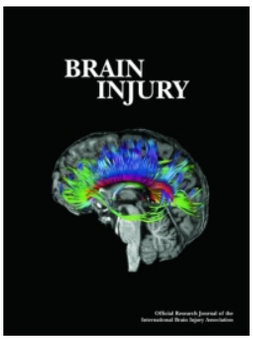

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Emotion regulation after acquired brain injury: a study of heart rate variability, attentional control, and psychophysiology

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ABSTRACT

Primary objective: To examine the efficacy of heart rate variability biofeedback (HRV-BF) to treat emotional dysregulation in persons with acquired brain injury.
Design: A secondary analysis of a quasi-experimental study which enrolled 13 individuals with severe chronic acquired brain injury participating in a community-based programme. Response-to-treatment was measured with two HRV resonance indices (low frequency activity [LF] and low frequency/high frequency ratio [LF/HF]).
Main outcome: Behavior Rating Inventory of Executive Function-informant report (emotional control subscale [EC]).
Results: Results show significant correlation between LF and EC with higher LF activity associated with greater emotional control; the association between LF/HF pre-post-change score and EC is not statistically significant. A moderation model, however, demonstrates a significant influence of attention on the relation between LF/HF change and EC when attention level is high, with an increase in LF/HF activity associated with greater emotional control.
Conclusions: HRV-BF is associated with large increases in HRV, and it appears to be useful for the treatment of emotional dysregulation in individuals with severe acquired brain injury. Attention training may enhance an individual's emotional control.

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Emotional regulation; attention; heart rate variability biofeedback; acquired brain injury

In a previous study, our research group demonstrated that individuals with severe acquired brain injury (ABI) can learn to alter their cardiovascular activity in a beneficial way through heart rate variability biofeedback (HRV-BF) (1). In the current work, we performed a secondary analysis on this dataset to investigate the association of the changes in cardiovascular function with changes in the participants' level of emotional control. In addition, the moderating influence of attention on this association was tested.

Emotions are physiological states that are manifested in characteristic behavioural responses to environmental stimuli and interpreted as positive or negative feelings (2); emotional regulation is the ability to control or direct one's own emotional behaviours (3). Autonomic nervous system (ANS) activity both reflect and influence emotions (4–9) and modulate cardiovascular activity such as blood pressure and heart rate (10).

During moments of stress, brain regions such as the cingulate cortex, amygdala and insula can effect a simultaneous rise in blood pressure and heart rate (10) by modulation of the sympathetic and parasympathetic branches of the ANS. In turn, the baroreflex, a homeostatic mechanism, is activated, which produces changes in heart rate that help to modulate blood pressure changes. Activity in the baroreceptors (stretch receptors in the walls of blood vessels) is controlled through the nucleus tractus solitarius, which communicates directly with the limbic system through the insula and amygdala (11,12). This circuitry is related intimately to emotional regulation (13).

Heart rate variability (HRV) is a naturally occurring variation in heart rate, which is modulated by the ANS and the higher brain centers that connect with it. Based on the connection between emotions and these physiological mechanisms, HRV can reflect an individual's emotional state (14), and furthermore, there is evidence that manipulation of HRV via HRV-BF can have beneficial clinical effects on conditions such as hypertension (15–17), and aspects of emotional dysregulation such as anxiety (18–26), hostility (27,28), and depression (25,29–31). Individuals with greater ability to regulate emotions have been shown to have greater levels of resting HRV (32,33), a phenomenon referred to as *resonance* (34), and this high amplitude oscillation of heart rate is attained only at the system's *resonant frequencies* (35).

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Individuals with ABI have demonstrated deficits in their ability to regulate emotional behaviour (36–39), which can lead to deficits in social functioning (36–39), loss of employment, and increased risk of suicide (3,40,41). In our previous study (1), people with ABIs were found to have low HRV resonance, consistent with findings from other studies on the ABI population (42–44) and they were able to increase resonant activity through HRV-BF training (1). The pre-post mean differences in HRV measures were found to be significant, however, the difference in pre-post means for the measure of emotional control used was not found to be significant. It is possible that the large interindividual differences in this measure obscured an actual within-individual effect. In the current study, a more sensitive analysis is conducted in which pre-post change scores are computed to control for interindividual variability. It is posited that pre-post measures will reveal a significant positive relation between HRV resonance and emotional control. Furthermore, a moderation model will be used to test for the influence of attention on this relation given the known role of attention in emotional regulation (45,46).

