

## REVIEW

# Heart Rate Variability: New Perspectives on Physiological Mechanisms, Assessment of Self-regulatory Capacity, and Health Risk

心率变异性: 关于生理机制、自律能力和健康风险评估的新观点

Variabilidad de frecuencia cardiaca: Nuevas perspectivas sobre mecanismos fisiológicos, valoración de la capacidad autorreguladora y riesgo de la salud

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## ABSTRACT

Heart rate variability, the change in the time intervals between adjacent heartbeats, is an emergent property of interdependent regulatory systems that operates on different time scales to adapt to environmental and psychological challenges. This article briefly reviews neural regulation of the heart and offers some new perspectives on mechanisms underlying the very low frequency rhythm of heart rate variability. Interpretation of heart rate variability rhythms in the context of health risk and physiological and psychological self-regulatory capacity assessment is discussed. The cardiovascular regulatory centers in the spinal cord and medulla integrate inputs from higher brain centers with afferent cardiovascular system inputs to adjust heart rate and blood pressure via sympathetic and parasympathetic efferent pathways. We also discuss the intrinsic cardiac nervous system and the heart-brain connection pathways, through which afferent information can influence activity in the subcortical, frontocortical, and motor cortex areas. In addition, the use of real-time HRV feedback to increase self-regulatory capacity is reviewed. We conclude that the heart's rhythms are characterized by both complexity and stability over longer time scales that reflect both physiological and psychological functional status of these internal self-regulatory systems.

## 摘要

心率变异性 (HRC) (在相邻心跳之间的时间间隔的变化) 是相互依存的调节系统的一种紧急特性, 在不同时段内发生, 以适应环境和心理挑战。这篇文章简要回顾了心脏的神经调节, 在心率变异性的极低频率节奏机制方面, 提供了一些新的观点。在健康风险和生理及心理自我调节能力评估讨论的背景下解读 HRV 节律。伴有心血管系统输入功能的更高级的大脑中枢集成输入的脊髓和延髓心血管监管中心, 通过交感和副交感神经传出通路调节心率和血压。我们还讨论了先天性心脏神经系统和心脏大脑连接通路, 借以传入信息并可以影响皮质下区, 皮质前区和运动皮质区的活动。此外, 审查了使用实时的 HRV 反馈以提高自我调节能力。我们的结论是, 心脏节律的特征在于在更长的时段上既有复杂性又有稳定性, 这反映出这些内部自我调节系统的生理和心理功能状态。

## SINOPSIS

La variabilidad de la frecuencia cardiaca, o modificación de los intervalos de tiempo entre los latidos consecutivos del corazón, es una propiedad emergente de los sistemas reguladores interdependientes que opera sobre diferentes escalas temporales para adaptarse a los retos ambientales y psicológicos. Este artículo revisa brevemente la regulación nerviosa del corazón y ofrece nuevas perspec-

tivas sobre los mecanismos subyacentes al ritmo de muy baja frecuencia de la variabilidad de la frecuencia cardiaca. Se analiza la interpretación de los ritmos de la variabilidad de la frecuencia cardiaca en el contexto del riesgo para la salud y la valoración de la capacidad autorreguladora fisiológica y psicológica. Los centros reguladores cardiovasculares de la médula espinal y del bulbo raquídeo integran entradas de centros cerebrales superiores con entradas de sistemas cardiovasculares aferentes para ajustar la frecuencia cardiaca y la tensión arterial por vías eferentes simpáticas y parasimpáticas. También hablamos sobre el sistema cardiaco nervioso intrínseco y las vías de conexión corazón-cerebro, a través de las cuales la información aferente puede influir sobre la actividad en las áreas subcortical, frontocortical y de la corteza motora. Además, se revisa el uso de retroalimentación de variabilidad de la frecuencia cardiaca a tiempo real para aumentar la capacidad autorreguladora. Concluimos que los ritmos cardiacos se caracterizan tanto por su complejidad como por su estabilidad sobre escalas temporales más largas que reflejan los estados funcionales tanto fisiológicos como psicológicos de estos sistemas internos autorreguladores.

## INTRODUCTION

Since Walter Cannon introduced the concept of homeostasis,<sup>1</sup> the study of physiology has been based on the principle that all cells, tissues, and organs strive to maintain a static or constant “steady-state” condi-

tion. However, with the introduction of signal processing technologies that can acquire continuous time series data from physiological processes such as heart rate (HR), blood pressure (BP), and nerve activity, it has become abundantly apparent that biological processes

vary in complex and nonlinear ways, even during so called “steady-state” conditions. These observations have led to the understanding that healthy, optimal function is a result of continuous, dynamic, bi-directional interactions among multiple neural, hormonal, and mechanical control systems at both local and central levels. In concert, these physiological and psychological regulatory systems are never truly at rest and are certainly never static. For example, we now know that the normal resting rhythm of the heart is highly variable rather than being monotonously regular, which was the widespread notion for many years.

### HEART RATE VARIABILITY

The investigation of the heart’s complex rhythms or what is now called heart rate variability<sup>2</sup> (HRV) began with the emergence of modern signal processing in the 1960s and 1970s, and has rapidly expanded in more recent times. The irregular behavior of the heart-beat is readily apparent when HR is examined on a beat-to-beat basis, but is overlooked when a mean value over time is calculated. These fluctuations in HR result from complex, nonlinear interactions among a number of different physiological systems. HRV is thus considered a measure of neurocardiac function that reflects heart–brain interactions and autonomic nervous system (ANS) dynamics.<sup>3,4</sup>

An optimal level of HRV within an organism reflects healthy function and an inherent self-regulatory capacity, adaptability, or resilience.<sup>4-10</sup> Too much instability, such as arrhythmias or nervous system chaos, is detrimental to efficient physiological functioning and energy utilization. However, too little variation indicates age-related system depletion, chronic stress, pathology, or inadequate functioning in various levels of self-regulatory control systems.<sup>2,11,12</sup>

The importance of HRV as an index of the functional status of physiological control systems was noted as far back as 1965 when it was found that fetal distress is preceded by reductions in HRV before any changes occur in HR itself.<sup>13</sup> In the 1970s, reduced HRV was shown to predict autonomic neuropathy in diabetic patients before the onset of symptoms.<sup>14-16</sup> Reduced HRV was also found to be a greater risk factor of death post–myocardial infarction than other known risk factors.<sup>17</sup> It has clearly been shown that HRV declines with age and age-adjusted values should be used in the context of risk prediction.<sup>18</sup> Age-adjusted HRV that is low has been confirmed as a strong, independent predictor of future health problems in both healthy people. Age-adjusted HRV correlates with all-cause mortality.<sup>19,20</sup> In prospective studies reduced HRV has been the strongest independent predictor of the progression of coronary atherosclerosis.<sup>21</sup> A number of studies have shown that reduced HRV is associated with measures of inflammation in subjects with no apparent heart disease.<sup>22</sup> Reduced HRV is also observed in patients with autonomic dysfunction, anxiety, depression, asthma, and sudden infant death.<sup>23-26</sup>

Reduced HRV may correlate with disease and mortality because it reflects reduced regulatory capacity and ability to adaptively respond to physiological challenges such as exercise. For example, in the Chicago Health, Aging, and Social Relations Study, separate metrics for the assessment of autonomic balance and overall cardiac autonomic regulation were developed and tested in a sample of 229 participants. In this study, overall regulatory capacity was a significant predictor of overall health status, but autonomic balance was not. In addition, cardiac regulatory capacity was negatively associated with the prior incidence of myocardial infarction. The authors suggest that cardiac regulatory capacity reflects a physiological state that is more relevant to health than the independent sympathetic or parasympathetic controls or the autonomic balance between these controls as indexed by different measures of HRV.<sup>27</sup>

When speaking of autonomic balance, it should be kept in mind that a healthy system is constantly and dynamically changing. Therefore, an important indicator of the health status of the regulatory systems is the capacity to respond to and adjust the relative autonomic balance (eg, HR) to the appropriate state for the context the person is engaged in at any given moment. In other words, does the HR dynamically respond? Is it higher during the daytime or when someone is dealing with challenging tasks and lower when at rest or during sleep? The inability of the physiological self-regulatory systems to adapt to the current context and situation is associated with numerous clinical conditions.<sup>28</sup> Also distinct, altered, circadian patterns in 24-hour heart rates are associated with different and specific psychiatric disorders, particularly during sleep.<sup>29,30</sup>

HR estimated at any given time represents the net effect of the neural output of the parasympathetic (vagus) nerves, which slow HR, and the sympathetic nerves, which accelerate it. In a denervated human heart where there are no connections from the ANS to the heart following its transplantation, the intrinsic rate generated by the pacemaker (SA node) is about 100 beats per minute (bpm).<sup>31</sup> Parasympathetic activity predominates when HR is below this intrinsic rate during normal daily activities and when at rest or sleep. When HR is above about 100 bpm, the relative balance shifts and sympathetic activity predominates. Therefore, HR best reflects the relative balance between the sympathetic and parasympathetic systems. The average 24-hour HR in healthy people is approximately 73 bpm. Higher HRs are independent markers of mortality in a wide spectrum of conditions.<sup>28</sup>

It is important to note the natural relationship between HR and amount of HRV. As HR increases there is less time between heartbeats for variability to occur, thus HRV decreases. At lower HRs there is more time between heartbeats and variability naturally increases. This is called cycle length dependence, and it persists in the healthy elderly to a variable degree,

even at a very advanced age. However, elderly patients with ischemic heart disease or other pathologies develop less variability at increasingly lower HRs and ultimately lose the relationship between HR and variability, to the point that variability does not increase with reductions in HR.<sup>32</sup> Even in healthy subjects, the effects of cycle length dependence should be taken into account when assessing HRV. HR values should also always be reported, especially when HRs are increased due to factors like stress reactions, medications, and physical activity.

