Vagal Tone: A Physiologic Marker of Stress Vulnerability

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ABSTRACT. Vagal tone is proposed as a novel index of stress vulnerability and reactivity with applications in all branches of medicine, and with particular value in pediatrics. The paper proposes a model emphasizing the role of the parasympathetic nervous system and particularly the vagus nerve in mediating homeostasis and defining stress. Measurement of cardiac vagal tone is proposed as a method to assess on an individual basis both the stress response and the vulnerability to stress. The method monitors the neural control of the heart via the vagus (ie, vagal tone) as an index of homeostasis. The method provides a standard instrument with statistical parameters that are comparable between patients and throughout the life span. This noninvasive method will allow the assessment of the stressful impact of various clinical treatments on the young infant and permit the identification of individuals with vulnerabilities to stress. *Pediatrics* 1992;90:498–504; vagal tone, stress, autonomic nervous system, heart rate.

ABBREVIATIONS. ANS, autonomic nervous system; PNS, parasympathetic nervous system; SNS, sympathetic nervous system; NICU, neonatal intensive care unit.

Routine medical procedures are often stressful and produce periods of physiologic and behavioral instability. However, given the same treatment, all children do not respond alike. Some children exhibit prolonged periods of instability, while other children are virtually insensitive to the treatment. Although clinicians are concerned with the potential vulnerability associated with stressful events, a standard approach does not exist to address both the measurement of stress and the indexing of stress vulnerability.

Research on stress has often focused on the description of events that are considered stressful (eg, life stress scales) and not on the functional impact of these events on physiology. In contrast, in pediatrics, stress is assumed to be a physiologic construct that is observed when behavior becomes disorganized and homeostatic processes are disrupted. In clinical settings this is often labeled physiologic instability.

Although we are aware that there are individual differences in vulnerability to the same medical procedures, current definitions of stress emphasize either the treatment or the response to treatment and not the neurophysiologic status prior to treatment. However, it is this neurophysiologic state that may index the stress vulnerability of the child.

This paper proposes a method to assess on an individual basis both the stress response and the vulnerability to stress. This method monitors the neural control of the heart via the vagus (ie, vagal tone) as an index of homeostasis. The method permits the assessment of the effects of disrupting homeostatic processes (ie, stress) and the vulnerability of homeostasis to disruption by various clinical treatments (ie, stress vulnerability).

STRESS: A STATE OF AUTONOMIC NERVOUS SYSTEM COMPROMISE

The autonomic nervous system (ANS) regulates homeostatic function. The ANS is composed of two subsystems, the parasympathetic (PNS) and sympathetic nervous systems (SNS). The PNS and SNS represent neural systems that originate in the brainstem and contribute to the regulation of a variety of target organs including the eyes, lacrimal glands, salivary glands, sweat glands, blood vessels, heart, larynx, trachea, bronchi, lungs, stomach, adrenal, kidney, pancreas, intestine, bladder, and external genitalia. In general, the PNS promotes functions associated with a growth and restorative system. In contrast, the SNS promotes increased metabolic output to deal with challenges from outside the body.

In general, when a visceral organ is innervated by both the SNS and PNS, the effects are antagonistic. For example, SNS neurons dilate the pupil, accelerate the heart, inhibit intestinal movements, and contract the vesical and rectal sphincters. The PNS neurons constrict the pupil, slow the heart, potentiate peristaltic movement, and relax the vesical and rectal sphincters.

The PNS deals primarily with anabolic activities concerned with the restoration and conservation of bodily energy and the resting of vital organs. This view was clearly stated by Cannon[1]:

[A] glance at these various functions of the cranial division reveals at once that they serve for bodily conservation; by narrowing the pupil they shield the retina from excessive light; by slowing the heart rate they give the cardiac muscle longer periods for rest and invigoration; and by providing for the flow of saliva and gastric juice, and by supplying the necessary muscular tone for the contraction of the alimentary canal, they prove fundamentally essential to the processes of proper digestion and absorption by which energy-yielding material is taken into the body and stored. To the cranial division belongs the great service of building up reserves and fortifying the body against time of need and stress.

Stimulation of the SNS prepares the individual for the intense muscular action required to protect and defend in response to external challenges. The SNS quickly mobilizes the existing reserves of the body. The eyes dilate, the rate and force of the heart contractility increase, blood vessels constrict, and blood

pressure increases. Blood is drained from the intestinal reservoir to foster availability and transport of oxygenated blood to the skeletal muscles, lungs, heart, and brain. Peristalsis and alimentary secretion are inhibited, and sphincter contractions block urinary and rectal outlets.

