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SPECIAL ISSUE

History of Heart Rate Variability Biofeedback Research: A Personal and Scientific Voyage

Paul Lehrer, PhD

Rutgers, Robert Wood Johnson Medical School, Piscataway, NJ

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This paper reviews the history of heart rate variability biofeedback. Interest in the method has evolved from several directions, eventually mutually influencing each other, and often through workshops provided by the Association for Applied Psychophysiology and Biofeedback. My own work was influenced by long-term use of the technique in Russia, and from research by Evgeny Vaschillo using transfer function analysis among heart rate, respiration, and blood pressure, to show how the technique stimulates the baroreflex; also by Richard Gevirtz in frequent workshops given together. Work at the HeartMath Institute independently evolved from experience with music relaxation and "heartfelt emotion," and other research evolved from American psychophysiological research. Brief descriptions of the development of interest and work in this field are provided by Richard Gevirtz, Rollin McCraty (HeartMath), Fredric Shaffer, and Robert Nolan, as well as myself.

As often happens in the history of science, interest in heart rate variability (HRV) biofeedback developed simultaneously in different places and by different pathways. The centers conducting much of the original work were my laboratory in New Jersey at the Robert Wood Johnson Medical School of the University of Medicine and Dentistry of New Jersey (now Rutgers, The State University of New Jersey), and Richard Gevirtz's laboratory at the California School of Professional Psychology at Alliant University, San Diego. Both of our research programs were heavily influenced by the contributions of people like Stephen Porges and Paul Grossman, who had pioneered the use of HRV as a tool in psychophysiology. They primarily were using measures of respiratory sinus arrhythmia (the variability in heart rate that is linked to respiration) as an index of vagus nerve influence on the heart (Grossman, Stemmler, & Meinhardt, 1990; Porges, 1991). Simultaneously, people at the HeartMath Institute in the mountains above Santa Cruz, California, were developing a broad range of clinical and personal enhancement applications for essentially the same phenomenon.

As early as the 1960s and 1970s, there was a smattering of interest in HRV from the fields of obstetrics (Welford, Sontag, Phillips, & Phillips, 1967) and cardiology (Burdick, Brinton, Goldstein, & Laszlo, 1970). The beginning of interest in HRV in psychophysiology also arose at this time (Blitz, Hoogstraten, & Mulder, 1970; Haber & Luninet, 1970). Up until then, HRV had been mostly a nuisance for psychophysiologists. Psychophysiologists at that time were mostly interested in changes in tonic heart rate after exposure to various stimuli, but it was always difficult to figure out what "tonic heart rate" actually *was*. Heart rate was constantly varying. The problem researchers faced was how to get rid of the influence of HRV, so they could assess changes in tonic levels. Little did they know then that the "noise" they were trying to eliminate actually should have been the signal, with much greater implications for psychophysiology than average heart rate over periods of time.

Although psychophysiological research on HRV primarily focused on autonomic balance, the medical field became much more interested in HRV as an index of adaptability. The first articles linking HRV to survival in cardiac patients appeared in the late 1980s (Bigger et al., 1988; Kleiger, Miller, Bigger, & Moss, 1987), and the first articles linking it to general adaptability appeared in the mid 1990s (Kresh & Izrailtyan, 1998; Schwarz et al., 1994), a little before interest started developing in chaotic properties in HRV, showing that nonlinear complexity in heart rate variability was related to health and survival (Goldberger, Mietus, Rigney, Wood, & Fortney, 1994; Sugihara, Allan, Sobel, & Allan, 1996; Zwiener, Hoyer, Luthke, Schmidt, & Bauer, 1996), when it became known that heart rate variability was related to such modulatory mechanisms as the baroreflex (Hughson et al., 1994; Pagani & Malliani, 2000; Wagner, Nafz, & Persson, 1996; Wang, Zhang, Wang, & Cheng, 2000), through which changes in heart rate modulate changes in blood pressure. It then gradually became obvious that complexity in heart rate variability was related to the number of negative feedback loops, and thus the number of "backup systems" preserving cardiovascular function. We have recently conceptualized this in terms of cybernetic systems theory (Lehrer & Eddie, in press). In addition to health and viability in utero (Karin, Hirsch, & Akselrod, 1993; Soothill, Ajayi, Campbell, & Nicolaides, 1993) and in severe cardiac disease (Bigger et al., 1988; Kleiger et al., 1987), early on it became known that HRV was related to youth aerobic fitness (Berntson et al., 1997).