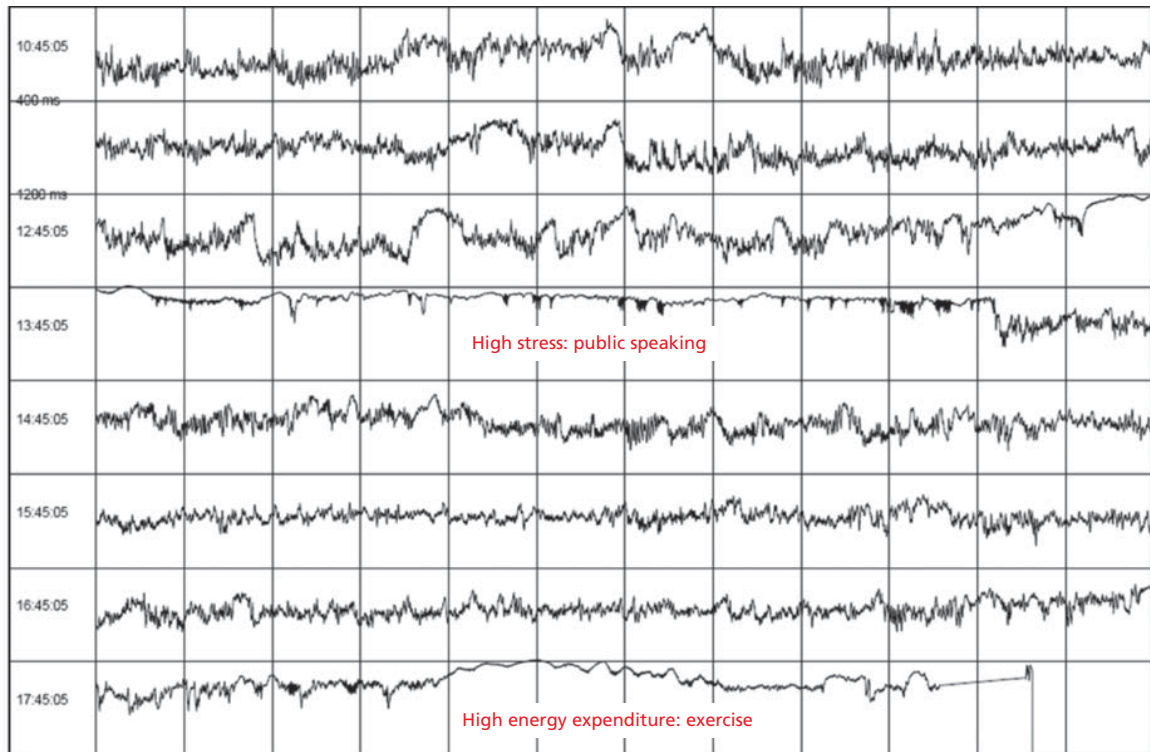
Efferent (descending) sympathetic nerves target the SA node via the intrinsic cardiac nervous system and the bulk of the myocardium. Action potentials conducted by these motor neurons trigger norepinephrine and epinephrine release, which increases HR and strengthens the contractility of the atria and ventricles. Following the onset of sympathetic stimulation, there is a delay of up to 5 seconds before the stimulation induces a progressive increase in HR, which reaches a steady level in 20 to 30 seconds if the stimulus is continuous.<sup>33</sup> Even a brief sympathetic stimulus can affect the HR and the HRV rhythm for 5 to 10 seconds. The relatively slow response to sympathetic stimulation is

in direct contrast to vagal stimulation, which is almost instantaneous. Thus, any sudden change in HR, up or down or between one beat and the next, is primarily parasympathetically mediated.<sup>33,34</sup>

Patient age may mediate the relationship between reduced HRV and regulatory capacity of physiological control systems. Age-related reductions in HRV<sup>18</sup> may reflect the loss of neurons in the brain and spinal cord, resulting in degraded signal transmission and reduced regulatory capacity. Reduced physiological regulatory capacity may contribute to functional gastrointestinal disorders, inflammation, and hypertension.<sup>35,36</sup>

#### HEART RATE VARIABILITY ANALYSIS METHODS

HRV can be assessed with various analytical approaches, although the most commonly used are frequency domain (power spectral density) analysis and time domain analysis. The interactions between autonomic neural activity, BP, respiration, and higher level control systems produce both short and longer term rhythms in HRV measurements.<sup>4,12,37</sup> The most common form for observing these changes is the HR tachogram, a plot of the sequence of time intervals between heartbeats (Figure 1).



**Figure 1** An example of the heart rate (HR) tachogram, a plot of the sequence of time intervals between heartbeats over an 8-hour period in ambulatory recording taken from a 36-year-old male. Each of the traces is 1 hour long, with the starting time of the hour on the left hand side of the figure. The time between each vertical line is 5 minutes. The vertical axis within each of the hourly tracings is the time between heartbeats (inter-beat-intervals) ranging between 400 and 1200 milliseconds (label shown on second row). The hours beginning at 10:45 through 12:45 were during a time when he was in a low-stress classroom setting. His overall HR increased, and the range of the HRV is considerably less during the hour starting at 13:45 (public speaking), when he was presenting to the class. In this case, the relative autonomic nervous system balance is shifted to sympathetic predominance due to the emotional stress around presenting to a group of his peers. Once the presentation completed near the end of the hour, his HR dropped and normal HRV was restored. In the following hours, he was listening to others present and providing feedback. In the hour starting at 17:45, he was engaged in physical exercise (walking up a long steep hill) starting about 20 minutes into the hour where his HR is increased and the HRV is reduced due to cycle-length dependence effects.

## HEART RATE VARIABILITY FREQUENCY BANDS AND PHYSIOLOGICAL MECHANISMS

The European Society of Cardiology and the North American Society of Pacing and Electrophysiology Task Force Report on HRV divided heart rhythm oscillations into 4 primary frequency bands: high-frequency (HF), low-frequency (LF), very-low-frequency (VLF), and ultra-low-frequency (ULF).<sup>12</sup> Most HRV analysis is done in 5-minute segments (of a 24-hour recording), although other recording periods are often used. When other recording lengths are analyzed, the length of the recording should be reported since this has large effects on both HRV frequency and time domain values.

### High-frequency Band

The HF range is from 0.15 Hz to 0.4 Hz, which equates to rhythms with periods that occur between 2.5 and 7 seconds. This band reflects parasympathetic or vagal activity and is frequently called the respiratory band because it corresponds to the HR variations related to the respiratory cycle known as respiratory sinus arrhythmia. The mechanisms linking the variability of HR to respiration are complex and involve both central and reflex interactions.<sup>38</sup> During inhalation, the cardiorespiratory center inhibits vagal outflow resulting in accelerating the HR. Conversely, during exhalation, vagal outflow is restored resulting in slowing the HR.<sup>39</sup> Although the magnitude of the oscillation is variable, in healthy people it can be increased by slow, deep breathing. In younger healthy individuals, it is not uncommon to see an obvious increase in the HF band at night with a decrease during the day.<sup>40,41</sup>

In terms of psychological regulation, reduced vagally mediated HRV has been linked to reduced self-regulatory capacity and cognitive functions that involve the executive centers of the prefrontal cortex. This is consistent with the finding that lower HF power is associated with stress, panic, anxiety, or worry. Lowered parasympathetic activity, rather than reduced sympathetic functioning, appears to account for the reduced HRV in aging.<sup>18</sup>

A number of studies have shown that total vagal blockade essentially eliminates HF oscillations and reduces power in the LF range.<sup>42,43</sup> Some investigators have used pharmacological blockade (eg, atropine) and found greatly reduced HRV, including the LF and VLF bands. As a result, they have concluded that all HRV is produced by parasympathetic mechanisms (eg, breathing)<sup>44,45</sup> However, these investigations did not take into account that atropine and related agents have much broader effects than only blocking parasympathetic activity. These substances also target the intrinsic cardiac nervous system, especially the local circuit neurons, which are critical in cardiac control, afferent communication, and the generation of HRV.<sup>46</sup> It has been shown that atropine and similar substances also affect sympathetic neurons,<sup>46</sup> so it would be expected that these blockades would affect HRV across all frequency bands.