The SNS and PNS are reciprocally innervated and their responses are coordinated to provide the appropriate internal state to meet shifts in both internal and external demands. The PNS is modulated primarily by internal changes in the viscera. The SNS is primarily activated by exteroceptive impulses via somatic afferent fibers in response to changes in the external environment.

The PNS facilitates digestion and conserves energy by slowing heart rate. In the absence of external challenges (eg, ambient temperature shifts, noise, pain, pyrogenic agents, etc), the PNS optimizes the function of the internal viscera. In contrast, by increasing metabolic output to deal directly with external challenges, the SNS attempts to optimize the organism's relationship with the environment. Thus, increases or decreases in ambient temperature, noise, pain, and pyrogenic agents will produce attenuated PNS tone and increased SNS activity. Consistent with this functional description of the ANS, Gellhorn[2] labeled the PNS as a trophotropic system and the SNS as an ergotropic system.

Early investigators defined the ANS as purely visceral motor.[3] This limited definition did not acknowledge the contribution of visceral afferents. The afferent fibers accompany most visceral efferent fibers and form the afferent limb for visceral reflexes. The contemporary view of the ANS is that it is a complex system containing both peripheral efferent and afferent fibers as well as central neural structures. Thus, as Hess[4] stated, the function of the ANS reflects more a visceral nervous system than a vegetative or automatic nervous system. It is because the ANS is an integrated system with both peripheral and central neurons that measurement of peripheral visceral activity provides a window to the brain structures that regulate visceral function and state.

The ANS responds to both internal and external stimuli. Although the ANS is often viewed as a motor system controlling visceral organs, most autonomic neurons are afferent. In the maintenance of bodily functions and in the reaction to stressful situations, ANS afferents are crucial. Afferent feedback from visceral organs often regulates PNS tone and has little impact on SNS tone. For example, distension of the stomach or stimulation of baroreceptors will result in reflexive increases in PNS tone. Afferent feedback from sensory organs produces a different response profile. Autonomic responses to external stimuli, including nociception or attention, produce a decrease in PNS tone. There is a complementary increase in SNS tone only if the stimulus is of high intensity and prolonged duration or is associated with conditions of nociception or intense stimulation. In response to metabolic demands, the two branches of the ANS often function synergistically to maximize cardiovascular output. For example, during exercise there is a progressive decrease in PNS tone and a parallel increase in SNS tone. There are unique situations in which the autonomic response is characterized by either dual activation or dual inhibition. For example, in human adults, sexual arousal is characterized by a dual excitation.

The ANS is not merely a response system, quiescently awaiting challenges from the external environment. Rather, the ANS is continuously servicing the visceral afferents in an attempt to maintain homeostasis and promote physiologic stability. This regulatory process is primarily mediated by the PNS. Unfortunately, there are disease states that compromise the regulatory function. Some disease states (eg, hypertension) are characterized by a depression of PNS tone with a compensatory SNS excitation. Other disease states (eg, diabetes) are characterized by a depression of the PNS tone without eliciting a reciprocal SNS excitation, while other disease states may be characterized by dual inhibition.

The ANS is involved in the physiologic expression of stress. Shifts in ANS activity that disrupt homeostatic processes seem to characterize the common theme associated with physiologically based definitions of stress. More specific investigation of the literature suggests that the PNS, virtually independent of the SNS, regulates homeostatic processes and would, thus, be most sensitive to stress.

STRESS AND HOMEOSTASIS: NEW DEFINITIONS

There have been many definitions of stress. Because most definitions are structured in terms of the causal influences (ie, stimulus or context) and not in terms of the variables commonly measured in a clinical setting, the definitions tend to be limited in their use in the medical environment. Often the definitions are circular because stress is defined both in terms of the context (eg, medical treatment) and the response (eg, behavioral and physiologic responses). For example, is the medical treatment stressing because it elicits an increase in blood pressure and heart rate? Or, do increases in blood pressure and heart rate reflect stress independent of the specific medical treatment? Or, do the physiologic responses reflect stress because the clinician assumes that there is stress associated with the medical treatment? The definition is further confounded because we assume that there are individual differences in responsiveness or vulnerability to the stressful event. Thus, the stressful treatment might not elicit a stress response in one patient while a nonstressful treatment might elicit a stress response in another patient.

