HRV in Smartphone for Biofeedback Application

Michel Maurício Mendes Cânovas

November 2011

Abstract

Biofeedback is the process of inducing a physiological state change by conveniently displaying accurate information of the body's current state.

Heart Rate Variability (HRV) is related to several physiological factors. In particular, it is consensual that the HRV reflects the *Autonomic Nervous System* (ANS) activity, namely in its Low Frequency (LF) and High Frequency (HF) spectral components which relate to the activity of the ANS sympathetic and parasympathetic components. This makes HRV analysis a window to the ANS state that can be used to biofeedback.

Real-time HRV spectral analysis for biofeedback purposes, though are usually performed in full size computers, which withdraw liberty to the protocols.

Thereby, the purpose of this work was to overcome the lack of freedom imposed by the hardware to these biofeedback procedures, with an application that uses a wireless monitoring belt to gather the HRV information and the ubiquitous smartphone to process and display real time information for biofeedback purposes.

Application outputs reveal results coherent with bibliography concerning HRV analysis, which enabled the successful implementation of a Resonant Frequency Training (RFT) biofeedback feature, hopefully bringing this form of therapy closer to the general population.

Key Words: Heart rate variability, Physiological Monitoring Belt, Mobile Phone, Biofeedback.

---

1 Introduction

Stimuli invade our senses in a constant basis. It is a central nervous system (CNS) responsibility to treat and produce a real-time adequate response to that information, in order to provide an effective and efficient fit of the organism to the environment[1].

However, though a great portion of this information and adaption process may be conscious, specific situations or stimuli produce particular sensations and responses that we can not always understand, and rarely control. This is the *autonomic* branch of the nervous system jurisdiction.

What if we could access real-time state information about the autonomic nervous system (ANS), could we induce a transition to a different state?

Variations of the heart rate are directly related with the ANS through both its main efferent pathways: *Symphatetic* and *Parasymphatetic* nervous systems. Measuring or indirectly estimating the activity of the ANS can be valuable in the diagnosis of several pathologies.

In a first approach, abnormal heart rate variation patterns reflect malfunctions of the ANS, called *Dysautonomia*. These variations may also be related with malfunctions of other systems involving the ANS, such as the cardio-vascular or cardio-respiratory systems.

Heart Rate Variability (HRV) is nowadays one of the preferred non-invasive methods to assess and monitor the activity of the ANS[2]. However, as mentioned before, the ANS also depends on the *Central Nervous System* and therefore the HRV can be used to infer pathological or non pathological conditions related with brain. Several publications on the literature correlate the HRV with anxiety [3], panic [4] or *Attention Deficit Hyperactivity Disorder* (ADHD) [5].

As an answer to our previous question, other field of research and clinical applications where HRV is used is *Biofeedback* (BF)[6]. Bio and Neuro feedback are frameworks where physiological information is provided, through appropriated computer user interfaces, mainly to help the improvement of brain features and skills, e.g. short term memory, or to help inducing changes on certain brain states, such as, relaxation or concentration.

2 Fundamentals and Background

2.1 Heart Rate Variability

Heart rate Variability (HRV) is the variation over time of the period between two consecutive heartbeats, or correspondingly, the variation in the instantaneous heart rate. It is thought to reflect the heart's ability to adapt to changing circumstances by detecting and quickly responding to unpredictable stimuli. Its analysis is the ability to assess overall cardiac health and state of the ANS which is responsible for regulating cardiac activity[7].

Generally, in a spectrum calculated from short-term recordings (no more than 5 minutes), three main components are distinguished: very low (VLF; $\leq 0.04HZ$), low (LF; $0.04 - 0.15Hz$) and high (HF; $0.15 - 0.4Hz$) frequency components[2, 8–10].

The HF component is mainly composed by efferent vagal activity, proven by clinical and experimental observations of autonomic maneuvers such as electrical vagal stimulation, muscarinic receptor blockade and vagotomy[2, 10–12]. Less consensual is the interpretation of the LF component which is considered as marker of sympathetic modulation for some and as a parameter that is composed by both sympathetic and vagal activity for others. This discrepancy is due to the fact that a decrease in the absolute power of the LF component is observed in some conditions associated with sympathetic excitation. Consequently, the LF/HF ratio is considered by some investigators to mirror sympathovagal balance or to reflect the sympathetic modulations[2].

