

## Sudarshan Kriya Yogic Breathing in the Treatment of Stress, Anxiety, and Depression: Part I—Neurophysiologic Model

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### ABSTRACT

Mind–body interventions are beneficial in stress-related mental and physical disorders. Current research is finding associations between emotional disorders and vagal tone as indicated by heart rate variability. A neurophysiologic model of yogic breathing proposes to integrate research on yoga with polyvagal theory, vagal stimulation, hyperventilation, and clinical observations. Yogic breathing is a unique method for balancing the autonomic nervous system and influencing psychological and stress-related disorders. Many studies demonstrate effects of yogic breathing on brain function and physiologic parameters, but the mechanisms have not been clarified. Sudarshan Kriya yoga (SKY), a sequence of specific breathing techniques (ujjayi, bhastrika, and Sudarshan Kriya) can alleviate anxiety, depression, everyday stress, post-traumatic stress, and stress-related medical illnesses. Mechanisms contributing to a state of calm alertness include increased parasympathetic drive, calming of stress response systems, neuroendocrine release of hormones, and thalamic generators. This model has heuristic value, research implications, and clinical applications.

### INTRODUCTION

The origins of yoga have been traced as far back as the ancient rishis, 8000 years ago (Feuerstein, 1998). Over many centuries different forms of yoga developed that have been used to restore and maintain health and to elevate self-awareness and consciousness. “Prana” translates as “life force” or “energy.” The ancient science of breath is called pranayama meaning both “control of energy” and “expansion of energy” (Sovik, 2000). Although the scientific exploration of pranayama by Western medicine is in its infancy, these breathing techniques have the potential to relieve anxiety, depression, post-traumatic stress disorder, chronic pain, and many stress-related medical illnesses. In addition, they may provide new approaches to the treatment of behavioral disorders of children, attention deficit disorder, violence, alcoholism, and rehabilitation of prisoners and terrorists.

Integrating knowledge about yoga breath techniques into a unifying neurophysiologic theory is fraught with difficulties. Myriads of breathing patterns and specialized tech-

niques (for example, abdominal breathing, alternate nostril breathing, breathing against airway resistance, physical postures, breath holding) and variations within each technique as practiced by different schools create a field of study that is both dazzling and daunting.

Many research studies have used small samples and outdated methodologies. Rigorous studies have been done on only a fraction of the available breath techniques and these have measured limited sets of parameters. The use of mixed combinations of breathing techniques, inadequate documentation of breathing patterns, and differences in length of practice and level of experience of the subjects make it difficult to compare or apply findings from studies of one breathing practice to another.

Keeping in mind the many challenges of our task, we have attempted to develop a neurophysiologic integration by breaking down different breathing practices into their common elements and applying research from related fields such as polyvagal theory and vagal nerve stimulation, to enhance our understanding. This paper is Part I of a two-part series. Here we will propose a neurophysiologic theory that we

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hope will be of heuristic value and that will identify future research directions. Part II will address clinical applications.

Hundreds of scientific studies have found that mind–body interventions, including yoga practices, are effective in treating stress-related mental and physical disorders (Becker, 2000; Benson, 1996; Jacobs, 2001). Reduced sympathetic and increased parasympathetic nervous system activity have been implicated in such therapeutic action. Recent research has focused on cardiac vagal tone as a marker of emotional regulation, psychologic adaptation (Beauchaine, 2001; Sargunraj, et al. 1996), emotional reactivity and expression, empathic response, and attachment (Porges, 2001). A growing body of research is extending the associations between emotional disorders and autonomic function across the lifespan, including infants and children (Bazhenova et al., 2001; Boyce et al., 2001; Mezzacappa et al., 1997; Monk et al., 2001), attention deficit/hyperactivity disorder (Beauchaine et al., 2001), autism (Porges, 2004), and adults with anxiety (Friedman and Thayer, 1998; Kawachi et al., 1995; Thayer et al., 1996), panic (Friedman and Thayer, 1998), depression (Carney et al., 1995; Lehofer et al., 1997) post-traumatic stress disorder (Sahar et al., 2001), and hostility and aggression (Beauchaine et al., 2001; Mezzacappa et al., 1997).

The relationship between breathing and emotion is bidirectional (Ley, 1999). Breathing is under both voluntary and involuntary control via complex feedback mechanisms involving autonomic visceral networks, brain stem nuclei, the limbic system, cortical areas, and the neuroendocrine system. Yogic breathing provides a unique and powerful tool for adjusting imbalances in the autonomic nervous system and thereby influencing a broad range of mental and physical disorders (Sovik, 2000).

By voluntarily controlling breathing patterns, it is possible to influence autonomic nervous system functions, including heart rate variability and cardiac vagal tone (Fokkema, 1999; Lehrer et al., 1999; Sovik, 2000) chemoreflex sensitivity (Spicuzza et al., 2000), baroreflex, and central nervous system (CNS) excitation as indicated by electroencephalogram (EEG; Balzamo et al., 1991; Roldan and Dostalek 1983, 1985), magnetoencephalography (Carbon et al., 2000), and magnetic resonance imaging (MRI; Posse et al., 1997a, 1997b). Neuroendocrine functions, including the release of cortisol (Gangadhar et al., 2000), prolactin (Janakiramaiah et al., 1998), and possibly vasopressin and oxytocin can also be affected by yogic breathing. Many studies have demonstrated effects of yoga techniques on brain function and physiologic parameters, but the underlying mechanisms have not been adequately elucidated.

We will focus on a yoga breathing program called Sudarshan Kriya Yoga (SKY) as taught by The Art of Living Foundation (a nonprofit service organization) because it has been widely used across many cultures (over 6 million people worldwide), it follows a reproducible sequence, and both research and clinical experience demonstrate that it signifi-

cantly alleviates stress, anxiety (Gangadhar et al., 2000; Suarez 2002; Vedamurthachar, 2002; Vedamurthachar et al., 2002), and depression (Bhatia et al., 2002; Janakiramaiah et al., 1998, 2000; Naga Venkatesha Murthy et al., 1997, 1998; Weintraub, 2004).

First we describe the sequence of breathing techniques that comprise SKY. Next, we present animal and human data relevant to the neurophysiologic changes induced by SKY, focusing on the autonomic, stress response, and neuroendocrine systems. Third, we develop a neurophysiologic model of the effects of SKY.