### Low-frequency Band

The LF range is between 0.04 Hz and 0.15 Hz, which equates to rhythms or modulations with periods that occur between 7 and 25 seconds. This region was previously called the “baroreceptor range” or “mid-frequency band” by many researchers, since it primarily reflects baroreceptor activity while at rest.<sup>43</sup> Baroreceptors are stretch-sensitive mechanoreceptors located in the chambers of the heart and vena cavae, carotid sinuses (which contain the most sensitive mechanoreceptors), and the aortic arch. As discussed previously, the vagus nerves are a major conduit through which afferent (ascending) neurological signals from the heart are relayed to the brain, including baroreflex signals. Baroreflex gain is commonly calculated as the beat-to-beat change in HR per unit of change in systolic BP.<sup>47</sup> Decreased baroreflex gain is related to aging and impaired regulatory capacity.<sup>36</sup>

The cardiovascular system resonance frequency is a distinctive high-amplitude peak in the HRV power spectrum around 0.1 Hz. It has long been established that it is caused by a delay in the feedback loops within the baroreflex system between the heart and brain.<sup>48,49</sup> In humans and many other mammals, the resonance frequency of the system is approximately 0.1 Hz, which is also characteristic of the coherent state described later.

The sympathetic nervous system does not appear to have much influence in rhythms above 0.1 Hz, while the parasympathetic system can be observed to affect heart rhythms down to 0.05 Hz (20-sec rhythm). Therefore, during periods of slow respiration rates, vagal activity can easily generate oscillations in the heart rhythms that cross over into the LF band.<sup>50-52</sup> Therefore, respiratory-related efferent vagally mediated influences are particularly present in the LF band when respiration rates are below 8.5 breaths per minute (approximately 1 breath every 7 seconds) or when an individual sighs or takes a deep breath.<sup>52,53</sup>

In ambulatory 24-hour HRV recordings, it has been suggested that the LF band reflects sympathetic activity and the LF/HF ratio has been controversially used to assess the balance between sympathetic and parasympathetic activity.<sup>54-56</sup> A number of researchers have challenged this perspective and have persuasively argued that in resting conditions, the LF band reflects baroreflex activity and not cardiac sympathetic innervation.<sup>39,57-61</sup>

### Very-low-frequency Band

The VLF is the power in the range between 0.0033 and 0.04 Hz, which equates to rhythms or modulations with periods that occur between 25 and 300 seconds. Although all 24-hour clinical measures of HRV reflecting low HRV are linked with increased risk of adverse outcomes, the VLF band has stronger associations with all-cause mortality than the LF and HF bands.<sup>20,62-64</sup> Low VLF power has been shown to be associated with arrhythmic death<sup>65</sup> and posttraumatic stress disorder

(PTSD).<sup>66</sup> Additionally, low power in this band has been associated with high inflammation<sup>67,68</sup> and has been correlated with low levels of testosterone. In contrast, other biochemical markers, such as those mediated by the hypothalamic-pituitary-adrenal (HPA) axis axis (eg, cortisol), did not.<sup>69</sup> Longer time periods using 24-hour HRV recordings should be obtained to provide comprehensive assessment of VLF and ULF fluctuations.<sup>70</sup>

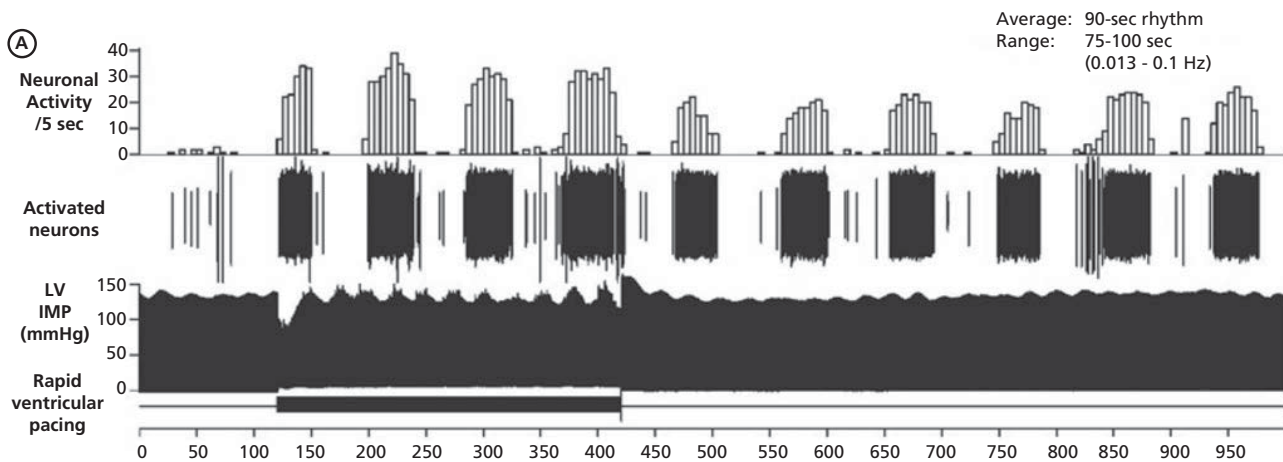
Historically, the physiological explanation and mechanisms involved in the generation of the VLF component have not been as well defined as the LF and HF components. This region has been largely ignored even though it is the most predictive of adverse outcomes. Long-term regulatory mechanisms and ANS activity related to thermoregulation, the renin-angiotensin system, and other hormonal factors appear to contribute to this band.<sup>71,72</sup>

Recent work by Armour has shed new light on the primary mechanisms underlying the VLF rhythm. This line of research began after some surprising results from a study looking at HRV in auto-transplanted hearts in dogs. In auto-transplants, the heart is removed and placed back in the same animal so there is no need for anti-rejection medications. The primary purpose of the study was to determine if the autonomic nerves re-innervated the heart posttransplant. Monthly 24-hour HRV recordings were done over a 1-year period on all the dogs with auto-transplanted hearts as well as the control dogs. The nerves did re-innervate but in a way that was not accurately reflected in HRV. It showed that the intrinsic cardiac nervous system has neuroplasticity and re-structured its neural connections. The truly surprising result was that these de-innervated hearts had higher levels of HRV, including HRV that is typically associated with respiration, than control dogs immediately posttransplant. These levels were sustained over a 1-year period.<sup>73</sup> This was unexpected as there is very little HRV in human transplant recipients.<sup>74</sup>

Following up on these results, Armour and colleagues developed methods to obtain long-term single-neuron recordings from a beating heart, and simultaneously, from extrinsic cardiac neurons.<sup>75</sup> Figure 2 shows the VLF rhythm obtained from an afferent neuron located in the intrinsic cardiac nervous system in a dog heart. In this case, the VLF rhythm is generated from intrinsic sources and cannot be explained by sources such as movement. The black bar at the bottom of the figure labeled “rapid ventricular pacing” shows the time period where efferent spinal neurons were stimulated. The resulting increase in efferent sympathetic activity clearly elevates the amplitude of the afferent neuron’s intrinsic VLF rhythm (top row).

Work by Armour and other investigators imply that the VLF rhythm is generated by the stimulation of afferent sensory neurons in the heart, which in turn activate various levels of the feedback and feed-forward loops in the heart’s intrinsic cardiac nervous system, neurons in the extrinsic cardiac ganglia, and spinal column.<sup>57,76</sup> Thus, the VLF rhythm appears to be produced by the heart itself and may be an intrinsic rhythm that is fundamental to health and wellbeing. This cardiac origin of the VLF rhythm is also supported by studies showing that sympathetic blockade does not affect VLF power. Furthermore, VLF activity remains in quadriplegics, whose sympathetic innervation of the heart and lungs is disrupted.<sup>77</sup>

Thus, experimental evidence suggests that the VLF rhythm is intrinsically generated by the heart and that the amplitude and frequency of these oscillations are modulated by efferent sympathetic activity. Normal VLF power appears to indicate healthy function, and increases in resting VLF power and or shifting of their frequency can reflect efferent sympathetic activity. The modulation of the frequency of this rhythm due to physical activity,<sup>78</sup> stress responses, and other factors that increase efferent sympathetic



**Figure 2** Long-term single-neuron recordings from an afferent neuron in the intrinsic cardiac nervous system in a beating dog heart. The top row shows neural activity. The second row is the actual neural recording. The third row is the left ventricular pressure. This intrinsic rhythm has an average period of 90 seconds with a range between 75 to 100 seconds (0.013 Hz - 0.01 Hz), which falls within the VLF band. Used with permission from Dr J. Andrew Armour.

