Respiratory Sinus Arrhythmia: Methods of Measurement and Interpretations of Tonic and Dynamic Vagal Cardiac Drive Index in Psychophysiology of Emotions

Estate M.Sokhadze, Jong-Mi Lee, Mi-Kyung Park and Jin-Hun Sohn+

+Corresponding author

(Supported by KOSEF research grant to J.-H.Sohn)

Department of Psychology, Chungnam National University
jhsohn@hanbat.chungnam.ac.kr

Abstract

Beat-to-beat changes in heart period (heart period variability, HPV) are mediated by fluctuations in autonomic activity. Spectral analysis is used to quantify such fluctuations in the range of 0.15-0.40 Hz (high frequency, HF), which are influenced primarily by parasympathetic factors. These fluctuations are often referred to as RSA (respiratory sinus arrhythmia), the physiological phenomenon extracted by spectral analysis and other methods including histograms of heart rate (HR), deviations of HR etc. Respiratory sinus arrhythmia indexing with peak-to-valley method suggested by Grossman et al., (1987) yields a simple range statistic and is quantified on breath-by-breath basis, thus being quite sensitive and less dependent on recording time as compared to spectral analysis. It is strongly recommended to use at least 1 min epoch to asses HF component of HPV and at least 2 min for low frequency (LF) of HPV and even 5 min for valid clinical assessment. Peak-to-valley statistic is limited to RSA index only, but has its pragmatic advantages. Most important is possibility of its application for relatively small epoch analysis. We used short periods (20,30, 40 sec only) and off-line analysis of RSA using ECG and respiration curve this method of assessment and proved that this method is more practically effective. The RSA index was not so far dependent on respiration pattern differences and reflected actual vagal control of HR and were accompanied by low HR under some high stress conditions and in an aversive affective visual stimulation experiments. Another factor that might modulate cardiac chronotropic response is the interaction of sympathetic and parasympathetic inputs on sino-atrial (SA) node level, because responses to vagal influences are known to be proportional to ongoing sympathetic activity, that is so called accentuated antagonism. Since sympathetic outflow (increment of influences on SA) under negative emotions or stress was high in almost all physiological responses, vagal effects on HR could be therefore potentiated, leading to masking of output cardiac response seen in HPV. In the case of moderate sympathetic activation, on the other hand, autonomic interactions in cardiac control appear to be minimal. Thus RSA index appears to be an effective alternative method to assess and measure spectral HPV.

Introduction

There exist many arguments for the utility of the simultaneous use of heart rate (HR), heart period variability (HPV) and respiration rate (RESP) parameters in assessment of autonomic nervous (ANS) system-mediated cardiac responses in affective stimulation mode.

One of the main reasons of necessity to use cardiac measures beyond HR is that HR discrimination of emotions is not always sufficiently reproducible (Boiten, 1996, Cacioppo et al., 1993). Heart is an example of an end-organ innervated dually by sympathetic and parasympathetic system and output response (e.g., HR) is influenced by both autonomic inputs (Cacioppo et al., 1993). For further differentiation of the concrete mechanisms of cardiac reactivity to emotional stimulation, obviously HPV analysis seems more feasible, especially considering increased awareness about the role of respiratory sinus arrhythmia (RSA), relevant to high frequency (HF) component of HPV, and its effectiveness to indicate non-invasively parasympathetic cardiac control (Berntson et al., 1997; Grossman, 1983; Grossman et al., 1991; Porges, 1991, 1995).

The nominal respiratory frequency band is considered to range at rest from about 0.15 Hz to 0.40 Hz in humans but may extend below 0.15 and up to 1 Hz or more during exercise. As it was mentioned, RSA is generally believed to be mediated predominately by fluctuations of vagal-cardiac nerve traffic and may provide an index of vagal activity. The time between heart beats(R-R interval oscillations in electrocardiogram (ECG) is variously designated also as heart period or inter-beat interval. Heart period is a more abstract terminology that is not tied to any specific starting point or measurement interval, whereas R-R interval of ECG is more closely corresponds to what is actually measured in most cases. We consider HPV as more appropriate term. The HPV also occurs at low frequencies (about 0.05-0.15 Hz), including a 0.10-Hz component, that is sometimes referred to as the Mayer wave (Berntson et al., 1997). This frequency range has been termed the mid-frequency band by some authors (e.g., Mulder, 1992), but the designation of low frequency (LF) is more common one. The LF heart rate rhythms have been suggested to reflect mainly sympathetic outflow, but are thought by most investigators to be of both sympathetic and vagal origin (Akselrod et al., 1985 cited by Berntson et al., 1997).