Basic SKY is taught in a 22-hour course. Although we can describe the breathing techniques, in actual practice a trained instructor is required to convey the subtleties and to ensure they are done correctly. Follow-up sessions are strongly recommended to correct and refine each person's practice. With proper instruction anyone can learn the complex skills involved in SKY. But just as one needs coaching to learn weightlifting or rock climbing, one needs coaching in pranayama. While SKY has many potential physical and emotional benefits, improper or excessive practice may have no benefit and may cause harm. Furthermore, the techniques are modified for individuals who are pregnant or who have medical conditions such as high blood pressure, cardiovascular disease, seizure disorders, reduced lung capacity, severe depression, panic disorder, and bipolar disorder. Advanced SKY courses teach alternate nostril breathing, bandhas (breath holding with locks), and advanced meditations.

Pranayama are forms of voluntarily controlled breathing. The psychophysiologic effects of different pranayama are believed to derive from differences in duration of the phases of the breathing cycle, tidal volume, and other factors including the use of the mouth, nostrils, constriction of the laryngeal muscles, position of the glottis, and asanas (body postures) (Telles and Desiraju, 1992).

The SKY program has four breath components: three-stage slow ujjayi; bhastrika; chanting of "om"; and Sudarshan Kriya (cyclical breathing). All components are done sitting with the spine erect with legs folded under (vajrasana or *seiza*), cross-legged or on a chair. Participants are instructed to focus on their breathing and the sensations it produces in the body. During all components the eyes are closed and breathing is through the nostrils. The breath work is followed by meditation and rest. Variations of these techniques are used in many traditions including Raja yoga, Hatha yoga, Iyengar yoga, and Zen (Feuerstein, 1998; Iyengar, 1989; Rama, 1998; Rama et al., 1998; Telles et al., 1993; Vivekananda, 1973)

Ujjayi means victorious breath. It is practiced in many schools of yoga with differences in the frequency and length of breath cycles and in the presence or absence of breath holding. In SKY, the first component, three-stage breathing, consists of slow ujjayi (2–4 cycles per minute or cpm) against airway resistance. Mild airway resistance is main-

tained throughout inspiration and expiration by a slight contraction of the laryngeal muscles and partial closure of the glottis, creating a soft sound, like the sound one hears inside a conch shell. Each breath cycle consists of four phases: inspiration; end-inspiration breath-holding (kumbhak); expiration; and end-expiration breath-holding (kumbhak). The time ratio of the four phases is 4:4:6:2.

The three stages of breathing refer to the use of three asanas believed to maximize expansion and awareness of each lobe of the lungs according to yoga science. In the first stage, hands are held at the waist while inspiration is focused on expanding the lower lobes using abdominal breathing. In the second stage, the hands are held at chest level while expanding the middle lobes and chest. In the third stage, elbows point upward and the palms are placed on the upper back while expanding the upper lobes. There are 10 breath cycles in each stage followed by 20 seconds of rest after each stage.

We present research literature to support the hypothesis that the specific characteristics of three-stage breathing—slow breathing, airway resistance, breath holding, and expansion of the lungs and chest wall—all contribute to increasing parasympathetic tone, balancing and conditioning the autonomic nervous system.

The second component is *bhastrika* (bellows breathing), a technique in which the breath is forcefully inhaled and then exhaled using strong abdominal muscle contractions. *Bhastrika* is done through the nostrils with the eyes closed at a rate of approximately 30 breaths per minute. During inspiration the arms go straight upwards, the hands open with fingers extended. During expiration the elbows come down while the hands close. Three rounds of *bhastrika* with 15–20 breath cycles each are followed by 20-second periods of rest.

After *bhastrika*, “om” is chanted three times using a prolonged expiration and a 15-second rest after each chant.

The fourth component is *Sudarshan Kriya*, a unique form of cyclical breathing (no pause between inspirations and expirations). No airway resistance is used. The inspiratory and expiratory phases are approximately equal. Learning *Sudarshan Kriya* requires extensive demonstration and coaching by a trained instructor. Subtle aspects such as the quality, intensity, timing, and balance of the breath cycles cannot be conveyed in written text. Concurrent instruction on how to quiet the mind, to focus on the breath, and the sensations it engenders is essential.

In *Sudarshan Kriya* three different rates of breathing are used: slow (8–14 cpm), medium (30 cpm), and rapid (150–180 cpm). The number of breaths, the intensity, and the sequence of cycles varies depending upon whether the *kriya* is done with an instructor or whether it is done as a short home practice (three repetitions of 20 slow, 40 medium, and 40 rapid cycles). Each set of 40 rapid cycles must be followed by a set of slow cycles for rest. We must emphasize the importance of proper instruction in learning this technique because we cannot fully describe some of the critical nuances, nor can we

present individual modifications that may be recommended. The *kriya* ends with 8–10 slow cycles, a 5-minute period of supine rest with specific instruction regarding postures for getting up, and increased water intake to prevent dizziness, lightheadedness, or headaches.

The psychophysiological state achieved with SKY practice is one of calmness and alertness. Practitioners often describe feeling peaceful, clear-minded, happy, focused, and connected to others.

## NEUROPHYSIOLOGIC MODEL

### *Component I—ujjayi*

We propose that slow *ujjayi* breathing enhances parasympathetic activity and increases indicators of vagal tones: respiratory sinus arrhythmia [RSA] and heart rate variability (HRV). Slow *ujjayi* also decreases chemoreflex sensitivity, improves baroreflex response, and increases exercise and stress tolerance.

Research suggests that the effects on the autonomic nervous system may be the result of all of the following characteristics of *ujjayi* breathing:

1. Slow breathing (2–4 cpm),
2. Laryngeal contracture,
3. Inspiration against airway resistance,
4. Prolonged expiration against airway resistance,
5. Breath-holding.

*Slow breathing.* Eastern religions and martial arts have used slow breathing techniques for centuries to produce psychophysiological effects (Lehrer et al., 1999). Although these practices vary in their emphasis (for example, *zazen* “tanden breathing” focuses on lower abdominal breathing), it is likely that yoga breathing practices that utilize slow rates of breathing share certain neurophysiological mechanisms and effects.