activation can cause it to cross over into the lower region of the LF band during ambulatory monitoring or during short-term recordings when there is a significant emotional stressor.<sup>4</sup>

### Ultra-low-frequency Band

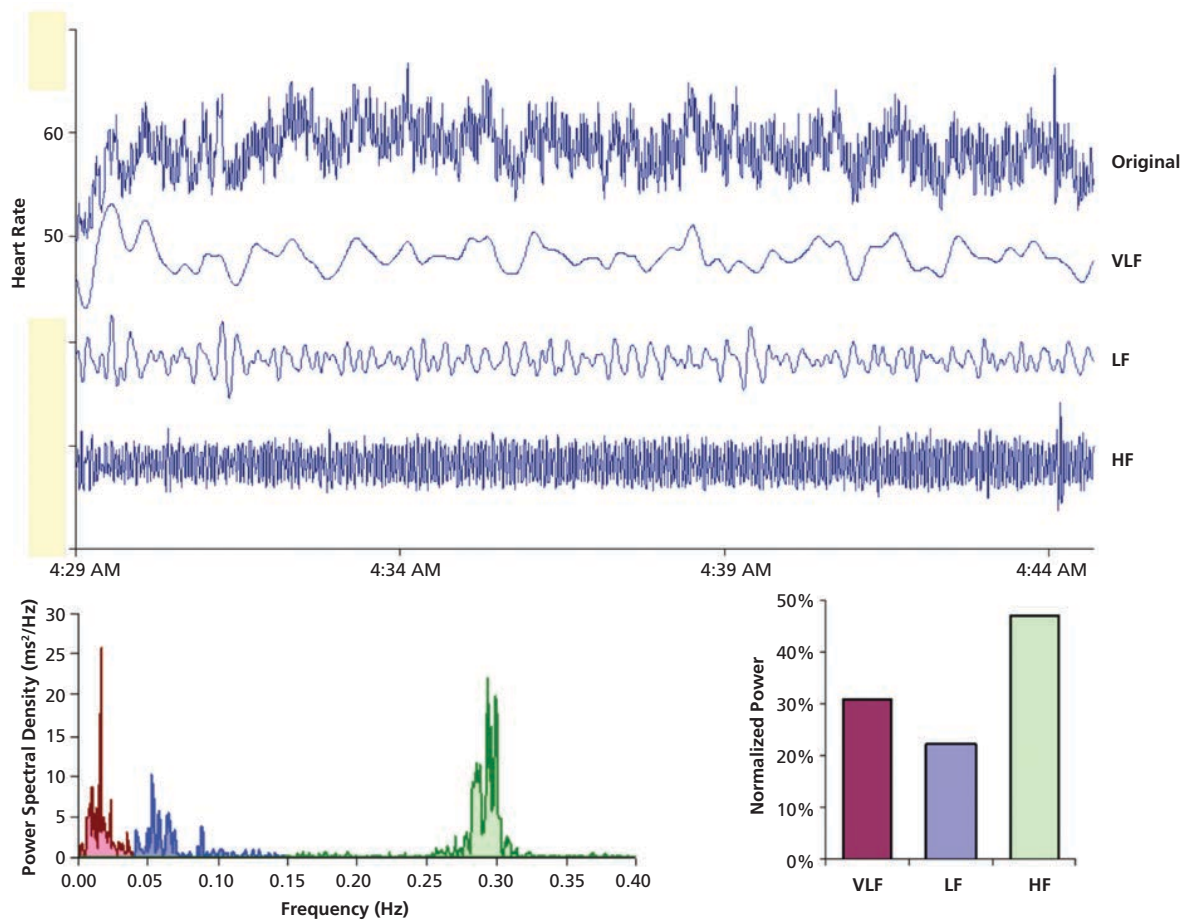
The ultra-low-frequency band (ULF) falls below 0.0033 Hz (333 seconds or 5.6 minutes). Oscillations or events in the heart rhythm with a period of 5 minutes or greater are reflected in this band and it can only be assessed with 24-hour and longer recordings.<sup>70</sup> The circadian oscillation in HR is the primary source of the ULF power, although other very slow-acting regulatory processes, such as core body temperature regulation, metabolism, and the renin-angiotensin system likely add to the power in this band.<sup>12</sup> The Task Force Report on HRV suggests that 24-hour recordings should be divided into 5-minute segments and that HRV analysis should be performed on the individual segments prior to the calculation of mean values. This effectively filters out any oscillations with periods longer than 5 minutes. However, when spectral analysis is applied to entire 24-hour records, several lower frequency rhythms are

easily detected in healthy individuals.<sup>3</sup>

Circadian rhythms, core body temperature, metabolism, hormones, and intrinsic rhythms generated by the heart all contribute to lower frequency rhythms (eg, VLF and ULF) that extend below 0.04 Hz. In healthy individuals, there is an increase in VLF power that occurs during the night and peaks before waking.<sup>79,80</sup> This increase in autonomic activity appears to correlate with the morning cortisol peak.

### Power Spectral Analysis

Power spectral analysis is used to separate the complex HRV waveform into its component rhythms that operates within different frequency ranges (Figure 3). Spectral analysis provides information regarding how power is distributed (the variance and amplitude of a given rhythm) as a function of frequency (the time period of a given rhythm). The main advantages of spectral analysis are that it supplies both frequency and amplitude information on the specific rhythms that exist in the HRV waveform, providing a means to quantify these oscillations over any given period. The values are expressed as the power spectral density,



**Figure 3** A typical heart rate variability (HRV) recording over a 15-minute period during resting conditions in a healthy individual. The top tracing shows the original HRV waveform. Filtering techniques were used to separate the original waveform into VLF, LF, and HF bands as shown in the lower traces. The bottom of the figure shows the power spectra (left) and the percentage of power (right) in each band.

**Abbreviations:** HF, high frequency; LF, low frequency; PSD: power spectral density; VLF, very low frequency.

which is the area under the curve (peak) in a given bandwidth of the spectrum. The power or height of the peak at any given frequency indicates the amplitude and stability of the rhythm. The frequency reflects the period of time over which the rhythm occurs. For example, a 0.1 Hz frequency has a period of 10 seconds.

### Autonomic Balance and the Low-frequency:High-frequency Ratio

The autonomic balance hypothesis assumes that the sympathetic and parasympathetic competitively regulate HR (accentuated antagonism), where increased sympathetic activity is paired with decreased parasympathetic activity. While some orthostatic challenges can produce reciprocal changes in sympathetic activation and vagal withdrawal, psychological stressors can also result in independent changes in sympathetic or parasympathetic activity. It is now generally accepted that both branches of the ANS are simultaneously active.<sup>27</sup>

The ratio of LF to HF power is controversial due to the issues regarding the LF band described above. It is often assumed that a low LF:HF ratio reflects greater parasympathetic activity relative to sympathetic activity. However, this ratio is often shifted due to reductions in LF power. Therefore, the LF:HF ratio should be interpreted with caution and the mean values of HF and LF power taken into consideration. In contrast, a high LF:HF ratio may indicate higher sympathetic activity relative to parasympathetic activity as can be observed when people engage in meeting a challenge that requires effort and increased sympathetic activation. Alternatively, it can indicate increased parasympathetic activity as occurs during slow breathing. Again, the same cautions must be taken into consideration, especially in short-term recordings.

### TIME DOMAIN MEASUREMENTS OF HEART RATE VARIABILITY

Time domain measures are the simplest to calculate. Time domain measures do not provide a means to adequately quantify autonomic dynamics or determine the rhythmic or oscillatory activity generated by the different physiological control systems. However, since they are always calculated the same way, data collected by different researchers are comparable but only if the recordings are exactly the same length of time and the data are collected under the same conditions. Time domain indices quantify the amount of variance in the inter-beat-intervals (IBI) using statistical measures. The three most important and commonly reported time domain measures are the standard deviation of normal-to-normal (SDNN), the SDNN index, and the root mean square of successive differences (RMSSD) are the most commonly reported metrics.