Current definitions of stress are not very useful in the clinical setting. Even if stress were operationally defined by labeling the stressing stimulus as the *stressor* and the behavioral and physiologic response to the stressor as *stress*, at least two problems would remain: (1) the definitions of stress and stressor would be circular, and (2) there would be situations in which individual differences and state might mediate the degree of responsivity (ie, *stress*) of a patient to constant medical treatments (ie, *stressor*). For example, the same treatment that may physiologically compromise one patient may not produce a discernible behavioral or physiologic response in another patient or

even in the same patient a second time. Alternatively, the same treatment that did not produce a response during the first administration may result in a massive physiologic compromise during subsequent administrations. Thus, stress must not be conceptualized simply in terms of the stressor and observed response, but also in terms of the physiologic state of vulnerability of the patient at the time of treatment.

New definitions of stress and stress vulnerability can be derived and operationally defined based on the function of the ANS. Physiologically based measures can be objectively assessed within clinical settings with on-line monitoring of stress and stress vulnerability. In developing this approach two essential areas must be discussed: (1) the rationale for evaluating specific autonomic variables as indices of stress; and (2) the measurement technology necessary to measure the autonomic indices of stress on-line in a clinical setting.

AN ANS DEFINITION OF STRESS: A RATIONALE

The ANS deals both with servicing the needs of the internal viscera and with responding to external challenges. The central nervous system mediates the distribution of resources to deal with internal and external demands. Perceptions and assumed threats to survival, independent of the actual physical characteristics of the stimulation, may promote a massive withdrawal of PNS tone and a reciprocal excitation of SNS tone. The trade-off between internal and external needs may be used in developing definitions of stress and homeostasis. Based on this model, stress and homeostasis are interdependent. Homeostasis reflects the regulation of the internal viscera and stress reflects the subjugation of internal needs in response to external needs. Thus, measurement of PNS tone may provide the indexing variable for defining stress and stress vulnerability.

The concept of homeostasis is not new. Walter Cannon[5] coined the term and stated that "the coordinated physiological reactions which maintain most of the steady states in the body are so complex, and so peculiar to the living organism, that it has been suggested that a specific designation for these states be employed—*homeostasis*." Cannon's views are dependent on the earlier work of Claude Bernard. Bernard's construct of "*le milieu interieur*" included physiologic mechanisms responsible for the maintenance of the constancy of the internal environment. As Bernard's work evolved, he emphasized the dynamic and oscillatory nature of the nervous system in maintaining the "internal milieu" within a limited range.[6]

Homeostasis as a construct was never meant to reflect a static state. Rather it defined the dynamic feedback and regulation processes necessary for the living organism to maintain internal states within a functional range. Over time the concept has lost much of its rich meaning and has often been interpreted to represent a static internal level. Clinically, stasis or lack of endogenous variability in neurally mediated peripheral systems, such as gastric motility and heart rate, is a sign of severe physiologic compromise.

In the proposed model, the PNS fosters visceral needs (ie, homeostasis) and the SNS responds to external challenges. Thus, status of the PNS state parallels homeostasis. Alternatively, withdrawal of PNS tone in response to a challenge may define stress, and PNS tone prior to the challenge may represent physiologic or stress vulnerability. With this physiologic model, SNS state is not the defining characteristic of stress or stress vulnerability; and stress responses and stress vulnerability may be indexed in the absence of major shifts in SNS tone. It is important to note that in many situations with healthy children, the transitory withdrawal of PNS tone will be paralleled by an increased expression of SNS tone. In contrast, severely compromised children may not exhibit SNS reactivity and SNS tone might be low. Moreover, these children would have low PNS tone, virtually no PNS reactivity, and would be clinically assessed as being chronically stressed or exhibiting physiologic instability.

This view suggests that homeostasis may be defined as the autonomic state that fosters visceral needs in the absence of external challenge. This state would be defined by a high degree of PNS tone. Stress may be defined as the autonomic state that reflects a disruption of homeostasis. This state would be defined by the withdrawal of PNS tone. Thus, the degree of stress can be quantified on a physiologic level. Moreover, the chronic autonomic state before a clinical event would index the patient's stress vulnerability; individuals exhibiting problems of homeostasis will have the greatest stress vulnerability.