*Zen* “tanden breathing” as practiced by the *Rinzai* sect is a form of slow breathing into the lower abdomen usually at a rate of 3–9 breaths per minute, a rate comparable to the slow *ujjayi* of SKY. Slow *tanden* breathing significantly increased HRV in the low respiratory frequency range, which is associated with both the sympathetic and parasympathetic systems and with baroreflex activity. Slow breathing with prolonged expiration reduced physiologic and psychologic arousal in an anxiety-provoking (but not dangerous) situation in a randomized study of 39 male and 21 female college students (Cappo and Holmes, 1984).

*Ujjayi* with alternate nostril breathing during expiration at a rate of 2 cpm (comparable to SKY) resulted in increased Na-wave amplitude and decreased latency during the practice of the *pranayama*. This was interpreted to indicate changes in information processing at the primary thalamocortical level (Telles and Desiraju, 1992).

Chemoreflex sensitivity (mediated by the vagus nerve) accounts for changes in breathing rate in response to changes in the concentration of oxygen and carbon dioxide in the blood. Slow yoga breathing (6 breaths per minute with 5-second inspiration and 5-second expiration) decreases chemoreflex sensitivity (Spicuzza et al., 2000), improves cardiovascular and respiratory function, and increases RSA, arterial baroreflex sensitivity (Bernardi et al., 2001), oxygenation, and exercise tolerance (Bernardi et al., 1998).

Reducing chemoreflex sensitivity enables the body to tolerate higher levels of carbon dioxide (generated by exercise) such that one can do more exercise without feeling short of breath. In the 2000 study by Spicuzza and colleagues, recordings were taken during spontaneous, slow (6 per minute) and fast (15 per second) breathing through the mouth without airway resistance. However, all of the subjects in Spicuzza's study also commonly practiced ujjayi breathing with Hatha yoga (L. Bernardi, personal communication, July 5, 2004). In a study of elite athletes, those given pranayam (including ujjayi) training achieved higher work rates with reduced oxygen consumption than a control group of elite athletes who did not practice pranayam (Raju et al., 1994). Spicuzza and colleagues (2000) suggest that long-term practice of yoga breathing (as opposed to regular slow breathing) independently reduces chemoreflex sensitivity. Adaptation of peripheral/central chemoreceptors to chronic carbon dioxide retention and/or adaptation of pulmonary stretch receptors to a habit of deep slow respiration may increase vagal afferent discharge to the brainstem center (nucleus tractus solitarius [NTS]) that sends projections to the thalamus and limbic systems (Fig. 1) (Bernardi et al., 1998; Friedman and Coats, 2000). These vagal effects are physically and emotionally calming.

In healthy elderly people the effects on the baroreflex (mediated by the vagus nerve) of yoga postures (asanas) and breathing (including ujjayi) were compared to aerobic exercise training. Six weeks of training, 3 hours per week, in yoga led to a decreased heart rate, increased vagal tone, and an increase in aerobic capacity of approximately 11%. The yoga improved baroreflex sensitivity whereas aerobic training did not (Bowman et al., 1997). Slow breathing normalizes baroreflex sensitivity, which tends to become impaired with aging, cardiac disease, and hypertension.

*Laryngeal contracture.* Contraction of laryngeal muscles with partial closure of the glottis increases airway resistance during inspiration and expiration. This stimulates somatosensory vagal afferents (originating in the pharynx and baroreceptors in lung tissue) activating vagal afferents to the brain. Furthermore, the increased airway resistance provides the breath control that is needed to prolong inspiratory and expiratory phases.

*Inspiration and expiration against airway resistance.* In addition to being a form of slow breathing, ujjayi is a gentle kind of "pressure breathing" against airway resistance.

A study of resistive loading throughout the respiratory cycle found a correlation between increased resistive loads and increased HRV and RSA. Resistive loading increases intrathoracic pressure and arterial baroreceptor stimulation. The increase in HRV and RSA showed a linear correlation to the increase in respiratory period in response to resistive loading. Resistive loading also prolonged the respiratory period. (Calabrese et al., 2000)

MRI studies in humans have shown that mild to moderate inspiratory resistive loads increase signal intensity in discrete locations including the parabrachial nucleus (PBN) and the locus coeruleus (Figs. 1 and 2). The PBN, "receives significant afferent inputs via vagal and spinal sources from the lungs and chest wall stretch receptors, which are activated by the inspiratory loading task" (Gozal et al., 1995). The locus coeruleus recruits adrenergic fibers for arousal and has primary vagal afferent depolarization (Gozal et al., 1995). These findings support the hypothesis that the inspiratory resistance created during ujjayi breathing activates vagal afferents leading to the PBN and locus coeruleus.

An ujjayi-like form that Fokkema (1999) calls "strained breathing" has been observed in animals. Contraction of the laryngeal muscles with slowed breathing against airway resistance was found to occur when an animal is defeated in battle. In animals the original stimulus for the strained breathing pattern derives from the hypothalamic vigilance area, travels to the dorsomedial nucleus (DMNX) in the brain stem and from there to vagal efferents (Fig. 1). If an animal is unable to escape and use "fight or flight reflexes," it becomes extremely vigilant. It is postulated that ujjayi breathing activates vagal afferents to the NTS in the brain stem, which send projections via the parabrachial nucleus (PBN) to the limbic system, activating the hypothalamic vigilance areas (increasing attention and vigilance) and feeding back through the DMNX to vagal efferents. Stimulation of the vagal efferent neurons would then induce an increase in parasympathetic and a decrease in sympathetic input to the sinoatrial node. At high levels of vagal stimulation, parasympathetic inhibitory effects (slowed heart rate) occur. During ujjayi, vagal efferents would slow the heart rate (indicating a high level of parasympathetic activation). Slowing the heart rate conserves energy and allows organisms to replenish energy reserves. In animals, ujjayi-like breathing occurs under the threat of danger and prepares for self protection (Fokkema, 1999). However, ujjayi-like breathing occurs in humans under nonthreatening conditions as well.