#### The Standard Deviation of the Normal-to-Normal

The SDNN is the standard deviation of the normal-to-normal (NN) sinus-initiated IBIs measured in milli-

seconds. This measure reflects the ebb and flow of all the factors that contribute to HRV. In 24-hour recordings, the SDNN is highly correlated with ULF and total power.<sup>18</sup> In short-term resting recordings, the primary source of the variation is parasympathetically mediated, especially with slow, deep breathing protocols. However, in ambulatory and longer term recordings the SDNN values are highly correlated with lower frequency rhythms.<sup>3</sup> Thus, low age-adjusted values predict morbidity and mortality. For example, patients with moderate SDNN values (50-100 milliseconds) have a 400% lower risk of mortality than those with low values (0-50 milliseconds) in 24-hour recordings.<sup>81,82</sup>

#### Standard Deviation of the Normal-to-Normal Index

The SDNN index is the mean of the standard deviations of all the NN intervals for each 5-minute segment. Therefore, this measurement only estimates variability due to the factors affecting HRV within a 5-minute period. In 24-hour HRV recordings, it is calculated by first dividing the 24-hour record into 288 five-minute segments and then calculating the standard deviation of all NN intervals contained within each segment. The SDNN index is the average of these 288 values.<sup>12</sup> The SDNN index is believed to primarily measure autonomic influence on HRV. This measure tends to correlate with VLF power over a 24-hour period.<sup>3</sup>

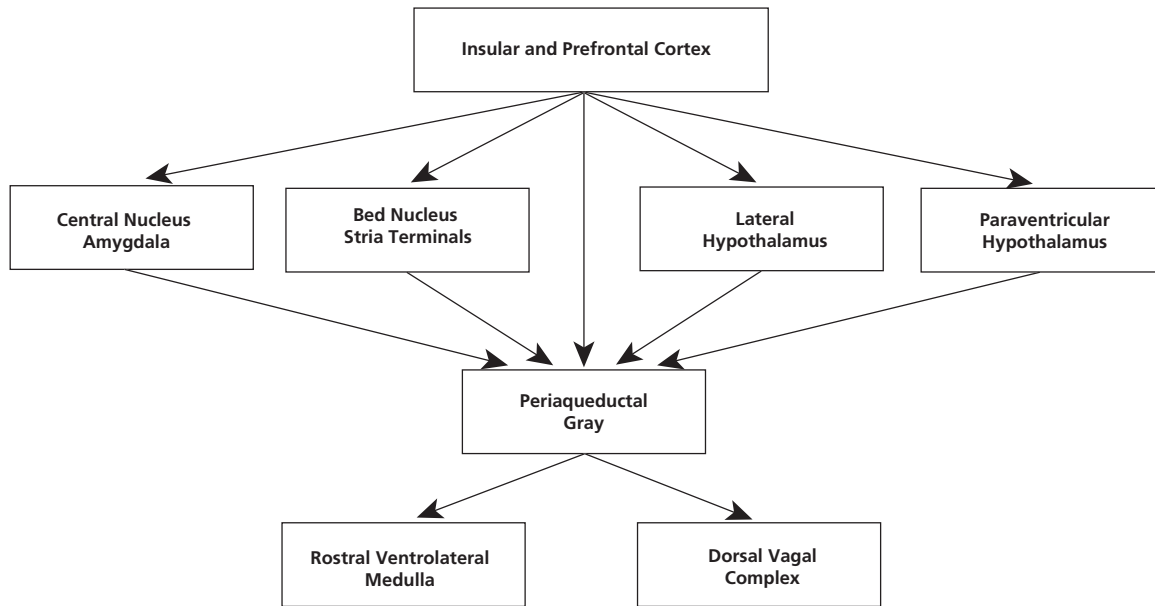
#### The Root Mean Square of Successive Differences

The RMSSD is the root mean square of successive differences between normal heartbeats. This value is obtained by first calculating each successive time difference between heartbeats in milliseconds. Each of the values is then squared and the result is averaged before the square root of the total is obtained. The RMSSD reflects the beat-to-beat variance in HR and is the primary time domain measure used to estimate the vagally mediated changes reflected in HRV.<sup>12</sup> The RMSSD is correlated with HF power and therefore also reflects self-regulatory capacity as discussed earlier.<sup>3</sup>

### NEUROBIOLOGY OF SELF-REGULATION

Considerable evidence from clinical, physiological, and anatomical research has identified cortical, subcortical and medulla oblongata structures involved in self-regulation. Oppenheimer and Hopkins mapped a detailed hierarchy of cardiac control structures among the cortex, amygdala and other subcortical structures, all of which can modify cardiovascular-related neurons in the lower levels of the neuraxis (Figure 4).<sup>83</sup> They suggest that the amygdala is involved with refined integration of emotional content in higher centers to produce cardiovascular responses that are appropriate for the emotional aspects of the current circumstances.

The insular cortex and other centers such as the orbitofrontal cortex and cingulate gyrus can overcome (self-regulate) emotionally entrained responses by inhibiting or enhancing them. They also point out that



**Figure 4** Schematic diagram showing the relationship of the principal descending neural pathways from the insular and prefrontal cortex to subcortical structures and the medulla oblongata as outlined by Oppenheimer and Hopkins.<sup>83</sup> The insular and prefrontal cortexes are key sites involved in modulating the heart's rhythm, particularly during emotionally charged circumstances. These structures alone with other centers such as the orbitofrontal cortex and cingulate gyrus can inhibit or enhance emotional responses. The amygdala is involved with refined integration of emotional content in higher centers to produce cardiovascular responses that are appropriate for the emotional aspects of the current circumstances. Imbalances between the neurons in the insula, amygdala and hypothalamus may initiate cardiac rhythm disturbances and arrhythmias. The structures in the medulla represent an interface between incoming afferent information from the heart, lungs and other body systems and outgoing efferent neuronal activity.

imbalances between the neurons in the insula, amygdala and hypothalamus may initiate cardiac rhythm disturbances and arrhythmias. The data suggest that the insular and medial prefrontal cortexes are key sites involved in modulating the heart's rhythm, particularly during emotionally charged circumstances.

Thayer and Lane have also have described the same set of neural structures which they call the central autonomic network (CAN). The CAN is involved in cognitive, affective, and autonomic regulation. The CAN is related to HRV and linked to cognitive performance. In their model, the CAN links the nucleus of tractus solitarius (NTS) in the medulla with the anterior cingulate, insula, prefrontal cortex, amygdala, and hypothalamus through a series of feedback and feed-forward loops. They also propose that this network is an integrated system for internal self-regulation by which the brain controls the heart, other visceromotor organs, and neuroendocrine and behavioral responses that are critical for goal-directed behavior, adaptability, and sustained health. They suggest that these dynamic connections explain why vagally mediated HRV is linked to higher-level executive functions and reflects the functional capacity of the brain structures that support working memory and emotional and physiological self-regulation. They have shown that vagally mediated HRV is correlated with prefrontal cortical performance and the ability to inhibit unwanted memories and intrusive thoughts. Furthermore, the prefrontal cortex can be taken "offline" when individ-

uals are stressed or threatened and prolonged prefrontal inactivity can lead to hypervigilance, defensiveness, and social isolation.<sup>11</sup>

#### Vagal Control System

The cardiovascular control system is highly distributed throughout the central nervous system and interacts both widely and reciprocally with many other neural control systems, especially with the respiratory system. The final common output pathways for the cardiorespiratory control system are located in the medulla oblongata. The medulla contains many neurons that act as interneurons and premotor neurons as well as separate neuronal populations for respiratory and cardiovascular regulation. The cell groups forming the cardiorespiratory control system have an intimate relationship, which allows for a highly integrated regulation of motor output. The medulla represents an interface between incoming afferent information and outgoing efferent neuronal activity. An important function of the cardiorespiratory control system is the respiratory modulation of both sympathetic and parasympathetic outflow that is present in the activity patterns of spinal preganglionic neurons.<sup>38</sup>

The NTS of the medulla oblongata integrates afferent sensory information from proprioceptors (body position), chemoreceptors (blood chemistry), and mechanoreceptors (also called baroreceptors) from the heart, lungs, and face. The NTS connects to the dorsal motor nucleus of the vagus nerve and the nucleus



ambiguous (NA). Neurocardiology research indicates that the efferent vagal fibers that innervate the heart are primarily A-fibers, the largest and fastest conducting axons that originate from somata located primarily in the NA. The NA also receives and integrates information from the cortical and subcortical systems.<sup>38</sup> Thus, the vagal regulatory centers respond to peripheral sensory (afferent) inputs and higher brain center inputs to adjust efferent neuronal outflows, which results in the vagally mediated beat-to-beat changes in HR.