2.2 Autoregressive (AR) model spectral analysis

AR modeling uses the time history of a signal to extract important information. The model predicts the current values of a time series from its past values, assuming that the most recent data contain more information than the older, and that each value of the series can be predicted as a weighted sum of the previous values of the series, plus an error term, being defined as:

$$x[n] = \sum_{i=1}^{M} a_i x[n-i] + \epsilon[n] \tag{1}$$

where $x[n]$ is the current value of the time series, a_1,...,a_M are the weighting AR coefficients, M is the model order, and $\epsilon[n]$ the difference between the predicted value and the current value at this point, i.e. the prediction error. The AR model determines an analysis filter, through which the time series is filtered. If we manipulate the equation, we get the filter with an impulse response $[1, -a_1, ..., -a_M]$, that produces the prediction error sequence(PES) $\epsilon[n]$.

The AR coefficients are calculated in order to minimize the PES using the least squares minimization technique. Having the AR coefficients, the spectrum of the modeled time series, $R(e^{j\omega})$ is obtained by multiplying the PES variance with the square of the transfer function $H(e^{j\omega})$ of the filter:

$$R(e^{j\omega}) = |H(e^{j\omega})|^2 \sigma_p^2 \tag{2}$$

$$= \frac{\sigma_p^2}{|1 - a_1 e^{-j\omega} - ... - a_M e^{-jM\omega}|^2} \tag{3}$$

The highest the M chosen, the better will the identified model fit the measurements. The frequency resolution grows with M, however, a greater M means a greater computational effort and less robust power estimates. So here must be a compromise in order to choose the ideal model order.

2.3 Data acquisition: monitoring belt and ***Android*** device

The data acquisition is made using a Zephyr BioHarness® physiological monitoring belt that communicates via Bluetooth® with an Android OS running mobile device (mobile phone or tablet), in which all the signal processing and display is done. The belt is able to measure the body temperature, posture, acceleration, heart and breathing rates, electrocardiogram (ECG), R to R period, which is the one we use, amongst other. The signal is sampled at 18 Hz, and transmitted to the mobile device every second. The device then stores and processes the signal displaying its real-time varying power spectrum.

3 Biofeedback

The process is one of displaying involuntary physiological processes, and learning to voluntarily influence those monitored and "fed back" processes by making changes in cognition. This provides a visible and experiential demonstration of autonomic functions for improving health. The term was coined in 1969 to describe laboratory procedures, developed almost 30 years earlier, in which subjects learned to modify heart rate, blood flow and other physiologic functions that were not normally thought of as consciously controllable[13, 14]. McKee[14], even states that *"feedback itself has been present through much of human history, particularly through the use of mirrored surfaces to practice the expression of emotion"*.

One or more physiological processes are monitored by biofeedback instruments as they measure and transform that information into simple, direct, immediate, human readable/sensible signals. Typically, biofeedback equipment is noninvasive and current computerized instruments can provide simultaneous displays and recordings of multiple channels of physiologic information. This enables the individual being monitored to change some physiologic process under the biofeedback equipment guidance. The number of sessions needed may vary from a few to 50 or more, depending on the individual and the disorder. Normally, though, the great majority of patients obtain benefit in 8 to 12 sessions[14, 15].

HRV biofeedback is designed to control oscillatory variability in heart rate, thus exercising and focusing in the physiological control mechanisms of the own body. Generally, other biofeedback methods influence these pathways more indirectly by teaching people to control tonic level of various physiological functions (as muscle tension, finger temperature, heart rate, blood pressure, etc.). However, controlling tonic levels is noticeably more difficult than learning to increase HRV[16]. Moreover, HRV feedback is much simpler and straightforward to learn and use, compared to neurofeedback, which facilitates rapid improvement[17].

Whenever the cardiovascular system is stimulated (by anything: physical exercise emotionally-relevant events or even thoughts, changes in posture or head tilt, breathing, etc.), a set of oscillations takes place which gradually decrease in amplitude over time. This oscillations are caused by the interplay of heart rate and blood pressure, and baroreflex mechanism[18].