Here are some statements from prominent heart rate variability biofeedback researchers and clinicians about how they became interested in this approach.

Richard Gevirtz

Dr. Gevirtz sent me the following paragraphs describing his path to heart rate variability biofeedback.

In the early eighties I was interested in biofeedback applications for hypertension. I began reviewing the outcome literature for a variety of interventions and began to realize that the parasympathetic system was being completely ignored, especially by biofeedback practitioners.

I had played around with pulse transit time (PTT) and, as it happened, I got a grant to bring Peter Lang to Winona, Minnesota for a couple of days. He pointed out the strengths and weaknesses of the PTT measure and feedback. So that's when I thought that "RSA" biofeedback might be the piece that was missing from finger temperature biofeedback. Along with a student, Dianne Herbs, we did a comparison of the two and we were off and running. That led me to investigate the idea of the vagus, and when Steve Porges came along with polyvagal theory, I realized that I had no real idea of what we were doing, but it was worth pursuing. That's when we started talking and the rest is history.

Since then, the focus of our group has been threefold:

1. Investigate the autonomic mechanisms (mediators and/or moderators) of disorders such as functional gastrointestinal disorders (IBS, etc.), headache, chronic muscle pain, fibromyalgia, and anxiety disorders (panic, generalized anxiety, PTSD).
2. Evaluate HRV biofeedback as a treatment modality for most of the above-named disorders.
3. Investigate the components of HRV biofeedback (baroreceptor, central, and peripheral effects).

The HeartMath Institute

Dr. Rollin McCraty sent me this excerpt from a piece he had written about the experience of the HeartMath Institute.

After we had found, through a series of laboratory and field studies in the late 1980s … and early 1990s, that the patterns reflected in the heart's rhythm tend to covary, not only with breathing, physical demands, etc., but also with emotions. … Positive emotions tended to naturally induce a more sine wave pattern in the HRV rhythm without any conscious change in breathing patterns. We coined the terms physiological and psychophysiological coherence to help distinguish between breathing-induced coherence[1] and positive emotion-driven coherence (Tiller, McCraty, & Atkinson, 1996).

This work was presented at various biofeedback conference meetings starting in 1993. Interestingly, the concept of using HRV feedback to improve outcomes of any kind or that the afferent activity of the heart could have an influence on brain function was met with, at best, skepticism and, in some cases, outright hostility at these early meetings when these concepts were first introduced. Karl Pribram was also present at some of these meetings and helped some of the critics understand the support for the role of the cardiovascular afferent systems and the long history of work in this area, which most in the biofeedback community were surprisingly unaware of given that it was one of the most influential hypothesis in the psychophysiology community with numerous publications on the topic dating back to the 1970s.

HRV feedback was introduced in our various training programs, which focused on self-regulation of emotional stress, in 1992. At that time, the HRV feedback had to be done with rather expensive and complex data acquisition equipment and software (we used BioPac systems after trying out various alternatives). It became clear that providing feedback to the participants quickened skill acquisition and their ability to shift into a coherent state, and better manage their thoughts, emotions, and behaviors. This process

[1] Although we were already using the term heart "coherence" in-house, it took two years for our Scientific Advisory Board to agree on the best term—this involved a rather lively debate by Karl Pribram, Joe Kamiya, Don Singer (who coined the term HRV), David Joffee, and others. We settled on the term "coherence," as it was appropriate for a more complete description of what we were talking about, which was not limited to just the physiology, but embraced all the physiological aspects (entrainment, resonance, cross coherence, auto-coherence, global coherence), as well as the social aspects of intelligent self-regulation, and the alignment of one's physical, mental, emotional, and energetic systems.