Since BP regulation is a central role of the cardiovascular system, the factors that alter BP also affect beat-to-beat fluctuations and therefore, the heart rhythms. Intrinsic cardiac afferent sensory neurons transduce and distribute mechanical and chemical information regarding the heart to the intrinsic cardiac nervous system.<sup>46</sup> The afferent impulses from the intrinsic cardiac neurons travel via the vagal nerves to the nodose ganglia and then to the NTS. The NTS has connections with the NA and spinal cord resulting in modulation of activity patterns in both parasympathetic and sympathetic outflow to the heart and the blood vessels.<sup>38</sup> There is controversy regarding any inhibitory role of parasympathetic efferent preganglionic neurons in the dorsal motor vagal (DMV) complex of the medulla as a number of anatomical studies suggest that virtually all efferent projections from the DMV are to subdiaphragmatic structures.<sup>83</sup>

The vagus nerves innervate the intrinsic cardiac nervous system. A few of these connections synapse on motor neurons in the intrinsic cardiac nervous system that project directly to the SA node (and other tissues in the heart) where they trigger acetylcholine release to slow HR.<sup>84</sup> However, the majority of the efferent preganglionic vagal neurons (~80%) connect to local circuitry neurons in the intrinsic cardiac nervous system where motor information is integrated with inputs from mechanosensitive and chemosensory neurons in the heart.<sup>85</sup> Thus, efferent sympathetic and parasympathetic activity is integrated in and with the activity occurring in the heart's intrinsic nervous system. This includes the input signals from the mechanosensitive and chemosensory neurons within the heart, all of which ultimately contribute to beat-to-beat cardiac functional changes.<sup>46</sup>

The response time of a single efferent vagal impulse on the sinus node is very short and results in an immediate response that typically occurs within the cardiac cycle in which it occurs and affects only 1 or 2 heartbeats after its onset.<sup>33</sup> After cessation of vagal stimulation, HR rapidly increases to its previous level. An increase in HR can also be achieved by reduced vagal activity (vagal withdrawal). Thus, any sudden change in HR, up or down, or between 1 beat and the next, are primarily parasympathetically mediated.<sup>33,34</sup>

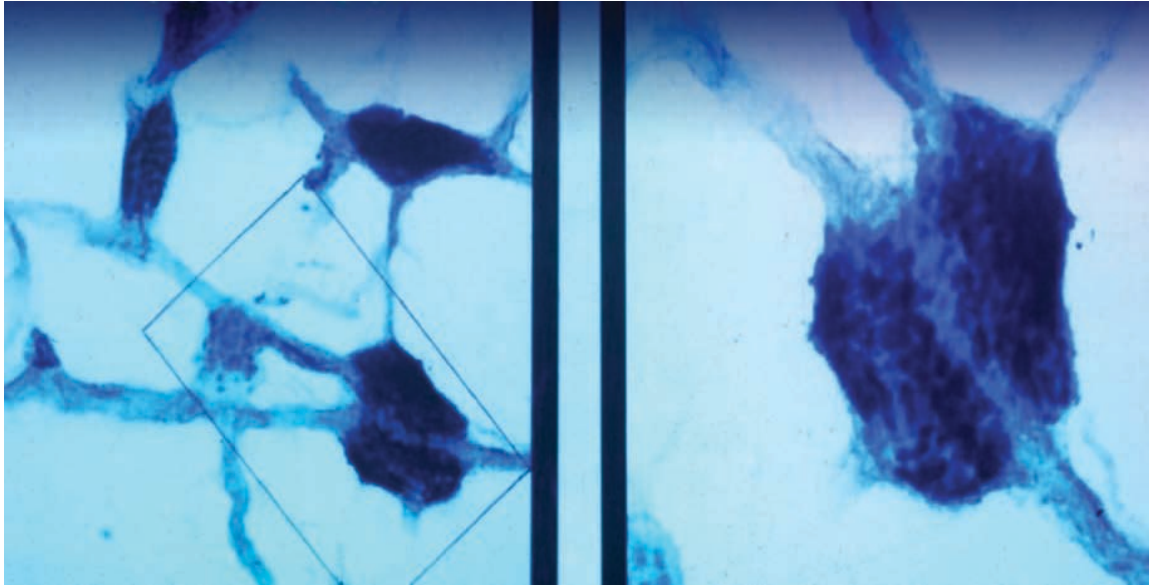
In summary, the cardiorespiratory control system is complex, and information from many inputs is integrated at multiple levels of the system, all of which are important for the generation of normal beat-to-beat

variability in HR and BP. The medulla oblongata is the major structure integrating incoming afferent information from the heart, lungs and face with inputs from cortical and subcortical structures and is the source of the respiratory modulation of the activity patterns in sympathetic and parasympathetic outflow. The intrinsic cardiac nervous system integrates mechanosensitive and chemosensitive neuron inputs with efferent information from both the sympathetic and parasympathetic inputs from the brain. As a complete system, it affects HRV, vasoconstriction, venoconstriction, and cardiac contractility in order to regulate HR and BP.<sup>33</sup>

#### Afferent Modulation of Cardiac and Brain Activity

The field of neurocardiology has extensively explored the anatomy and functions of the intrinsic cardiac nervous system along with its connections with the brain.<sup>75,86</sup> While efferent regulation of the heart by the vagus nerves is generally well known, the majority of fibers in the vagus nerves are afferent in nature. Furthermore, more vagal fibers are related to cardiovascular pathways than other organs.<sup>87</sup> Complex patterns of cardiovascular afferent nerve activity occur across time scales from milliseconds to minutes.<sup>88</sup> The intrinsic cardiac nervous system has both short-term and long-term memory functions, which can influence HRV and afferent activity related to BP, rhythm, rate, and hormonal factors.<sup>70,88,89</sup> The intrinsic cardiac neurons (sensory, interconnecting, afferent, and motor) can operate independently of central neuronal command, and their network is sufficiently extensive to be characterized as its own "little brain" in the heart (Figure 5).<sup>84,90</sup> The afferent nerves play a critical role in physiological regulation and affect the heart's rhythm and HRV. Efferent sympathetic and parasympathetic activity is integrated in the heart's intrinsic nervous system, with the signals arising from the mechanosensory and chemosensory neurons in the heart (Figure 6). The neural output of the intrinsic cardiac nervous system then travel to the brain via afferent pathways in the spinal column and vagus nerve. Intrinsic cardiac afferent neurons project to nodose and dorsal root ganglia, the spinal cord, brainstem, hypothalamus, thalamus, or amygdala and then to the cerebral cortex.<sup>4,46,91</sup>

John and Beatrice Lacey were the first to suggest a causal role of the heart in modulating cognitive functions such as sensory-motor and perceptual performance.<sup>92-94</sup> They suggested that cortical functions are modulated via afferent input from pressure sensitive neurons in the heart, carotid arteries, and aortic arch.<sup>93</sup> Their research focused on activity occurring within a single cardiac cycle, and they confirmed that cardiovascular activity influences perception and cognitive performance. Research by Velden and Wölk later demonstrated that cognitive performance fluctuated at a rhythm around 10 Hz and showed that the modulation of cortical function via the heart's influence was due to afferent inputs on the neurons in the thalamus, which globally synchronizes cortical activity.<sup>95,96</sup> An



**Figure 5** Microscopic image of interconnected intrinsic cardiac ganglia in the human heart. The thin, light blue structures are multiple axons that connect the ganglia. Used with permission from Dr J. Andrew Armour.

important aspect of their work was the finding that it is the “pattern and stability” (of the rhythm) of the heart’s afferent inputs, rather than the number of neural bursts within the cardiac cycle, that are important in modulating thalamic activity, which in turn has global effects on brain function.

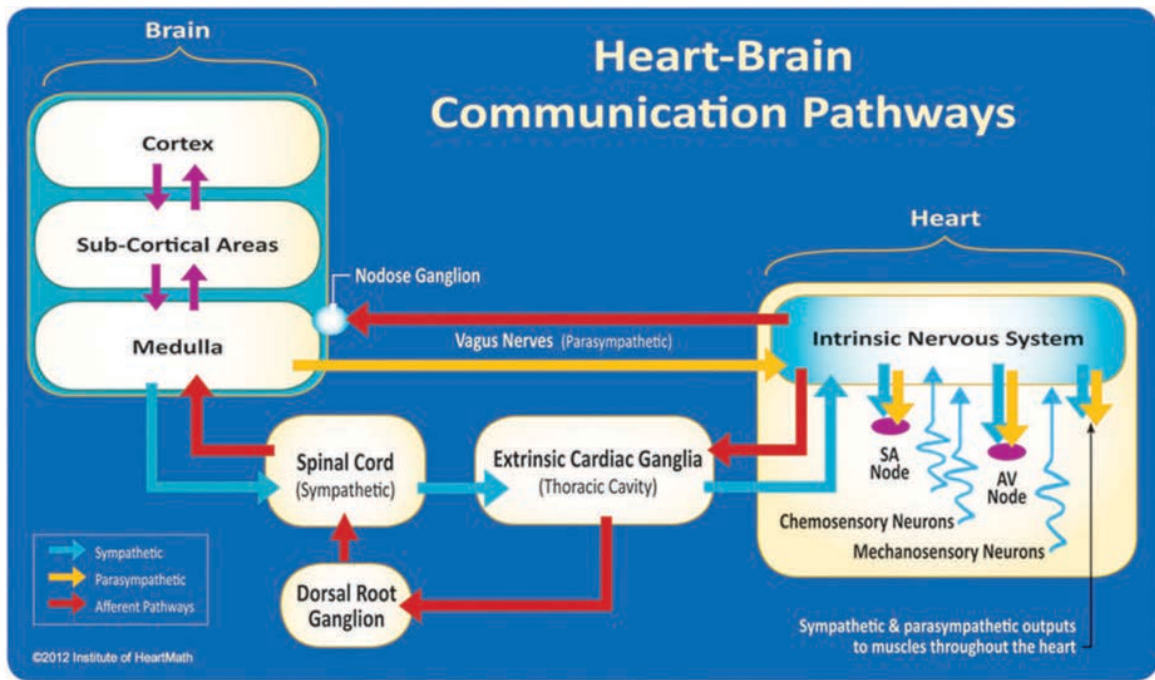
There has since been a growing body of research indicating that afferent information processed by the intrinsic cardiac nervous system can influence activity in the frontocortical areas<sup>4,97,98</sup> and motor cortex,<sup>58</sup> affecting psychological factors such as attention level, motivation,<sup>99</sup> perceptual sensitivity,<sup>100</sup> and emotional processing.<sup>101</sup>