Depending on the timing of the stimulus (*i.e.*, if it comes when the heart rate is rising or falling), if the system is stimulated at the resonant frequency, its effects will either smooth the amplitude of the heart rate or oscillation or augment it. When a person breathes at sensibly 6 breaths per minute (the resonant frequency), due to phase relationships between heart rate and blood pressure at this frequency, the respiratory stimulus causing heart rate to rise occurs precisely at the same time as the baroreflex impulse causing heart rate to rise. The same occurs in the inverse direction, causing heart rate to fall. This causes a persistence of the augmented heart rate oscillation at the resonant frequency. At this frequency, and only at this frequency, heart rate and respiration are perfectly in phase with each other and heart rate oscillations become very large. Additionally, heart rate and blood pressure oscillate in perfectly opposite directions. This means that the baroreflexes are stimulated with every breath, causing an increase in heart rate oscillations[18].

The stimulation of the baroreflex with every breath, as in the exercise of any reflex, leads to an evolution of the reflex, making it more efficient. Lehrer and Vaschillo[18] found that in healthy people practicing HRV biofeedback daily for about three months, the gain in resting baroreflex increases (*i.e.*, a bigger change in heart rate for each mm Hg change in blood pressure), which means a stronger modulation of blood pressure[18].

There are a few HRV training strategies which can be used to increase cardiac variability in a health enhancing way including psychophysiological or heart rhythm coherence feedback, or oscillatory biofeedback, and resonant frequency training (RFT)[17, 19, 20].

4 System architecture

The application hereby presented is basically composed by three main parts: the bluetooth connection, for data exchange; the signal processing; and the processed data display. These are directly associated with the three biofeedback cycle intervenients: the monitoring device, the smartphone and the subject (see

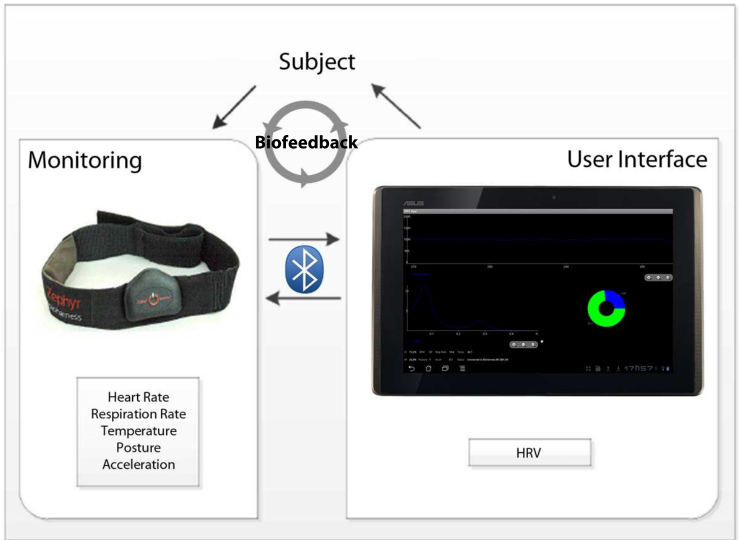


Figure 1: System architecture.

Figure 1).

The system is composed by a Zephyr BioHarness® belt able to acquire physiological data. This device communicates via Bluetooth® with the client application running in an Android OS enabled device, where all the signal processing and displaying is done. Among other physiological data the BioHarness® device is able to acquire the R-R interval data at a sampling frequency of $18Hz$.

To limit the required computation time, the signal is downsampled, this allows the assessment of the spectral information in the range of interest while maintaining a low model order. This downsampling is preceded by a first order low pass filtering (cutoff $0.6Hz$), to avoid aliasing artifacts.

The maximum frequency that contain ANS information is below 0.5 Hz [2]. This means that, satisfying the Nyquist sampling theorem, the signal can be downsampled by a factor superior to ten, to a sampling frequency of 1.2 Hz, and still possess the information needed [21].

Having all these routines implemented in the device all that has to be done is to receive the signal, store it until enough data is collected, then filter, downsample, calculate the AR filter parameters, and choose the number of points to plot when generating the power spectrum, and re-do it over time as new data enters the window. It then displays the real-time R-R interval data, spectra and LF and HF percentage, as shown in Figure 2.

