Introduction

The previous chapter presented an overview of the equipment and methods use in the study. The present chapter reports in more depth on the development of the measurement protocol, the problems encountered in the initial phase of this study and on the repeatability testing.

After development of the channel sets to be used in the assessment of the stress levels by means of electro-encephalographic, electromyographic, photoplethysmographic, electrodermal, fingertip temperature and respiration recordings, a group of individuals involved in a high stress occupation were tested. The aim was to compare the biofeedback results to that obtained by heart rate variability as assessed by conventional heart rate variability equipment, to allostatic loads and to results of psychometric tests. Biofeedback results were not satisfactory and a major signal quality issue was observed during analysis of the results. It was suspected that electromagnetic interference may be present at the venue where the recordings were done.

It is obvious that there was no point in carrying on with studies on the validity of biofeedback measurement as indication of stress levels before the “interference” found in the analyses of the previous study could be identified. It was subsequently decided to test the assumption of interference, and to assess the reliability or repeatability of the assessments, by doing the same biofeedback recordings on four individuals for at least six sessions.

Test-retest reliability was assessed in accordance with the definition of test-retest reliability and in line with the requirements of testing. Reliability refers to the consistency of a measuring instrument or method and does not imply validity. General reliability classes include inter-rate reliability, inter-method reliability, inter-consistency reliability and test-retest reliability (1). Test-retest reliability, also referred to as repeatability, is the variation in measurements when the measurements are performed under the following conditions (2):

- The same individual is doing the measurements
- The same measurements procedures are followed
- The same instrument is used
- The same location is used
- The repeated measurements are done over a short period of time

Coefficient of variation gives a reasonable account of the repeatability or reliability of measurements, but does not say anything about the validity.

3.2. Aim

The purpose of the pilot study described in this chapter was therefore to test the reliability rather than the validity of the biofeedback results.

3.3. Materials and Methods

3.3.1. Equipment

The biofeedback equipment used was the Thought Technology Procomp Infinity encoder unit (Thought Technology, Montreal West, Quebec, Canada), with the following sensors and electrodes:

- For electro-encephalography (EEG), two EEG-Z sensors, 2 DIN cable extender kits with connectivity cables, gold-plated cup electrodes and gold-plated ear clip electrodes
- For electromyography (EMG), a pro/flex EMG sensor used with a disposable triode sticker
- For electrocardiography (ECG), a pro/flex ECG sensor with extender cables and disposable paediatric Ag/AgCl multi-purpose ECG electrodes
- For the electrodermal response, a skin conductivity (SC) sensor
- For blood-volume pulse (BVP), a pro/flex BVP sensor, also called a photoplethysmography (PPG) sensor
- a fingertip temperature sensor
- a respiration sensor.

The Biograph Infinity version 5 biofeedback software was used to run the measurement sessions.

As certain terms are not generally known, they are briefly explained in this paragraph. The encoder unit samples the information from the sensors. For each sensor input, it produces a string of measured values. Each string of measured values from a specific sensor is called a *physical channel*. The laptop/computer receives the physical channel information from the encoder. The information can now be processed in various ways, from simple algebraic operations to complex Fast Fourier Transformations (FFT), as well as statistical calculations. The output string from each calculation is called a *virtual channel.* A *channel set* includes physical channels, virtual channels and all the optional settings associated with them, and can be thought of as a measurement protocol.

The Biograph Infinity Developer Tools program was used to develop customised channel sets for the study, as well as user-interface screens and script sessions. Scripts manage the order and duration of display of the screens during a measurement session.

3.3.2. Channel Sets

The customised channel sets included eight physical channels, corresponding with the eight sensors used; namely two EEG channels, ECG, EMG, BVP, SC, temperature and respiration channels.

3.3.3. Virtual Channels

The ECG virtual channels were calculated from the ECG physical channel. To determine the heart rate variability (HRV), the first step in the calculation was to obtain the inter-beat-interval (IBI) from the raw ECG trace. The IBI virtual channel was used as source for all subsequent ECG calculations.

Frequency domain HRV calculations were done by applying an FFT calculation on the IBI data, and then determining the percentage power of each frequency band in the FFT spectrum. From each virtual channel containing the percentage power of a frequency band, statistical channels calculated the mean, standard deviation and

coefficient of variation of that frequency band's percentage of power. For this pilot study, the LF/HF ratio was calculated by taking the final mean LF % power value and dividing it by the final mean HF % power value. The peak frequency calculation was also applied to the FFT spectrum channel, after which the mean, standard deviation and coefficient of variation of the peak frequency was determined.

The time-domain HRV channels available in the developer software included determination of the heart rate from the IBI, the standard deviation of the IBI channel, the NN50 intervals and pNN 50 intervals. The NN50 calculation yielded an integer count of the number of inter-beat-intervals that lasted 50 milliseconds or less, and the pNN50 channel gave the proportion of the inter-beat-intervals lasting 50 ms or shorter compared to the total number of IBI's measured.

The BVP virtual channels were calculated from the BVP physical channel. The HRV calculations were done in the same way as described in the ECG results above. The BVP channel was also used to calculate the amplitude of the signal during- and in between heart beats.

Mean, standard deviation and coefficient of variation was determined for frequency and time domain HRV variables, as well as for the BVP amplitude channel.

The EMG physical channel has a built-in RMS envelope, and was used as source for a virtual channel that applies a smoothing average filter. The physical input channel sampled at 2048 Hertz, and the filter was set to average the values over 10 data points.

Skin conductivity and fingertip temperature mean, standard deviation and coefficient of variation values were calculated directly from the skin conductivity and temperature physical channels.

The respiration physical channel was used as source for two virtual channels, one calculating respiration period and one calculating respiration amplitude. The respiration period channel was used as source for a virtual channel calculating rate from time period. Mean, standard deviation and coefficient of variation values were calculated for respiration rate and amplitude.

The EEG results were divided into single hemisphere and inter-hemisphere (connectivity) groups. The single hemisphere values are reported as either left- or right hemisphere, and are a reflection of the activity measured on the scalp over that hemisphere, as compared to a ground electrode.

The left and right EEG physical channels were each used as source for a virtual channel that applies an FFT calculation. Each hemisphere's FFT channel was used as source for virtual channels computing the percentage of power of the frequency band components making up the EEG trace, namely Delta, Theta, Alpha, SMR, Beta and Gamma. The Beta rhythm was sub-divided into Beta1 and High Beta (incorporating Beta 2-5).

The left and right FFT virtual channels were also used to calculate the peak frequency in the whole EEG range (0.5 to 42 Hertz), as well as in the Alpha band (8 to 12 Hertz).

The connectivity virtual channels use both EEG physical channels as input and were meant to compare the activity in the left hemisphere to the activity in the right hemisphere. The three calculation types used were amplitude asymmetry, phase and coherence.

As before, mean, standard deviation and coefficient of variation was determined for each EEG variable.

3.3.4. User Interface Screens

The screens display virtual channel information through *screen instruments*; graphs and charts that represent real-time feedback or statistical summaries of the information. Three screen types were developed for the study; namely a baseline monitoring screen, an activity screen and various review screens.

The baseline monitoring screen had line graph instruments to display the raw data input received from the physical channel sensors. It allowed verification of the signal quality, so that sensors and electrodes could be adjusted if necessary.

The activity screen included an animated bowling ball striking pins. The animation instrument was connected to both the left- and right hemisphere sensorimotor rhythm (SMR) percentage of power channels, and whether the animation ran or paused depended on the SMR power being greater than a threshold value. The threshold was set to dynamically increase if it was met, adjusting the difficulty of the activity to the subject's level of ability.

The review screens contained various raw input and signal specific screen instruments and were created for post-recording analysis of the signal quality and the behaviour of the variables measured.

3.3.5. Session Script

A script schedules the display of the interface screens during a recording session. The custom script created for the study was structured to have three steps, each lasting five minutes. The script also saves the channel set values for each step separately, so that values can be compared across steps. The first step was to allow the subject to relax and normalize after all the electrodes were placed on him/her, and the baseline monitoring screen allowed the researcher to check that all the sensors were giving satisfactory output. The second step was the baseline recording, and the baseline monitoring screen allowed continued surveillance of the signal quality. The third step introduced the activity screen, and challenged the subject to increase his/her SMR rhythm in order for the bowling ball animation to run.

The virtual channel values for the baseline and challenge steps were extracted from the program database and imported into a spread sheet, where the response to the challenge was calculated by subtracting the baseline value from the challenge value and dividing the result by the baseline value.

3.3.6. Study Subjects

Four individuals gave informed consent to participate in six or seven recording sessions each, done over a period of two weeks. The demographic information for the study subjects are summarized in Table 3.1.

Table 3.1. Demographics

STUDY NUMBER	SEX	AGE
A	F	25
E	F	25
G	M	29
T	M	26

The exclusion criteria were a history of convulsive disorders, noradrenergic stimulants, anti-depressants and beta-blockers.

3.4. Results

Perusal of the signal quality during the recording sessions lead to the recognition of a significant problem with four of the physical channels, namely EMG, ECG and the two EEG channels. The nature of the problem is described in detail in the discussion.

To spare the reader from going through all the information only the indicators that gave acceptable repeatability are shown here (Table 3.2).

For each person, the coefficient of variation of each variable across the six to seven sessions was taken. Then the average of the four persons' coefficient of variation was calculated. Because some of the response variables had negative coefficients of variability, the absolute values were used.

Table 3.2 The variables that had an acceptable repeatability.

Variable name	Average absolute coefficient of variation across sessions
	<10%
Temperature mean baseline	6.99%
Temperature mean challenge	7.21%
BVP Heart rate mean baseline	7.25%
BVP Heart rate mean challenge	7.46%
Left Alpha peak frequency mean baseline	5.38%
Left Alpha peak frequency mean challenge	6.68%
Right Alpha peak frequency mean baseline	6.55%
Right Alpha peak frequency mean challenge	4.72%
	<20%
BVP VLF%Power Standard deviation challenge	17.91%
BVP LF%Power Mean Baseline	16.51%
BVP LF%Power Mean Challenge	16.30%
BVP LF%Power Standard deviation Challenge	17.71%
BVP LF%Power Coefficient of variation Challenge	19.47%
BVP HF%Power Mean Baseline	15.85%
Right Beta1%Power Mean Baseline	19.31%
Right Beta1%Power Mean Challenge	17.04%

BVP – Blood volume pulse, VLF – Very low frequency, LF – Low Frequency, HF – High Frequency

3.5. Discussion

As can be seen from Table 3.2, only eight of the variables had a coefficient of variability below 10%. Eight variables had a coefficient of variability higher than 10% but still below 20%. The repeatability of the other variables was thus not good enough and an investigation as to the reason for the unacceptable results was launched.

3.5.1. Identification of the Problem

In following the recording displays on the monitor screen it was observed that periodically the raw EEG signals displayed a rhythmic pattern of massive amplitude that could not have originated from the subject being tested. Occasionally, the raw ECG and EMG inputs were also involved. See Figure 3.1 in Appendix A for a screenshot of the typical pattern seen during these 'interference' periods. Using the spectral display instruments to analyse the nature of the signal, it was noted that it seemed to be made up of well-defined frequency sub-components (Figure 3.2 in Appendix A).

The signal also displayed a downward 'drift' in frequency over time (Figure 3.3 and Figure 3.4, Appendix A), and seemed to have an exponential rise and fall in amplitude when it manifested or disappeared (Figure 3.5, Appendix A).

The first steps taken in trying to remedy the situation were to remove and re-apply the electrodes, and to check that the impedance levels between the EEG electrodes were at acceptable levels. The encoder's self-calibrating routine was also activated. Since the 'interference' appeared only on the 4 physical channels measuring electrophysiological currents (two EEGs, ECG and EMG) and not on the channels dedicated to BVP, temperature, respiration and skin conductivity, it seemed that an electromagnetic source was responsible. One by one, of the possible sources were eliminated; cell phones, fluorescent lighting and air conditioning, even the power supply of the researcher's laptop.

Advice was sought from the product agent in Honeydew, South Africa, as well as a technical biofeedback expert in Montreal, Canada, who suspected a loose connection. With the help of the agent, each component was in turn substituted with

a control unit to see if the faulty component could be identified, beginning with the encoder unit itself. After that the sensor units, electrodes and extender cables were each checked. Finding no answers, different combinations of units were tested, but the 'interference' remained. Eventually the system was comprised entirely of control units known to be in working order, even the laptop had been exchanged for another one, but the 'interference' was *still* present. As a last resort the linked-ear EEG assembly was divided into two separate monopolar assemblies (Figure 3.6 & Figure 3.7, Appendix A), each with its own ground and reference ear clips. This lead to a total removal of the "interference". The assembly was re-linked, but this time a common ground and common reference electrode ear clip was chosen (Figure 3.8, Appendix A), and the 'interference' did not manifest again.

3.5.2. Explanation of the Mistake Made

The researcher had used a principle applicable to a single monopolar assembly, namely that the reference electrode ear clip must always be on the same side of the head as the active electrode, as rationale for the original configuration of the two monopolar assemblies with linked ear clip electrodes (Figure 3.6, Appendix A). The EEG-Z sensors have a pre-amplification function (3,4), and this configuration allowed a resonant feedback loop between the two sensors to develop. The instruction leaflet accompanying the connectivity cables that make linked-ear assembly possible illustrates the configuration seen in Figure 3.8, but neglects to warn the user about the consequences of an incorrect configuration.

The technical support expert consulted about the 'interference' suspected a short-circuit created by a loose connection in the hardware, but did not realize that the way the linked-ear assembly was configured could lead to a 'functional' short circuit and influence the recorded signal so profoundly. Hopefully, the rookie mistake made by the researcher will motivate the manufacturer of the equipment to revise the relevant paragraphs in the user's manual to warn others and prevent similar errors in the future.

3.6. Conclusions

Portable biofeedback equipment is much more accessible to clinicians, researchers and the general public than the specialized laboratory equipment conventionally used in healthcare and medical science. While manufacturers do advise you to receive training in the use of portable biofeedback equipment and various organizations exist that provide training in the theory and application of biofeedback, there is a relative lack of information on the technical aspects of operating biofeedback equipment. It is therefore easy for a clinician or researcher, even though well versed in theory, to commit a simple technical error while using portable biofeedback equipment. Simple or not, technical errors can have serious effects, especially when treating patients and doing research.

3.7 Bibliography

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3. Bolek, JE. Electrical Concepts in the Surface Electromyographic Signal. Appl Psychophysiol Biofeedback. 2010;35(2):171–5.

4. Thompson M, Thompson L. Measuring the EEG: Instruments & Electronics. The Neurofeedback Book: an introduction to basic concepts in applied psychophysiology. Wheat Ridge: Association For Applied Psychophysiology And Biofeedback; 2003. p. 52.

Appendix A

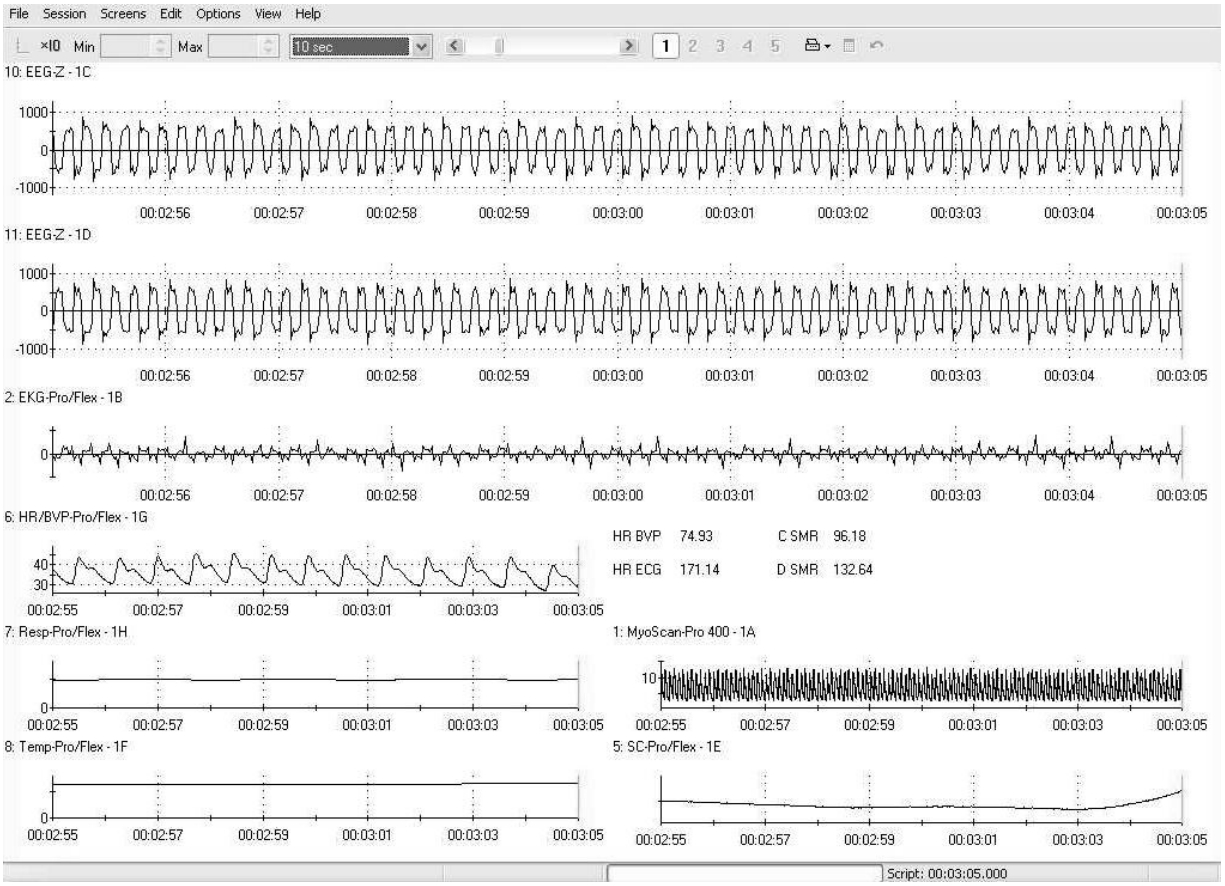

Figure 3.1. A screenshot of the baseline monitoring screen during a period of interference.