enabled people to more easily develop an association between a shift to a coherent mode and the positive internal feeling experience that helps induces such a shift. It was clear that a low cost, simple to use and understand heart rhythm coherence monitor was needed. A study showing that emotions induce pattern changes independent of any conscious changes in breathing was published in the *American Journal of Cardiology* (McCraty, Atkinson, Tiller, Rein, & Watkins, 1995), *Subtle Energies* (McCraty, Atkinson, & Tiller, 1993), and *Alternative Therapies in Health and Medicine* (Tiller et al., 1996).[2]

The first challenge was developing an algorithm that would provide a quantitative measure of coherence independent of heart rate or how much HRV a person has. This was not a trivial issue as it is the pattern of the heart's rhythm that is primarily reflective of the emotional and coherent states and changes in patterns can be independent of changes in the amount of HRV that is occurring at any given time (although coherence is often associated with a state-specific increase in HRV, looking at only an increase or the max HRV is not accurate in detecting coherence in all contexts). In addition, the amount of HRV one has is greatest when we are young, and as we age the range of variation in our resting heart rate becomes smaller. The changes in rhythmic patterns are also independent of heart rate; that is, one can have a coherent or incoherent pattern at higher or lower heart rates. Thus, the algorithm had to detect the patterns of the rhythm yet not be influenced by the amount of HRV or heart rate. In fact, the work now being done in Army Advanced Performance Training centers is able to train soldiers to shift into coherent states at heart rates above 120 BPM. In this context, coherence training is about efficient energy regulation and maintaining composure over longer time periods.

After we had tested a number of approaches and settled on an algorithm that worked well for detecting the coherent state (1996 & 1997), we outlined the design parameters for what became the Freeze-Framer® Interactive Learning System, which was introduced to the public in 1998. The name was derived from one of the more popular HeartMath self-regulation techniques called Freeze Frame. The initial device was primarily designed for consumers—people that were looking for effective approaches to reducing stress or enhancing meditation, intuition, prayer, and performance. This meant that we had to develop a pulse sensor that had high accuracy in order to accurately measure the interbeat intervals of each heartbeat. Using the ECG was too complex and meant the users would have to attach electrodes which would greatly limit the applications. Great care went into making the user interface simple and easy to use. To increase user engagement, we included three games which were designed to reinforce the coherence-building self-regulation skills. These were intentionally created as simple and easy to use and understand games. We also included four challenge level settings. The coherence level was fed back to the user in a variety of ways: as an accumulated score, success in playing the games, audio tones, and as a coherence ratio (percent time in low, medium, or high coherence in a given session). We also included a database so users could store data and track their progress over time, a detailed tutorial with guided instruction for the Quick Coherence technique, and suggestions for a variety of uses and applications. We often hear from users that they discover that they can use the Heart Focused breathing technique to sustain coherence on challenge levels one and two, but that without a positive emotional shift, they are not able to sustain coherence on the higher challenge levels.[3]

We did not anticipate how successful the product would actually be. Although it was originally designed for individuals, many health professionals found it to be an effective tool to support and facilitate a wide variety of therapies, both conventional and complementary. Many clinicians have since found heart rhythm coherence feedback to be an effective addition to treatment approaches for many chronic conditions that are associated with or exacerbated by ANS imbalances or emotional stress, including fibromyalgia, chronic fatigue, hypertension, asthma, environmental sensitivity, sleep disorders, diabetes, and cardiac arrhythmias, among many others. Health practitioners also use the devices to monitor the real-time psychophysiological effects of various therapeutic interventions that affect autonomic nervous system dynamics. Because of the sensitivity of HRV patterns to changes in psychophysiological state, many psychologists, to use their words, utilize heart rhythm monitoring effectively as a "camera on the emotions." Continuous monitoring of clients' HRV throughout a therapy session is easily

[2] This is not to say that respiration does not also change with emotional state changes and is not an important aspect of the physiological mechanisms, but it does imply that emotions operate at a level above the cardiorespiratory control centers. We also found that for many people they cannot maintain coherence through cognately directed paced breathing alone for longer than about one minute, but when focusing on a positive emotion they can easily maintain coherence for much longer periods. This was also found independently in a hypertension study conducted in Saudi Arabia (Alabdulgader, 2012).