5 Application Testing and Outputs

Although the HRV analysis alone is not the main focus of this application, in order to grant that it properly fulfills its purposes, namely display the correct information for biofeedback features, HRV spectral analysis made with the system, as it is built, has to lead to results physiologically coherent, thus consistent with studies in bibliography.

A study made by Pagani *et al.*[8] may serve as a simple test to the system reliability. In this study, the HRV of several experimental subject is analyzed in the frequency domain during two different circumstances:

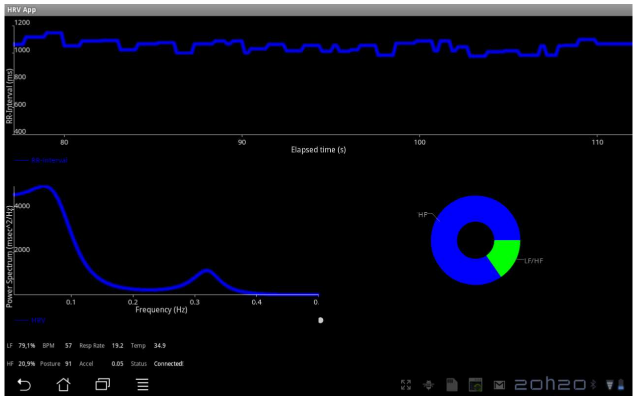


Figure 2: Display representation

rest and 90° head up tilt.

This study shows that the HRV spectra has a distinct and very characteristic behavior in each of the two circumstances (see figure 3). At rest, the presence of two major spectral components is very clear, the LF and HF components. The LF component is slightly predominant with a LF/HF ratio around 3.6.

During tilt the results show a great change, revealing a largely predominant LF component with an HF component barely present. Consequently the LF/HF ratio increases to a value around 21.

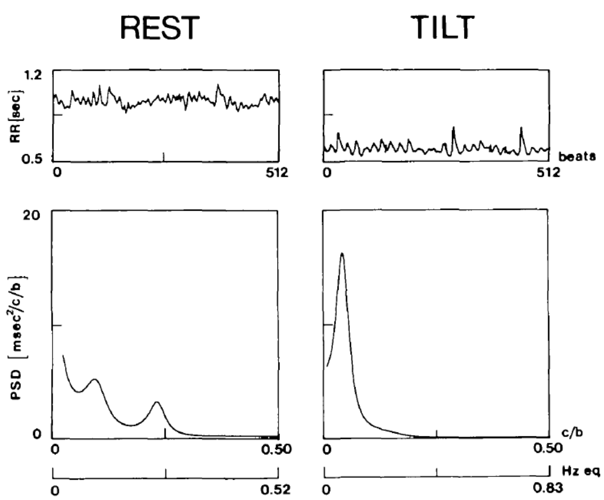
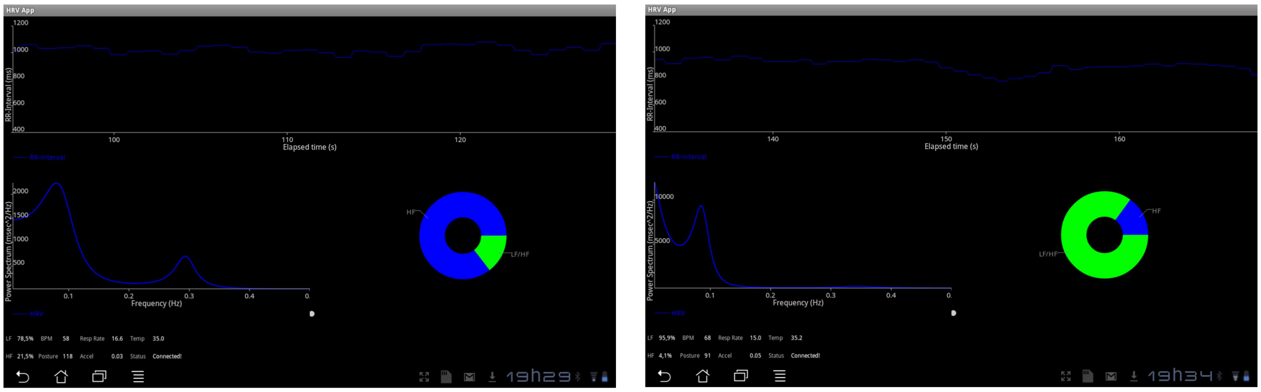


Figure 3: R to R interval series (top panel): tachogram at rest and during 90° head up tilt. AR spectra of the above time series (bottom panel), (From [8]).