The level of one's attention has been shown to influence the ability to regulate emotions, and this function appears to depend on interactions between the prefrontal cortex (PFC) and the amygdala (3,47–50). Individuals with ABI show a pattern of decreased PFC activation and increased amygdala activation which result in emotional dysregulation. Increased baroreflex activity can inhibit activity in the amygdala indirectly through its effects on the nucleus tractus solitarius. Given these connections, it is possible that emotional dysregulation, particularly in individuals with ABI, may be ameliorated by increasing baroreflex activity. In the current study, we posit that this goal may be accomplished through heart rate variability (HRV) biofeedback. Furthermore, we investigate the possible role of attention as a moderating factor on the relation between heart rate variability and emotional regulation.

Methods

Participants

Thirteen participants were drawn from a metropolitan, community-based, structured day program that provides long-term rehabilitation services for individuals with moderate-to-severe acquired brain injury. Twelve of the thirteen participants were under 24-hour supervision by an aide or a family member. Participant recruitment, procedures and treatment have been described previously (1). Table 1 contains participants' injury characteristics (i.e., severity and cause), demographics, work history and cognitive functioning. The wide range of age of onset of the ABI should be noted: four were under the age of ten years, six were adolescents between the ages of 10–17, and the remaining participants were adults of ages 22, 37, and 49.

HRV biofeedback treatment

Ten 60-minute individual sessions were provided which included a breathing pacer set at six breaths per minute to train the participants to increase their RSA (35). For HRV biofeedback, HeartMath's emWave PC was used. Treatment sessions also involved using HeartMath interactive games such as the Garden Game and the Emotion Visualizer, selected by the participant. After four biofeedback treatment sessions, the participants were given the cell-phone-size handheld biofeedback devices for home practice (see Kim et al. 2013 (1) for treatment protocol description).

Table 1. Participant characteristics.

Variable		*n*	%	Variable	Median (range)
Gender	Male	7	53.8	Age	40 (23–63)
	Female	6	46.2	Onset age (years)	13 (birth to 49)
Race	White non-Hispanic	7	53.8	Years post-injury	23 (13–40)
	Black non-Hispanic	5	38.5	Education (years)	12 (2–20)
	Hispanic, White	1	7.7		
Work History				Intellectual Testing	
	Lawyer	1		Full Scale IQ	62 (50–88)
	Salesman	1		Verbal IQ	66 (55–109)
	College student	1		Performance IQ	64 (54–100)
	No work experience	10			
Loss of Consciousness[a]				Impairment Index[b]	1.00 (.70–1.00)
	Not TBI – not applicable	5		Category Test (baseline) [c]	118.5 (53–137.5)
	1–4 weeks (severe)	2			
	4 weeks + (severe)	4			
	Not available	2			
Etiology					
TBI					
	MVA[d]	6			
	Fall	1			
	Assault	1			
Non-TBI					
	Aneurysm	1			
	Anoxia	1			
	Ataxia, cerebral palsy, progressive dementia	1			
	Brain tumor	2			

[a] loss-of-consciousness classification (Kraus, 1999)
[b] this score indicates that the participants as a group were functioning in the significantly impaired range.
[c] 51 and above represent impaired range
[d] Motor Vehicle Accident

Measures

Heart rate variability (HRV) indices

The Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology (51) established standards for HRV recording and measurement. For this study, we recorded successive heartbeats with the use of infrared plethysmograph. Cyclical oscillations in blood flow, which drive volumetric and oxygenation changes in the peripheral microvasculature, are directly driven by left ventricular contractions. Photoplethysmography (PPG) is an optical technique capable of recording these changes in the microvasculature of peripheral tissues. Outliers from the interbeat cardiac intervals were removed when they exceeded the local median value by more than 200 milliseconds. One-sided power spectral densities (PSD) were obtained using the Welch method implemented in Matlab R2008b (The Mathworks, Nattick, MA) (52). A window size of 64 seconds and a 50% overlap was used. Spline fitting was used for integration of the PSD. Frequency domain variables were calculated using nonparametric power spectral density (PSD) analysis (PSA) of 5-minute recordings. HRV signals are defined by the following three frequency bands: High frequency [HF] (0.15–0.4 Hz), low frequency [LF] (0.04–-0.15 Hz) and very low frequency [VLF] (< 0.04). The total power (TP) is the sum of the power in these three frequency bands .

The sensor was placed on either the left or right earlobe with the participant at rest, sitting upright, while a computer monitor displayed the individual's HRV patterns in real time. During the testing sessions when the HRV was recorded, the participants did not see their HRV patterns (see Kim et al., 2013 (1) for description of signal processing).

For the current analyses, the following three implementations were performed in an effort to identify the most precise measure of treatment response: 1) change scores (53) (pre-to-post treatment) were computed for the power of the low frequency band [LF]; 2) change from pre-to-post treatment in the ratio of the power of the LF to the power of the HF band, LF/HF, where higher ratios indicate greater resonance (54,55)[1]; 3) in an effort to explore whether collecting more than the five minutes of data recommended by the HRV Task Force would result in greater predictive power, we recorded the participants' HRV for a duration of 10 minutes as well.