Fokkema (personal communication, July 8, 2004) has observed a mild form of "strained breathing" that occurs naturally in toddlers playing with building blocks, children doing math problems, and adults exerting effort under stress such as giving a long presentation. It is associated with social factors, attention, expectation, or anxiety (Fokkema, 1999). Ujjayi-like breathing also occurs in humans during sexual arousal (Fox and Fox, 1969), more commonly in women. Thus, ujjayi-like breathing can occur naturally in humans even

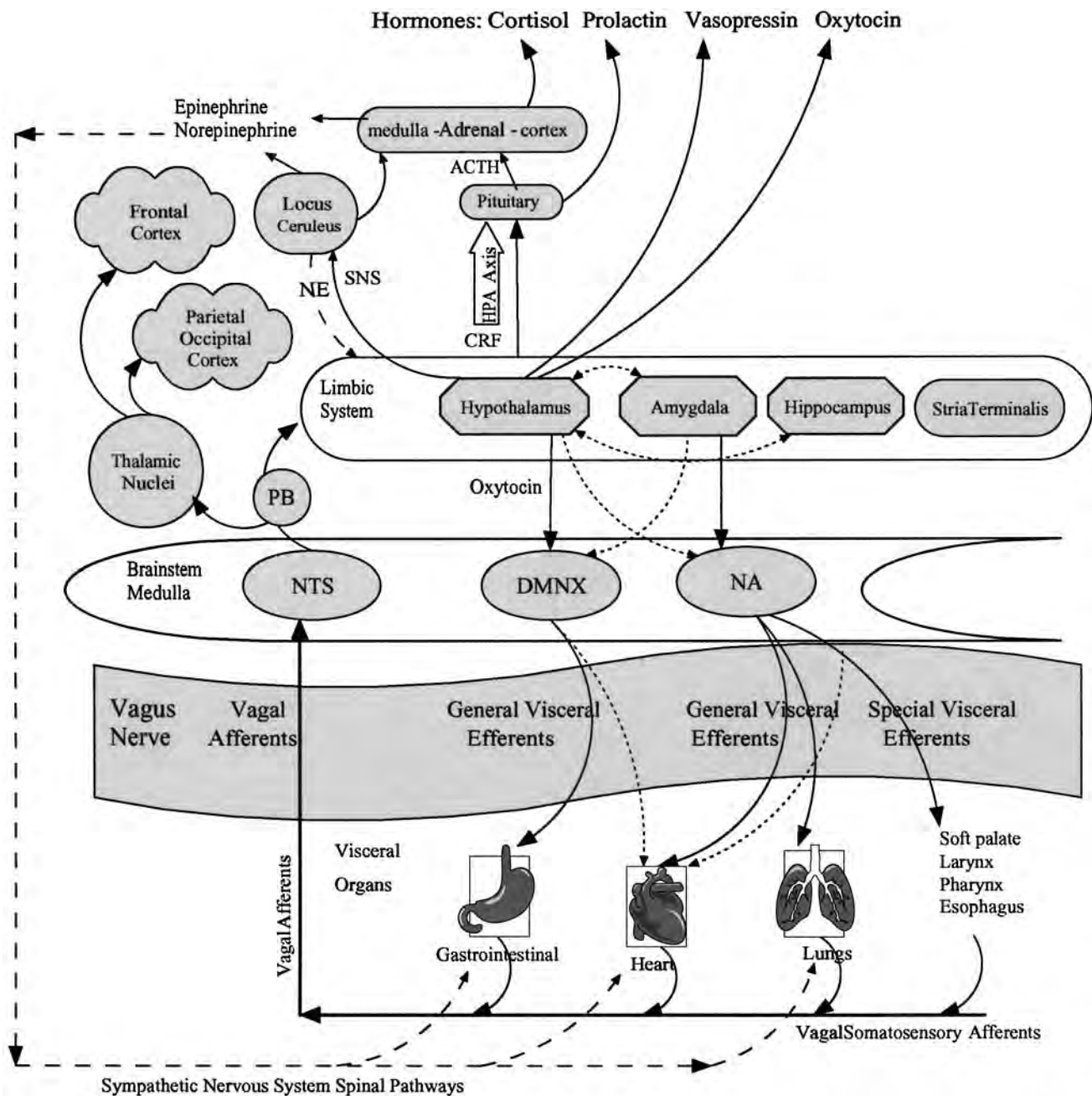
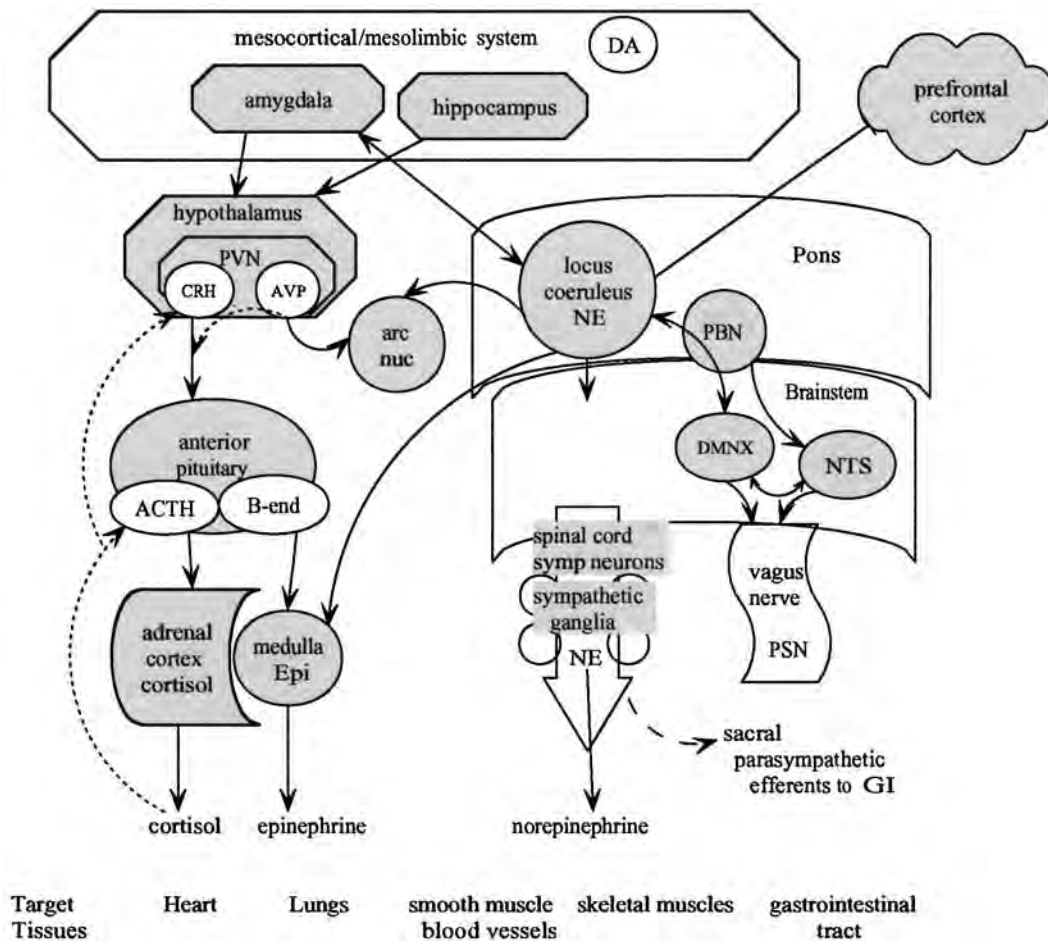