### COHERENCE

The various concepts and measurements embraced under the term *coherence* have become central to fields as diverse as quantum physics, cosmology, physiology, and brain and consciousness research.<sup>5</sup> Coherence always implies connectedness, correlations, stability and efficient energy utilization. For example, we refer to people’s speech or thoughts as coherent if the words fit together well and incoherent if they are uttering meaningless nonsense or ideas that make no sense as a whole. In physics and physiology, the term *coherence* is used to describe the degree of synchronization between different oscillating systems. This type of coherence is called cross-coherence which occurs when two or more of the body’s oscillatory systems, such as respiration and heart rhythms, become entrained and operate at the same frequency. The term *auto-coherence* describes coherent activity within a single oscillatory system. An example is a system that exhibits sine wave like oscillations; the more stable the frequency, amplitude and shape, the higher the degree of coherence. When coherence is increased in a system that is coupled with other sys-

tems, it can pull the other systems into increased synchronization and more efficient function. For example, frequency pulling and entrainment can easily be seen between the heart, respiratory, and BP rhythms as well as between very-low-frequency brain rhythms, craniosacral rhythms, and electrical potentials measured across the skin.<sup>52,102</sup>

We (McCraty and colleagues) introduced the term *physiological coherence* to describe the degree of order, harmony, and stability in the various rhythmic activities within living systems over any given time period.<sup>52</sup> This harmonious order signifies a coherent system that has an efficient or optimal function directly related to the ease and flow in life processes. By contrast, an erratic, discordant pattern of activity denotes an incoherent system whose function reflects stress and inefficient utilization of energy in life processes. Specifically, heart coherence (also referred to as cardiac coherence or resonance) can be measured by HRV analysis wherein a person’s heart rhythm pattern becomes more ordered and sine-wave like at a frequency of around 0.1 Hz (10 seconds). A coherent heart rhythm is defined as a relatively harmonic, sine wave-like, signal with a very narrow, high-amplitude peak in the LF region of the HRV power spectrum with no major peaks in the VLF or HF regions. Coherence is assessed by identifying the maximum peak in the 0.04 Hz to 0.26 Hz range of the HRV power spectrum, calculating the integral in a window 0.030 Hz wide, centered on the highest peak in that region, and then calculating the total power of the entire spectrum. The coherence ratio is formulated as:  $(\text{Peak Power}/[\text{Total Power} - \text{Peak Power}])$ .<sup>4</sup> Physiological coherence includes specific approaches for quantifying the various types of coherence measures, such as cross-coherence (frequency entrainment between respiration, BP, and heart



**Figure 6** The neural communication pathways interacting between the heart and the brain are responsible for the generation of heart rate variability. The intrinsic cardiac nervous system integrates information from the extrinsic nervous system and from the sensory neurites within the heart. The extrinsic cardiac ganglia located in the thoracic cavity have connections to the lungs and esophagus and are indirectly connected via the spinal cord to many other organs such as the skin and arteries. The vagus nerve primarily consists of afferent fibers that connect to the medulla after passing through the nodose ganglion. *Used with permission from the Institute of HeartMath, Boulder Creek, California.*

rhythms), synchronization among systems (eg, synchronization between various electro-encephalography [EEG] rhythms and the cardiac cycle), auto-coherence (stability of a single waveform such as respiration or HRV patterns), and system resonance.<sup>4</sup>

Interestingly, we have found that positive emotions such as appreciation and compassion, as opposed to negative emotions such as anxiety, anger, and fear, are reflected in a heart rhythm pattern that is more coherent.<sup>4,5,103</sup> The coherent state has been correlated with a general sense of wellbeing, and improvements in cognitive, social, and physical performance. We have observed this association between emotions and heart rhythm patterns in studies conducted in both laboratory and natural settings and for both spontaneous and intentionally generated emotions.<sup>52,102</sup>

We introduced the Heart Rhythm Coherence Hypothesis, which states that the pattern and stability of beat-to-beat HR activity encodes information over “macroscopic time scales” (ie, over many seconds to minutes rather than only within a single cardiac cycle) that can impact cognitive performance and emotional experience.<sup>4,8</sup> The coherence model takes a dynamic systems approach that focuses on increasing individuals’ self-regulatory capacity through self-management techniques that induce a physiological shift reflected in the heart’s rhythms. We suggest that rhythmic activity in living systems reflects the regulation of interconnected biological, social, and environmental networks and that important biologically relevant

information is encoded in the dynamic patterns of physiological activity. The afferent pathways from the heart and blood vessels are given more relevance in this model due to the significant degree of afferent cardiovascular input to the brain and the consistent generation of dynamic patterns generated by the heart. It is our thesis that positive emotions in general, as well as self-induced positive emotions, shift the system as a whole into a more globally coherent and harmonious physiological mode associated with improved system performance, ability to self-regulate, and overall wellbeing. The psychophysiological coherence model predicts that different emotions are reflected in state-specific patterns in the heart’s rhythms<sup>4</sup> independent of the amount of HRV or HR. Recent independent work has verified this by demonstrating a 75% accuracy in detection of discrete emotional states from the HRV signal using a neural network approach for pattern recognition.<sup>104</sup> Several studies in healthy subjects, which helped inform the model, show that during the experience of positive emotions, a sine wave-like pattern naturally emerges in the heart’s rhythms without any conscious changes in breathing.<sup>52,103</sup> This is likely due to more organized outputs of the subcortical structures involved in processing emotional information described by Pribram,<sup>59</sup> Porges,<sup>60</sup> Oppenheimer and Hopkins,<sup>83</sup> and Thayer,<sup>11</sup> in which the subcortical structures influence the oscillatory output of the cardiorespiratory control system in the medulla oblongata.

### Heart Rate Variability Coherence Increases Vagal Afferent Traffic

One of the properties of sensory neurons is that they are most responsive to increases in rate of change in the function to which they are tuned to detect (eg, HR, BP).<sup>86</sup> During periods of increased cardiac coherence, there is typically an increased range of variability in both BP and HR, which is detected as increases in the rate of change by the sensory neurons, resulting in increased firing rates that increase vagal afferent traffic. There is also a more ordered pattern of activity. A recent study using heartbeat-evoked potentials showed that using paced breathing at a 10-second rhythm increased both the range of HRV and the coherence in the rhythms as expected and also increased the N200 amplitude potential in the EEG heartbeat-evoked potentials, which indicates increased afferent input.<sup>61</sup>

Anatomical and stimulation studies have shown that the thalamic pain pathways in the spinal cord are inhibited by increases in vagal afferent nerve traffic over normal intrinsic levels.<sup>105-107</sup> Several studies have demonstrated that teaching patients self-regulation techniques that increase HRV coherence is associated with reduced pain and physical activity limitations.<sup>108,109</sup> In a study of patients with severe brain injury, it was found that emotion-self-regulation training resulted in significantly higher coherence ratios and higher attention scores. Ratings of participants' emotional control correlated with improved HRV coherence measures.<sup>110</sup> Regular practice of HRV biofeedback results in lasting improvements in baroreflex gain, independent of cardiovascular and respiratory effects. This indicates neuroplasticity within the baroreflex system, likely within the intrinsic cardiac nervous system.<sup>111</sup> Thus, repeated sessions of heart coherence practice can reset the baroreflex system resulting in increased afferent nerve activity noninvasively.