The top two line graphs represent the left and right EEG traces, the third graph from the top represents the ECG. Underneath the ECG on the left hand side is the BVP graph. Below the BVP is the respiration graph on the left and the EMG on the right. The bottom graphs are fingertip temperature on the left and skin conductivity on the right. It is immediately evident that the two EEG graphs, the ECG- and EMG graphs are abnormal.

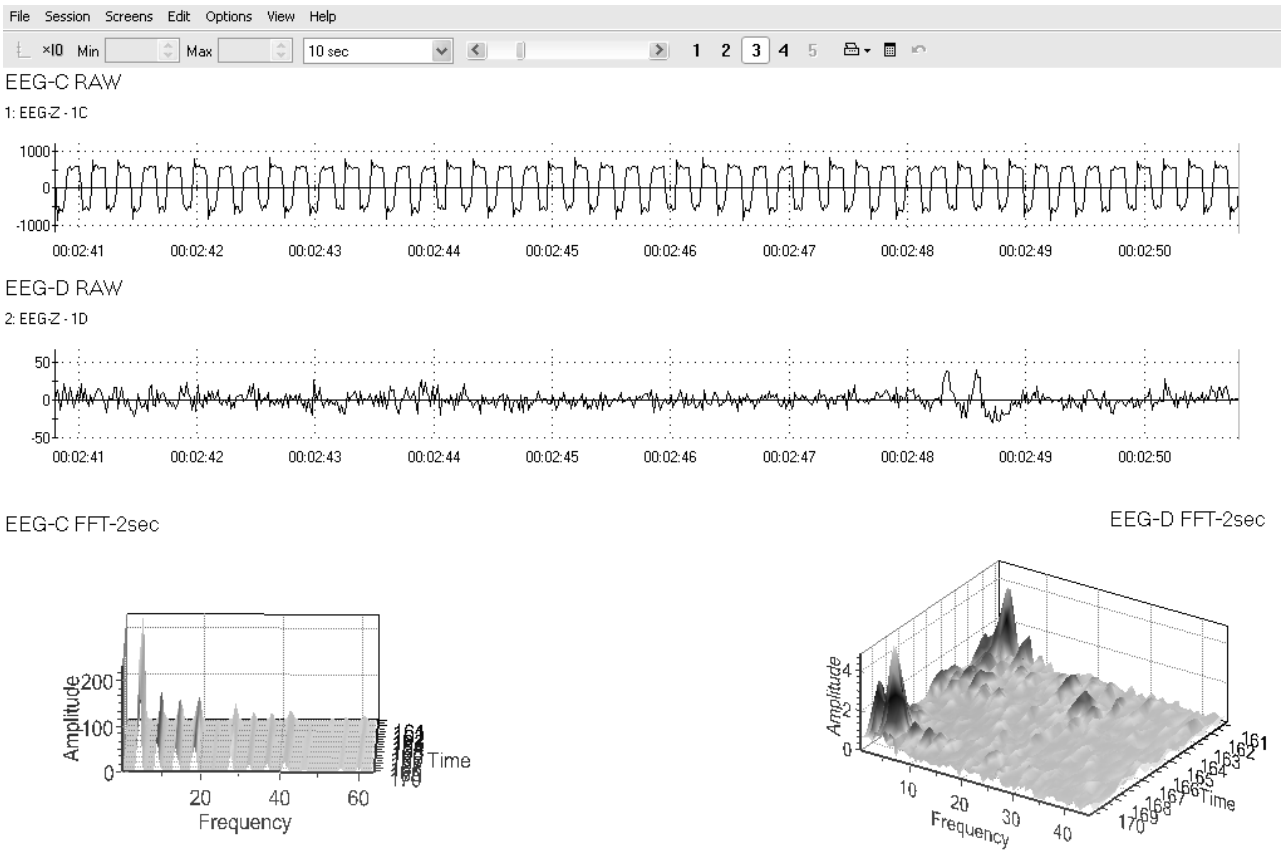

Figure 3.2. A screenshot of an EEG review screen.

The two line graphs represent the left and right EEG traces. Below them are three dimensional spectrograms, one each for the left and right EEG channels respectively. The interference is only registered on the top (left EEG) line graph, the bottom (right EEG) line graph appears normal. The Left EEG spectral instrument is rotated and viewed from the front to illustrate the sharply defined frequency components.

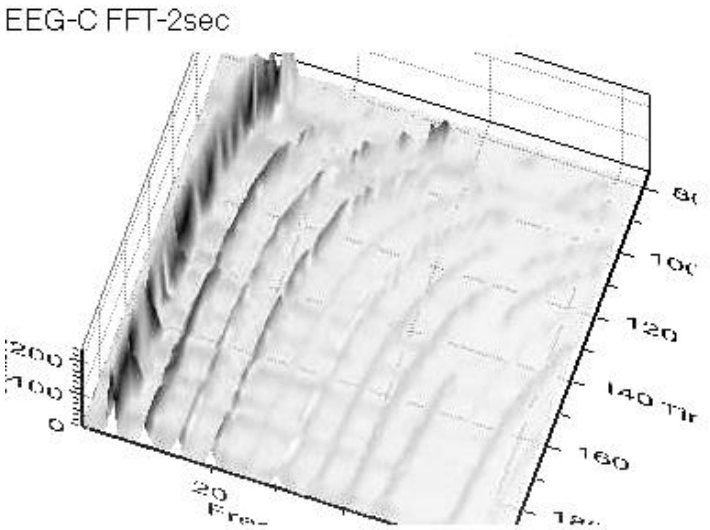

Figure 3.3 A screenshot of a three dimensional spectral display instrument.

The instrument displays the frequency components of an EEG channel. It is rotated and viewed from above to illustrate the downwards drift in frequency of the ‘interference’ components over time.

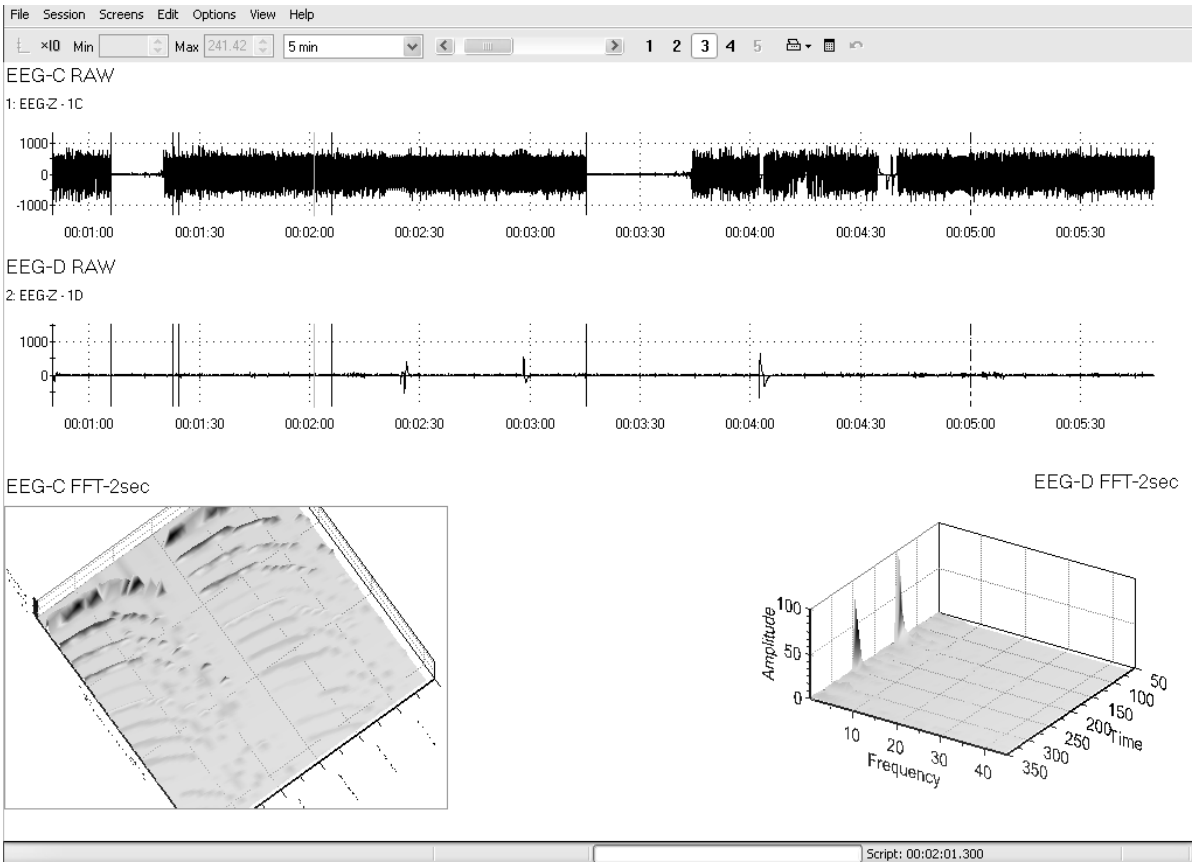

Figure 3.4. A screenshot of an EEG review screen.

The two line graphs represent the left and right EEG traces, and below them are the three dimensional spectrograms for the left and right EEG channels. On the top line graph (left EEG) the ‘interference’ comes and goes. The spectrogram for the left EEG is rotated and viewed from above, to illustrate the repetition of the downwards drift whenever the ‘interference’ appears.

Figure 3.5. A screenshot of an EEG line graph instrument.

The line graph is scaled to illustrate the beginning and end phases of the ‘interference’. The changes in amplitude during these phases appear exponential in nature.

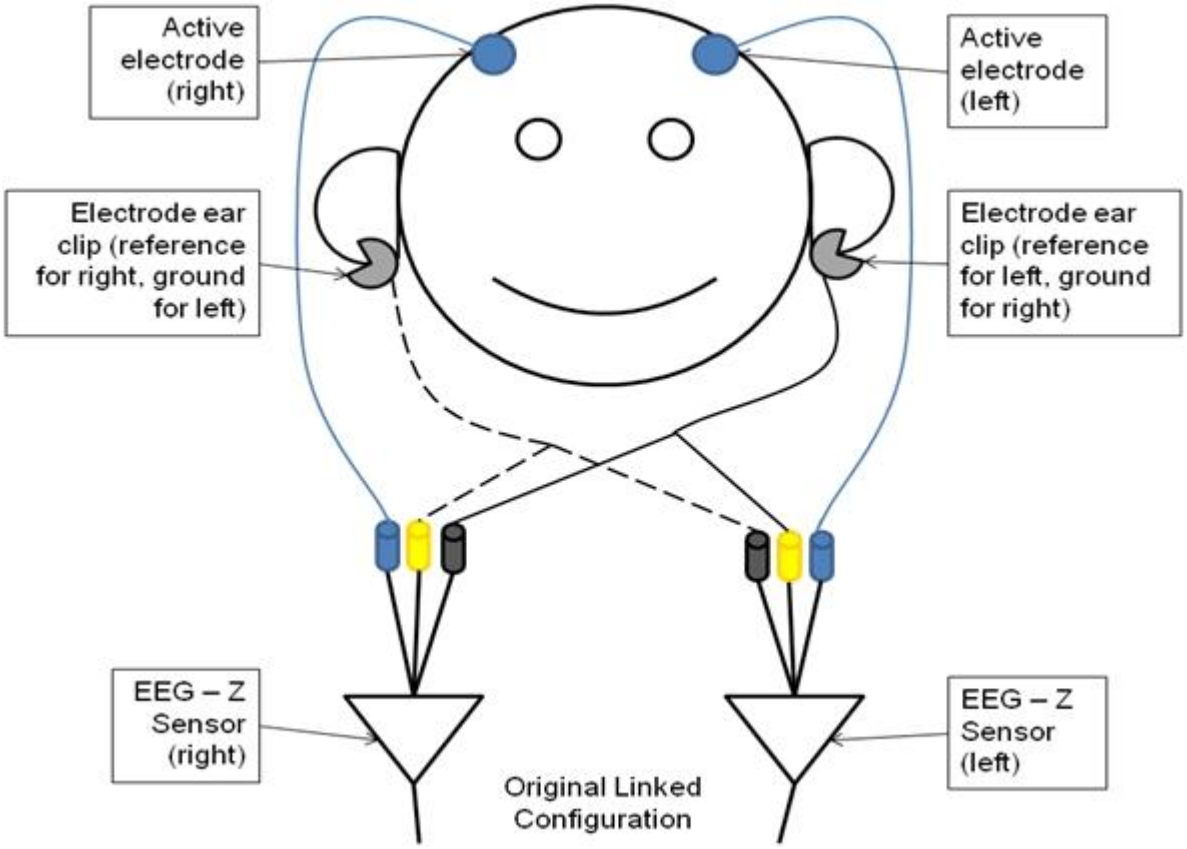

Figure 3.6. A diagrammatic representation of the original placement of the EEG electrodes.

The diagram illustrates the placement of the active electrodes on the scalp and the reference and ground ear clip electrodes. Also shown are the EEG sensors and the DIN cables that connect them to the electrodes. The DIN cables are colour coded; blue for active, yellow for reference and black for ground.

In this original configuration, the two monopolar assemblies use splitter cables to divide the output from each ear clip into two. The splitter cables are then connected to the DIN cables in such a way that the ear clip serves as reference electrode to the active electrode on the same side of the head, and as ground electrode to the active electrode on the opposite side of the head.

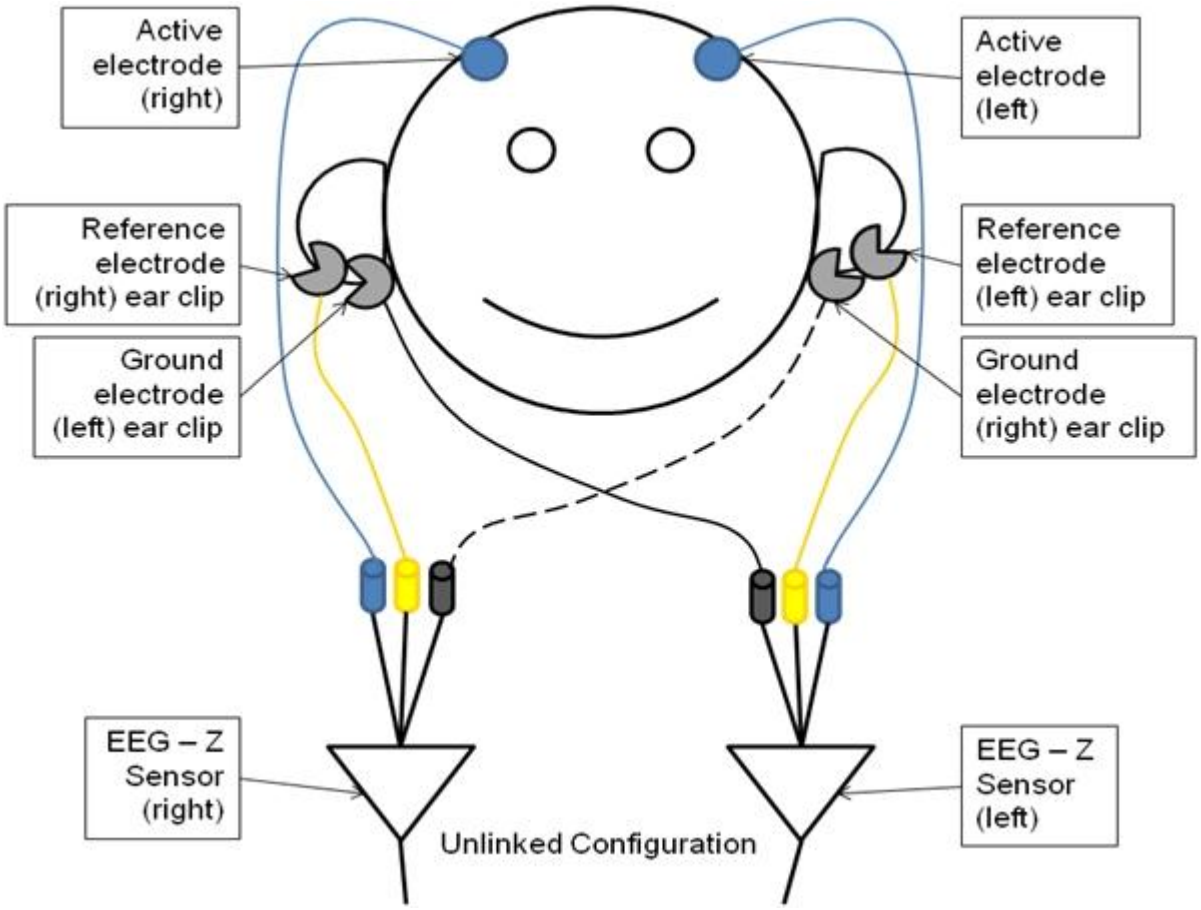

Figure 3.7. A diagrammatic representation of the placement of the EEG electrodes when the two monopolar assemblies are un-linked.