FIG. 1. Neurophysiological model. NTS, nucleus tractus solitarius; DMNX, dorsal medial nucleus; NA, nucleus ambiguus; PB, parabrachial nucleus; ACTH, adrenocorticotrophic hormone; CRF, corticotrophin; HPA Axis, hypothalamic-pituitary-adrenal axis; NE, norepinephrine; E, epinephrine; SNS, sympathetic nervous system.

under nonthreatening conditions when concerted effort is required for a challenging task and during sexual arousal.

During the SKY practice of ujjayi, people feel calm but alert and attentive. The proposed mechanism is a shift to parasympathetic dominance via vagal stimulation from vagal somatosensory afferents in the glottis, pharynx, lungs, and abdominal viscera.

*Breath holding.* A 52% increase in oxygen consumption and metabolic rate occurred after ujjayi with short breath-holding at the end of inspiration (Telles and Desiraju, 1991). Another study of four different patterns of kumbhak (breath holding during pranayam) found that the two varieties with end-expiratory and end-inspiratory kumbhak phases were associated with no increase in overall heart rate as compared



**FIG. 2.** Stress response system: HPA and LC/NE. HPA, hypothalamic-pituitary-adrenal axis; LC/NE, locus coeruleus/norepinephrine; ACTH, adrenocorticotrophic hormone; AVP, arginine-vasopressin; B-end,  $\beta$ -endorphin; DA, dopamine; DMNX, dorsal medial nucleus; NTS, nucleus tractus solitarius; PVN, paraventricular nucleus; PSN, parasympathetic nervous system; Epi, epinephrine; NE, norepinephrine; GI, gastrointestinal.

to an increase in heart rate with the two types that had no end-inspiratory and only a short end-expiratory kumbhak. This is consistent with a possible further enhancement of parasympathetic dominance in three-stage ujjayi breathing, which has an even longer end-inspiratory kumbhak as well as an equivalent end-expiratory kumbhak. In this study, the pranayama had slow breath rates (2–5 cpm) that were comparable to three-stage ujjayi (Telles and Desiraju, 1992).

### NEURAL PATHWAYS OF THE PARASYMPATHETIC NERVOUS SYSTEM

Vagus nerve afferents synapse in the NTS (Fig. 1). From the NTS fibers ascend to the parabrachial nucleus (PB), which diverges into two pathways. One sends projections to

the hypothalamus, amygdala, stria terminalis, and limbic cortex, affecting autonomic, endocrine, and emotional processes. The other pathway from the PBN goes to several thalamic nuclei and thence to the cerebral cortex. At least 80% of the vagal fibers are afferents to the brain (Porges, 1995). Within the brain stem, the vagal nuclei (nucleus ambiguus [NA] and DMNX) regulate autonomic functions (Fig. 1). According to Porges' polyvagal theory, mammals, similar to reptiles, have a vegetative vagal system regulating reflex visceral functions (such as heart rate, bronchial constriction, and gastrointestinal activity), but they also possess a "smart" vagal system that probably plays an important role in social behavior (emotion, facial expression, attachment, communication, and attention) (Porges, 1995). Sensory feedback from visceral organs travels to the NTS where it provides direct input to the vegetative and smart

vagal nuclei and is modulated by oxytocin (Carter, 1998; Higa et al., 2002).

RSA refers to normal heart rate increases during inspiration and heart rate decreases during expiration. RSA is influenced by sympathetic and vagal (parasympathetic) input and by respiratory rate and volume. HRV is a spectral analysis of the variations in heart rate based on electrocardiographic readings. Parasympathetic function can be estimated from the high frequency bands (0.12–0.40 Hz) of the HRV (Sahar et al., 2001). Slow yoga breathing induces oscillations of blood pressure and an exaggeration of the normal RSA. Consequently, a strong respiratory rhythm is set up in the vagus nerve, such that enhanced RSA occurs (Sovik, 2000). An increase in pulmonary tidal volume during ujjayi breathing probably prevents a tendency toward hypoxia/hypercapnia (decreased oxygen/increased carbon dioxide), which might otherwise occur during slow breathing.

Polyvagal theory proposes that vagal activity is linked to attention, emotion, and communication (Porges, 2001). Increased RSA in infants correlates with better capacity to respond to the environment. Low RSA is found in fearful or depressed infants (Beauchaine, 2001). The low RSA and low heart rate found in aggressive (Beauchaine et al., 2001) or antisocial adolescent males (Mezzacappa et al., 1996) and hostile adults is consistent with decreased sympathetic and decreased parasympathetic activity (Carney et al., 1995). Low RSA was also found in individuals with depression (Carney et al., 1988, 1995), anxiety, panic disorder (very low RSA), and functional dyspepsia (Beauchaine, 2001; Haug et al., 1994; Mezzacappa et al., 1997). Ujjayi breathing is postulated to increase parasympathetic influence (as do other forms of slow yoga breathing), increase RSA and HRV, activate the hypothalamic vigilance area and induce a calm but alert state, recharge energy reserves, and prepare for whatever action may be necessary.