Lombardi *et al.*[22] found very similar results in a study made ten years later.

Figure 4 shows the display of the system during rest and 90° head up tilt. Results are in agreement with those found by Pagani and Lombardi. Similar results were found through the orthostatic test, as shown in Figure 5.

Regarding the biofeedback features, as explained in the beginning of the last chapter, the *Real Time HRV Analysis* tool not only serves as an immediate display of the system potentialities but can also be used for biofeedback purposes. HRV training strategies similar to heart rhythm coherence can be easily



A B

Figure 4: Display during (A) rest and (B) 90º head up tilt.

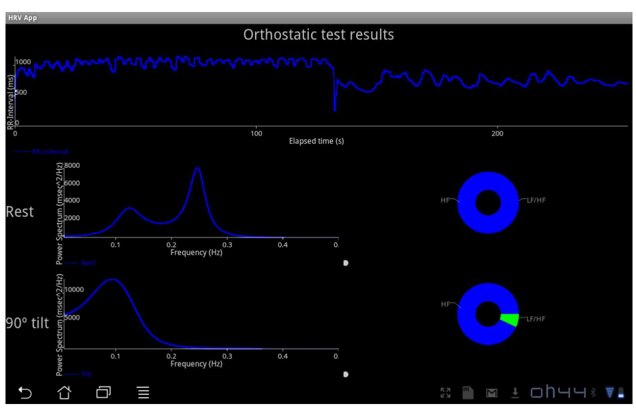


Figure 5: Orthostatic test results.

reproduced, since the real time R-R interval is displayed. Figure 6 shows the display during a procedure where the subject was told to try and produce the highest oscillations in his heart rate by controlling the respiration rate.

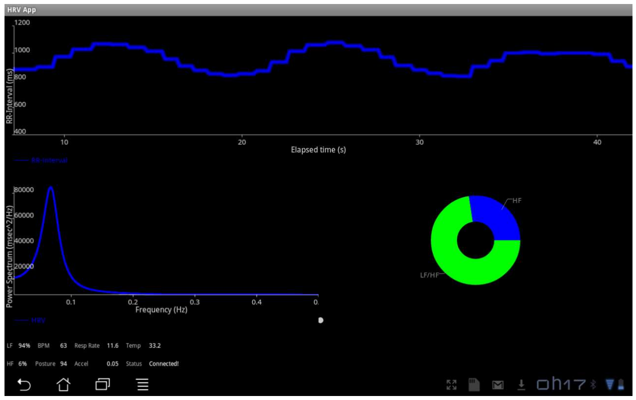


Figure 6: HRV oscillation

Moreover, in the *RF Biofeedback Training* functionality, results clearly show that the HRV total spectrum power increases at breathing frequencies near $0.1Hz$, as expected. Figure 7-A illustrates the application status when the subject starts the biofeedback training and is not yet breathing at the blue bar's pace, in opposition to the results after a brief period of training (Figure 7-B).

It can also be seen, from the second green bar, that the shape of the R-R interval series approximates a sinusoidal wave, and that the oscillations are higher than in the beginning of the session.

However, although this results meet the expectations regarding the bibliography they were produced after only two training sessions. It is possible that more expressive results can be found after a higher number of longer sessions.