The diagram illustrates the placement of the active electrodes on the scalp and the reference and ground ear clip electrodes. Also shown are the EEG sensors and the DIN cables that connect them to the electrodes. The DIN cables are colour coded; blue for active, yellow for reference and black for ground.

In this un-linked configuration, the splitter cables are removed and the two monopolar assemblies each use their own sets of ear clip electrodes. The ear clip electrodes are connected directly to the DIN cables, and each active electrode has a reference ear clip on the same side of the head, and a ground ear clip on the opposite side of the head.

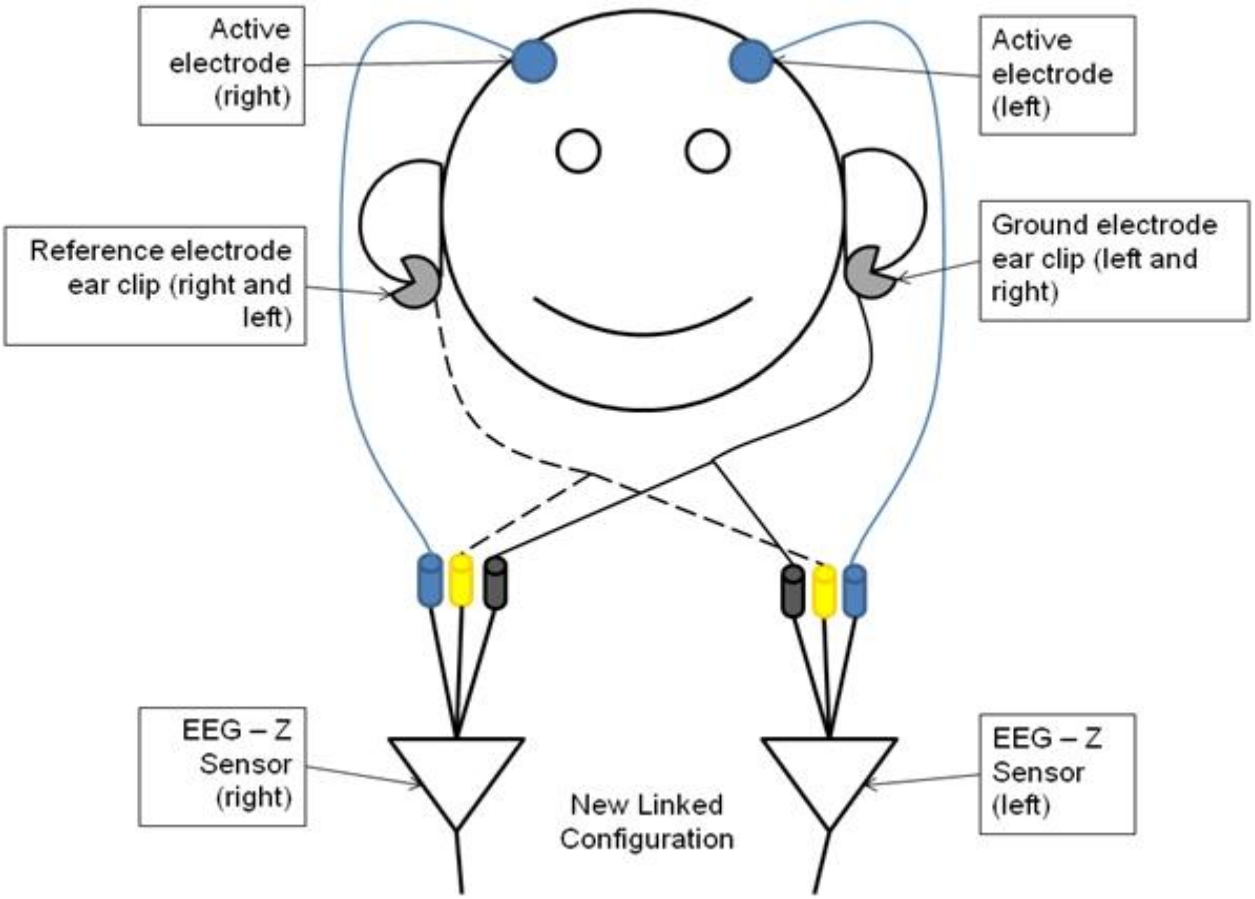

Figure 3.8. A diagrammatic representation of the new placement of the EEG electrodes.

The diagram illustrates the placement of the active electrodes on the scalp and the reference and ground ear clip electrodes. Also shown are the EEG sensors and the DIN cables that connect them to the electrodes. The DIN cables are colour coded; blue for active, yellow for reference and black for ground.

In this new configuration, the two monopolar assemblies again use splitter cables to divide the output from each ear clip into two, but the splitter cables are now connected to the DIN cables in such a way that one of the ear clip serves as common reference electrode to both of the active electrodes, and the other ear clip serves as common ground to both of the active electrodes.

4 Comparison of HRV results recorded with the Procomp Infinity Biofeedback Apparatus and the Actiheart monitor

4.1 Background

In the Introduction chapter it was seen that heart rate variability (HRV) can be used as an indicator of autonomic nervous system (ANS) status, and that various techniques and types of equipment exist for the calculation of HRV indices. In line with the aim of this dissertation, the reliability of HRV measurements using a portable biofeedback apparatus was tested against a more conventional two lead heart rate monitor during simultaneous recordings of inter-beat-interval heart rate data on the same subjects.

4.2 Materials and Methods

Clearance for the study was obtained from the Ethics Committee of the Faculty of Health Sciences (reference number S56/2010), University of Pretoria and all subjects signed informed consent documents.

4.2.1 Study Subjects

Eight individuals volunteered to take part in the study. There were three women and five men, with a mean age of 25.5 (SD=2.33) years and a mean body mass index (BMI) of 25.9 (SD=5.16) $kg.m^{-2}$. The exclusion criteria were a history of convulsive disorders, noradrenergic stimulants, anti-depressants, beta-blockers or any medication that could influence autonomic nervous system (ANS) functioning. The demographic information for the study subjects are summarized in Table 4.1.

Table 4.1 Demographics of the study subjects

Study Number	Age (yrs)	Sex	Height (m)	Weight (kg)	BMI ($kg.m^{-2}$)	Smoker Number of Cigarettes	Chronic Conditions	Medication
A32	25	F	1.75	75	24.49	0	None	None
C30	26	F	1.70	56	19.38	20	None	None
D28	27	F	1.55	68	28.30	25	None	Warfarin
F26	21	M	1.74	74	24.44	10	None	None
G33	29	M	1.88	85	24.05	0	None	None
K24	26	M	1.80	120	37.04	0	Hypertension	None
L29	26	M	1.85	80	23.38	20	None	None
S25	24	M	1.74	79	26.09	6	None	None

4.2.2 Biograph Infinity Biofeedback Equipment

The biofeedback equipment used was the Thought Technology Procomp Infinity encoder unit (Thought Technology, Montreal West, Quebec, Canada), with the following sensors and electrodes:

- For electro-encephalography (EEG), two EEG-Z sensors, 2 DIN cable extender kits with connectivity cables, gold-plated cup electrodes and gold-plated ear clip electrodes. The two cortical sites used were F3 and F4 of the international 10/20 system.
- For electromyography (EMG), a pro/flex EMG sensor used with a disposable triode sticker was placed on the body of the left trapezius muscle
- For electrocardiography (ECG), a pro/flex ECG sensor with extender cables and disposable paediatric Ag/AgCl multi-purpose ECG electrodes. The active and ground leads were placed on the left forearm and the reference lead on the right forearm
- For the electrodermal response, a skin conductivity (SC) sensor was strapped to the middle phalanx of the index and little fingers of the left hand

- For blood-volume pulse (BVP), a pro/flex BVP sensor, also called a photoplethysmography (PPG) sensor was held to the palmar surface of the tip of the right index finger with an elastic band
- a fingertip temperature sensor was strapped to the palmar surface of the tip of the right ring finger
- a respiration sensor with an elastic band placed around the thorax

The Biograph Infinity version 5 biofeedback software was used to run the measurement sessions, and the Developer Tools were used to create custom channel sets, screens and scripts, as described in Chapter 2 and Chapter 3.

As in Chapter 3, the ECG virtual channels were calculated from the ECG physical channel, starting with a channel that determines inter-beat-interval (IBI). The frequency domain variables were obtained by applying a Fast Fourier Transformation to the IBI data. The only change from the frequency domain variables described in Chapter 3 was the way the LF/HF ratio was calculated. Rather than taking the final mean low frequency (LF) % power value and dividing it by the final mean high frequency (HF) % power value, in this part of the study a virtual channel was created that divided the moment-to-moment LF % power value with the moment-to-moment HF % power value. From this virtual channel, a mean statistical virtual channel was calculated.

The time-domain HRV calculations available in the software included determining the heart rate from the IBI, the NN50 intervals and pNN 50 intervals. The NN50 calculation yielded an integer count of the number of inter-beat-interval differences of 50 milliseconds or more, and the pNN50 channel gave the percentage of the inter-beat-interval differences of 50 ms or longer compared to the total number of IBIs measured. The BVP virtual channels were calculated from the BVP physical channel in exactly the same way as the ECG channels.

The HRV indicators obtained with the biofeedback equipment and used in this part of the study are summarized in Table 4.2.

Table 4.2 HRV variables obtained by Procomp Infinity encoder and analysed with Biograph Infinity v5 software.

ECG Channels
Frequency Domain
LF % Power Mean
HF % Power Mean
LF/HF Ratio Mean
Time Domain
Heart Rate Mean
Heart Rate StdDev
NN50 Intervals
pNN50 (%)
BVP Channels
Frequency Domain
LF % Power Mean
HF % Power Mean
LF/HF Ratio Mean
Time Domain
Heart Rate Mean
Heart Rate StdDev
NN50 Intervals
pNN50 (%)

ECG – Electrocardiogram, LF – Low frequency, HF – High Frequency, StdDev – Standard Deviation,NN50 – Count normal-to-normal interval differences of 50ms or more, pNN50 – Percentage of NN50 intervals, BVP- Blood volume pulse

4.2.3 Actiheart Equipment

The Actiheart two lead chest-worn heart rate monitor (from CamNtech Ltd, Cambridge, UK) was used to record IBI by digitising the ECG signal from the R-to-R interval with a 1 ms resolution. Following the recording session, the stored recording was transferred to a computer for storage and data analysis. IBI data series were stored in a Polar Precision Performance Software template file (*.hrm) to enable error correction using the Polar Precision Performance Software version 4.03.040 (Polar Electro Oy, Kempele, Finland). Error correction was done by selecting the very low filter power with a minimum protection zone of 5 beats.min^{-1}. The identified errors over the recorded interval for all the recordings were less than 1%. HRV analysis was carried out using the advanced HRV Analysis 1.1 software for windows, developed by The Biomedical Signal Analysis Group, University of Kuopio, Finland (1). Time-domain measures and nonparametric frequency-domain analysis based on FFT were employed for calculation of power spectral density (PSD) of the IBI data series (2). Before the FFT were employed all imported data was detrended using the smoothness priors method (3) to remove the disturbing low frequency baseline trend component. Because the IBI data series are known to be unequally spaced, it needed to be interpolated before computing the FFT. The IBI data series was interpolated at a sampling rate of 4 Hz (4).

Frequency-domain analysis information on the relative power of underlying intrinsic rhythms involved in the regulation of heart rate include the HF band (0.15–0.4 Hz),which is known to represent mainly parasympathetic activity and the LF band (0.04–0.15 Hz), a combination of parasympathetic and sympathetic activity. This makes the information captured in the LF band more difficult to interpret. By calculating the power in the very low frequency (VLF) band, the LF band can be expressed in normalised units (LF / (Total power - VLF)), which tends to mirror sympathetic activity (2), VLF is the frequency band 0.003–0.04 Hz. As the LF/HF ratio is interpreted as an index of sympatho-vagal balance, an increase can be considered as increase in sympathetic activity.

The Actiheart system also allows PSD to be calculated using autoregression instead of FFT (2). Separate frequency domain measures were obtained with FFT and

autoregression, and compared to each other as well as to the measures obtained with the biofeedback equipment.

Time-domain measures, which are calculated from the raw RR interval series, included the standard deviation of all normal RR intervals (SDNN, describing the overall variation of RR intervals and interpreted as an estimate of overall HRV), and the root mean square of the differences between successive RR intervals (RMSSD, for estimation of short-term components of HRV (1).

The HRV parameters obtained with the Actiheart system that were used in this part of the study are summarized in Table 4.3.

Table 4.3 HRV variables obtained by Actiheart equipment and analysed with advanced HRV Analysis 1.1 software for windows

Frequency Domain	
FFT	
	$LFms^2$
	$HFms^2$
	LF % Power
	HF % Power
	LF/HF Ratio
	LF n.u.
	HF n.u.
Autoregression	
	$LFms^2$
	$HFms^2$
	LF % Power
	HF % Power
	LF/HF Ratio
	LF n.u.
	HF n.u.
Time Domain	
	Heart Rate Mean
	Heart Rate StdDev
	NN50 Intervals
	pNN50 (%)

FFT – Fast Fourier Transformation, LF – Low frequency, HF – High Frequency, n.u. – normalized units, StdDev – Standard Deviation, NN50 – Count normal-to-normal interval differences of 50ms or more, pNN50 – Percentage of NN50 intervals

4.2.4 Recording Sessions

The same three screen types described in Chapter 3 was used in this study; namely a baseline monitoring screen, an activity screen and various review screens.

The custom script created for this part of the study was structured to have four steps, each lasting five minutes, with a five minute break during which the encoder unit was switched off. The first five minute step was called Baseline 1, and allowed the subject to relax after all the electrodes were attached. The baseline monitoring screen allowed the researcher to check that all the sensors gave satisfactory output. Thereafter the encoder unit was switched off for five minutes to rule out warming of the circuitry. The second step was Baseline 2, and again the baseline monitoring screen allowed continued surveillance of the signal quality. The third step introduced the activity screen, and challenged the subject to increase the amplitude of his/her sensorimotor rhythm (SMR) in order for the bowling ball animation to run. The fourth and last step was called Recovery, and monitored the subject's physiological responses after the challenge was removed. The session script saved the channel set values for each step separately, so that values could be compared across the four steps.

4.2.5 Statistics

The HRV measures made by the Biograph Infinity and Actiheart apparatuses were evaluated separately for Baseline 1, Baseline 2, Challenge and Recovery. The response of the subject to the cognitive stressor in the Challenge step was calculated by subtracting the Baseline 2 value from the Challenge value and dividing the result by the Baseline 2 value ((Ch-B2)/B2). When multiplied by 100, the percentage change from Baseline 2 to Challenge (the Response) was obtained.

The Response values, as well as descriptive statistics for each data set, were calculated in Microsoft Office Excel (2007) spread sheets.

The comparison of the results of different equipment systems and calculation techniques were done by Spearman's Ranked Correlations (2-tailed), using STATISTICA version 10 data analysis software (5).

4.3 Results

The Spearman Ranked Correlations and p-values are summarized in Table 4.4 to Table 4.12.