Increased vagal modulation is necessary for cardiovascular recovery from psychologic stress (Mezzacappa et al., 2001). Decreased vagal reflexes have been associated with increased risk of cardiovascular disease and death after myocardial infarction (La Rovere et al., 1998). Furthermore, the correlation between depressed mood and decreased parasympathetic cardiac control was demonstrated in a group of 53 healthy college students (Hughes and Stoney, 2000).

### *Component II—Bhastrika*

Bhastrika, the second breathing technique, causes autonomic sympathetic activation and CNS excitation on EEG (Roldan and Dostalek, 1983, 1985) with activation of temporoparietal cortical areas, producing rhythms that are similar to the gamma frequency bands hypothesized to reflect synchronization of neural assemblies (Kwon et al., 1999). The subjective experience is of excitation during bhastrika followed by emotional calming with mental activation and alertness.

The sympathetic nervous system (SNS) is an adaptive system that mobilizes energy for “fight or flight” behaviors. The higher brain control centers include the mesocortical/mesolimbic system (affect and anticipation), the amygdala/hippocampal complex (initiates, perpetuates, and terminates stress response system action), and the arcuate nucleus (pain sensation control) (Fig. 2). These centers affect target organs via the hypothalamic-pituitary-adrenal (HPA) axis, the locus ceruleus-norepinephrine (LC/NE) system, and the PNS (gut response to stress) to prepare the body to respond to stress by increasing cardiac output, enhancing respiration, increasing muscular activity, and inhibiting the gastrointestinal tract (Habib et al., 2001; Porges, 2001; Tsingos and Chrousos, 2002).

In addition to activating the cortex, bhastrika may enhance SNS reserves and the capacity to continue functioning effectively over time as opposed to becoming depleted and (in reaction to multiple stressors) becoming hypo-reactive or hyper-reactive. In effect, the daily practice of bhastrika provides a mild sympathetic stimulation much like regular physical exercise and thereby may increase the capacity of the SNS to respond to acute stressors without rapidly exhausting its reserves.

### *Component III—Chanting*

The ujjayi and bhastrika breathing practices are followed by a chanting of “om” three times. Our model hypothesizes that the “om” chant has complex effects on the brain. The verbal stimulation and the vibrational component of the chant probably contribute to activation of Wernecke’s area and the thalamus. However, other complex physiologic effects are contributory. Even just mentally chanting “om” showed decreased metabolism, decreased heart rate, and increased peripheral vascular resistance in seven experienced yogic meditators. These findings were interpreted as signs of increased mental alertness with increased vagal tone and decreased sympathetic activation in the context of physiologic relaxation (Telles et al., 1995).

### *Component IV—Sudarshan Kriya*

Sudarshan Kriya (SK) consists of cyclical breathing of three different rhythms of different lengths and repetitions depending on the specific practice situation and conditions. For example, the home practice differs from the protocol when a teacher is present.

It is reasonable to assume that the effects of the slow cycles of SK (10–14 cpm) are similar to those of other slow breathing practices with comparable frequencies. Thirty-six (36) alcohol-dependent inpatients with high anxiety scores were randomly assigned to slow-breathing training (10 cycles per minute) or to a control group instructed to simply count the pacing tones. Those in the paced slow-breathing group showed greater reductions in tension, state anxiety, and skin conductance (Clark and Hirschman, 1990).

In a study of healthy college students, assigned to slow (8 per minute), fast (30 per minute) and nonpaced breathing for 5 minutes, followed by 2 minutes of stress anticipating an electric shock, the amplitude of high frequency component of HRV (index of cardiac vagal tone) was found to be significantly decreased in the fast and nonpaced breathing groups, while it was unchanged in the slow breathing group. This observation suggests that slow breathing decreases parasympathetic withdrawal in response to threat and provides a basis for the use of slow breathing to attenuate autonomic responses in patients with anxiety disorders (Sakakibara and Hayano, 1996).

The medium and rapid cycles of SK are a controlled physiologic form of mild hyperventilation that may stimulate the vagus nerve and activate thalamic oscillators. During voluntary hyperventilation, modest hypocapnia and normal  $PO_2$  lead to peripheral physical effects: increased cardiac output, increased renal blood flow, increased lithium and sodium excretion (Vidiendal Olsen et al., 1998), and a minor increase in renal sympathetic activity (Vidiendal Olsen et al., 1998).

Novices, when first learning SK, sometimes experience paresthesias or mild peripheral cramping. With practice these symptoms abate. One possibility is that a better oxygen/carbon dioxide ratio is achieved by learning to maintain the balance between inspiratory and expiratory volumes. However, studies would be needed to better understand this phenomenon. Changes in respiratory volumes during SK are considerably less than those caused by mechanical hyperventilation and other forms of hyperventilation used in research studies.

### SUDARSHAN KRIYA AND HYPERVENTILATION

Although there are no studies recording EEG effects or brain imaging during SK, there is a large body of data on voluntary hyperventilation in humans, mechanical ventilation in brain-injured patients, and animal models of hyperventilation.

An excellent review by Patel and Maulsby (1987) found no substantive evidence to support the theory that EEG slowing with either voluntary or mechanical hyperventilation is due to cortical hypoxia (decreased oxygen secondary cerebral vasoconstriction and/or secondary to hypocapnia (decreased carbon dioxide). EEG slowing is caused by input from the thalamic nuclei that are activated by vagal nerve afferents (Fig. 1). Hypocapnia suppresses activity in the brain stem mesencephalic reticular activating system, blocking other nonvagal sensory input to the thalamus. In effect, this further increases dominance by vagal afferents. They propose that activation of the thalamus and suppression of the reticular activating system are associated with the slow wave states found on EEG during hyperventilation, states similar to drowsiness.

Practitioners of SK commonly experience drowsiness during or at the end of the hyperventilation (rapid cyclical breathing) followed by an "edge of sleep" state.

The most common EEG response to voluntary hyperventilation in a normal individual consists of diffuse slowing; in adults this response is most prominent at the biparietal cortical areas. Slowing will disappear within a minute after stopping hyperventilation. The diffuse slowing response to hyperventilation can be abolished by lesions of the nonspecific thalamic projection system (NSTPS) and the thalamus or by destruction of both vagal nerves (Balzamo et al., 1991). Peripheral vagal afferents from the respiratory system play a major role in EEG changes caused by mechanical or voluntary hyperventilation.