[3] I was not aware of your work, Dr. Lehrer, or your use of the term resonance in this context until we met much later. I forgot when we first meet—but I do remember our first introduction was arranged through a chance meeting between you and Debbie Rozman at a nursing home.

accomplished and can give both therapist and clients immediate insight into clients' emotional responses, often enabling a more efficient and effective session. The insight that emotions are reflected in changes in ANS activity and thus, in HRV patterns, has since received support from many sources. One in particular is the work of psychop-sychologist Enrique Leon (Spain) who has developed a neural network approach that is 75% accurate in detecting discrete emotional states from only the HRV signal (Leon, Clarke, Callaghan, & Doctor, 2010).

[The HeartMath] mission statement is: To help people bring their physical, mental and emotional systems into balanced alignment with their hearts intuitive guidance. This unfolds the steps to becoming "who we truly are"—heart empowered individuals who choose the way of love, demonstrated through compassionate care for the well-being of others, ourselves, and planet earth.

Our focus is on helping people in all walks of life to better self-regulate, and we use the HRV devices to facilitate skill acquisition—the goal is to maintain composure and make better choices, especially in challenging situations with or without the aid of a device. Our goal is to help people become more kind, compassionate, loving, and appreciative of each other, and to work collaboratively and in support of each other.

Our research has led to the development of evidenced based self-regulation programs for children from preschool age to university level, for hospital staff (we have data from hospitals on reduced health care costs, turnover, improved social harmony, etc.), law enforcement, and the military (the Navy chose us to develop their predeployment resilience program [in] which thousands of military personal in all branches of the military have since been trained). . . . We have certification programs for health care professionals, community service and business organizations, and, of course, various programs for the public. There are HeartMath trainers literally all over the world that are using HRV feedback to help many people each year become more intelligently self-regulated, which, from my perspective, is the ultimate goal of biofeedback.)

Fredric Shaffer, Truman State University

My interest in HRV biofeedback resulted from my early research collaboration with Erik Peper on effortless breathing and reading seminal articles by Berntson et al. (1997), Gevirtz (2000), and Lehrer, Vaschillo, and Vaschillo (2000). Like countless colleagues, my students and I have learned a great deal from workshops taught by Paul Lehrer and Dick Gevirtz, and eagerly read their latest manuscripts. "We stand on the shoulders of giants" has never been more true.

The Truman State University Applied Psychophysiology Laboratory's HRV research has spanned three arcs of randomized controlled trials: techniques to improve breathing mechanics, training to increase HRV, and adjunctive methods to reinforce HRV biofeedback training. Shawn Bergman, Richard Gevirtz, Paul Lehrer, Jerry Mayhew, Donald Moss, and Erik Peper, along with Didier Combatalade and Ron Krebill have served as consultants in research design and analysis.

The breathing mechanics studies demonstrated that shoulder tension and tight clothing reduce inhalation volume (Shaffer, Mayhew, Bergman, Dougherty, & Irwin, 1999; Shaffer et al., 1992), effortless breathing training increases inhalation volume, tidal volume, and end-tidal CO_2 (Shaffer, Greve, & Parmenter, 1996), a 1:2 inhalation-to-exhalation ratio increases end-tidal CO_2 more than a 1:1 ratio (Shaffer, Mayhew, Bergman, & Wheelehon, 1997), high abdominal breathing effort decreases end-tidal CO_2 compared to low effort (Shaffer, Bergman, & Gannon, 1998; Shaffer, Bergman, & Hopkins, 1997), and the cause of CO_2 loss during high breathing effort is larger tidal volumes (Shaffer, Mayhew, Bergman, Dougherty, & Koester, 1999).