The HPV analysis may provide powerful instrument for the understanding of relationship (e.g., emotion) and physiological (HR) processes. At the same time, there are many different approaches in the measurement, analysis, and interpretation of HPV. Though heart rate variability hold considerable advantage for the psychophysiology of emotions, the inappropriate quantification and interpretation of the HPV may complicate rather than advance the development of psychophysiological applications for interpretation of such processes as emotion and attention.

ANS mechanisms - deciphering involvement of sympathetic and vagal inputs

Following potential autonomic mechanisms of HR control could be involved in mediation of physiological responses observed in emotional manifestations : (1) sympathetic activation with parasympathetic withdrawal (HR acceleration, LF increase, HF and RSA decrease), (2) simultaneous activation of sympathetic (HR and LF of HPV increase) and parasympathetic (as indexed by RSA increase, moderate HR and RESP increase) systems, and (3) parasympathetic activation without changes in sympathetic activity (RSA increase, HF increase, but no changes in LF). The latter case (3) is a ralatively rare case in emotions manifestations, but is more typical for attention and orienting response.

However, it should be considered existence of the phenomena which is characteristic of certain states of stress in accordance with Gellhorns (1970) data, where he demonstrated that both the sympathetic and parasympathetic systems were concurrently active in the prolonged stress, and that their synergetic activation is typical for experimental neurosis and of chronic activation generally. In some cases of stress, sympathetic signs even can be masked by concurrent parasympathetic effects as suggested by (Gellhorn, 1970), and this might be one the reason why we found only modest changes in some cardiac variables (e.g., HR, LF/HF ratio in HPV) even in strong emotional manipulations.

Because respiratory and slower rhythms are apparent in the activity of both branches of the autonomic nervous system, studies of the functional effects of phasic modulation of sympathetic and vagal activities are especially relevant to patterns of HPV and psychophysiological responses of the heart (Berntson et al., 1997). These studies reveal that the cardiac response to vagal activity is rapid, whereas that to sympathetic activity is characterized by certain time delay and lead to a slower cardiac response. In summary, vagal responses are faster with little delay, whereas sympathetic responses are slower with a 1-2 sec time delay.

The slower dynamics of sympathetic actions at the SA node limit sympathetic contributions to respiratory modulations of heart rate variability. The frequency characteristics of heart rate and that the high-frequency-filter characteristics of the sympathetic innervation preclude appreciable contributions to RSA at frequencies beyond 0.15 Hz. Different reports confirmed the differential frequency response to the sinus node to parasympathetic and sympathetic modulation and reveal the high-frequency (HF) cardiac rhythms are mediated primarily by vagal innervation of the SA node (Berntson et al., 1993, 1997).

Interaction of respiration rate and RSA

Given that the respiration is centrally coupled with cardiac control mechanisms and HPV in high frequency (HF) range (so called RSA) is assumed as an index of parasympathetic (vagal) influences on cardiac chronotropy, recording of respiration parameters (respiration rate, respiration volume and peak respiration frequency) seems also desirable to assess correctness of HPV data especially during affective manipulations when respiration pattern changes are expected (Grossman et al., 1991; Grossman, & Kollai, 1993) .

One of the methodological approaches to keep influences of respiration on HPV under control is spectral analysis of respiration rate and its comparison with the relevant respiratory frequency peak in HPV. If peak frequency of respiration rate and peak of HF power in HPV are matching and show high correlation, it could be concluded that HF peak is correctly reflecting RSA and represents an index of parasympatheticaly mediated respiratory influences on heart rate (Bernston et al., 1997; Grossman, & Svebak, 1987, Porges, 1995).

Another potential reason of RSA increase (and that may be independent from vagal influences on heart as such) lies in method of measurement of the parameter, which is in fact vulnerable to artifacts related to respiration rate changes. Recent research on emotions, mental challenges and active coping tasks have found certain problems using RSA to predict vagal control of HR (Grossman & Kollai, 1993). Namely, differences in respiration pattern (respiration rate, inspiration volume) can influence RSA to such extent that parasympathetic cardiac control cannot be assessed reliably (Grossman et al., 1991). It was shown that inspiratory vagal control is decreasing when respiration period and tidal volume increase and increasing when respiration is quicker and shallower (Grossman & Kollai, 1993). RSA can be substantially greater during slow than during fast breathing because of the low-pass-filter characteristics of the autonomic-cardiac innervations (Grossman et al., 1991). These findings suggest that , at slow breathing frequencies, the phasic cholinergic influence on HR has sufficient time to achieve full effect, while at more rapid breathing frequencies, however, phasic cardiochronotropic responses decrease in amplitude (Berntson *et al.*, 1997). In our studies on affect responses using visual and auditory stimuli as emotion-inducing cues, however, RESP did not changed at the extent requiring special adjustments, while inspiration amplitude was even lower in more stressful condition .