Speech sound perception test (SSPT)

The SSPT consists of 60 spoken nonsense words, which are variants of the *ee* sound. A man's voice speaks the stimulus – the nonsense word – on a tape recording. The examinee listens and then chooses one of the four options printed for each item on the test form, depending on which option best fits the sound the man on the recording said – for example, *which option of the nonsense word did the man announce in the tape recording*: "*theeks, zeeks, theets, zeets*." The SSPT measures attention and sustained concentration (56). The score is the total number of errors. A score of eight errors or more is considered impaired (57). Test-retest reliability (at a three-week interval) is $r = .73$ (58).

Behavior rating inventory of executive function-adult version (BRIEF-A)

A well-established instrument, the BRIEF-A is a self-report and informant-report measure that captures individuals' views of their own executive functioning as well as their informants' views (see Roth et al. (59) for scoring information and psychometric properties). For this reanalysis, only the informants' ratings of the participants' "emotional control" subscale was used. Unawareness of their emotional state is particularly common in individuals with

ABI (60).

Procedures

All procedures were conducted in compliance with the American Psychological Association's (APA) Ethical Principles in the Conduct of Research with Human Participants (61). The Institutional Review Boards of the two sponsoring institutions – Albert Einstein College of Medicine, Yeshiva University and AHRC – both approved the study. Written informed consent was obtained from the participants; where applicable, a signed Authorization to Use or Disclose Protected Heath Information for a Research Study form was obtained from the participants' "advocate."

The original study on which these secondary analyses are based featured a single-treatment, nonrandomized, quasi-experimental design with measures repeated at three time points: Pretreatment Time 1 and Time 2 and posttreatment Time 3. Times 1 and 2 were separated by a 10-week waiting period. In this design, the two pretreatment times served as baselines against which the posttreatment scores were compared. Testing at each time point included 5–6 hours of neuropsychological testing and completion of self-reports. Informants completed reports and questionnaires on the participants at Times 2 and 3. Participants' HRV was recorded at three time points as well, but in separate sessions within two days of the neuropsychological testing conducted at the time points mentioned above. For purposes of these secondary analyses, only the Speech Sound Perception Test (SSPT) and the informant reports on the emotional control subscale of the Behavior Rating Inventory of Executive Function (BRIEF) are reported. Following baseline testing, the participants received the specially tailored HRV biofeedback sessions. The participants were paid $10 for participating in each 5–6 hour testing session, and an additional $5 for each individual treatment session and $5 for completing questionnaires after treatment ended (for further details see Kim et al. 2013 (1)).

Data analyses

Statistical analysis was based on analyzing the difference in scores for the three variables of interest – HRV low frequency, HRV low frequency/high frequency ratio, and emotional control BRIEF informant ratings – all of which were calculated between pretreatment (average of two pretreatment measures) and posttreatment (one measure). Because the intraclass correlation coefficients at pretreatment testing were moderate for the LF/HF ratio (.61) and high for the LF power (.80), scores for Times 1 and 2 (pretreatment test times) were averaged. The BRIEF was collected only once at pretreatment (Time 2) and once at posttreatment (Time 3).

We evaluated the prediction of improved emotional control index (BRIEF) from the HRV indices. Our analysis used the HRV LF/HF ratio to specifically measure resonance effects. In a resonant system stimulated at its resonance frequency, variability from all frequencies is recruited to a single frequency. As a result, we anticipated a big decrease in HF and a big increase in LF, since RSA and the baroreflex would be resonating at a single frequency in the LF range. This approach serves as a method to check whether participants were breathing at resonance frequency, demonstrating their capability of following the procedure.

The correlation coefficient between HRV measures (change from pretreatment- to posttreatment, both for HRV LF and HRV LF/HF) and emotional control was computed first to establish the presence of a relationship between the two variables. This was followed by a regression analysis that included an interaction term between the HRV measure and attention. Moderation analysis was performed using the Process add-on for SPSS (62). Predictors were mean centered before running the model. Effects of HRV on emotional control were calculated at different levels of attention (SSPT). Effect sizes are emphasized, presented along with *p*-values.

Given the variability in age of onset of the ABI, a scatterplot and bivariate correlation were computed with change in emotional control as measured by change in the BRIEF informant report to explore the possible role of age of onset and time post-injury as covariates in the analyses. The literature is variable with respect to the degree of "recovery" and "learning" that occur according to the age of onset and time post injury with some supporting greater neuroplasticity, others indicating greater vulnerability, less recovery and rehabilitation (63–65), and some other reports stating that plasticity or "critical period" for recovery is ongoing (66). According to our data, no relation was found between these variables, and therefore, age of onset nor time post-injury were not included as covariates. Cognitive function was severely impaired in all participants and an inspection of a scatterplot and correlation of change in emotional control vs. level of cognitive function (as measured by the Category Test, a robust measure of brain integrity (57)) was not significant, and therefore, also not included as a covariate in the analyses.