The HRV training experiments showed that a 1:2 inhalation-to-exhalation ratio is superior to a 1:1 ratio in increasing SDNN (Grant, Korenfeld, Wally, & Truitt, 2010), breathing at 6 breaths per minute reduces systolic blood pressure and increases SDNN and HR Max–HR Min more than rates of 3 and 12 breaths per minute (Wally, Korenfeld, Brooks, Peterson, & Schafer, 2010), HRV biofeedback training can reduce C-reactive protein 60% (Purcell, Shaffer, & Urlakis, 2011), a serial sevens stressor is an effective HRV tracking test (Kabins, Brenner, & Pacanowski, 2007), and the 2-week test–retest reliability of resonance frequency measurements is an acceptable 0.73 (Fuller, Wally, Korenfeld, & Carrell, 2011).

The adjunctive methods studies showed that the Norman Cousins relaxation exercise increases SDNN more than repetition of autogenic phrases (Bax, Robinson, Goedde, & Shaffer, 2007), singing a fundamental note increases SDNN and HR Max–HR Min (Grant, Wally, & Truitt, 2010), chanting "om" increases SDNN and HR Max–HR Min (Wally, Fuller, Carrell, Korenfeld, & Westermann-Long, 2011), and heartfelt emotion does not increase HRV (Fuller et al., 2012a; Fuller et al., 2012b), prevent HRV reductions in response to experimental stressors (Korenfeld et al., in press-a), or promote HRV recovery after exposure to these stressors (Korenfeld et al., in press-b).

Robert Nolan

My interest in HRV biofeedback began around 1990, during my postdoctoral fellowship in Cardiovascular Health Psychology, at a University of Ottawa teaching hospital (the Ottawa General Hospital). I was conducting research on cardiovascular reactivity to stress and the Type A behavior pattern. During this time, my mentor, Dr. Andreas Wielgosz, cardiologist, and I became interested in assessing efforts of postmyocardial infarction patients to self-regulate psychological stress and Cardiovascular reactivity. This work included the assessment of behavioral compensation for stress, which included countering procedures for acute stress such as self-guided relaxation (Nolan & Wielgosz, 1991; Nolan, Wielgosz, Biro, & Wielgosz, 1994). Our findings suggested that this was an adaptive behavior that may be underutilized among many cardiac patients. The challenge was to specify how this adaptive coping strategy could be objectively assessed and taught to these patients, while monitoring the impact of this treatment on cardiovascular functioning. At the same time, a large part of my clinical work included biofeedback-assisted training for the management of chronic pain and/or psychological distress. I was inspired when I came across a couple of articles by Stephen Porges, which highlighted the clinical importance and evaluation of vagal-heart rate modulation and respiratory sinus arrhythmia (Porges, 1992; Porges & Byrne, 1992). This was an exciting discovery that radically changed both my clinical work as well as my research interests. Soon afterward (in the mid to late 1990s), I sat in on my first HRV training workshop, which was conducted by someone who I have come to regard as a friend and colleague, Dr. Paul Lehrer, Psychology. It was a delight to discover the clinically applied research that was being conducted by both Paul Lehrer and Richard Gevirtz. I also made contact with Dr. Markad Kamath in Medical Engineering at McMaster University in Canada, who together with Dr. Ernie Fallens, a cardiologist, helped to develop the field of HRV assessment from its infancy. Since that time, my clinical and research interests have focused on the use of biofeedback for heart rate variability and baroreflex sensitivity to evoke therapeutic change in heart rate and blood pressure among patients with cardiovascular conditions. This work has evolved into a treatment protocol that is called Behavioral Neurocardiac Training (Nolan et al., 2005; Nolan et al., 2010; Nolan et al., 2012).

My own History with HRV Biofeedback (Paul Lehrer)

My own involvement in HRV research began with an interest in measuring vagus nerve activity in patients with asthma. It has long been known that the autonomic nervous system has a profound influence on the lung, with sympathetic activity causing bronchodilation and parasympathetic activity bronchoconstriction. It had seemed rather paradoxical, then, that stress was a common asthma trigger (Isenberg, Lehrer, & Hochron, 1992), when parasympathetic activity was generally associated with relaxation.

My main interest in applied psychophysiology at the time was in muscle relaxation. I had studied the technique with Edmund Jacobson, and had become convinced that his detailed approach to relaxation had profound psychophysiological effects (Lehrer, 1978; Lehrer, Schoicket, Carrington, & Woolfolk, 1980). In trying to resolve the stress paradox in asthma, our work led us to look at some of the autonomic complexities of the stress response, and how this response and the lung are influenced both by stress and relaxation.