Respiratory arrhythmia indexing with peak-to-valley method yields a simple range statistics and is quantified on breath-by-breath basis, thus being quite sensitive and less dependent on recording time as HPV (spectral) analysis is. General recommendation is to use at least 1 min epoch to asses HF component of HPV and at least 2 min for LF of HPV. and even 5 min for valid clinical assessment (Berntson *et al.*, 1997). Peak-to-valley statistic is limited to RSA only, but has its pragmatic advantages. Most important is possibility of its application for relatively small epoch analysis. Thus, in our study with short periods (20, 30 or 40 sec only) and off-line analysis of RSA using ECG and respiration curve this method of assessment proved to be more effective practically. We do not think that RSA index was so far dependent on respiration pattern differences and was not reflecting actual vagal control of HR, otherwise there are obvious difficulties in explanation of low HR observed in some high stress conditions and in an affective visual stimulation experiments (Sokhadze et al., 1999).

One more factor that might modulate cardiac chronotropic response is potential sympathetic-parasympathetic interaction on sino-atrial (SA) node level, because responses to vagal influences have been shown to be proportional to ongoing sympathetic activity, demonstrating so called accentuated antagonism (Levy, 1971). Since sympathetic outflow in negative emotions was high in almost all physiological responses we recorded (Sohn et al., 1998, 2000; Sokhadze at al., 1999, 2000) suggesting as well increased sympathetic influences on SA node, vagal effects on HR could be therefore potentiated, leading to masking of output cardiac chronotropic response. With moderate level levels of sympathetic activation (as in positive emotion and passive avoidance task conditions), on other hand, autonomic interactions in chronotropic control appear to be minimal (Berntson *et al.*, 1997). However, observed effect of decreased HR reactivity in stress might be only short-term, since in other study we demonstrated that HF and LF changes correlated only during the first minutes of prolonged (30 min) stimulation with aversive white noise, but then were followed by marked dissociating with obvious take-over of cardiac control by sympathetic system (Sokhadze *et al.*, 1999) . Relatively low sensitivity of LF and LF/HF ratio in some of our studies (Sokhadze at al., 1999, 2000) can be explained assuming that both sympathetic and parasympathetic systems and their interaction can substantially contribute to LF cardiac rhythms (Berntson *et al.*, 1997), or was a result of short epoch of heart period analysis which could lead to lower accuracy of HPV, especially in LF range.

Cardiac responses to external affective stimulation

Potential cardiac autonomic mechanisms underlying attention and emotion processes evoked by affective stimulation should be sought in understanding of the role of differential cardiac reactivity in the behavioral context (e.g., approach-avoidance tendencies, orienting-defense responses dichotomy etc.). Cardiovascular changes in response to external stimuli have been considered in general to be indicative of psychological processes related to the facilitation or inhibition of information processing (Coles, 1984; Jennings, 1986). Briefly, according to Vlila et al. (1997) the cardiac defense response (expressed as well in strong negative emotions, Sanchez et al., 1998, Vila 1999) could be defined as the pattern of HR changes to intense stimuli consists of a sequence of phasic cardiac changes with four observable components within 60 sec after the onset of eliciting stimulus, and is mediated by both the sympathetic and parasympathetic branches of the ANS. The first two components are mediated predominantly by vagus inputs, whereas the last two reflect sympathetic-parasympathetic reciprocal interaction (Fernandez, & Vila, 1989; Sanchez et al., 1998; Villa et al., 1996, 1997; Vila, 1999).