THE ASSESSMENT OF STRESS: VAGAL TONE MONITORING

Given the above justification, it is necessary to identify and quantify an index of PNS activity. The most readily indexed measure of PNS activity is derived from the heart rate pattern. The amplitude of respiratory sinus arrhythmia provides a validated and easily obtainable index of PNS tone via the cardiac vagus.[7] In the sections below this will be described as vagal tone. With modern technology it is possible to monitor on-line the changing influence of the vagus on the heart and to estimate shifts in general vagal tone.[8]

Physiologic and behavioral processes are dependent on neural feedback. Information is received at the periphery and transmitted to the central nervous system, and appropriate physiologic reflexes or overt behaviors are emitted. Feedback loops typical of many homeostatic processes produce a rhythmic pattern characterized by phasic increases and decreases in neural efferent output to organs such as the heart. In many physiologic systems, efficient neural control is manifested as rhythmic physiologic variability, and within normal parameters the greater the amplitude of oscillation, the healthier the individual. Thus, the amplitude of rhythmic physiologic processes may index the status of the individual's nervous system and capacity to respond. In other words, the greater the amplitude of *organized* rhythmic physiologic variability, the greater the response potential or possible range of behavior. Individuals with attenuated physiologic variability would then exhibit a lack of physiologic and behavioral flexibility in response to envi-

ronmental demands. This is observed in very ill infants. Thus, in terms of stress reactions, one would expect these individuals to lack the self-regulatory capacity to adjust rapidly to stressful stimuli.

Research in areas of cardiology, gerontology, physical therapy, and diabetology demonstrate that general PNS deficits are reflected in cardiac vagal tone. Moreover, stimulation of other PNS afferents results in reflexive increases in cardiac vagal tone.[9,10] Since cardiac vagal tone reflects the general PNS input to the viscera, it may be used to monitor stress and index individual differences in stress vulnerability.

We have developed a vagal tone index ($\hat{V}$) that is a noninvasive measure of cardiac vagal tone.[7] The vagal tone index is a measure of the nervous system modulation of heart rate activity via the vagus. The vagal tone index reflects rhythmic vagal efferent influences on the cardiac pacemaker modulated by respiratory processes in the medulla. Heart rate patterns, like behavioral processes, are dependent on the status of the nervous system and the quality of neural feedback. Stress results in a disorganization of the rhythmic structure of both behavior and autonomic state. Thus, measures of cardiac vagal tone provide an important window into the central control of autonomic processes and by inference into the central processes necessary for organized behavior.

Vagal tone is reflected in the amplitude of a heart rate rhythm associated with frequency of spontaneous breathing. This rhythmic process, respiratory sinus arrhythmia, has been observed and studied for more than 100 years. Speculations regarding the neural mechanisms were reported as early as 1910, when a relation between respiratory sinus arrhythmia and vagal tone was proposed by Hering.[11] Hering clearly stated that ". . . it is known with breathing that a demonstrable lowering of heart rate . . . is indicative of the function of the vagi." Derivations of this method with paced breathing techniques are currently used to diagnose peripheral neuropathy in diabetic patients. Contemporary research has provided empirical evidence that the amplitude of respiratory sinus arrhythmia accurately maps the efferent influence of the vagus nerve on the heart. Based on electrophysiologic studies of vagal efferents, it has been proposed that central respiratory drive gates the source nuclei of the vagal cardioinhibitory fibers.[12]

If vagal tone is a sensitive index of the functional status of the nervous system, then we would predict that individuals with greater vagal tone would exhibit a greater range of competent behaviors. We would also expect that conditions that compromise the central nervous system (eg, medical complications, anesthesia, and illness) would result in an attenuation of vagal tone.

In building a model that relates vagal tone to stress, we will first describe a global metaphor characteristic of homeostatic processes and then more specific pathways related to the vagus. Heart rate in a healthy human is not steady. The pattern of heart rate reflects the continuous feedback between the central nervous system and the peripheral autonomic receptors. The primary source of heart rate variability is mediated by phasic increases and decreases in neural efferent output via the vagus to the heart.[13] Under most conditions, like other measures of homeostatic control, the greater the range of the phasic increases and decreases, the "healthier" the individual. For example, with high-risk neonates, there is an attenuation of the range of homeostatic function. Paralleling this process is a reduction in vagal tone.[14,15]

Heart rate variability is a marker of the efficiency of neural feedback mechanisms and may index health status or the individual's capacity to organize physiologic resources to respond appropriately. Thus, the better the "organized" physiologic variability, the greater the range of behavior. Organized variability is due to dynamic feedback and thus is characterized by rhythmic deviations from a constant level. An optimum feedback system allows large deviations from the mean with negative feedback occurring at constant intervals. Neural regulation of the heart in healthy individuals is similar to the optimal feedback system described above. In the neural control of the heart, the vagus serves as the primary negative feedback mechanism. Thus, states of attenuated heart rate variability would have attenuated vagal influences on the heart. Returning to our metaphor, states characterized by attenuated vagal influences should be paralleled by reduced behavioral flexibility in response to environmental demands.