Table 4.4 Spearman Correlations of the heart rate values measured by Actiheart and Biofeedback equipment (ECG based and BVP based). N=8

	Spearman r	p-value
Actiheart Mean HR & Biofeedback ECG Mean HR		
Baseline 1	1.0000	
Baseline 2	0.9762	0.00003
Challenge	0.9286	0.0009
Recovery	0.9762	0.00003
Response (Ch-B2)/B2	0.8333	0.0102
Actiheart Mean HR & Biofeedback BVP Mean HR		
Baseline 1	0.9762	0.00003
Baseline 2	1.0000	
Challenge	0.9762	0.00003
Recovery	1.0000	
Response (Ch-B2)/B2	0.881	0.0039
Biofeedback ECG Mean HR & Biofeedback BVP Mean HR		
Baseline 1	0.9762	0.00003
Baseline 2	0.9762	0.00003
Challenge	0.9762	0.00003
Recovery	0.9762	0.00003
Response (Ch-B2)/B2	0.8333	0.0102

HR – Heart Rate, ECG – Electrocardiogram, BVP- Blood volume pulse, Ch – Challenge, B2 – Baseline 2

Table 4.5 Spearman Correlations of the standard deviation of the heart rate values measured by Actiheart and Biofeedback equipment (ECG based and BVP based). N=8

	Spearman r	p-value
Actiheart StdDev HR & Biofeedback ECG StdDev HR		
Baseline 1	0.2857	0.4927
Baseline 2	0.5952	0.1195
Challenge	0.3571	0.3851
Recovery	0.1905	0.6514
Response (Ch-B2)/B2	0.3095	0.4556
Actiheart StdDev HR & Biofeedback BVP StdDev HR		
Baseline 1	0.381	0.3518
Baseline 2	0.7143	0.0465
Challenge	-0.0952	0.8225
Recovery	0.5238	0.1827
Response (Ch-B2)/B2	-0.5476	0.16
Biofeedback ECG StdDev HR & Biofeedback BVP StdDev HR		
Baseline 1	0.2857	0.4927
Baseline 2	0.5476	0.16
Challenge	-0.7143	0.0465
Recovery	0.1905	0.6514
Response (Ch-B2)/B2	-0.2143	0.6103

StdDev – Standard deviation, HR – Heart Rate, ECG – Electrocardiogram, BVP- Blood volume pulse, Ch – Challenge, B2 – Baseline 2

Table 4.6 Spearman Correlations of the NN50 intervals measured by Actiheart and Biofeedback equipment (ECG based and BVP based). N=8, except where marked with * N=7

	Spearman r	p-value
Actiheart NN50 & Biofeedback ECG NN50		
Baseline 1	0.4286	0.2894
Baseline 2	0.4541	0.2584
Challenge	0.8675	0.0052
Recovery	0.6854	0.0606
Response (Ch-B2)/B2 *	-0.036	0.9389
Actiheart NN50 & Biofeedback BVP NN50		
Baseline 1	0.5	0.207
Baseline 2	0.4182	0.3025
Challenge	0.4524	0.2604
Recovery	0.6627	0.0733
Response (Ch-B2)/B2 *	0.6786	0.0938
Biofeedback ECG NN50 & Biofeedback BVP NN50		
Baseline 1	0.7143	0.0465
Baseline 2	0.4074	0.3164
Challenge	0.5784	0.1331
Recovery	0.7101	0.0484
Response (Ch-B2)/B2 *	-0.4144	0.3553

ECG – Electrocardiogram, BVP- Blood volume pulse, NN50 – Count normal-to-normal interval differences of 50ms or more, Ch – Challenge, B2 – Baseline 2

Table 4.7 Spearman Correlations of the pNN50 intervals measured by Actiheart and Biofeedback equipment (ECG based and BVP based). N=8, except where marked with * N=7

	Spearman r	p-value
Actiheart pNN50 & Biofeedback ECG pNN50		
Baseline 1	0.3571	0.3851
Baseline 2	0.3234	0.4346
Challenge	0.8333	0.0102
Recovery	0.5855	0.1272
Response (Ch-B2)/B2 *	-0.036	0.9389
Actiheart pNN50 & Biofeedback BVP pNN50		
Baseline 1	0.381	0.3518
Baseline 2	0.3095	0.4556
Challenge	0.5238	0.1827
Recovery	0.5238	0.1827
Response (Ch-B2)/B2 *	0.6786	0.0938
Biofeedback ECG pNN50 & Biofeedback BVP pNN50		
Baseline 1	0.6667	0.071
Baseline 2	0.8982	0.0024
Challenge	0.619	0.1017
Recovery	0.6099	0.1084
Response (Ch-B2)/B2 *	-0.0541	0.9084

ECG – Electrocardiogram, BVP- Blood volume pulse, pNN50 – Percentage of NN50 intervals, Ch – Challenge, B2 – Baseline 2

Table 4.8 Spearman Correlations of the LF% variables measured by Actiheart (FFT and autoregression) and Biofeedback equipment (ECG and BVP derived). N=8

	Spearman r	p-value
Actiheart LF% FFT & Biofeedback ECG LF% FFT		
Baseline 1	0.881	0.0039
Baseline 2	0.7619	0.028
Challenge	0.619	0.1017
Recovery	0.8095	0.0149
Response (Ch-B2)/B2	0.881	0.0039
Actiheart LF% FFT & Biofeedback BVP LF% FFT		
Baseline 1	0.7857	0.0208
Baseline 2	0.7857	0.0208
Challenge	0.7143	0.0465
Recovery	0.881	0.0039
Response (Ch-B2)/B2	0.8095	0.0149
Actiheart LF% AR & Biofeedback ECG LF% FFT		
Baseline 1	0.6429	0.0856
Baseline 2	0.7381	0.0366
Challenge	0.5952	0.1195
Recovery	0.6667	0.071
Response (Ch-B2)/B2	0.5714	0.139
Actiheart LF% AR & Biofeedback BVP LF% FFT		
Baseline 1	0.5714	0.139
Baseline 2	0.881	0.0039
Challenge	0.6905	0.058
Recovery	0.7619	0.028
Response (Ch-B2)/B2	0.6429	0.0856

FFT – Fast Fourier Transformation, LF – Low frequency, AR – Autoregression, ECG – Electrocardiogram, BVP- Blood volume pulse, Ch – Challenge, B2 – Baseline 2

Table 4.9 Spearman Correlations of the HF% variables measured by Actiheart (FFT and autoregression) and Biofeedback equipment (ECG and BVP derived). N=8

	Spearman r	p-value
Actiheart HF% FFT & Biofeedback ECG HF% FFT		
Baseline 1	0.8571	0.0065
Baseline 2	0.4524	0.2604
Challenge	0.9286	0.0009
Recovery	0.5238	0.1827
Response (Ch-B2)/B2	0.119	0.7789
Actiheart HF% FFT & Biofeedback BVP HF% FFT		
Baseline 1	0.7143	0.0465
Baseline 2	0.3333	0.4198
Challenge	0.4048	0.3199
Recovery	0.8571	0.0065
Response (Ch-B2)/B2	0.7143	0.0465
Actiheart HF% AR & Biofeedback ECG HF% FFT		
Baseline 1	0.7857	0.0208
Baseline 2	0.6667	0.071
Challenge	0.3333	0.4198
Recovery	0.1905	0.6514
Response (Ch-B2)/B2	0.0000	1.0000
Actiheart HF% AR & Biofeedback BVP HF% FFT		
Baseline 1	0.6429	0.0856
Baseline 2	0.7143	0.0465
Challenge	0.3095	0.4556
Recovery	0.5476	0.16
Response (Ch-B2)/B2	0.381	0.3518

FFT – Fast Fourier Transformation, HF – High frequency, AR – Autoregression, ECG – Electrocardiogram, BVP- Blood volume pulse, Ch – Challenge, B2 – Baseline 2

Table 4.10 Spearman Correlations of the LF/HF ratio variables measured by Actiheart (FFT and autoregression) and Biofeedback equipment (ECG and BVP derived). N=8

	Spearman r	p-value
Actiheart LF/HF FFT & Biofeedback ECG LF/HF FFT		
Baseline 1	0.9286	0.0009
Baseline 2	0.7619	0.028
Challenge	0.5714	0.139
Recovery	0.8095	0.0149
Response (Ch-B2)/B2	0.5714	0.139
Actiheart LF/HF FFT & Biofeedback BVP LF/HF FFT		
Baseline 1	0.8095	0.0149
Baseline 2	0.5952	0.1195
Challenge	0.5476	0.16
Recovery	0.9102	0.0017
Response (Ch-B2)/B2	0.8095	0.0149
Actiheart LF/HF AR & Biofeedback ECG LF/HF FFT		
Baseline 1	0.7619	0.028
Baseline 2	0.6905	0.058
Challenge	0.5952	0.1195
Recovery	0.5238	0.1827
Response (Ch-B2)/B2	0.6429	0.0856
Actiheart LF/HF AR & Biofeedback BVP LF/HF FFT		
Baseline 1	0.5476	0.16
Baseline 2	0.9286	0.0009
Challenge	0.6429	0.0856
Recovery	0.6587	0.0757
Response (Ch-B2)/B2	0.3095	0.4556

FFT – Fast Fourier Transformation, LF/HF – Ratio of low frequency to high frequency, AR – Autoregression, ECG – Electrocardiogram, BVP- Blood volume pulse, Ch – Challenge, B2 – Baseline 2

Table 4.11 Spearman Correlations of the frequency domain HRV variables measured by Actiheart and calculated using FFT and autoregression. N=8

	Spearman r	p-value
Actiheart LF% FFT & Actiheart LF% AR		
Baseline 1	0.8333	0.0102
Baseline 2	0.7143	0.0465
Challenge	0.8571	0.0065
Recovery	0.8095	0.0149
Response (Ch-B2)/B2	0.6667	0.071
Actiheart HF% FFT & Actiheart HF% AR		
Baseline 1	0.7857	0.0208
Baseline 2	0.7619	0.028
Challenge	0.4524	0.2604
Recovery	0.8571	0.0065
Response (Ch-B2)/B2	-0.0238	0.9554
Actiheart LF/HF FFT & Actiheart LF/HF AR		
Baseline 1	0.619	0.1017
Baseline 2	0.7619	0.028
Challenge	0.7619	0.028
Recovery	0.881	0.0039
Response (Ch-B2)/B2	0.0714	0.8665
Actiheart LF n.u. FFT & Actiheart LF n.u. AR		
Baseline 1	0.5952	0.1195
Baseline 2	0.7857	0.0208
Challenge	0.7381	0.0366
Recovery	0.9524	0.0003
Response (Ch-B2)/B2	0.381	0.3518
Actiheart HF n.u. FFT & Actiheart HF n.u. AR		
Baseline 1	0.6429	0.0856
Baseline 2	0.7619	0.028
Challenge	0.7857	0.0208
Recovery	0.881	0.0039
Response (Ch-B2)/B2	0.0476	0.9108

FFT – Fast Fourier Transformation, LF – Low frequency, HF – High Frequency, n.u. – normalized units, AR – Autoregression, Ch – Challenge, B2 – Baseline 2

Table 4.12 Spearman Correlations of the frequency domain HRV variables measured by Biofeedback equipment (ECG and BVP derived). N=8

	Spearman r	p-value
Biofeedback ECG LF% FFT & BVP LF% FFT		
Baseline 1	0.7857	0.0208
Baseline 2	0.7381	0.0366
Challenge	0.3333	0.4198
Recovery	0.7857	0.0208
Response (Ch-B2)/B2	0.7619	0.028
Biofeedback ECG HF% FFT & BVP HF% FFT		
Baseline 1	0.5238	0.1827
Baseline 2	0.4524	0.2604
Challenge	0.5	0.207
Recovery	0.6667	0.071
Response (Ch-B2)/B2	0.2857	0.4927
Biofeedback ECG LF/HF% FFT & BVP LF/HF% FFT		
Baseline 1	0.6667	0.071
Baseline 2	0.6429	0.0856
Challenge	0.8571	0.0065
Recovery	0.8982	0.0024
Response (Ch-B2)/B2	0.7143	0.0465

FFT – Fast Fourier Transformation, LF – Low frequency, HF – High frequency, LF/HF – Ratio of low frequency to high frequency, ECG – Electrocardiogram, BVP- Blood volume pulse, Ch – Challenge, B2 – Baseline 2

4.4 Discussion

The Thought Technology developer software has the capacity to create channel sets that calculate HFms^2 and LFms^2, but at the time when the channel sets for this study was developed the % power approach appeared more attractive, as it was argued that relative power can be more readily compared between individuals than absolute power values. In retrospect, it would have been better to calculate both relative and absolute power for a more comprehensive comparison of the HRV data obtained with the biofeedback equipment and the Actiheart equipment.

4.4.1 Time Domain: Actiheart versus ECG and BVP derived Biofeedback

As seen in Table 4.4, in the time domain the mean Heart Rate as measured by Actiheart and by Biofeedback ECG had very high correlations and strong significance for Baseline 1, Baseline 2, Challenge and Recovery ($r=0.9286$ to 1.0000, $p<0.001$) and high correlations with good significance for the Response ($r=0.8333$, $p=0.0102$). The same was seen for Actiheart and BVP derived Biofeedback heart rate, with high correlations for Baseline 1, Baseline 2, Challenge and Recovery ($r=0.9761$ to 1.0000, $p<0.0001$), and Response ($r=0.881$, $p=0.0039$). The ECG and BVP derived Biofeedback heart rate was highly correlated for Baseline 1, Baseline 2, Challenge and Recovery ($r=0.9762$, $p<0.0001$), and the correlation for the Response was $r=0.8333$ ($p=0.0102$). If Actiheart heart rate values are taken as the gold standard, both ECG and BVP derived Biofeedback heart rate measurements have a high degree of accuracy.

Standard deviation of heart rate is an important indicator of global heart rate variability. In contrast to the correlations with the heart rate, the Standard Deviation of the Heart Rate as measured with Actiheart and Biofeedback had no consistent or meaningful correlations (Table 4.5). In fact, conflicting results were found between Actiheart and BVP derived Biofeedback standard deviation of the heart rate, as well as between ECG and BVP derived Biofeedback standard deviation of heart rate values. A possible explanation of the discrepancies between Actiheart and Biofeedback standard deviation of the heart rate is the fact that the Actiheart data was corrected for artefact and the Biofeedback data was not. In uncorrected data, standard deviation would not only be a reflection of variation introduced by autonomic

control, but also of any artefact contaminating the recording. The reasons for the discrepancies between the ECG and BVP derived Biofeedback standard deviation of heart rate will be discussed further with the frequency domain results.

NN50 and pNN50 are indicators of vagal cardiac control. The NN50 and pNN50 correlations that were significant were also sporadic and uninformative (Table 4.6 and Table 4.7). Neither ECG nor BVP derived Biofeedback results had good correlations to Actiheart results, nor did the ECG and BVP derived Biofeedback results correlate with each other.

4.4.2 Frequency Domain: Actiheart FFT and Autoregression versus ECG and BVP derived Biofeedback

Conventionally, the main frequency domain indicators are considered HFms^2, HF % Power, HF n.u., LFms^2, LF % Power, LF n.u. and LF/HF Ratio. HF indicators reflect parasympathetic cardiac control, while LF indicators reflect sympathetic cardiac control with a parasympathetic component. The Biofeedback frequency domain variables did not include HFms^2 or LFms^2, so only the % power Actiheart results are presented here.

For LF% power (see Table 4.8), the Actiheart FFT method correlated well with the Biofeedback ECG derived results for Baseline1, Baseline2, Recovery and Response, with r = 0.7619 to 0.881 ($p<0.03$), but not during the Challenge ($r=0.6190$, $p=0.1017$). The BVP derived Biofeedback LF% power retained a strong correlation to the Actiheart FFT LF% power during Baseline 1, Baseline 2, Challenge, Recovery and the Response ($r=0.7143$, $p<0.05$). Autoregression LF% results didn't correlate well with the Biofeedback LF% power results. There was one significant correlation with the ECG results (Baseline 2) and two significant correlations with the BVP derived results (Baseline 2 and Challenge). This is in line with the fact that the Biofeedback results are obtained with FFT and not autoregression.

Significant correlations for HF% power were less numerous than the LF% power results (see Table 4.9). ECG derived HF% correlated strongly to FFT Actiheart HF% power during Baseline 1 ($r=0.8571$, $p=0.0065$) and Challenge ($r=0.9286$, $p=0.0009$). BVP derived HF% power correlated significantly with Actiheart FFT HF% power for

Baseline 1, Recovery and for the Response (r=0.7143 to 0.8571, p<0.05), but not Baseline 2 or Challenge. Actiheart Autoregression HF% power and ECG Biofeedback HF% power correlated significantly for Baseline 1 (r=0.7857, p=0.0208) and approached significance with Baseline 2 (r=0.6667, p=0.071). Actiheart Autoregression and BVP derived HF% power correlated significantly for Baseline 2 (r=0.7143, p=0.0465) and approached significance with Baseline 1 (r=0.6429. p=0.0856). For Challenge, Recovery and the Response there were no significant correlations between the Actiheart autoregression and Biofeedback (ECG and BVP derived) HF% power. Once again the Biofeedback results correlate better with the Actiheart FFT results that with the Actiheart autoregression results.