We found that active coping with stress actually caused *dilation* of the bronchi, along with a depression in vagal influence on the heart as reflected in respiratory sinus arrhythmia (Lehrer et al., 1996). Conversely, we also found that acute effects of relaxation were related to increased respiratory sinus arrhythmia and deterioration in measures of pulmonary function, including peak expiratory flow and flow in the first second of a forced exhalation from maximal vital capacity (FEV1; Lehrer et al., 1997). The tasks that showed bronchodilation with inhibition of vagal activity were mental arithmetic and a reaction time. In later exploration of our data, we found an *increase* in respiratory sinus arrhythmia while watching two gory films, one shop accident film and the other a film of thoracic surgery. These results are consistent with other research showing an increase in vagal tone among blood phobics when exposed to blood, along with symptoms of faintness. Porges has described this vasovagal response to stress as a "freeze" and "shutdown" response. Interestingly, research studies showing acute stress-induced deterioration in asthma tended to be situations in which the threat was intense and the individual did not have adequate coping abilities, for example, difficult or embarrassing social situations. A vasovagal reaction would be expected in response to passive coping with unavoidable stress for which coping responses are not possible. Thus it appeared that the acute effects of stress that might trigger an asthma exacerbation might be one in which the individual does not engage in a coping response, and that relaxation should not be used as an acute "rescue" strategy during an asthma attack.

This was where I was in the fall of 1992, when my wife and I got onto an airplane to make our first visit to St. Petersburg, Russia, where our son was then doing graduate study of Russian language and culture at the St. Petersburg State University, as part of a program that eventually culminated in his joining the U.S. diplomatic corps. En route, while perusing the latest issue of the *APA Monitor*, I noticed a classified advertisement, inviting any American psychologist visiting St. Petersburg to pay a visit to the Psychology Department at the university. When the plane landed, I called the department, and, a few days later, found myself in a spirited conversation with the assembled Psychology Department faculty. During my visit I also went next door to the Pavlov Institute, and saw Pavlov's original laboratory (complete with cannula for collection of canine saliva, used in his famous classical conditioning experiments), and visited some psychophysiologists who were continuing work in the distinguished tradition of Russian psychophysiology, most of it held secret by the Soviets, and just beginning to be known in the West. Dissemination of this work was then impeded mostly by the exodus of many academics to former Soviet republics, now independent, or to various other countries in the world.

While there, I asked if anyone in town was doing biofeedback research. Although no one in the academic community was doing it, I was told about a private clinic downtown that had a large biofeedback program. I asked if I could visit them.

I was taken to a large institute, corporate offices for a group involved in the importation of medical equipment and in the manufacture of biofeedback equipment and provision of biofeedback services.

As a backdrop, it should be noted that this was a rather grim time in Russia. Communism had just fallen apart, and the new system had not yet taken hold. Inflation, crime, and corruption were rampant, and the Russian ruble was almost worthless. Most people found their meager salaries and pensions (when received at all) to be inadequate for more than the bare necessities of housing, shelter, rudimentary medical care, and bread, which were still subsidized and cheap. To make ends meet, people were lining entrances to metro stations selling personal belongings, in the dark –40°C late November afternoons and evenings. Many medicines were expensive and difficult to find. This, along, with a longstanding Russian penchant for accepting nondrug approaches to health care (what we called "alternative medicine"), created a fertile environment for biofeedback to blossom in St. Petersburg as a treatment for asthma.

Although it did not have the gleaming, antiseptic, and (by contrast) almost luxurious feel of the contemporary American medical center, the clinic run by the Biosvyaz Corporation was obviously set up for serious and large-scale work. The president of Biosvyaz, Dr. Alexander Smetankin, was generous with his time and patient with me in demonstrating his work. The Biosvyaz people had developed a device for giving HRV biofeedback, called the "cardiosignalizer," and were using this device for training children with asthma, often five or six at a time, using very ingenious software. The best one involved a paint brush painting a fence that was filled with apparently rather funny Russian graffiti. If the amplitude of heart rate fluctuations was high enough, the fence was completely painted. If not, part of the fence was missed. The program automatically adjusted the sensitivity of the instrument to "shape" the response.