STRESS VULNERABILITY IN THE NEONATE: AN EXAMPLE OF VAGAL TONE MONITORING

Figure 1 illustrates 2 minutes of the heart rate pattern and cardiac vagal tone ($\hat{V}$) for two sleeping neonates. The top panel illustrates the pattern of a high-risk preterm neonate monitored at approximately term. The bottom panel illustrates the pattern of a healthy term neonate monitored within 36 hours of delivery. The top line on each panel illustrates the continuous heart rate over the 2 minutes. The bottom line on each panel represents the cardiac vagal tone calculated for each sequential 10 seconds within the 2 minutes. Clarification of the vagal tone concept may be obtained by observing the differences between the top and bottom panel. Notice that even during sleep, heart rate is not constant. Although the heart rate levels are similar for the two neonates, the healthy term neonate has much greater beat-to-beat variability relative to the high-risk preterm. Close inspection of the two beat-to-beat patterns identifies a striking difference in the rapid changes in heart rate that occur every 1 to 3 seconds. These oscillations are associated with respiration and reflect cardiac vagal tone. The cardiac vagal tone reflects the amplitude of these rapid oscillations and is reported in natural logarithm units.

Figure 2 illustrates the frequency distributions of vagal tone for both high-risk and normal full-term neonates. The subject samples were 125 full-term neonates and 112 neonatal intensive care unit (NICU) residents. The full-term neonates were all residents of a full-term normal nursery and were tested during the second day following delivery. The vagal tone values for the premature NICU neonates were derived during the first recording made with the neonates not
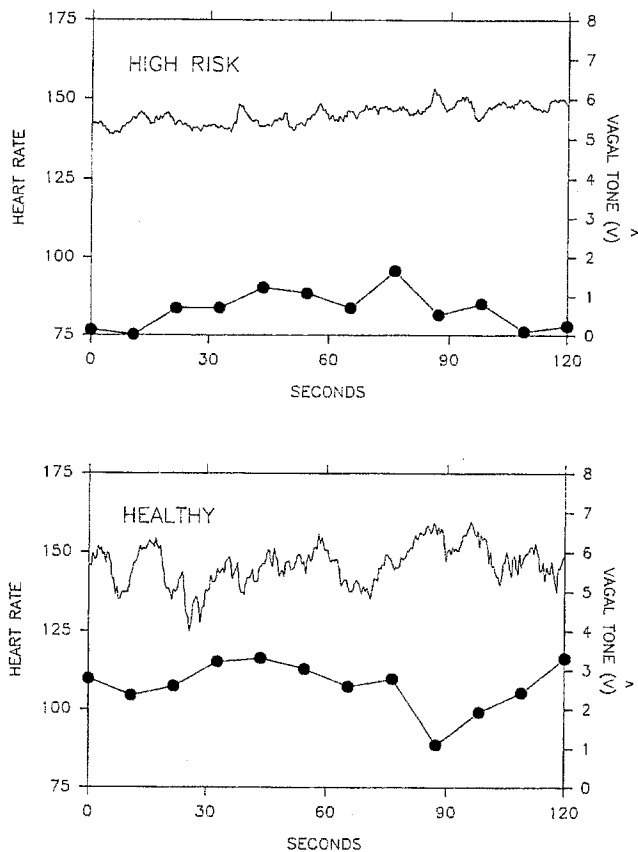
Fig 1. Beat-to-beat heart rate and cardiac vagal tone ($\hat{V}$). Top panel illustrates data from a high-risk preterm neonate monitored at approximately term. Bottom panel illustrates data from a healthy normal full-term neonate monitored within 36 hours of delivery. Data were collected during sleep. In both panels the top line illustrates the beat-to-beat heart rate and the bottom line illustrates cardiac vagal tone ($\hat{V}$) calculated for sequential 10-second segments. $\hat{V}$ values are in natural logarithm units per millisecond squared.
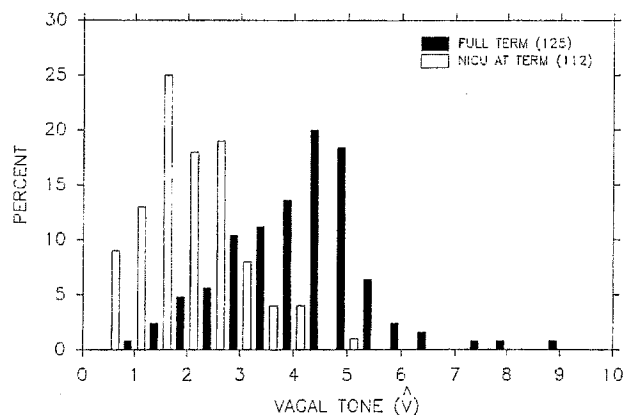