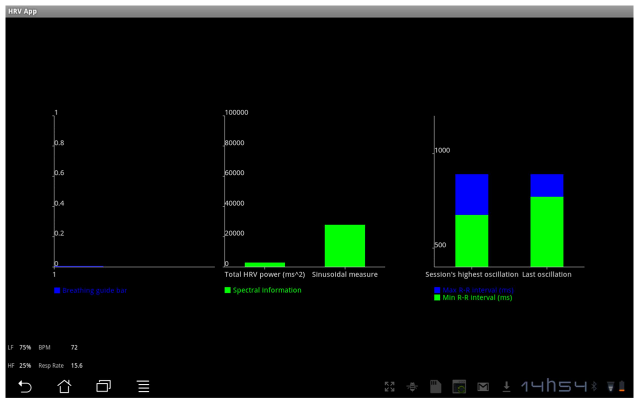
6 Conclusion

The description of a system designed to perform wireless real-time HRV assessment for biofeedback purposes was presented. The main goal was to take this alternative way of treatment out of the lab with good results.

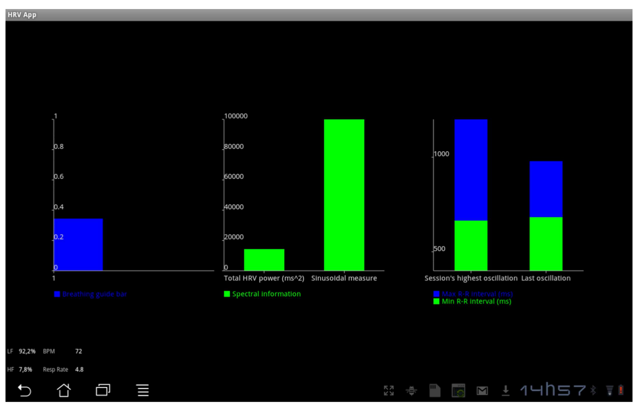
Certain conditions like stress, fatigue or anxiety, among a variety of others mentioned throughout this thesis, highly related to modern lifestyles, can be considerably eased if not even cured/controled with HRV biofeedback techniques. Yet, in-lab training sessions may not be enough for the complete understanding and mastering of the mechanisms involved in the physiological changes at aim during biofeedback.

The architecture, combining the Zephyr® BioHarness monitoring belt, communicating via Bluetooth® connection, with a signal processing smartphone, successfully solves the mobility issue enabling the real-time HRV assessment in time and frequency domains. Thus, not only does it open the window of investigation of new methodologies of psychophysiological self-regulation using HRV information, but also, albeit not the main purpose of the system, of the HRV itself.

Test results are in agreement with the expected from procedures documented in bibliography, showing the system's ability, not only to detect the LF and HF components of HRV, but also to do so reliably and



A



B

Figure 7: Display during RFT biofeedback session: (A) in the very beginning, (B) after a while breathing at the resonant frequency.

in agreement with physiology. The designed user interface simplifies the biofeedback process and results show that as much as two training sessions already produce noticeably higher HRV oscillations.

Now that the mobility is no longer a hindrance, features such as biofeedback games, which are available for personal computers, where a physiological state change has to be achieved in order to succeed, should become a reality in smartphones. Pattern recognition might be used to predict and alert imminent dangerous psychophysiological states, and integration of this kind of information with other platforms, like actigraphy, for instance, might be used for sleep staging purposes; all this in a real-time mobile basis. At long last, further applications of this system are endless.

In conclusion, even though some of the mentioned pathologies might have an established and consensual treatment, an alternative as HRV biofeedback, that turns towards self-healing using the least resources, either economic or pharmacological, should always be preferable. For that to be achieved, a system such as the one here presented should be seen as a first step regarding the evolution of such methodologies, taking them from indoors to the patient's pocket.

References

[1] G. Tortora and B. Derrickson, *Principles of Anatomy and Physiology*. John Wiley & Sons, 12 ed., 2008.

[2] T. F. of the European Society of Cardiology, the North American Society of Pacing, and Electrophysiology, "Heart rate variability: standards of measurement, physiological interpretation, and clinical use," *Circulation*, vol. 93, pp. 1043–1065, 1996.

[3] C. M. M. Licht, E. J. C. de Geus, R. van Dyck, and B. W. J. H. Penninx, "Association between anxiety disorders and heart rate variability in the netherlands study of depression and anxiety (nesda).," *Psychosom Med*, vol. 71, no. 5, pp. 508–18, 2009.

[4] B. H. Friedman and J. F. Thayer, "Autonomic balance revisited: Panic anxiety and heart rate variability," *Journal of Psychosomatic Research*, vol. 44, no. 1, pp. 133 – 151, 1998.