Given my own understanding of psychophysiology at the time, the reader probably could surmise my astonishment that anyone would want to *increase* respiratory sinus arrhythmia among people with asthma. If anything, this should cause asthma to get *worse*. I tried to remain diplomatic during my visit, but somehow figured out a way to ask why they weren't killing all of their patients with this obviously inappropriate treatment that should cause iatrogenic bronchoconstriction.

Smetankin's response was nondefensive and direct. He said that all of their patients were getting better. So self-evident was this to him that he and his colleagues also asked how they could market their equipment in the United States for this purpose. I suggested that some controlled research might be in order before anyone would believe them.

At the time, I had been working under a small grant from a private foundation, the Fetzer Institute, to continue my research on relaxation therapy for asthma. I asked my funding agency if I could try this unusual Russian technique as well. Their response was understandably skeptical. They refused to give me more money. However, in their wisdom, they allowed me to test the procedure in my current small project as long as additional funds were not needed. Smetankin provided me with some of his instruments, gave me some cardiosignalizers, and even sent some staff to New Jersey to train us. The results were startling. With only about six subjects in a group, we found huge and statistically significant effects (Lehrer et al., 1997). Relaxation therapy was barely different from a waiting list condition; HRV biofeedback did significantly better than both. Smetankin and his colleagues also provided me with data from 20 of their consecutive cases. Again, in this uncontrolled multiple case study, improvements in pulmonary function tests were highly significant (Lehrer, Smetankin, & Potapova, 2000).

A couple of years later, I again visited St. Petersburg, this time because my wife, a concert pianist, had developed a relationship with the Rimsky Korsakov Institute there, and had been invited to play a concert and give some master classes. I tagged along, this time during the glorious "white nights" of early summer, and I again visited the Biosvyaz Corporation, this time in hopes of finding out *how* this technique worked. At about this time I was engaged in all sorts of intellectual contortions in order to figure out a theory of mechanism. None of them really made much sense to me.

By this time, the economy in Russia had deteriorated still further. The Biosvyaz Corporation now was "taking in" various academicians from surrounding universities, who now were earning essentially nothing for their work. One of the scientists working there was a gentleman named Dr. Evgeny Vaschillo, a physiologist and engineer, and then head of the physiology department at the Peter Lesgaft Institute of Physical Culture, a training institute for elite athletes. Vaschillo said he knew how HRV biofeedback worked. He had done his doctoral dissertation on the topic. However, because of the paranoia of the times, and perhaps because some of his work was done in the military establishment (as, by the way, was Pavlov's), his work had been kept so secret that even Soviet scientists knew little about it. By 1994 the secrecy strictures had been loosened, but by this time the academic community was in such shambles that the work still was unknown outside the small circle of scientists who had worked on it. The next day, I returned to the Biosvyaz clinic, and then Vaschillo showed me his dissertation. Because of my unfamiliarity with engineering concepts and terminology and difficulty in understanding Russian conventions in presenting scientific data, I must admit that I was poorly prepared to receive this gift of information, and I only dimly understood it.

However, I did realize that Vaschillo had discovered something very important: that by using breathing at particular rates people could maximize respiratory sinus arrhythmia by the influence of respiration on the baroreflex, a reflex that controls blood pressure and modulates autonomic reactivity. He performed "transform function" analyses on interrelationships among heart rate, blood pressure, and respiration on people who were prompted to produce heart rate oscillations at various particular rates. He found a single specific oscillation frequency in each person where the following combination of phase relationships occurred: (a) heart rate was completely in phase with breathing (0° phase relationship), such that heart rate went up exactly when the individual inhaled and down exactly when the individual exhaled; and (b) heart rate was completely out of phase with blood pressure (180° phase relationship), such that blood pressure went down exactly as heart rate went up, and up exactly as heart rate went down. Aha!!! So respiration was now stimulating the baroreflex at the same time that it stimulated respiratory sinus arrhythmia. Vaschillo went on to explain that this characteristic of the baroreflex system set conditions for resonance. A system has resonance characteristics, he explained, when it contains a negative feedback loop with a constant delay. In the baroreflex system, feedback from blood pressure changes causes modulatory changes in heart rate, and the delay is caused by the time it takes for heart rate changes to produce changes in blood pressure, by changing the amount of blood going through the same size tube (Lehrer, 2013). Breathing then stimulates this resonance system, causing very high-amplitude oscillations at the resonance frequency. In the baroreflex system, these oscillations occur, on the average, with periods of about 5.5 to 6 times each minute.