Carbon and associates (2000) most recently have shown that in humans, 100 to 300 seconds of hyperventilation increased sensorimotor cortex excitability measured by direct current magnetoencephalography. The underlying basis of these cortical changes, particularly in the sensorimotor cortex is probably thalamic activation. Using positron emission tomography (PET) scans, Prevett and associates (1995) showed that hyperventilation increased blood flow to the thalamus in patients with generalized epilepsy. Increased perfusion and activation of the thalamus leads to increased excitation of sensorimotor cortex and decreased excitation of frontal and parietal cortical areas. Voluntary hyperventilation quieted the frontal and parietooccipital cortex but not subcortical areas on functional MRI imaging (Posse et al., 1997a). This evidence supports the hypothesis that, similar to hyperventilation, medium and rapid SK cycles activate thalamic projections that excite sensorimotor cortex and quiet frontal and parieto-occipital cortex.

### SUDARSHAN KRIYA AND VAGAL NERVE STIMULATION

Unilateral vagal nerve stimulation (VNS) (Nahas, 2003; Rush et al., 2000) is an effective treatment in many cases of epilepsy and a promising experimental treatment for improving mood and cognitive function in treatment-resistant depression (Sackeim et al., 2001; Schachter and Saper, 1998). In animals, lower frequency stimulation (1 to 17 Hz) causes EEG synchronization while high-frequency stimulation (greater than 30 Hz) results in EEG desynchronization. Two PET studies of the effects of VNS on activation of the human brain reported thalamic activation and variable effects in areas of the cortex and subcortical structures (Schachter and Saper, 1998).

In a 1-year open follow up study of 30 patients given VNS for treatment-resistant major depression, a significant response rate was sustained (Marangell et al., 2002). Additional research has shown that VNS helped depression (Nahas, 2003) with activation of anterior paralimbic areas on functional magnetic resonance imaging (fMRI) and in-



creases in cerebrospinal fluid dopamine, norepinephrine, and serotonin metabolites as well as  $\gamma$ -amino-butyric acid (GABA). VNS improved memory in studies of rats and humans (Clark et al. 1998, 1999) and improved cognition in patients with Alzheimer's disease (Sjogren et al., 2002).

VNS and SKY differ in several important aspects. Stimulation of the left vagal nerve produces few autonomic effects. For example, it does not change heart rate. In contrast, SKY has numerous autonomic effects including changes in heart rate, HRV, improved bowel function, etc. VNS consists of electrical stimulation (usually of a fixed frequency and amplitude) applied to the left vagal nerve only. The use of different electrical pulse widths (PW) produced different patterns of brain activation on fMRI (Mu et al., 2004). More research is needed to determine the best stimulation parameters (intensity, frequency, PW, "on" time, and "off" time) to optimize antidepressant effects of VNS.

In contrast, during SKY a sequence of breathing techniques of different frequencies, intensities, lengths, and with end-inspiratory and end-expiratory holds creates variegated stimuli from multiple visceral afferents, sensory receptors, and baroreceptors. These probably influence diverse fiber groups within the vagus nerves (Porges, personal communication 2003), which in turn induce physiologic changes in organs, glands, and ascending fibers to thalamic generators, the limbic system, and cortical areas. This may account for the rapidity and diversity of SKY effects. The authors have observed that many people respond to SKY within days with immediate improvements in mood and anxiety. Further research would help to understand the nature of these complex stimuli arising within body tissues and neuronal pathways (Clark et al., 1999; Sjogren et al., 2002)

### **SKY, THALAMIC OSCILLATORS, SENSORIMOTOR RHYTHM, AND POSTREINFORCEMENT SYNCHRONIZATION**

Sterman (1996) found an EEG pattern of 12 to 20 Hz (beta) localized to the sensory motor cortex, which was labeled (SMR) for sensorimotor rhythm. SMR originates in the somatosensory ventrobasal nuclei of the thalamus, which relay information to the cortex and to cells in the adjacent thalamic nucleus (nucleus reticularis). Oscillations of activity between these nuclei set up the SMR recorded on the cortex. The use of biofeedback to train animals and humans to produce the SMR pattern has resulted in a more focused state, improved memory, vigilance, attention, and sleep, and a decrease in seizure frequency (Sterman, 1996). SMR is enhanced by the following: physical relaxation (reduced muscle tone and stretch reflex excitability); suppression of extraneous somatosensory information; and decrease in eye movements (most easily achieved with the eyes closed). These conditions are all part of the SKY practice.

Postreinforcement synchronization (PRS) appears on EEG as a 4–12 Hz (theta/alpha) frequency localized in the parietal cortex. PRS is related to a thalamocortical gating mechanism involving thalamic reticular nuclei. The PRS sequence in humans is related to reward, satiety, and pleasure (Sterman, 1996). In humans, PRS is associated with a dreamy "edge of sleep" state and reduced cortical excitability. Sterman notes that the "edge of sleep" state is therapeutically useful in allowing suppressed emotional content to emerge. He suggests that withdrawal of brain stem and normal thalamocortical regulatory influences leads to relative cortical disinhibition. This allows suppressed emotion and thoughts to be evoked while preserving a state of calmness and relaxation.

Sterman's group found that when an animal became satiated and sat quietly, alternating SMR and PRS frequencies could be seen in the sensory motor cortex and the ventrobasal thalamus. They hypothesized that the alternation of SMR and PRS frequencies reflected excitation–inhibition sequences in thalamocortical circuits.

A pilot study by Bhatia and colleagues (2002) compared 19 Art of Living teachers who regularly practice SK to 15 control subjects. EEGs of Art of Living teachers during periods of rest showed increased 13–30 Hz (beta) activity (similar to SMR) in the right and left parieto-occipital regions indicating cortical activation by the underlying thalamic generator (a set of neurons in the thalamus that sets up a clear rhythm in a related cortical area). This occurred with increased alpha activity suggesting increased calm and relaxation combined with increased vigilance and attention (Bhatia et al., 2002). Decline in activation and electrical symmetry of the cerebral hemispheres has been noted in depressed patients (Kinsbourne, 2005). SKY improved cerebral symmetry on EEG (Bhatia et al., 2002).