Fig 2. Distribution of cardiac vagal tone estimates ($\hat{V}$) for normal full-term neonates and neonates in the neonatal intensive care unit (NICU). $\hat{V}$ values are in natural logarithm units per millisecond squared.

using the ventilator and breathing room air. The vagal tone was assessed during sleep when the NICU neonates were between 35 and 37 weeks corrected gestational age.

From the data in Fig 2, it is obvious that high-risk neonates, as a group, have significantly lower vagal tone than do full-term neonates (F [1, 235] = 226.3, $P < .0001$). Since respiration frequency might influence the vagal tone estimate, respiration was monitored on a subset of 47 full-term and 62 NICU neonates. Respiration was significantly faster for the NICU neonates (F [1, 107] = 23.5, $P < .0001$). However, even when this significant influence was removed with analysis of covariance, there was still a highly significant difference between the two groups in vagal tone (F [1, 107] = 82.2, $P < .0001$). The group classification (full-term vs NICU) accounted for 53.1% of the vagal tone variance. When the influence of respiration was removed, group classification accounted for 43.7% of the vagal tone variance.

Recent research in our laboratory suggests only subtle maturational increases and great stability of these estimates under standard sampling conditions during residency within the NICU. For example, a sample of 16 preterm neonates was tested during sleep on five separate days starting at least 1 day following delivery. Although there was a significant relationship between severity of clinical condition and vagal tone (ie, healthier neonates had higher vagal tone), the average correlation among the vagal tone values approached .9.

The above provides an example of how monitoring of vagal tone in the NICU may provide a sensitive index of stress vulnerability. Data from our laboratory and the laboratories of others demonstrate that the more compromised NICU residents have lower vagal tone. Consistent with the above model of stress and stress vulnerability, the NICU neonates have limited PNS tone to regulate their internal state and are simultaneously confronted with demands from the environment, including the necessity to thermoregulate and to deal with sensory stimuli including medical procedures assumed to be painful.

The vagal system is responsive to the changing needs of the organism. Often the vagal system will react by selectively increasing or decreasing its influence on the periphery. This might be observed as a withdrawal of vagal tone to increase heart rate to support metabolic demands or an increase in vagal tone to regulate digestive polypeptides and gastric motility. The adaptive success of the infant is not based merely on the tonic level of the ANS, but on the ability of the ANS to respond appropriately to environmental and interval challenges. For example, during painful medical manipulations, such as circumcision, vagal tone is suppressed.[16] In contrast, during gavage feeding of premature neonates, vagal tone is increased.[10] If infants exhibited a vagal tone increase during gavage feeding and a depression of vagal tone below pregavage levels following feeding, they were discharged approximately 2 weeks earlier than were infants who did not exhibit this response. These effects were independent of birthweight, gestational age at birth, and other clinical factors. Although pregavage vagal tone was not related to the response pattern or discharge, it did predict weight gain trajectories. Thus, vagal reactivity provides another dimension related to clinical risk.

Measures of vagal tone provide an important window to the central modulation of autonomic function.