The ratio LF/HF is an indicator autonomic balance. ECG derived Biofeedback and Actiheart FFT results correlated well for Baseline 1, Baseline2 and Recovery (r=0.7619 to 0.9286, p<0.03) (see Table 4.10). BVP derived LF/HF and FFT Actiheart LF/HF correlated well for Baseline1, Recovery and for the Response (r=0.8095 to 0.9102, p<0.02). Autoregression correlated with ECG derived LF/HF only during Baseline 1(r=0.7619, p=0.0280), and with BVP derived LF/HF only during Baseline 2 (r=0.9286, p=0.0009).

In summary, the Biofeedback FFT based results for frequency domain analysis correlated much better to the Actiheart FFT results than the time domain indicators. Although $HFms^2$ and $LFms^2$ were not available, in view of the % power results (which are internally calculated from ms^2) it can be surmised that they would also have corresponded in a similar way. Throughout it was seen that the Biofeedback FFT results correlated less well with the Actiheart autoregression results. Subsequently, Actiheart FFT results were compared to Actiheart autoregression results.

4.4.3 Frequency Domain: Actiheart FFT versus Actiheart Autoregression

Using the data recorded with the Actiheart device, frequency domain variables were calculated with both FFT and autoregression methods (see Table 4.11). The LF% power correlated well between FFT and autoregression methods for Baseline 1, Baseline 2, Challenge and Recovery, with r between 0.7143 and 0.8571 (p<0.05), and for the Response the correlation approached significance (r= 0.6667, p=0.071). With HF% power, autoregression and FFT methods correlated well for Baseline1,

Baseline 2 and Recovery (r=0.7619 to 0.8571, p<0.03), but not for Challenge or Response. The LF/HF ratio correlated during Baseline 2, Challenge and Recovery (r=0.7619 to 0.881, p<0.05), but not Baseline1 or the Response. The LF n.u. and HF n.u. values correlated well for Baseline 2 and Challenge (r=0.7381 to 0.7857, p<0.05), and very well for Recovery (r=0.881 to 0.9524, p<0.01), but for Baseline 1 the correlations were weaker and only approached significance (r=0.5952 to 0.6429, p=0.0856 to 0.1195). There were no correlations for the Response values. In the literature, other studies comparing parametric and non-parametric HRV analyses have also found that the two methods are not interchangeable, even though they often yield similar trends (2). Pichon *et al* (3) found that the FFT method overestimated the HF component, possibly due to the pre-processing of the FFT algorithm and the tail effect, whereas AR analysis was not affected by these factors, and they concluded in favour of the AR method. On the other hand, Chemla *et al* (6) preferred the FFT method of HRV analysis in diabetic patients because of the superior day-to-day reproducibility of the FFT, and because it always yielded spectral component values, as opposed to numerous missing or null values obtained with AR. Silva and Ushizima *et al* (8) summarized the advantages of FFT as simplicity of algorithm, fast processing speed and good reproducibility, the disadvantages are the relatively complex post-recording windowing and filtering that needs some experience to master (8). The advantages of AR are superior performance with shorter recordings (reduced data points), simpler post-recording data processing and smoother spectral components obtained without the need for pre-determined frequency bands; the disadvantage of the parametric technique is the need to test and verify that the proper order of model was chosen (8).

4.4.4 Frequency Domain: Biofeedback ECG versus BVP

HRV is determined by calculating the changes of the interval between each successive heartbeat. The inter-beat-interval can be derived by timing the appearance of the R-spike in the ECG signal or the point of maximum deviation in the BVP signal. These critical points are sometimes called the fiducial point (9). In previous paragraphs it was seen that the results obtained by ECG and BVP do not always correspond. The correlations of the ECG and BVP derived Biofeedback frequency domain HRV values are in Table 4.12. LF% power values correlated well

with each other for Baseline 1, Baseline 2, Recovery and for the Response (r=0.7381 to 0.7857, p<0.05), but not at all during Challenge (r=0.3333, p=0.4198). No significant correlations could be found between ECG and BVP derived Biofeedback HF% power, but during Recovery the correlation approached significance (r=0.6667, p=0.071). The ECG and BVP derived Biofeedback LF/HF ratio correlated for Challenge, Recovery and for the Response (r=0.7143 to 0.8982, p<0.05), but during Baseline 1 and Baseline 2 the correlations only approached significance (r=0.6429 to 0.6667, p<0.1).

In the introduction it was mentioned that BVP was not only an indicator of cardiac rhythm, but also of vasomotor activity, and prone to disturbances by movement. Medeiros and Martins *et al* (10) reported very high levels of correlation between HRV measures based on ECG and BVP. In their study done on 18 healthy volunteers they did caution that subjects must remain very still (10), and perhaps achieved more success in that regard. The good correlations seen in the study by Medeiros and Martins are supported by other studies comparing HRV obtained with ECG and BVP respectively (11-13).

Possible drawbacks of using BVP in the determination of HRV include, as mentioned above, the vulnerability to movement (10,14). However, other factors may also confound the results. The ECG signal allows much more precision in the detection of beats because the QRS complex of the ECG wave is more sharply defined than the rounded fiducial point of the BVP signal (15). Another drawback of BVP is the fact that it is based on measuring reflected infrared light rather than an electrical signal and instability of sensor attachment can create wide fluctuations in the waveform that drown out the BVP signal completely, causing missed or extra beats to be registered when determining IBI (9).

4.5 Conclusions

In conclusion;

- It appears that the hardware capabilities of the two systems are comparable when it comes to registering heartbeats and calculating heart rate, but when the data is further processed to obtain time domain HRV variables the differences between Actiheart and Biofeedback results are unacceptable.
- The frequency domain Biofeedback HRV variables had relatively good correlations to the Actiheart FFT results.
- The frequency domain Biofeedback HRV variables had poor correlations to the Actiheart autoregression results. However, the Actiheart FFT and Actiheart autoregression results also differed – a phenomenon previously seen in the work from other laboratories.
- ECG based frequency domain HRV variables are preferable to BVP based frequency domain results due to the fact that the BVP signal is prone to movement artefact and other forms of interference.

The relatively good correlations found between the Biofeedback FFT frequency domain results and the Actiheart FFT frequency domain results are encouraging. The potential exists to adapt Biofeedback data processing in order to render it even more suitable for HRV assessment. It is already possible to change the virtual channel set calculations in order to obtain ms^2 values and n.u. values, and the results can be further improved by more advanced data filtering and correcting capabilities. In view of the success of Biofeedback practices such as upregulation of HRV and improvement of sympathetic and parasympathetic balance (16-18), improvement of the assessment processes can be of great value. Some of the newer Thought Technology products offer IBI normalization to more advanced users (9), which in view of the results of this study would likely yield high quality HRV determination tools, but it falls on future research to validate.

In the next chapter the HRV indicator values obtained by the two instruments are compared in a clinical application exercise.

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5 Association between autonomic nervous system status and response and the levels of anxiety and burnout in a normal population: Does biofeedback results mirror that of conventional methods?

5.1 Introduction

Until recently the chronic increased heart rate associated with certain psychological states or disorders has primarily been ascribed to increases in the activity of the sympathetic nervous system. This approach probably originated as an outflow of Cannon's fight or flight concept of sympathetic nervous system activation in the face of a threat (1). Unfortunately, the belief that chronic increases in heart rate in all stress-associated conditions are the direct result of sympathetic activation is still widely propagated and even appears as such in a number of text books. Heart rate is the product, not only of the balance between sympathetic and parasympathetic activity, but is influenced by several other factors. Although the sympathetic nervous system can increase the heart rate, moderate increases in heart rate with increased work loads are, with other influential factors being equal, almost entirely the result of the withdrawal of the inhibitory vagal (parasympathetic) tone to the sino-atrial node (2). However, vagal withdrawal on its own is said to be able to increase the heart rate only up to 100 beats per minute. Further increases are reliant on the slower developing excitatory drive of the sympathetic nervous system (2). More significant increases in heart rate, whether due to an increase in physical activity or in response to an aversive psychological challenge, will therefore nearly always lead to the typical stress response of vagal withdrawal and sympathetic activation (3).

In many, but not all studies, the focus on the chronic heart rate upregulation associated with emotional states is shifting from the primarily sympathetic nervous system approach to the more balanced concept of interaction between the sympathetic and parasympathetic nervous systems. In anxious individuals, studies on baseline autonomic nervous system functioning, by means of heart rate variability techniques, generally, but not all, point towards a causal link between increased heart rate and a low parasympathetic tone (4). Findings of lower resting vagal control with anxiety are supported by the vagal-suppressive effect seen when control

subjects are subjected to stimuli that induce anxiety and worry (5). Low parasympathetic activity has also been described in a number of anxiety disorders (4). Despite some contradictions between findings it would by and large appear that anxiety disorders, and perhaps also excessive worrying in individuals not diagnosed with anxiety disorders, are associated with subnormal resting vagal control of the heart, as well as a decrease in vagal-related baseline heart rate variability (4,6).

Heart rate variability studies on resting sympathetic tone in anxious individuals and anxiety disorders are less conclusive. The most probable reason for this is that the vagal tone is much easier to assess by heart rate variability than sympathetic tone. While some studies found decreased resting parasympathetic, as well as sympathetic activity in anxiety and anxiety disorders, others are of the opinion that only parasympathetic activity is decreased and that sympathetic activity is increased, while others could not show any difference from normal (4,5,7,8).

Perhaps of greater concern with regard to anxiety and anxiety disorders are findings of an autonomic inflexibility or decreased response in the face of a stimulus or stressor. This is usually expressed in terms of a subnormal vagal reactivity (4,6). However, indications of a low electrodermal response when faced with a challenge or stressor (9) suggest that a decrease in the responsitivity of the sympathetic nervous system may contribute to overall autonomic nervous system inflexibility. In view of the wide spectrum of bodily functions controlled by the autonomic nervous system, this does not augur well for the general health of the individual with chronically high levels of anxiety.

In 1974 Herbert Freudenberger coined the term burnout. In his book *Burnout: The High Cost of High Achievement* he defined burnout as the extinction of motivation or incentive, especially where one's devotion to a cause or relationship fails to be rewarded (10). Although not a psychiatric diagnosable entity, there are a number of corresponding features between burnout and conditions such as anxiety and affective disorders, and scores on both trait and state anxiety have on occasion been shown to correlate to that on burnout (11).

Burnout is generally considered to be the result of high work-related stress levels. One of the main features of burnout is emotional exhaustion. According to Selye’s general adaptation syndrome, exhaustion is the third and final stage in this model of

stress (12). Although not much is available on autonomic nervous system functioning and burnout, some conflicting results are published on the association between resting HRV values, as well as the response of the autonomic nervous system, on the one hand, and emotional/cognitive exhaustion on the other. Autonomic nervous system function differs between acute and chronic mental or emotional fatigue or exhaustion. With acute fatigue, induced by periods of intense cognitive or emotional activity, indications are that the autonomic balance, as for acute stress in general, shifts in the direction of sympathetic activity with an increase in sympathetic and a decrease in the parasympathetic control of the heart (13). With chronic mental fatigue or exhaustion as in the burnout syndrome the picture, in the otherwise healthy, is less clear and less well-studied. Indications vary from a decrease in resting parasympathetic control, to no significant difference between burnout and normal, to increased parasympathetic control in individuals with burnout (14-16). Perhaps of greater interest are results showing the expected vagal reactivity during a cognitive challenge to be lower than normal with the exhaustion of burnout (17), pointing to a degree of vagal inflexibility and, by implication, a decrease in general well-being.

We live in a time marked by information overload and many individuals appear to be chronically tired or anxious. This state has become the norm for many and very little thought is given to it. The question is whether any association exists between heart rate indicators of autonomic function on the one hand, and levels of anxiety or burnout on the other, in individuals not diagnosed with and without complaints of anxiety or burnout. The first aim of this study was therefore to assess whether any correlation exist between levels of anxiety and burnout on the one hand, and resting autonomic nervous system functioning or the autonomic response to a mild to moderate cognitive stressor, on the other. In line with the aim of this dissertation the results obtained by means of biofeedback apparatus were compared to that derived from more conventional Actiheart heart rate monitor assessments.

5.2 Materials and methods

5.2.1 Subjects

Eight individuals volunteered to take part in this pilot study. Clearance for the study was obtained from the Ethics Committee of the Faculty of Health Sciences (reference number S56/2010), University of Pretoria and all subjects signed informed consent. Exclusion criteria included individuals previously diagnosed with an anxiety disorder, individuals suspected to suffer from burnout, individuals taking medication that could influence heart rate or blood pressure, anti-depressants and individuals diagnosed with convulsive disorders.

5.2.2 HRV Analysis

As in Chapter 4, tachograms for the analyses of heart rate variability were recorded by means of the Actiheart and by biofeedback monitors. The Actiheart chest-worn heart rate monitor (CamNtech Ltd, Cambridge, UK) was used, error correction was done using the Polar Precision Performance Software version 4.03.040 (Polar Electro Oy, Kempele, Finland) and HRV analysis was carried out using the advanced HRV Analysis 1.1 software for windows, developed by The Biomedical Signal Analysis Group, University of Kuopio, Finland (18).

Time-domain measures and nonparametric frequency-domain analysis based on fast Fourier transformations (FFT) were employed for calculation of power spectral density (PSD) of the IBI data series (19). Before the FFT were employed all imported data were detrended using the smoothness priors method (20) to remove the disturbing low frequency baseline trend component. Because the IBI data series are known to be unequally spaced, it needs to be interpolated before computing the FFT. The IBI data series was interpolated at a sampling rate of 4 Hz (21).

Time-domain measures, which are calculated from the raw RR interval series, included the standard deviation of all normal RR intervals (SDNN, describing the overall variation of RR intervals and interpreted as an estimate of overall HRV), and the root mean square of the differences between successive RR intervals (RMSSD, for estimation of short-term components of HRV). Frequency-domain analysis

informs on the relative power of underlying intrinsic rhythms involved in the regulation of HR. The high frequency (HF) band (0.15–0.4 Hz) is known to represent mainly parasympathetic activity and the low frequency (LF) band (0.04–0.15 Hz) largely sympathetic, but with a parasympathetic component. This makes the information captured in the LF band more difficult to interpret. If the LF band is expressed in normalised units (LF n.u. = LF / (Total power - VLF)) or percentage power (LFperc = LF/Total power percentage) it tends to mirror sympathetic activity (19). Very low frequency (VLF) is the frequency band 0.003–0.04 Hz. The LF/HF ratio is interpreted as an index of sympathico-vagal balance, where an increase in the ratio can be considered as an increase in sympathetic activity. Although the focus with Actiheart assessments on frequency-domain analysis was primarily based on FFT, autoregression (AR) was also applied and where significant differences were found results are so indicated. In addition, Poincare analysis was performed where SD1(ms) is seen as an indicator of the standard deviation of the immediate or short-term RR variability as a result of parasympathetic efferent influences on the sino-atrial node, and SD2(ms) as an indicator of the long-term or slow variability of heart rate and seen as representative of the global variation in HRV (19).

HRV recordings with Biograph Infinity biofeedback equipment (Thought Technology, Montreal West, Quebec, Canada) were performed simultaneously with the Actiheart recordings. Tachograms were obtained from BVP and ECG. The HRV analysis with the biofeedback apparatus was also discussed in more detail in Chapter 4.

As in Chapter 4, the recording session consisted of four steps; two successive baseline recordings, one recording during a cognitive challenge and a recording during the recovery period.

The cognitive stressor involved an activity screen with a bowling ball animation, with the playback of the animation contingent to the test subject increasing the relative power of his SMR rhythm. The channel sets, screens and scripts were described more extensively in Chapter 3 and 4.

5.2.3 Psychometric Tests

Trait anxiety was assessed by the State-Trait Anxiety Inventory for Adults (STAI). The State-Trait Anxiety Inventory for Adults (STAI) consists of two self-report scales, the state anxiety scale consisting of twenty statements about how the respondent feels at the very moment and the trait anxiety scale about how the respondent feels in general. The primary feelings assessed by the anxiety scales are that of apprehension, tension, nervousness and worry (22). Trait anxiety is the relatively stable tendency of a person to perceive potentially threatening situations as dangerous and to respond to it by increasing the intensity of their anxiety reactions. State anxiety, on the other hand, refers to a reaction or process taking place at a specific time and at a specific level of intensity. The stronger the anxiety trait the more likely it is that the individual will experience more intense elevations in state anxiety in threatening situations (22).