### Resilience and Self-regulatory Capacity

HRV also indicates psychological resiliency and behavioral flexibility, reflecting an individual's capacity to self-regulate and effectively adapt to changing social or environmental demands.<sup>27,112</sup> A growing number of studies have specifically linked vagally mediated HRV to self-regulatory capacity,<sup>9,10,113</sup> emotional regulation,<sup>114,115</sup> social interactions,<sup>7,116</sup> one's sense of coherence,<sup>117</sup> the personality character traits of self-directedness,<sup>118</sup> and coping styles.<sup>119</sup>

More recently, several studies have shown an association between higher levels of vagally-mediated resting HRV and performance on cognitive performance tasks requiring the use of executive functions.<sup>11</sup> HRV coherence can be increased in order to improve cognitive function<sup>4,120-122</sup> as well as a wide range of clinical outcomes that have been shown to reduce healthcare costs.<sup>5,51,123-127</sup>

Porges suggests that the evolution of the ANS, specifically the vagus nerves, was central to the devel-

opment of emotional experience and the social engagement system. As human beings, we are not limited to fight, flight, or freeze responses. We can self-regulate and initiate pro-social behaviors when we encounter challenges, disagreements, or stressors. Porges suggests that the healthy function of the social engagement system depends upon the proper functioning of the vagus nerves, which act as a "vagal brake," and that measurements of vagal activity could serve as a marker for one's ability to self-regulate. His theory also suggests that the evolution and healthy function of the ANS determines the boundaries for the range of one's emotional expression, quality of communication, and the ability to self-regulate emotions and behaviors.<sup>60</sup>

### Self-regulation Techniques That Increase Cardiac Coherence

There is a paradigm shift occurring in the treatment of diverse disorders like depression, epilepsy, and pain by using vagal nerve stimulation, which stimulates afferent neural pathways.<sup>128-130</sup> New perspectives are emerging on behavioral intervention approaches that teach people self-regulation strategies that include a physiological aspect such as HRV biofeedback and that naturally increase vagal traffic. For example, there are many studies showing that the practice of breathing at 6 breaths per minute, supported by HRV biofeedback, induces the coherence rhythm and has a wide range of benefits.<sup>111,131-136</sup>

In addition to clinical applications, HRV coherence feedback training is often used to support self-regulation skill acquisition in educational, corporate, law enforcement, and military settings. Several systems that assess the degree of coherence in the user's heart rhythms are available. The majority of these systems—such as the emWavePro, or Inner Balance for iOS devices (HeartMath, Inc, Boulder Creek, California), Relaxing Rhythms (Wild Divine, Boulder City, Nevada), and the Stress Resilience Training System (Ease Interactive, San Diego, California)—use a noninvasive earlobe or finger pulse sensor and display the user's heart rhythm to provide feedback on their level of coherence.

Emotional self-regulation strategies may contribute to improved health and performance. Alone or in combination with HRV coherence biofeedback training, these strategies have been shown to increase resilience and accelerate recovery from stressors or trauma.<sup>5,8,136,137</sup> Self-induced positive emotions can initiate a shift to increased cardiac coherence without any conscious intention to change the breathing rhythm.<sup>52,103</sup> Typically, when people are able to self-activate a positive or calming feeling rather than remaining focused on their breathing, they enjoy the shift in feeling and are able to sustain high levels of coherence for much longer time periods.<sup>124</sup>

Heart-focused self-regulation techniques and assistive technologies that provide real-time HRV coherence feedback provide a systematic process for

self-regulating thoughts, emotions, and behaviors and increasing physiological coherence. Many of these techniques (eg, Heart-Focused Breathing, Freeze Frame, Quick Coherence<sup>139</sup>) are designed to enable people to intervene in the moment they start to experience stress reactions or unproductive thoughts or emotions. With practice, one is able to use one of the techniques to shift into a more coherent physiological state before, during, and after challenging or adverse situations, thus optimizing mental clarity, emotional composure, and stability.

The first step in most of the techniques developed by the Institute of HeartMath is called Heart-Focused Breathing, which includes putting one's attention in the center of the chest (area of the heart) and imagining the breath is flowing in and out of the chest area while breathing a little slower and deeper than usual. Conscious regulation of one's respiration at a 10-second rhythm (0.1Hz) increases cardiac coherence and starts the process of shifting into a more coherent state.<sup>4,124</sup> With conscious control over breathing, an individual can slow the rate and increase the depth of the breathing rhythm. This takes advantage of physiological mechanisms to modulate efferent vagal activity and thus the heart rhythm. This increases vagal afferent nerve traffic and increases the coherence (stability) in the patterns of vagal afferent nerve traffic. In turn, this influences the neural systems involved in regulating sympathetic outflow, informing emotional experience, and synchronizing neural structures underlying cognitive processes.<sup>4</sup>

Several studies using various combinations of these self-regulation techniques have found significant correlations between HRV coherence and improvements in cognitive function and self-regulatory capacity. For example, a study of middle school students with attention deficit hyperactivity disorder showed a wide range of significant improvements in short and long-term memory, ability to focus, and significant improvements in behaviors both at home and in school.<sup>120</sup> A study of 41 fighter pilots engaging in flight simulator tasks found a significant correlation between higher levels of performance and heart rhythm coherence as well as lower levels of frustration.<sup>140</sup> A study of recently returning soldiers from Iraq who were diagnosed with PTSD, found that relatively brief periods of HRV coherence training combined with practicing the Quick Coherence Technique resulted in significant improvements in the ability to self-regulate along with a wide range of cognitive functions. The degree of improvement correlated with increased cardiac coherence.<sup>121</sup> Other studies have shown increases in parasympathetic activity (vagal tone),<sup>52</sup> reductions in cortisol and increases in DHEA,<sup>127</sup> lowered BP and stress measures in hypertensive populations,<sup>124,126</sup> reduced healthcare costs,<sup>123</sup> and significant improvements in functional capacity in patients with congestive heart failure.<sup>141</sup> In addition, a study of correctional officers showed reduc-

tions in systolic and diastolic BP, total cholesterol, fasting glucose, overall stress, anger, fatigue and hostility.<sup>125</sup> Similar results were obtained in several studies with police officers.<sup>138,142</sup>

In addition to the emotional self-regulation techniques, there are other approaches that also increase HRV coherence. For example, a study of Zen monks found that monks with greater experience in meditation tended to have more coherent heart rhythms during their resting recording, while the ones who had been monks for less than 2 years did not.<sup>143</sup> A study of autogenic training also showed increased HRV coherence and found that cardiac coherence was strongly correlated with EEG alpha activity. The authors suggested that cardiac coherence could be a general marker for the meditative state.<sup>144</sup> However, this does not suggest that all meditation or prayer styles increase coherence, unless the coherence state is driven by a focus on breathing at a 10-second rhythm or the activation of a positive emotion.<sup>145-148</sup> For example, a study examining HRV while reciting rosary or bead prayers and yoga mantras found that a coherent rhythm was produced by rhythmically breathing but not by random verbalization or breathing. The authors ascribed the mechanisms for this finding to a breathing pattern of 6-cycles per minute.<sup>149</sup> In a study of the effects of five different types of prayer on HRV, it was found that all types of prayer elicited increased cardiac coherence. However, prayers of gratefulness and heart-felt love resulted in definitively higher coherence levels.<sup>148</sup> It has also been shown that tensing the large muscles in the legs in a rhythmical manner at a 10-second rhythm can induce a coherent heart rhythm.<sup>150</sup>

## CONCLUSION

HRV is an emergent property of interdependent regulatory systems that operate on different time scales to adapt to environmental and psychological challenges. The physiological mechanisms that contribute to HRV are complex and involve the neuraxis that spans from the prefrontal and insular cortex to the intrinsic cardiac nervous system, with the medulla oblongata and intrinsic cardiac nervous system providing major neural integration centers. HRV can be used as an index of the functional capacity of various regulatory systems and assessment of regulatory capacity may offer an alternative to autonomic balance models. Since the HRV LF band primarily reflects the vagally mediated transmission between the heart and medulla, resting measurements should not be used as markers of sympathetic activity. Based on 24-hour monitoring, ULF and VLF rhythms are more strongly associated with overall health status than HF rhythms. New perspectives on mechanisms underlying the VLF rhythm suggest that the primary source of this rhythm is within the heart itself. Recent findings demonstrate the importance of the intrinsic cardiac nervous system and cardiac afferents in generating the heart rhythm and modulating the intervals between

heartbeats. Vagally-mediated HRV appears to represent an index of psychological self-regulatory control, such that individuals with greater resting HRV have performed better on tests of executive function.

In addition to assessing regulatory capacity, HRV can also be used in the context of real-time feedback to help restore regulatory capacity. Heart rhythm coherence approaches train clients to produce auto-coherent heart rhythms with a single peak in the LF region (typically around 0.1 Hz) with no significant peaks in the VLF and HF regions. Emotional self-regulation strategies may contribute to improved client health and performance, alone, or in combination with HRV biofeedback training. Numerous studies have provided evidence that coherence training consisting of intentional activation of positive emotions paired with HRV coherence feedback may facilitate significant improvements in wellness and wellbeing indicators in a variety of populations.

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