[5] N. Borger, J. van Der Meere, A. Ronner, E. Alberts, R. Geuze, and H. Bogte, "Heart rate variability and sustained attention in adhd children," *Journal of Abnormal Child Psychology*, vol. 27, pp. 25–33, 1999. 10.1023/A:1022610306984.

[6] A. for Applied Psychophysiology and Biofeedback, "About biofeedback." `http://www.aapb.org/consumers_biofeedback.html`, December 2009.

[7] U. Rajendra Acharya, K. Paul Joseph, N. Kannathal, C. Lim, and J. Suri, "Heart rate variability: a review," *Medical and Biological Engineering and Computing*, vol. 44, no. 12, pp. 1031–1051, 2006.

[8] M. Pagani, F. Lombardi, S. Guzzetti, O. Rimoldi, R. Furlan, P. Pizzinelli, G. Sandrone, G. Malfatto, S. Dell'Orto, and E. Piccaluga, "Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog," *Circulation Research*, vol. 59, no. 2, pp. 178–193, 1986.

[9] S. Akselrod, D. Gordon, F. Ubel, D. Shannon, A. Berger, and R. Cohen, "Power spectrum analysis of heart rate fluctuation: a quantitative probe of beat-to-beat cardiovascular control," *Science*, vol. 213, no. 4504, p. 220, 1981.

[10] A. Malliani, M. Pagani, F. Lombardi, and S. Cerutti, "Cardiovascular neural regulation explored in the frequency domain," *Circulation*, vol. 84, no. 2, p. 482, 1991.

[11] B. Pomeranz, R. Macaulay, M. Caudill, I. Kutz, D. Adam, D. Gordon, K. Kilborn, A. Barger, D. Shannon, R. Cohen, *et al.*, "Assessment of autonomic function in humans by heart rate spectral analysis," *American Journal of Physiology-Heart and Circulatory Physiology*, vol. 248, no. 1, p. H151, 1985.

[12] S. Akselrod, D. Gordon, J. Madwed, N. Snidman, D. Shannon, and R. Cohen, "Hemodynamic regulation: investigation by spectral analysis," *American Journal of Physiology-Heart and Circulatory Physiology*, vol. 249, no. 4, p. H867, 1985.

[13] A. Brauer and D. Barlow, "Biofeedback and anxiety," *Psychiatric Times*, vol. 16, no. 2, pp. 1–2, 1999.

[14] M. McKee, "Biofeedback: an overview in the context of heart-brain medicine.," *Cleveland Clinic journal of medicine*, vol. 75, no. Suppl 2, p. S31, 2008.

[15] C. Yucha and D. Montgomery, "Evidence-based practice in biofeedback and neurofeedback," 2008.

[16] P. Lehrer, "Biofeedback training to increase heart rate variability," *Principles and practice of stress management*, pp. 227–248, 2007.

[17] A. Sutarto, M. Abdul Wahab, and N. Mat Zin, "Heart rate variability (hrv) biofeedback: A new training approach for operator's performance enhancement," *Journal of Industrial Engineering and Management*, vol. 3, no. 1, pp. 176–198, 2010.

[18] P. Lehrer and E. Vaschillo, "The future of heart rate variability biofeedback," *Biofeedback*, vol. 36, no. 1, pp. 11–14, 2008.

[19] P. Lehrer, E. Vaschillo, and B. Vaschillo, "Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training," *Applied Psychophysiology and Biofeedback*, vol. 25, no. 3, pp. 177–191, 2000.

[20] N. Suvorov, "Psychophysiological training of operators in adaptive biofeedback cardiorhythm control," *The Spanish journal of psychology*, vol. 9, no. 2, pp. 193–200, 2006.

[21] A. Oppenheim, R. Schafer, J. Buck, *et al.*, *Discrete-time signal processing*, vol. 1999. Prentice hall Englewood Cliffs, NJ:, 1989.

[22] F. Lombardi, A. Malliani, M. Pagani, and S. Cerutti, "Heart rate variability and its sympatho-vagal modulation," *Cardiovascular research*, vol. 32, no. 2, p. 208, 1996.