Burnout was assessed by the Maslach Burnout Inventory-General Survey. Various inventories for the assessment of burnout exist of which the Maslach Burnout Inventory – Human Services Survey (MBI-HSS) may be the most commonly used. The MBI-HSS was intended for use on people providing human services and assesses three subscales, i.e., emotional exhaustion, depersonalization and personal accomplishment. Emotional exhaustion is said to reflect the extent to which the individual is emotionally overextended and exhausted by his or her work, while depersonalization reflects disinterest or an insensitive or impersonal approach to individuals at the receiving end of the human service. The personal accomplishment subscale is intended to assess the individual's perception of his or her accomplishment and success in the work situation. The Maslach Burnout Inventory–General Survey (MBI-GS) is an adaptation of the MBI-HHS for use when the individual is not primarily involved with services such as teaching, nursing and similar occupations. It defines one's relationship with work and not exclusively one relationship with people at work. The three subscales of the MBI-GS are exhaustion, cynicism and professional efficacy. While exhaustion and professional efficacy for the MBI-GS measure very similar aspects to that of exhaustion and personal accomplishment on the MBI-HHS, cynicism, introduced in the place of depersonalization, is said to be a dysfunctional coping mechanism where the

individual becomes indifferent to his work in order to distance him- or herself from the demands imposed by the work (23).

5.2.4 Statistics

The HRV measures made by the Biograph Infinity and Actiheart apparatuses were evaluated separately for Baseline 1, Baseline 2, Challenge and Recovery. The response of the subject to the cognitive stressor in the Challenge step was calculated by subtracting the Baseline 2 value from the Challenge value and dividing the result by the Baseline 2 value ((Ch-B2)/B2). When multiplied by 100, the percentage change from Baseline 2 to Challenge (the Response) was obtained.

The Response values, as well as descriptive statistics for each data set, were calculated in Microsoft Office Excel (2007) spread sheets.

The results of the different equipment systems and calculation techniques were correlated with the psychometric scores using Spearman's Ranked Correlations (2-tailed), STATISTICA version 10 data analysis software (24).

5.3 Results

Table 5.1 shows the MBI-GS psychometric item scores for eight individuals tested with both the Actiheart and biofeedback equipment, Table 5.2 shows the STAI psychometric item scores. Table 5.3 illustrates the significant and approaching significant Spearman raked correlations between the MBI-GS items and the STAI items.

Table 5.1 MBI-GS psychometric item scores for eight individuals tested with both the Actiheart and Biofeedback equipment

Study Number	MBI EX			MBI CY			MBI PE		
	Raw	(Fr)	Rank	Raw	(Fr)	Rank	Raw	(Fr)	Rank
A32	23	4.6	High	11	2.2	Mod	34	5.7	High
C30	20	4	High	6	1.2	Mod	35	5.8	High
D28	20	4	High	22	4.4	High	31	5.2	High
F26	14	2.8	Mod	5	1	Low	34	5.7	High
G33	8	1.6	Mod	9	1.8	Mod	25	4.2	Mod
K24	20	4	High	14	2.8	High	29	4.8	Mod
L29	19	3.8	High	20	4	High	30	5	High
S25	14	2.8	Mod	19	3.8	High	24	4	Mod

MBI – Maslach burnout inventory, GS – General survey, EX – Exhaustion subscale, CY – Cynicism subscale, PE – Professional efficacy subscale, Fr – Subscale frequency, Mod – Moderate, MBI (EX): 8-15 = moderate, ≥16 = high; MBI (CY): 6-12 = moderate, ≥ 13 = high; MBI (PE): 24-29 = moderate, ≥ 30 = high;

Table 5.2 STAI psychometric item scores for eight individuals tested with both the Actiheart and Biofeedback equipment

Study Number	STAI - Y1		STAI - Y2	
	Raw	(Pr)	Raw	(Pr)
A32	29	34	53	93
C30	31	41	47	89
D28	37	62	42	76
F26	30	31	45	83
G33	47	85	37	63
K24	41	70	53	95
L29	28	25	40	71
S25	32	39	35	57

STAI – State-trait anxiety inventory, Y1 – Sheet Y1 or state anxiety, Y2 – Sheet Y2 or trait anxiety, (Pr) – Percentile rank; STAI-Y1 normal range: 36.54 SD 10.22; STAI-Y2 normal range: 35.55 SD 9.76;

Table 5.3 Significant and approaching significant Spearman ranked correlations between the MBI-GS items and the STAI items for the eight individuals tested with both the Actiheart and Biofeedback equipment. N=8

Psychometric Item		Spearman r	P - value
STAI Y2	MBI Ex (Fr)	0.7904	0.0245
STAI Y2 (Pr)	MBI Ex (Fr)	0.7611	0.0313
STAI Y2	MBI Pe (Fr)	0.6446	0.0827

STAI – State-trait anxiety inventory, Y1 – Sheet Y1 or state anxiety, Y2 – Sheet Y2 or trait anxiety, (Pr) – Percentile rank, MBI – Maslach burnout inventory, GS – General survey, EX – Exhaustion subscale, PE – Professional efficacy subscale

Table 5.4 to Table 5.8 gives the Spearman ranked correlations between STAI Items and HRV values obtained by Actiheart and Biofeedback, Table 5.9 to Table 5.13 gives the Spearman ranked correlations between MBI Items and HRV values obtained by Actiheart and Biofeedback devices.

Table 5.4 Baseline 1 Spearman ranked correlations between STAI items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
HF ms^2 AR	STAI Y1	-0.7143	0.0465
HF% AR	STAI Y1	-0.6429	0.0856
	Biograph		
ECG HR StdDev	STAI Y1	-0.8571	0.0065
ECG HR CoefVar	STAI Y1	-0.8571	0.0065
ECG HR StdDev	STAI Y1 Pr	-0.8571	0.0065
ECG HR CoefVar	STAI Y1 Pr	-0.8571	0.0065
ECG LF% CoefVar	STAI Y2	0.6707	0.0687
BVP HF% CoefVar	STAI Y2	-0.6347	0.0909
ECG LF% CoefVar	STAI Y2 Pr	0.7143	0.0465

AR – Autoregression, BVP- Blood volume pulse, CoefVar – Coefficient of variation, ECG – Electrocardiogram, HF – High Frequency, HR – Heart Rate, LF – Low frequency, Pr – Percentile rank, STAI – State-trait anxiety inventory, StdDev – Standard Deviation, Y1 – Sheet Y1 or state anxiety, Y2 – Sheet Y2 or trait anxiety

Table 5.5 Baseline 2 Spearman ranked correlations between STAI items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
			None
	Biograph		
BVP LF% CoefVar	STAI Y2	-0.7066	0.0501
BVP LF% CoefVar	STAI Y2 Pr	-0.7381	0.0366

BVP- Blood volume pulse, CoefVar – Coefficient of variation, LF – Low frequency, Pr – Percentile rank, STAI – State-trait anxiety inventory, Y2 – Sheet Y2 or trait anxiety

Table 5.6 Challenge Spearman ranked correlations between STAI items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
			None
	Biograph		
ECG HF% StdDev	STAI Y1	-0.7619	0.028
ECG HF% StdDev	STAI Y1 Pr	-0.7143	0.0465

ECG – Electrocardiogram, HF – High Frequency, HR – Heart Rate, Pr – Percentile rank, STAI – State-trait anxiety inventory, StdDev – Standard Deviation, Y1 – Sheet Y1 or state anxiety

Table 5.7 Recovery Spearman ranked correlations between STAI items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
HF ms^2 AR	STAI Y1	-0.8571	0.0065
HF ms^2 AR	STAI Y1 Pr	-0.7619	0.028
RMSSD ms	STAI Y2	-0.6347	0.0909
SD1 ms	STAI Y2	-0.6347	0.0909
RMSSD ms	STAI Y2 Pr	-0.6667	0.071
SD1 ms	STAI Y2 Pr	-0.6667	0.071
	Biograph		
BVP HF% CoefVar	STAI Y1 Pr	0.6667	0.071
BVP LF% StdDev	STAI Y2	-0.6826	0.0621
BVP LF/HF StdDev	STAI Y2	-0.6826	0.0621
ECG HF% CoefVar	STAI Y2	0.6347	0.0909
BVP LF% StdDev	STAI Y2 Pr	-0.6905	0.058
BVP LF/HF StdDev	STAI Y2 Pr	-0.6905	0.058

AR – Autoregression, BVP- Blood volume pulse, CoefVar – Coefficient of variation, ECG – Electrocardiogram, HF – High Frequency, LF – Low frequency, Pr – Percentile rank, RMSSD – Root mean square of the differences of successive RR intervals, SD1 – Short term RR variability with Poincare' analysis, STAI – State-trait anxiety inventory, StdDev – Standard Deviation, Y1 – Sheet Y1 or state anxiety, Y2 – Sheet Y2 or trait anxiety

Table 5.8 Response Spearman ranked correlations between STAI items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
StdDev RR	STAI Y1	-0.7381	0.0366
StdDev HR	STAI Y1	-0.7619	0.028
RMSSD ms	STAI Y1	-0.7381	0.0366
SD1 ms	STAI Y1	-0.7381	0.0366
LF ms^2 AR	STAI Y1 Pr	-0.6429	0.0856
StdDev RR	STAI Y1 Pr	-0.8333	0.0102
StdDev HR	STAI Y1 Pr	-0.7857	0.0208
RMSSD ms	STAI Y1 Pr	-0.8333	0.0102
NN50 count	STAI Y1 Pr	-0.7381	0.0366
pNN50%	STAI Y1 Pr	-0.7381	0.0366
TINN ms	STAI Y1 Pr	-0.7186	0.0446
SD1 ms	STAI Y1 Pr	-0.8333	0.0102
HF% FFT	STAI Y2	-0.6467	0.0831
LF/HF FFT	STAI Y2	0.6467	0.0831
	Biograph		
BVP LF/HF Mean	STAI Y2	0.6707	0.0687
BVP LF/HF Mean	STAI Y2 Pr	0.6429	0.0856

AR – Autoregression, BVP- Blood volume pulse, CoefVar – Coefficient of variation, FFT – Fast Fourier Transformation, HF – High Frequency, HR – Heart Rate, LF – Low frequency, NN50 – Normal-to-normal interval differences of 50ms or more, pNN50% – Percentage of Normal-to-normal interval differences of 50ms or more, Pr – Percentile rank, RMSSD – Root mean square of the differences of successive RR intervals, RR – R-R interval, SD1 – Short term RR variability with Poincare' analysis, STAI – State-trait anxiety inventory, StdDev – Standard Deviation, TINN – NN Triangular index, Y1 – Sheet Y1 or state anxiety, Y2 – Sheet Y2 or trait anxiety,

Table 5.9 Baseline 1 Spearman ranked correlations between MBI-GS items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
HF% FFT	MBI Ex	0.7489	0.0325
LFn.u. FFT	MBI Ex	-0.6506	0.0806
HFn.u. FFT	MBI Ex	0.6506	0.0807
LF/HF FFT	MBI Ex	-0.6506	0.0807
LF% AR	MBI Ex	-0.7488	0.0325
HF ms^2 AR	MBI Pe	0.6587	0.0757
HF% AR	MBI Pe	0.8024	0.0165
LFn.u. AR	MBI Pe	-0.6946	0.0559
HFn.u. AR	MBI Pe	0.6587	0.0757
LF/HF AR	MBI Pe	-0.7186	0.0446
pNN50%	MBI Pe	-0.6826	0.0621
	Biograph		
BVP HF% CoefVar	MBI Ex	-0.8961	0.0026
BVP HF% StdDev	MBI Ex	-0.8225	0.0122
BVP LF/HF StdDev	MBI Ex	-0.7243	0.0422
ECG HF% Mean	MBI Ex	0.6383	0.0885
BVP LF/HF CoefVar	MBI Ex	-0.6261	0.0968
ECG HF% Mean	MBI Pe	0.6946	0.0559

AR – Autoregression, BVP- Blood volume pulse, CoefVar – Coefficient of variation, ECG – Electrocardiogram, EX – Exhaustion subscale, FFT – Fast Fourier Transformation, GS – General survey, HF – High Frequency, LF – Low frequency, MBI – Maslach burnout inventory, n.u. – Normalized Units, PE – Professional efficacy subscale,pNN50% – Percentage of Normal-to-normal interval differences of 50ms or more, StdDev – Standard Deviation

Table 5.10 Baseline 2 Spearman ranked correlations between MBI-GS items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
HF% FFT	MBI Ex	0.7488	0.0325
LFn.u. FFT	MBI Ex	-0.7488	0.0325
HFn.u. FFT	MBI Ex	0.7488	0.0325
LF/HF FFT	MBI Ex	-0.7488	0.0325
LFn.u. AR	MBI Ex	-0.6506	0.0806
LF ms^2 AR	MBI Pe	-0.6587	0.0757
LFn.u. AR	MBI Pe	-0.6587	0.0757
StdDev RR	MBI Pe	-0.7186	0.0446
RMSSD ms	MBI Pe	-0.7186	0.0446
NN50 count	MBI Pe	-0.759	0.029
pNN50%	MBI Pe	-0.7545	0.0305
TINN ms	MBI Pe	-0.6807	0.0631
SD1 ms	MBI Pe	-0.7186	0.0446
	Biograph		
ECG LF/HF StdDev	MBI Ex	-0.8347	0.0099
ECG LF% StdDev	MBI Ex	-0.7488	0.0325
ECG NN50 count	MBI Ex	-0.6793	0.0639
ECG LF% Mean	MBI Ex	-0.6752	0.0662
ECG LF/HF Mean	MBI Ex	-0.6383	0.0885

AR – Autoregression, ECG – Electrocardiogram, EX – Exhaustion subscale, FFT – Fast Fourier Transformation, GS – General survey, HF – High Frequency, LF – Low frequency, MBI – Maslach burnout inventory, NN50 – Normal-to-normal interval difference of 50ms or more, n.u. – Normalized Units, PE – Professional efficacy subscale, pNN50% – Percentage of Normal-to-normal interval differences of 50ms or more, RMSSD – Root mean square of the differences of successive RR intervals, RR – R-R interval, SD1 – Short term RR variability with Poincare' analysis, StdDev – Standard Deviation, TINN – NN Triangular index

Table 5.11 Challenge Spearman ranked correlations between MBI-GS items and HRV values obtained with Actiheart and Biograph. N=8

		Spearman r	P-value
	Actiheart		
LF% AR	MBI Ex	-0.6383	0.0885
HF% AR	MBI Ex	0.6874	0.0596
HFn.u. AR	MBI Ex	0.6383	0.0885
LF/HF AR	MBI Ex	-0.6874	0.0596
LF ms^2 AR	MBI Pe	-0.6467	0.0831
NN50 count	MBI Pe	-0.6467	0.0831
pNN50%	MBI Pe	-0.6467	0.0831
TINN ms	MBI Pe	-0.7048	0.0509
	Biograph		
ECG LF/HF CoefVar	MBI Ex	-0.6506	0.0806
ECG LF% Mean	MBI Ex	-0.6261	0.0968

AR – Autoregression, CoefVar – Coefficient of variation, ECG – Electrocardiogram, EX – Exhaustion subscale, GS – General survey, HF – High Frequency, LF – Low frequency, MBI – Maslach burnout inventory, NN50 – Normal-to-normal interval differences of 50ms or more, n.u. – Normalized Units, PE – Professional efficacy subscale, pNN50% – Percentage of Normal-to-normal interval differences of 50ms or more, StdDev – Standard Deviation,

Table 5.12 Recovery Spearman ranked correlations between MBI-GS items and HRV values obtained with a) Actiheart and b) Biograph. N=8

a)

Actiheart		Spearman r	P-value
LF% FFT	MBI Ex	-0.6997	0.0534
HF% FFT	MBI Ex	0.6506	0.0806
LFn.u. FFT	MBI Ex	-0.6506	0.0806
HFn.u. FFT	MBI Ex	0.6506	0.0806
LF/HF FFT	MBI Ex	-0.6506	0.0806
HF% AR	MBI Ex	0.6261	0.0968
HFn.u. AR	MBI Ex	0.6261	0.0968
LF/HF AR	MBI Ex	-0.6261	0.0968
StdDev RR	MBI Ex	-0.6261	0.0968
HF% FFT	MBI Pe	0.6587	0.0757
LF ms^2 AR	MBI Pe	-0.7066	0.0501
LF% AR	MBI Pe	-0.6587	0.0757
HF% AR	MBI Pe	0.6946	0.0559
HFn.u. AR	MBI Pe	0.6946	0.0559
LF/HF AR	MBI Pe	-0.6946	0.0559
StdDev RR	MBI Pe	-0.6826	0.0621
pNN50%	MBI Pe	-0.6467	0.0831
RR tri index	MBI Pe	-0.7785	0.0229
TINN ms	MBI Pe	-0.6867	0.0599

b)