Role of parasympathetic system in mediation of emotions

According to the polyvagal theory of Porges (1995), in humans, the vagal efferent pathways to the heart functions as a brake. The intrinsic rate of the heart in the healthy human , even without sympathetic excitation, is significantly faster than the resting heart rate. thus under most conditions, the vagus, primarily via myelinated pathways originating in the nucleus ambiguus, actively inhibits heart rate. However, when there is a need to engage actively with select elements in the environment, cortical neurons inhibit homeostatic needs, and cardiac output is rapidly increased to match metabolic demands. Under these situations there is a transitory withdrawal of the vagal tone to the heart to increase heart rate, which defines the removal of the vagal brake (Porges, 1995). When demands require a calm behavioral state, the reengagement of the vagal brake slows heart rate and provides the physiological support for self-soothing behaviors. When the vagal brake is efficient , to support the changing metabolic demands, the neural modulation of RSA is paralleled by a monotonic change in heart rate. Within the context of the polyvagal theory (Porges, 1991,1995), the vagal brake is conceptualized as an adaptive neural physiological mechanism to foster engagement and disengagement with the environment. The efficiency of the vagal brake might be evaluated along several dimensions , including changes in the amplitude of RSA or an index of heart rate change relative to RSA change in response to a defined challenge. The definition of a challenge is arbitrary and often defined within specific experimental paradigms (e.g., mental effort, attention, social interaction). Especially during alert or vigilant states, responses to challenges must be rapid and continuous. For example, enviromental demands often dynamically change under real life conditions.

To evaluate whether the dynamic function of the vagal brake is state dependent it was necessary to generate measures of RSA and heart rate for short sequental epochs. Most methods for quantifying RSA, such as spectral analysis (Akselrod, et al., 1985) and peak-to-trough analysis (e.g., Fouad et al., 1984; Grossman & Wientjes, 1986) have assumed that the amplitude of RSA was a stationary characteristic of the heart rate time series. In general, these methods have been used to calculate an average amplitude of RSA over periods of several minutes. However, to evaluate the dynamic function of the vagal brake, the epoch-by-epoch shifts in RSA are not interpreted as measurement error distributed around a central tendency. Alternatively, the instability in RSA is interpreted as a measurable manifestation of dynamic changes in the vagal control of the heart. Therefore, it becomes necessary to quantify RSA over the periods of a few seconds and this is not possible to do with spectral analysis. Unlike other methods, the moving polinominal technology (i.e., Porges, 1995) provides a unique opportunity to study the dynamically changing amplitude of RSA independently of a potential non-stationary baseline representing dynamic changes in heart rate. A new procedure to evaluate this dynamic relationship was developed that calculates RSA and heart period for short duration epochs (i.e., 5 sec) and includes regression analyses applied to the epoch-to-epoch measures of RSA and heart period.

Conclusions

Numerous efforts has been applied to find the most reactive cardiac measure or pattern of several characteristics of herat ratel responses associated with the basic emotions in different psychophysiological experimental paradigms. Application of HPV measures provides with additional information on cardiac autonomic balance (or tone of b-adrenergic sympathetic and parasympathetic inputs to the heart). RSA is mediated predominantly by parasymphatetic influences on the sinus node, and HF heart rate variability is often employed as an index of vagal control. RSA appears to be associated with a number of different parasympathetic parameters, including central vagal outflow to the heart, cardiac vagal tone, baroreflex activity, and the phasic respiratory modulation of vagal activity. Simultaneous usage of the indicators of sympathetic and parasympathetic branches influences on heart rate along with traditional parameters such as respiratory activity enables to interpret more accurately the state of autonomic arousal during affective manipulations. However, measurement of heart rate variability in the respiratory frequencies, that is respiratory sinus arrhythmia related indices is not uniform, it can be proceeded with different methodological approaches. Our experimental data suggest that RSA index measurement by peak-to-valley method appears to be an effective alternative method to asess and measure high frequency component of HPV by spectral methods.

References

Akselrod, S et al. (1985) Hemodynamic regulation: Investigation by spectral analysis. *American J. of Physiology,* 18, H867-H875.

Bernston, G. et al. (1997) Heart rate variability: Origins, methods and interpretive caveates. *Psychophysiology, 34,* 623-648.

Bertson , G., Cacioppo, J., & Quigley, K. (1993). Respiratory sinus arrhythmia: Anatomical origins, physiological mechanisms, and psychophysiological implications, *Psychophysiology, 30,* 183-196.

Boiten, F. (1996). Autonomic response patterns during voluntary facial action. *Psychophysiology*, 33, 123-131.

Cacioppo J.T. et al. (1993). The psychophysiology of emotion. In : M.Lewis, & G.Haviland (Eds.). *Handbook of emotions.(* pp. 119-142). New York: Guilford.

Coles M.G.H. (1984). Heart rate and attention: The intake-rejection hypothesis and beyond. In: M.G.H. Coles, J.R. Jennings, & J.A.Stern (Eds.) *Psychophysiological perspectives* (pp. 276-295). N.Y.: Van Nostrand Reinhold.

Fernandez, M.C., & Vila, J. (1989) Sympathetic-parasympathetic mediation of the cardiac defense response in humans. *Biological Psychology*, 28, 123-133.