This was quite a bit to digest! But luck was with me. Vaschillo emigrated to the United States, where he and his wife Bronya, a public health physician, joined their son Alexander, who was studying computer science at Florida International University, in Miami. At the time, my in-laws were living in West Palm Beach, in rather poor health, so we were making regular visits. Each time I went, I met with Vaschillo and his son (his interpreter), and gradually I began to really understand his findings. Together we tried to put together a paper, where his dissertation research could be published in an English language journal. After several rejections, primarily because editors did not believe that such large oscillations in respiratory sinus arrhythmia were possible, we eventually were able to publish the work in *Applied Psychophysiology and Biofeedback* (Vaschillo, Lehrer, Rishe, & Konstantinov, 2002), although it required some effort to convince the journal that biofeedback researchers and practitioners might be interested in such abstruse work. At about the same time, the dramatic findings in our asthma research with Smetankin convinced the National Heart Lung and Blood Institute to fund a larger trial of HRV biofeedback. To help me carry out this work, I hired Evgeny and his wife Bronya Vaschillo, whose English was competent, and who I judged to be a warm and caring person, with a good clinical sense. She has since become my personal standard for how biofeedback should be carried out. This trial produced clinically and statistically significant results (Lehrer et al., 2004), and went a long way to making HRV biofeedback respectable.

Just as I was starting to work with Vaschillo to put our ideas into words, I noticed that Richard Gevirtz was giving a workshop on HRV biofeedback at an AAPB meeting. Intrigued, I listened in, and found that we were operating on exactly the same wavelength. We have been teaching and collaborating with each other ever since, in complementary areas. Also, several years after the paper by Vaschillo and colleagues was published, I met someone else working in the same field during a visit to my father-in-law's assisted living residence in Princeton, New Jersey. I met a woman who was visiting her aging mother, and who, like me, seemed to be a bit young and out of place in this environment. In a brief conversation, I found out that she, Dr. Deborah Rozman, was a psychologist, working on HRV biofeedback! Imagine my surprise! I thought that I, Vaschillo, and Gevirtz were the only ones who knew about this obscure field. Through her I found out about the HeartMath Institute, and met Dr. Rollin McCraty, a long term researcher in this field, and have worked with their instruments and closely followed their work ever since. The growing body of research literature in HRV biofeedback from our three centers, along with strong teaching and research activities from Donald Moss and Fredric Shaffer, have since made the field of HRV biofeedback one of the dominant trends in biofeedback research and application. I found Dr. Robert Nolan's early work on HRV through the literature.

The more recent literature on HRV biofeedback has become too large to review here in detail. In addition to students and collaborators of those contributing to this article, additions to the literature have come literally from all over the world, including Japan, China, Australia, South Africa, Spain, Belgium, Saudi Arabia, Italy, Germany, and Israel, to name only a few sources, with current research ongoing in many more places. Equipment to perform HRV biofeedback similarly has appeared all over the world in many ingenious forms, as has software for analyzing HRV. Conceptual advances have also occurred in many fields in addition to psychophysiology, including physics, engineering, cardiology, obstetrics, immunology, exercise science, the arts, and neurology, to name only a few. What an exciting time to be a worker in this field!

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Paul Lehrer

Correspondence: Paul Lehrer, PhD, Rutgers, Robert Wood Johnson Medical School, Department of Psychiatry, 671 Hoes Lane, Piscataway, NJ 08854, email: lehrer@umdnj.edu.