Biograph		Spearman r	P-value
ECG LF% Mean	MBI Ex	-0.933	0.0007
ECG LF% CoefVar	MBI Ex	0.8961	0.0026
ECG HF% CoefVar	MBI Ex	0.847	0.008
ECG HF% StdDev	MBI Ex	0.8347	0.0099
ECG LF% StdDev	MBI Ex	0.7979	0.0176
BVP LF% Mean	MBI Ex	-0.7243	0.0422
ECG LF/HF Mean	MBI Ex	-0.6752	0.0662
ECG LF/HF CoefVar	MBI Cy	0.6905	0.058

AR – Autoregression, BVP- Blood volume pulse, CoefVar – Coefficient of variation, CY – Cynicism subscale, ECG – Electrocardiogram, EX – Exhaustion subscale, FFT – Fast Fourier Transformation, GS – General survey, HF – High Frequency, LF – Low frequency, MBI – Maslach burnout inventory, n.u. – Normalized Units, PE – Professional efficacy subscale, pNN50% – Percentage of Normal-to-normal interval differences of 50ms or more, RR – R-R interval, SD1 – Short term RR variability with Poincare' analysis, StdDev – Standard Deviation, TINN – NN Triangular index

Table 5.13 Response Spearman ranked correlations between MBI-GS items and HRV values obtained with Actiheart and Biograph. N=8 except where marked with *, then N=7

		Spearman r	P-value
	Actiheart		
HF% FFT	MBI Ex	-0.9207	0.0012
HFn.u. FFT	MBI Ex	-0.8716	0.0048
LF/HF FFT	MBI Ex	0.9207	0.0012
HF% FFT	MBI Pe	-0.6228	0.0991
HFn.u. FFT	MBI Pe	-0.6467	0.0831
LF/HF FFT	MBI Pe	0.6228	0.0991
	Biograph		
ECG LF/HF StdDev	MBI Ex	0.712	0.0476
ECG LF% StdDev	MBI Ex	0.6997	0.0534
ECG NN50 count	MBI Ex *	0.7432	0.0556
BVP LF/HF Mean	MBI Ex	0.6752	0.0662
ECG HR CoefVar	MBI Ex	0.6261	0.0968
BVP LF/HF Mean	MBI Pe	0.6347	0.0909
ECG pNN50	MBI Cy *	0.8289	0.0212
ECG NN50 count	MBI Cy *	0.6847	0.0897

BVP- Blood volume pulse, CoefVar – Coefficient of variation, CY – Cynicism subscale, ECG – Electrocardiogram, EX – Exhaustion subscale, FFT – Fast Fourier Transformation, GS – General survey, HF – High Frequency, LF – Low frequency, MBI – Maslach burnout inventory, NN50 – Normal-to-normal interval differences of 50ms or more, n.u. – Normalized Units, PE – Professional efficacy subscale, pNN50% – Percentage of Normal-to-normal interval differences of 50ms or more,Pr – Percentile rank, StdDev – Standard Deviation

5.4 Discussion

The aim of this chapter was to test the performance of Biograph Infinity Biofeedback equipment and the Biograph Infinity software in a clinical application. This was done by using HRV data obtained by equipment specialized for HRV assessment (Actiheart) to study the relationship between autonomic function, anxiety and burnout and then to compare these findings to that obtained when HRV values were obtained by Biograph. Levels of anxiety and burnout in a group of normal, apparently healthy, professionals were compared to their baseline autonomic nervous system status and to their autonomic response to a moderate mental challenge. The rational for using ostensibly normal healthy individuals was that higher sensitivity and specificity would be required to detect smaller variation in autonomic function.

The mean scores on the burnout inventory (Table 5.1) were 17.3 (SD 4.9) for exhaustion, 13.3 (SD 6.5) for cynicism and 30.3 (SD 4.1) for professional efficacy which were all on the border of moderate and high. The mean state anxiety scores for the group (Table 5.2) was 34.4 (SD 6.7), and the mean percentile rank of the state anxiety scores was 48.4 (SD 21.4). The mean trait anxiety score (Table 5.2) was 44 (SD 6.8), and the mean percentile rank of the state anxiety scores was 78.4 (SD 14). State anxiety were thus very similar to the normative values (36.5, SD 10.2), while trait anxiety was higher than normative values (35.6, SD 9.8). The fact that the computer-based cognitive challenge in this study was not experienced as particularly stressful (as seen from state anxiety scores), despite the anxiety-proneness indicated by the high trait anxiety, could probably be partially be ascribed to the fact that the majority of the test subjects worked in the Information Technology field.

Results from the present study showed highly significant correlations (STAI Y2 *vs* MBI Ex Fr: r=0.7904, p=0.0245; STAI Y2 Pr *vs* MBI Ex Fr: r=0.7611, p=0.0313) between the trait anxiety scores and the levels of exhaustion on the MBI (Table 5.3). It has been said that a number of corresponding features exist between burnout and conditions such as anxiety (11). Anxiety scores have, indeed, on previous occasions, been shown to correlate to that on burnout (11). Whether this association, as well as the correlations found in other studies, is of specific significance or merely epiphenomenal in nature is open to conjecture.

With Actiheart assessments few associations were seen between the levels of anxiety and baseline autonomic status (Table 5.4 & Table 5.5). This lack of correlations with resting HRV assessments was previously seen in other studies (8). In the present study no significant results were found with Actiheart and FFT, but Actiheart HRV results obtained by means of autogression/frequency domain analyses were indicative of a negative correlation between state anxiety and parasympathetic (vagal) control of the heart. These indications of a negative association between indicators of parasympathetic control of the heart and state anxiety were seen for baseline 1 (Table 5.4) in terms of $HFms^2$ (r=-0.7143, p=0.0465) and HF percentage power (r= -0.6429, p=0.0856) and during recovery (r= -7381, p=0.0065). Negative correlations approaching statistical significance were also seen during recovery between trait anxiety and vagal control in terms of RMSSD and SD1 (Table 5.7).

The HRV indications for the baseline values obtained by biofeedback equipment (Table 5.4 & Table 5.5) showed a significant decrease in overall HRV with increases in the levels of state anxiety (ECG HR StdDev & STAI Y1: r= -0.-8571, p= 0.0065; ECG HR StdDev & STAI Y1 Pr: r= -0.8571; p=0.0065; ECG HR CoefVar & STAI Y1: r= -0.8571, 0.0065). It further showed increased levels of sympathetic variability with increases in levels of trait anxiety (ECG LF%Power CoefVar & STAI Y2 Pr: r = 0.7143, p= 0.0465; ECG LF%Power CoefVar & STAI Y2: r= - 0.6706, p=0.0687) and pointed towards decreased levels of parasympathetic variability of the heart with increased levels of trait anxiety (BVP HF%Power CoefVar & STAI Y2: r= -0.634742, p=0.0909)

These results suggest that even in individuals not diagnosed with anxiety disorders, subtle increases in worry and anxiety may influence autonomic nervous system functioning. The trend seen in the above discussed results showed that worry and anxiety may in essence be of a cardiac accelerating (decreased vagal control) nature and that it may have a further deleterious effect on the heart by decreasing heart rate variability.

The association between the level of anxiety and the autonomic responses to the cognitive challenge were subsequently examined. A marginal increase was seen from baseline to challenge in the parasympathetic (AR HFpercentage: p≤0.0516; AR

HF n.u.: p≤0.0549), and a significant decrease in sympathetic (AR LFpercentage: p≤0.0499; FFT LFpercentage: p ≤0.0185) cardiac control in response to the cognitive stressor. Despite a multitude of studies on the response of the autonomic nervous system to various kinds of stressors, many uncertainties still exist. Although the autonomic nervous system response to physical stressors, such as orthostatic stress is to a marked extent - but not completely - understood, a large degree of controversy still exists about the effect of cognitive stressors. The response to a cognitive stressor appears to be influenced by the intensity, as well as by the type, of stressor. In this study focussed attention was applied as a cognitive stressor. Narrowing it down to attention as the stressor, does not, however, solve the problem as different responses are known to occur depending on the type of attention. The so-called open attentional stance is said to lead to an autonomic shift in favour of cardiac deceleration, while the closed attentional stance appears to induce an autonomic shift that results in heart rate acceleration (25). The differences between the autonomic effects of the open and closed stances are equated to that between the orienting and the defensive response, respectively (25). The stressor task in this study, i.e., moving objects on the screen through concentration, was that of orienting and one would therefore expect an autonomic nervous system response in line with cardiac deceleration. In the response of the autonomic system from baseline to challenge this was, as discussed above, indeed observed in the trend towards an increase in the parasympathetic and a significant decrease in sympathetic control.

The next step was to examine the degree of autonomic responsitivity to the cognitive stressor (percentage change from baseline 2 to challenge) relative to the level of anxiety. The associations seen with Actiheart results were all negative (Table 5.8), indicating a lower responsitivity, i.e., a relative autonomic inflexibility in the face of a challenge with increases in the levels of anxiety. For the Actiheart recordings, this was seen in the negative associations varying from significant ($p<0.05$) to indicative of a correlation ($p\geq0.05$ to $p<0.1$), found between the intensity of the state anxiety and the percentage change in response to the challenge for the vagal indicators SD1 (Pr r= -0.8333, p=0.0102; r= -0.7381, p=0.0366), RMSSD (Pr r= -0.8333, p=0.0102; r=-0.7381, p=0.0366), NN50 (Pr r= -0.7381, p= 0.0366), TINN (PR r= -0.7186, p=0.0446) and pNN50 (PR: r= -0.7381, p=0.0366). Negative correlations were also found between the degree of state anxiety and the response of the indicators of

overall HRV variability StdDev HR (Pr: r= -0.7857, p=0.0208. r= -0.7619, p=0.0289), StdDev RR (Pr: r= -0.8333, p=0.0102, r= -0.7381, p=0.0480) and LFms^2 AR (r=-0.6429, p=0.0856). A negative correlation approaching significance was further found between trait anxiety and percentage change for frequency domain analysis HF% FFT (r= -06476, p= 0.0830).

These results, of a blunted autonomic response with increases in the levels of anxiety thus point towards a decrease in responsiveness, or rather a growing inflexibility, with increases in the level of anxiety in normal healthy individuals. This is in contradiction to the erstwhile concept of an anxiety-associated autonomic lability and hyper-reactivity that was an outflow of the work of Cannon (1), but in line with current concepts of high variability and flexibility as a reflection of coherence and viability (6).

When MBI results for exhaustion were examined in terms of resting (baseline) autonomic nervous system status, HRV data obtained by Actiheart indicated that exhaustion correlated positively with baseline parasympathetic control of the heart. This was seen in the FFT frequency domain analysis results for baseline 1 (HF percentage *vs* exhaustion: r= 0.7488, p=0.0325; HF n.u. *vs* exhaustion: r=0.6506, p=0.0806)(Table 5.9). The same association between vagal control and increased levels of exhaustion was observed for baseline 2 (HF percentage *vs* exhaustion; r=0.7488, p=0.0325; HF n.u. *vs* exhaustion: r= 0.7488, p=0.0325) (Table 5.10). Although only approaching significance the same was seen during challenge and recovery (Table 5.11 & Table 5.12 a&b). This, in other words showed that the higher the levels of exhaustion, the higher the parasympathetic autonomic cardiac control. When the status of the sympathetic control with varying degrees of exhaustion was examined by means of Actiheart, frequency domain analysis for Baseline 1 results showed a negative association between the level of emotional exhaustion and sympathetic nervous system activity. Results for baseline 1 (AR LF% *vs* exhaustion: r= -0.7488, p=0.0325; FFT LF n.u.: r= -0.6506, p=0.0806) were also supported by the results for baseline 2 (FFT LF n.u. : r= -0.7488, p=0.0325). Results obtained during the challenge and recovery, although only approaching significance were in agreement with that from baseline 1 and baseline 2. These negative correlations pointed towards a decline in sympathetic autonomic cardiac control with increased levels of exhaustion. The findings of increases in parasympathetic and decreases in

sympathetic control with intensification of exhaustion were supported by indications of a negative correlation between the level of exhaustion and the autonomic balance ($LFms^2/HFms^2$, baseline 1: r= -0.6506, p=0.0827; baseline 2: r= -0.7488, p=0.0325), which indicated a shift towards parasympathetic control with increases in exhaustion. The results on exhaustion and HRV indicators based on FFT frequency domain corresponded to those results obtained by means of autoregression frequency domain analyses (Table 5.9 to Table 5.12 a&b).

The results of increased vagal control with exhaustion is in agreement with a study on soldiers enrolled in a combat diver qualification course by Morgan *et al* (16) where the levels of emotional fatigue correlated positively with parasympathetic control of the heart. It is, however, in contrast to that of a study in postal workers that showed lower parasympathetic control and higher sympathetic control in burnout (15) and with a study by Zanstra (17) who found no difference in autonomic nervous system functioning at baseline. From a physiological point of view, the results of the present study and that of the study by Morgan *et al* (16) are in line with the concept of the sympathetic nervous system being instrumental in energy output and the parasympathetic system in energy conservation.

Correlations between exhaustion and HRV indicators obtained from Biograph results (e.g. Baseline 1 HF%power: r=0.6383, p=0.0885; Baseline 2 LF%power r= -0.6751, p=0.0661; Recovery BVP LF%power r= -0.7243, p= 0.0422; Recovery ECG LF%power= -0.09330, p=0.0007; Recovery LF/HF ratio -0.6752, p=0.0662) (Table 5.9 & Table 5.10), were in line with the indications of increased vagal and decreased sympathetic control with increases in exhaustion found by means of Actiheart. What is of interest with regard to the results obtained by Biograph was the consistent evidence that HRV decreases with increases in exhaustion (e.g. Baseline 1 BVP HF%Power CoefVar vs exhaustion r= -0.8961, p=0.0026; HF%Power StdDev vs exhaustion r= -0.8225, p=0.0122; LF/HF Ratio StdDev vs exhaustion r= -0.7243, p=0.0422; Baseline 2 ECG LF%Power StdDev vs exhaustion r= -0.7488, p=0.0325; LF/HF Ratio StdDev vs exhaustion r= -0.8347, p=0.0099). The latter is in agreement with the fact that decreased variability is generally present with physical or emotional unwellness (26). When the response of the autonomic nervous system, as reflected by HRV results obtained by Actiheart was examined relative to the level of exhaustion, it was seen that higher levels of exhaustion were associated with a lower

parasympathetic response to the cognitive challenge. This was seen in the negative correlations (Actiheart FFT frequency domain analyses) between exhaustion and the percentage change ((Challenge-Baseline 2)/Baseline 2) for the vagal indicators HFpercentage (r= -0.9207, p=0.0012), HF n.u. (r=-0.8716, p= 0.0048) and $HFms^2$ (r=-0.6997, p=0.0583). A significant positive correlation between exhaustion and the challenge-induced decrease in the autonomic balance indicator $LFms^2/HFms^2$ (r=0.9207, p=0.0012) pointed towards a greater shift, towards sympathetic, in the sympathetic/parasympathetic balance in response to the challenge. The latter does, however, not necessarily reflect on the responsitivity, but rather confirms the direction of change between sympathetic and parasympathetic activity. Biograph data did not contribute anything significant.

As was the case for increased levels of anxiety, increased levels of vital exhaustion were therefore associated with increased levels of autonomic inflexibility. These results of a fall in flexibility with increases in exhaustion, as assessed by a burnout inventory and in healthy individuals, are in agreement with that of a study by Zanstra *et al* that found depression of the autonomic response to a mental stimulus in individuals with burnout (17). The decline in the parasympathetic nervous system reactivity with increasing levels of burnout is in line with the concept of a decline in flexibility in conditions marked by a decrease in psychological and/or physical wellness.

When the relationship between professional efficacy and the autonomic nervous system was examined no significant correlations were found for FFT frequency domain analysis of Actiheart recordings at baseline 1, and none for the magnitude of the response to the cognitive stressor. However, AR frequency domain analysis results for baseline 1 pointed towards a positive association between feelings of professional efficacy and vagal tone (HF%: r=0.8024; p=0.0165; HF n.u.: r=0.6587, p=0.0757; $HFms^2$: r=0.6587, p=0.0757) and a negative association between feelings of professional efficacy and sympathetic tone (LF n.u.: r= -0.6946; p=0.0559). This trend of stronger vagal and lower sympathetic cardiac control with increased levels of professional efficacy was supported by the significant negative correlation between professional efficacy and the autonomic balance LF/HF (r= -0.7186; p=0.0446). Similar trends of a positive association between vagal control and professional efficacy and a negative association between professional efficacy and sympathetic

control were seen for baseline 2, recovery and challenge with AR frequency domain analysis of Actiheart data, but they were at best approaching significance. In contrast to the pattern seen with frequency domain analysis, Time Domain and Poincare analyses of Actiheart data suggested conflicting results showing a negative correlation between vagal and a positive correlation with sympathetic control. These indications were of statistical significance for baseline 2 (Table 5.10; RMSSD, pNN50, SD1). Indications of a positive association between professional efficacy and vagal tone were also seen with biofeedback recordings (baseline1: ECG HF%power r=0.6946, p=0.0559). No significant meaningful associations were found between the response of the autonomic nervous system and professional efficacy.