### **SUDARSHAN KRIYA: CYCLICAL BREATHING**

We hypothesize that the different cyclical rhythms of SK create a variety of vagal, thalamic, and cortical effects. Although many people experience SK as the most powerful part of the SKY program, there is a paucity of research on its specific modes of action. Further studies of the effects of SK cyclical breathing rhythms are needed to understand the power of these rhythms. Similar to a symphony, SK begins with slow cycles, becomes more active leading to a rapid crescendo, and closes with a slow rhythm.

### **ENDOCRINE EFFECTS: CORTISOL, PROLACTIN, AND OXYTOCIN**

The HPA axis is essential in the stress response and survival of mammalian species. The HPA axis is abnormally

overactivated during biologic depression. In patients with post-traumatic stress disorder it is acutely overactivated but then chronically depleted. Three weeks of SKY practice by a group of depressed patients resulted in significant reduction in cortisol (one measure of stress response system activation) and a concomitant decrease in depression scores (Gangadhar et al., 2000).

In a study comparing SKY, imipramine (tricyclic antidepressant), and electroconvulsive (ECT) treatment in patients hospitalized for severe depression, Janakiramaiah and colleagues found that both SKY and ECT caused significant transient elevations in prolactin (Janakiramaiah et al., 2000). Imipramine, which does not increase vagal nerve function, did not increase prolactin. Acute prolactin release reduces fear and anxiety in animal models (Torner et al., 2002).

Over the last 20 years, oxytocin has been recognized as crucial to social bonding in mammals, such that it is known as the "cuddle" hormone. It reduces the stress response to social separation and promotes formation of social bonds and affiliation (Nelson and Panksepp, 1998). When oxytocin is stimulated in voles they bond to the first vole of the opposite gender that they encounter (Carter, 1998). In humans, oxytocin causes uterine contractions in childbirth, generates milk let-down in new mothers, enhances the bonding and affection of the mother for her baby (Nelson and Panksepp, 1998), and is associated with sexual arousal. Many brain areas with oxytocin receptors are involved in behavior, memory, sensory processing, eating, satiety (Nelson and Panksepp, 1998), and reproduction. There is evidence of low oxytocin levels in major depression (Frasch et al., 1995). The antidepressant effect of selective serotonin reuptake inhibitors (SSRIs) may be partially mediated by oxytocin (Uvnas-Moberg et al., 1999).

Oxytocin is produced by neurosecretory cells in the supraoptic nucleus (SON) and the paraventricular nucleus (PVN) of the hypothalamus (Torner et al., 2002). Some oxytocin is released within the CNS, but most of it is stored in the posterior pituitary (neurohypophysis) to be released into the bloodstream. Oxytocin is associated with parasympathetic nervous system functions and is involved in regulating the HPA axis (Carter, 1998; Uvnas-Moberg et al., 1999). Oxytocin is released in response to activation of somatosensory afferents from different parts of the body (Stock and Uvnas-Moberg, 1988). Electrical stimulation of vagal nerve afferents caused significant increases in plasma levels of oxytocin in animals (Stock and Uvnas-Moberg, 1988). We propose that SKY practices elevate oxytocin levels, possibly via VNS and other somatosensory stimuli related to the breathing practices. Further studies of oxytocin release during SKY would clarify the importance of these mechanisms. A testable hypothesis is that yogic breathing during SKY increases the release of oxytocin as well as prolactin. This would account in part for the enhancement of feelings of closeness, bonding, attachment, belonging, and well-being that many people experience during and after SKY courses.

## RESEARCH CHALLENGES

The challenges of yoga breathing research include designing sham controls, double-blinding, fully documenting yoga procedures, obtaining instructors to ensure correctness of techniques, identifying components and characteristics being tested, and selection of measures that probe neurophysiologic and endocrine effects without impeding the practices.

Raters of study subject response can be double-blinded, but complete blinding of subjects as in the use of an identical placebo capsule, is not possible.

Certain procedures for documenting breathing techniques are available to generate respirographs that convey changes in length, frequency, and amplitude of respirations (Telles and Desiraju, 1992). The inclusion of such graphs in research publications would facilitate comparison of studies.

Researchers interested in studying yoga techniques can contact international organizations such as the Art of Living Foundation, sponsor of SKY, to obtain qualified instructors, experienced practitioners, and for collaborative projects.

Unfortunately, funding is a factor that has limited the use of fMRI and PET studies to explore central effects. Measurements of oxytocin, prolactin, vasopressin, and cortisol before, during and after practice would yield vital data. Long term effects could be assessed at 3 and 6 months.

Studies of effects on learning, attention, retention, anxiety, depression, suicidality, aggression, and socialization in normal children and in those with attentional, behavioral, and learning disorders would be invaluable. Reliable measures of psychologic function, scales for mood assessment, attention and cognitive function could be more uniformly applied. Part II of our series will explore these areas, including the feasibility of integrating yoga breath techniques into school curricula.

## CONCLUSIONS

SKY yogic breathing may work by activating vagal afferents to the nucleus tractus solitarius, the parabrachial nucleus, thalamic nuclei, the cerebral cortex, and mesolimbic areas. Activation of the limbic system, hippocampus, hypothalamus, amygdala, and stria terminalis may improve autonomic function, neuroendocrine release, emotional processing, and social bonding.

Our neurophysiologic model postulates:

1. Strengthening, balancing, and stabilizing the autonomic and stress response systems;
2. Decreasing chemoreflex sensitivity;
3. Improved baroreflex response;
4. Shifting to parasympathetic dominance via vagal stimulation;

5. Balancing of cortical areas (synchronization) by thalamic nuclei;
6. Quieting of cortical areas involved in executive functions (such as anticipation, planning and worry);
7. Activation of the limbic systems leading to stimulation of forebrain reward systems and emotional release; and
8. Increased release of prolactin and oxytocin enhancing feelings of calmness and social bonding.

The stress response system and the parasympathetic nervous system respond like an orchestra to the breath rhythms set by SKY. By taking the nervous system through its paces, similar to practicing musical scales, SKY provides a kind of autonomic/endocrine training exercise that ultimately may strengthen, stabilize, and enhance the flexibility of the system. This model may be of heuristic value in identifying areas for future clinical research. For further clinical discussion of this model, see Brown et al., (2003) and Part II of this series.

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