Fouad, F. et al. (1984) Assessment of parasympathetic control of heart rate by a non-invasive method. *American J. of Physiology, 246, H838-H842.*

Gellhorn, E. (1970). The emotions and the ergotropic and trophotropic systems. *Psychologische Forschung*, 34, 48-94.

Grossman, P. (1983). Respiration, stress and cardiovascular functions. *Psychophysiology,* 20, 284-300.

Grossman P., & Svebak, S. (1987). Respiratory sinus arrhythmia as an index of parasympathetic cardiac control during active coping. *Psychophysiology*, 24, 228-235.

Grossman, P., Karemaker, J., & Weiling, W. (1991) Prediction of tonic parasympathetic cardiac control using respiratory sinus arrhythmia: The need for respiratory control. *Psychophysiology, 28*, 201-216.

Grossman, P., & Kollai, M. (1993). Respiratory sinus arrhythmia, cardiac vagal tone, and respiration: Within- and between-individual relations. *Psychophysiology, 30,* 486-495.

Hare, R.D. (1973) . Orienting and defensive responses to visual stimuli. *Psychophysiology,* 27, 559-567.

Jennings, J.R. (1986) Bodily changes during attending. In M.G.H.Coles, E.Donchin, & S.W.Porges (Eds.), *Psychophysiology: Systems, Processes and Applications* (pp. 268-289), New York: Guilford.

Larsen, P.B., Schnerderson, N. & Pasin R.D.C. (1986). Physiological bases of cardiovascular psychophysiology. In M.G.H.Coles et al. (Eds.), *Psychophysiology: Systems, Processes and Applications*. (pp. 122-165). New York: Guilford Press.

Papillo, J.F., & Shapiro, D. (1990). Cardiovascular system. In: J.Cacioppo & L.Tassinary (Eds.) *Principles of Psychophysiology: Physical, social and inferential elements.(* pp. 451-512), Cambridge: Cambridge University Press.

Porges S. (1991) Vagal tone: An autonomic mediator of affect. In J. Garber & K.A. Dodge (Eds.) *The development of emotion regulation and dysregulation* (p. 111-128) Cambridge, UK: University Press.

Porges , S. (1995). Orienting in defensive world: Mammalian modifications of our evolutionary heritage, a polyvagal theory. *Psychophysiology,* 32, 301-318.

Sanchez, M., Ramirez, I., Fernandez, M.C., Vila, J., Bradley, M., & Lang, P. (1998). Emotional modulation of cardiac defense in humans, *Psychophysiology,* 35, S70

Shulman I., & Sokhadze, E. (1993). Patterns of short-term reactions of heart rate and dependence of CNS functions on heart events. *Psychophysiology, 30,* S60.

Sohn, J.-H., Yi, I., Lee, K.-H., & Sokhadze, E. (1998). ANS and EEG differentiation of emotions induced by pictorial stimuli. *Psychophysiology, 35,* S75.

Sohn J.-H., Sokhadze, E., Lee, K.-H., & Yi I. (2000) Basic emotions elicited by Korean Affective Picture System can be differentiated by autonomic responses. *Proceeding of the 2000 Spring Conference of KOSES & International Sensibility Ergonomics Symposium. Taejon, June, 2-3,* pp.370-379.

Sokhadze, E., Yi, I., Choi, S., Lee, K.-H., & Sohn J.-H. (1998). Physiological indicators of emotion and attention processes during affective and orienting auditory stimulation. *J. Acoustical Society of Korea,* 17, N 1(s), 291-296.

Sokhadze, E., Choi, S., Lee K.-H., Kim, Y.-K., & Sohn, J.-H. (1999). Effects of long-term exposure to noise on psychophysiological responses. *Proceedings of Korean Society for Emotion and Sensibility Fall99 Meeting, Seoul, Korea, November 11-27,* 211- 215.

Sokhadze, E., Lee, K.-H., Lee J.-M., Oh, J.-I.,& Sohn, J.H. (2000). Modulation of the time course of cardiac chronotropic responses during exposure to affective pictures. *Proceeding of the 2000 Spring Conference of KOSES & International Sensibility Ergonomics Symposium. Taejon, June, 2-3,* pp. 290-300.

Vila, J. (1999). Cardiac component of the defense response. *Psychophysiology,* 36, S3.

Vila J., Perez, M.N., Fernandez, M.C., Pegalajar, J., & Sanchez M. (1997) Attentional modulation of the cardiac defense response in humans. *Psychophysiology, 34,* 482-487.