The Actiheart AR frequency domain and Biograph FFT frequency domain findings above imply higher vagal and lower sympathetic cardiac control in individuals with stronger feelings of professional efficacy. The positive correlations with parasympathetic and negative correlation with sympathetic control both point towards a potential cardiac decelerating effect when individuals feel themselves professionally more efficient. In contrast, the time domain results pointed towards a cardiac accelerating effect for feelings of professional efficacy. The latter results are in agreement with that of Schwerdtfeger *et al* (27), which found self-efficacy to be associated with elevated heart rate and attenuated heart rate variability and suggested their results to be in line with speculations that self-efficacy may be a physiological toughening agent with possible health benefits. In view of the generally accepted view that both increased resting heart rate and decreased heart rate variability are associated with a decline in wellness, this does not seem plausible. In fact, within normal limits, a cardiac decelerating-associated shift in autonomic balance (increase in parasympathetic and/or decrease in sympathetic control) as implied by the frequency domain results of the present study (Actiheart and Biograph frequency domain analyses) would be more in line with a relaxed, cardiac health beneficiary status. These conflicting results between frequency domain and time domain analyses needs further investigation. It is, however, suggested that a totally different approach may be needed as feelings of high professional efficacy may be linked to personality type – for instance, type A personality is often assumed to be characterised by high sympathetic cardiac control. However, even this association is at present debatable (28). Nevertheless, any such factor may have a confounding

influence on the outcome of such studies where associations between professional efficacy and autonomic status could be merely epiphenomenological.

5.5 Conclusions

In summary, these results on autonomic nervous system status, the variability of the autonomic nervous system cardiac control, and the autonomic responsitivity with variations in the level of anxiety, indicate that worry and anxiety can have a cardiac accelerating effect with a decrease in resting autonomic variability and significant inflexibility in the face of a cognitive stressor. The fact that these results could be found in a non-pathology population with a mild to moderate non-aversive cognitive challenge is perhaps indicative of the influence of moderate levels of anxiety on the autonomic nervous system. These results suggest that increases in worry and anxiety found in the general professional population may be high enough to influence autonomic nervous system functioning, and by implication cardiac health. The results on the association between the autonomic nervous system and MBI scores showed an increase in vagal and a decrease in sympathetic cardiac control with increased levels of vital exhaustion. This is in agreement with the concept that sympathetic activity can increase the blood glucose levels, while the parasympathetic system is involved with energy conservation. As for anxiety, decreased HRV variability and autonomic inflexibility were found with increases in the level of exhaustion. In line with the view that exhaustion represents the core of burnout (23), as opposed to the perhaps more subjective phenomena of cynicism and self-rated professional efficacy, no associations were found between autonomic function and cynicism, and inconclusive results between autonomic function and professional efficacy. This exercise of evaluating the clinical application of biofeedback equipment for the assessment of stress and stress-associated conditions showed HRV assessment by more specialized software such as Polar Precision Performance Software and the advanced HRV Analysis 1.1 software for windows (Biomedical Signal Analysis Group) to be superior to assessments by means of the Biograph Infinity program. However, this cannot entirely be ascribed to the Biograph *per se* as the HRV values were derived from tachogram recordings that were uncorrected. It is highly likely that its performance would be improved by the IBI normalization functionality in the newer software packages (29). One aspect of HRV information in which the Biograph was

at least as good as, or perhaps better, than the Actiheart was in showing the decline in variability that occurred with increased levels of anxiety and with increased levels of exhaustion. In view of the fact that decreased heart rate variability has long been associated with both physical and psychological deterioration - particularly with an increased risk for cardiovascular morbidity (26) - coupled to the fact that biofeedback techniques have been shown to be effective in HRV-enhancement training (30-32), it may be of value to find ways of bringing HRV analyses by Biograph to a level of comparability in all aspects of HRV analysis. The technical expertise of the operator must also be taken into account; no matter how advanced the device and programs are, a novice user will not achieve the same quality results as a trained one.

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7 Summary and Conclusions

7.1 Summary of the Dissertation

A variety of factors are used in an attempt to assess stress levels. However, not one single measurement on its own can give a full account of the stress levels as different physiological functions are influenced by various stressful events. Blood tests, measurement of autonomic nervous system functioning and quantitative encephalographic assessments are often costly, time consuming and may require expensive equipment or specialized laboratories and highly trained operators. Portable biofeedback equipment, primarily intended to train individuals to control physiological functions such autonomic nervous system activity, offers the opportunity to measure a number of physiological variables – several of them influenced by stress. Biofeedback can be used to correct certain physiological processes which have been disturbed by stress-related events. It is, however, imperative to determine the efficacy of the portable devices in correctly measuring the real levels and not just the direction of change. The aim of the work for this dissertation was to evaluate the use of portable biofeedback equipment in the screening and monitoring of stress levels. This was done by comparing values obtained by biofeedback equipment to that obtained by conventional instrumentation and to anxiety levels and levels of burnout.

The physiological variables examined by means of biofeedback equipment included heart rate and heart rate variability (HRV) indicators of autonomic nervous system activity and balance, pulse volume variations, skin conductivity, muscle tension, electro-encephalography (EEG), fingertip temperature and respiration. The biofeedback equipment used was the Thought Technology Procomp Infinity encoder unit (Thought Technology, Montreal West, Quebec, Canada), with sensors and electrodes for electro-encephalography (EEG), electromyography (EMG), electrocardiography (ECG), electrodermal response, blood-volume pulse (BVP) also called a photoplethysmography (PPG) sensor, fingertip temperature sensors and a respiration sensor. The Biograph Infinity version 5 biofeedback software was used to run the measurement sessions. The Biograph Infinity Developer Tools program was used to develop customised channel sets for the study, as well as user-interface screens and script sessions. The Actiheart two lead chest-worn heart rate monitor

(from CamNtech Ltd, Cambridge, UK) was used to record tachograms by digitising the ECG signal from the R-to-R interval with a 1 ms resolution. Error correction was performed by using the Polar Precision Performance Software version 4.03.040 (Polar Electro Oy, Kempele, Finland). Actiheart HRV analysis was carried out using the advanced HRV Analysis 1.1 software for windows, developed by The Biomedical Signal Analysis Group, University of Kuopio, Finland. Time-domain measures and nonparametric frequency-domain analysis based on fast Fourier transformation were employed. Additionally, autorgression was also used with the Actiheart data for comparison to the FFT method. Anxiety and Burnout was assessed by the Maslach Burnout Inventory and the Spielberger State-Trait Anxiety Inventory.

After development of the channel sets to be used in the assessment of the stress levels by means of the biofeedback equipment a group of individuals in a high stress occupation was tested by Biograph, Actiheart, allostatic load and psychometric assessments. Biofeedback results were not satisfactory and a major signal quality issue was observed during analysis of the results. It was suspected that electromagnetic interference may be present at the venue where the recordings were done. The problem was eventually solved, but financial constraints prevented any further determinations of allostatic load. The protocol was subsequently revised but the aim remained the same.

In line with the aim of this dissertation, the results of the biofeedback equipment-based measurement of autonomic nervous system control of cardiac function was compared to the results obtained by the more conventional Actiheart system. Results showed that:

- The hardware capabilities of the two systems are comparable when it comes to registering heartbeats and calculating heart rate, but when the data is further processed to obtain time domain HRV variables the differences between Actiheart and Biofeedback results are unacceptable.
- The frequency domain Biofeedback HRV variables had relatively good correlations to the Actiheart results.
- The frequency domain Biofeedback HRV variables calculated with FFT had poor correlations to the Actiheart autoregression results. However, the

Actiheart FFT and Actiheart autoregression results also differed from each other – a phenomenon previously seen in the work from other laboratories.

- In comparing HRV results obtained by EEG and BVP measurements it was seen that ECG based frequency domain HRV variables are preferable to BVP based frequency domain results. This was due to the fact that the BVP signal is prone to movement artefact and other forms of interference.

Although the biofeedback HRV results were not satisfactory, the relatively good correlations found between the Biofeedback FFT frequency domain results and the Actiheart FFT frequency domain results are encouraging. The potential exists to adapt Biofeedback data processing in order to render it even more suitable for HRV assessment. It is already possible to change the virtual channel set calculations in order to obtain ms^2 values and nu values, and the results can be further improved by more advanced data filtering and correcting capabilities. In view of the success of Biofeedback practices such as up-regulation of HRV and improvement of sympathetic and parasympathetic balance, improvement of the assessment processes can be of great value. Some of the newer Thought Technology products offer IBI normalization to more advanced users, which in view of the results of this study would likely yield high quality HRV determination tools, but it falls on future research to validate that.

The next objective was to test the performance of Biograph Infinity Biofeedback equipment and the Biograph Infinity software for use in a clinical application. This was done by using HRV data obtained by Actiheart to study the relationship between autonomic function, anxiety and burnout and then to compare these findings to that obtained when HRV values were obtained by Biograph Biofeedback equipment. Levels of anxiety and burnout in a group of normal, apparently healthy, professionals were compared to their baseline autonomic nervous system status and to their autonomic response to a moderate mental challenge.

The results on autonomic nervous system status, the variability of the autonomic nervous system cardiac control, and the autonomic responsitivity (flexibility) with variations in the level of anxiety, indicated that worry and anxiety

- Can have a cardiac accelerating effect, predominantly mediated by vagal withdrawal
- Can lead to a decrease in resting autonomic variability
- Can cause significant autonomic nervous system inflexibility in the face of a cognitive stressor

The fact that these results could be found in a non-pathology population with a mild to moderate non-aversive cognitive challenge is perhaps indicative of the influence of moderate levels of anxiety on the autonomic nervous system. These results suggest that increases in worry and anxiety found in the general professional population may be high enough to influence autonomic nervous system functioning, and by implication cardiac health.

The results on the association between the autonomic nervous system and MBI scores showed:

- An increase in vagal and a decrease in sympathetic cardiac control with increased levels of vital exhaustion. This is in agreement with the concept that sympathetic activity can increase the blood glucose levels, while the parasympathetic system is involved with energy conservation
- Decreased HRV variability and autonomic inflexibility with increases in the level of exhaustion

In line with the view that exhaustion represents the core of burnout as opposed to the perhaps more subjective phenomena of cynicism and self-rated professional efficacy, no associations were found between autonomic function and cynicism, and inconclusive results between autonomic function and professional efficacy.

The exercise of evaluating the clinical application of biofeedback equipment for the assessment of stress and stress-associated conditions showed that:

- HRV assessment by more specialized software such as Polar Precision Performance Software and the advanced HRV Analysis 1.1 software for windows (Biomedical Signal Analysis Group) to be superior to assessments by means of the Biograph Infinity program. However, this cannot entirely be

ascribed to the Biograph *per se* as the HRV values were derived from tachogram recordings that were uncorrected. It is highly likely that its performance would be improved by the IBI normalization functionality in the newer software packages.

- One aspect of HRV information in which the Biograph was at least as good as, or perhaps better, than the Actiheart was in showing the decline in variability that occurred with increased levels of anxiety and with increased levels of exhaustion.

In view of the fact that decreased heart rate variability has long been associated with both physical and psychological deterioration - particularly with an increased risk for cardiovascular morbidity coupled to the fact that biofeedback techniques have been shown to be effective in HRV-enhancement training, it may be of value to find ways of bringing HRV analyses by Biograph to a level of comparability in all aspects of HRV analysis. The technical expertise of the operator must also be taken into account; no matter how advanced the device and programs are, a novice user will not achieve the same quality results as a trained one.

In the last assessment of the biofeedback apparatus as stress monitor, the correlation between BVP amplitude, BVP HRV, ECG HRV, pulse transit time, EMG, fingertip temperature, respiration rate and amplitude, skin conductivity and QEEG levels and the levels of anxiety and that of burnout were investigated. The following acceptable correlations between the psychological indicators and the physiological indicators were found:

- For BVP amplitude:
    - Decreased BVP amplitude variability with increased levels of cynicism
    - Increased BVP amplitude variability with increased professional efficacy
    - Decreased BVP amplitude variability with higher levels of state anxiety
- For BVP HRV:
    - Higher Professional efficacy with increased mean heart rate
    - State anxiety and decreased variability of the heart rate
    - Trait anxiety and decreased parasympathetic indicators (NN50 and pNN50)
    - Lower HF % power with cynicism

  - Higher HF % power with professional efficacy
  - Lower LF % power with professional efficacy
  - Lower LF/HF ratio with professional efficacy
  - Lower variability of HF % power with exhaustion
  - Lower HF % power with state anxiety
  - Lower variability of HF % power with state anxiety.
- For ECG HRV:
  - Higher mean heart rate with professional efficacy
  - Decreased heart rate variability with state anxiety
  - Lower parasympathetic indices (NN50 and pNN50) with increased trait anxiety
  - Reduced HF % power variability with exhaustion
  - Lower LF % power variability with exhaustion
  - Lower LF/HF ratio variability with exhaustion
  - A greater increase in the LF/HF ratio in response to the challenge with exhaustion
  - Lower HF % power variability with state anxiety
- For EMG:
  - Greater increases in EMG in response to the challenge with state anxiety
  - Lower variability with increased state anxiety
  - Lower variability with increased trait anxiety
- For fingertip temperature:
  - Decreased temperature variability with increases in cynicism
  - Decreased temperature variability with increased trait anxiety
- For pulse transit time:
  - Lower variability of pulse transit time with increased exhaustion
  - Increased PTT variability and professional efficacy
  - Lower variability with increases in state anxiety
  - Lower variability with increased trait anxiety
- For respiration:
  - exhaustion and increased respiration rate
  - Exhaustion and decreased variability of respiration rate

  - state anxiety and increased variability of respiratory amplitude
  - Trait anxiety and decreased variability of respiratory amplitude
- For skin conductivity:
  - Higher levels of skin conductivity with exhaustion
  - Higher variability of skin conductivity with exhaustion
  - Decreased skin conductivity with higher levels of professional efficacy
  - Decreased variability of skin conductivity with higher professional efficacy
  - Higher variability of skin conductivity and state anxiety
  - High levels of skin conductivity and trait anxiety
  - Higher variability of skin conductivity and trait anxiety
  - A lower skin conductivity response and state anxiety
  - A lower response and trait anxiety
  - Muted response of the variability of the skin conductivity and both state and trait anxiety
- For QEEG:
  - Exhaustion and an increase in Delta power in response to the challenge
  - Exhaustion and increased Theta power in response to the challenge
  - State anxiety and increased high Alpha power
  - Decreased alpha coherence in response to the challenge
  - Anxious subjects had less increase in SMR in response to the challenge
  - State anxiety and increased Beta 1 power
  - Cynicism and increased Right hemisphere high Beta power
  - Exhaustion and a diminished increase in high beta power in response to the challenge
  - Exhaustion and reduced Gamma power in response to the challenge
  - A higher Alpha/Theta ratio with increased anxiety
  - Exhaustion and a higher right Theta/Beta 1 ratio in response to the challenge

Not all the indicators tested had acceptable correlations with the psychometric items, and the significance of some of the other correlations is not yet known, but many of

the measurements had good correlations to the psychometric stress indicators. Skin conductivity stood out as an effective modality to detect the markers of stress.

7.2 Limitations of the Study

The limitations of this dissertation were:

- The small sample size of the group where the biofeedback equipment was compared to the Actiheart device (N=8)
- The sample size in Chapter 6 (N=21) was still too small to provide adequate power to the study. The original sample was 34 persons, but had to be reduced due to the use of medication that could confound the results
- The limited skill of the researcher in filtering and correcting the tachograms obtained with the biofeedback results. This improved as the study progressed
- The study did not take into account the handedness of the subjects

7.3 Overall Conclusions

In conclusion, relatively good associations were found between certain, but not all, Procomp Infinity biofeedback device results and that of other assessments, and to that of other studies on stress, anxiety and burnout. There exists potential to develop a program which would accurately reflect stress levels, but it would require more in-depth research to define the pattern of biometric indices disturbed by stress. Newer versions of the Biograph Infinity software, with more sophisticated processing algorithms, became available during the course of this dissertation, and in view of the success of many biofeedback practitioners in addressing conditions like uncontrollable seizures, ADHD, headache and incontinence it should be assessed for use in stress analysis.