Measures of vagal tone during sleep or nonchallenging conditions provide an index of normal homeostatic feedback, while measures during sensory or cognitive challenges provide an indication of adaptive functioning. Thus, low levels of vagal tone are associated with high-risk populations, while atypical vagal responsivity even in infants with normal basal levels of vagal tone seems to identify a subset of infants who have behavioral and regulatory problems.[10,17]

VAGAL TONE SHIFTS DURING STRESS: THE COST OF DOING BUSINESS

The ANS has many physiologic responsibilities. It must regulate the blood pressure to ensure that enough blood reaches the brain. It also monitors the blood gases. If there are shifts in oxygen and carbon dioxide, changes in cardiopulmonary parameters are immediately implemented by the direct neural modulation of the heart, vasomotor tone, and lungs. While these cardiopulmonary processes are being regulated, the ANS is also controlling digestion and metabolism. The actions of the ANS are related to life support: ergotropic (ie, work) and trophotropic (ie, growth) functions.[2]

The vagal system is critical to the regulation of both ergotropic and trophotropic process. Increases in vagal tone not only result in increases in metabolic output, but modulate the digestive polypeptides and gastric motility.[18] The vagus is also critical in the facilitation of trophotropic process. The vagus can have direct inhibitory influences on sympathetic excitation of the myocardium.[19] Moreover, the limbic system, assumed by psychophysiologists to modulate autonomic arousal solely through sympathetic excitation, has direct inhibitory influences on the cells of origin of the vagus.[20] The brainstem regions controlling the vagal efferents act to express greater vagal tone, thus maintaining trophotropic states, or to allow withdrawal of vagal tone to facilitate the immediate mobilization of the organism.

Research with other species demonstrates that vagal tone increases during development.[21] Paralleling this increase in vagal tone are increases in self-regulatory and exploratory behaviors. In research with infants we have reported that high vagal tone is associated with visual recognition memory.[22,23] An overview chapter summarizes the research on vagal tone and affect.[24]

DiPietro and Porges[10] also evaluated in preterm neonates the relationship between vagal tone and behavioral reactivity to gavage feeding. In this study, individual differences in vagal tone were significantly correlated with behavioral reactivity to the gavage method of feeding. Similarly, Huffman et al[25] observed that 3-month-old infants with high vagal tone habituated more rapidly to novel visual stimuli and exhibited more sustained attention than did infants with low vagal tone.

Drugs that depress vagal tone also seem to have a degrading effect on sustained attention. For example, in a study evaluating the effects of atropine sulfate on sensorimotor performance, we reported not only dose-dependent depression of vagal tone, but also dose-dependent decrements in performance.[26] We also have conducted research on the effects of inhalant anesthesia on the parallel between alertness and vagal tone. Inhalant anesthesia depressed vagal tone and as the patients regained consciousness, there was a parallel increase in vagal tone.[27]

With the development of the vagal tone index we have been able to obtain a more accurate assessment of vagal mechanisms and the relationship between vagal tone and autonomic reactivity. Studies using the vagal tone index support the hypothesis that vagal tone may index stress and stress vulnerability. Porter et al[16] demonstrated, in a sample of normal newborns, massive withdrawal of vagal tone during circumcision. Moreover, individual differences in vagal tone were correlated with heart rate reactivity to circumcision. Neonates with higher vagal tone exhibited not only larger heart rate accelerations but also lower fundamental cry frequencies during surgical procedures. Porter and Porges[28] also demonstrated in premature infants that individual differences in vagal tone were related to heart rate responses during lumbar puncture procedures.

CONCLUSION

There is a physiologic basis for defining stress and stress vulnerability. The concepts of stress and homeostasis are interdependent and manifested in the activity of the PNS. In contrast to traditional models of stress, the PNS is proposed as the modulator of stress vulnerability and reactivity. The model proposed suggests that accurate monitoring of PNS state will provide a window allowing the assessment of stress.

A physiologic justification is presented for the use of PNS, rather than or in addition to SNS, activity in the description of both stress vulnerability and stress reactivity. The quantification of cardiac vagal tone from spontaneous heart rate oscillations is described as a method for assessing the changing PNS state. The quantification of vagal tone provides a standard instrument with statistical parameters that are comparable between patients and throughout the life span. The method is not dependent on stages of motor or cognitive development and thus is practical for use even with neonates. This noninvasive method will allow the assessment of the stressful impact of various clinical treatments on the young infant and permit the identification of individuals with vulnerabilities to stress.

In conclusion, the usefulness of contemporary definitions of stress is limited, in part by circularity and in part by a tendency within stress research to focus narrowly on the contribution of the SNS. Vagal tone is proposed as novel index of stress vulnerability and reactivity with applications in all branches of medicine, and with particular value in pediatrics.

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