Results

The correlation between change in LF and change in emotional control is moderately high and statistically significant ($r = -.557$, $p = .048$ for 5-minute recording and $r = -.567$, $p = .044$ for 10-minute recordings). The regression results with LF/HF as the predictor show nonsignificant main effects. The longer 10-minute recording period of HRV LF/HF showed greater predictive power for emotional control, as reported by the informant rating scale, than did the 5-minute recording period, though still not significant (10-minute: $r = -.547$, $p = .053$ vs. 5-minute: $r = -.464$, $p = .110$).

Multiple regressions were fitted next using the four different measures of HRV. Each model included an interaction between HRV and attention. The regression coefficients were nonsignificant (see Table 2). Nonetheless, it is possible that the marginal effect of HRV – that is, the effect when attention is above or below its mean – may be significant (67). For this reason, a Johnson-Neyman analysis was performed. The moderation model is presented in Figure 1. The results are presented in Figure 2 for HRV LF/HF using the 5-minute epoch (similar results occurred for the 10-minute epoch).

The relation between the HRV indices and emotional control measured by the BRIEF is negative. Improvements are reflected in higher scores for HRV and lower scores on the BRIEF. The effect of HRV LF/HF and emotion regulation, at posttreatment, is also negative. The result was not significant, but the R^2 is high. The effect size thus is strong but the sample is just small, *and* the Johnson-Neyman analysis found significant marginal effects. A one-standard deviation increase in HRV (as recorded in a 5-minute epoch) leads to a statistically significant result; a 1.082 decrease in emotional regulation (lower score indicates better emotional control) occurs when attention error is one standard deviation ($SD = 13.9$) below the group mean. Similar results were obtained with the 10-minute epoch.

Discussion

This current study provides preliminary evidence that HRV is potentially a mechanism for emotion regulation and that using HRV biofeedback in rehabilitation programs can enhance cardiovascular resonance, and in turn, improve emotional regulation in individuals with severe chronic ABI. Emotional dysregulation is a common impairment following brain injury (68–70), because the injury from a brain injury can damage autonomic control centers within the brainstem, the subcortical limbic-related regions (such as the amygdala, hippocampus, and thalamus), and the higher cortical centers that mediate autonomic function (such as the dorsolateral

Table 2. Output coefficients for moderation models.

	Model 1 – LF/HF 10 Min		Model 2 – LF/HF 10 Min		Model 3 – LF 5 Min		Model 3 – LF 10 Min	
Variable	B	95% CI	B	95% CI	B	95% CI	B	95% CI
Constant	2.12	[−1.28, 5.52]	2.24	[−1.29, 5.77]	2.23	[−0.92, 5.37]	2.17	[−1.07, 5.40]
Attention	0.05	[−0.14, 0.24]	0.92	[−0.26, 0.28]	0.00	[−0.24, 0.24]	−0.03	[−.25, 0.18]
LF/HF 5 Min	−0.66	[−1.43, 0.12]	-	-	-	-	-	-
LF/HF 10 Min	-	-	0.10	[−1.55, 0.17]	-	-	-	-
LF 5 Min	-	-	-	-	0.00	[−0.0002, 0.0001]	-	-
LF 10 Min	-	-	-	-	-	-	0.00	[−0.0022, 0.001]
Interaction	0.03	[−0.02, 0.08]	0.60	[−0.06, 0.09]	0.00	[−0.0001, 0.0001]	0.00	-
R^2	0.30	-	0.33	-	0.31	-		-
F	2.90	-	2.39	-	1.36	-		-
ΔR^2	0.08	-	0.03	-	0.00	-		-
ΔF	1.72	-	0.30	-	0.02	-		-

N = 13, no p values < .05.

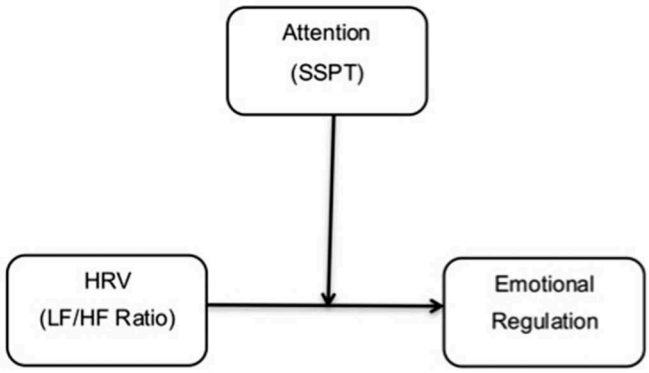

Figure 1. Moderation model for the influence of attention (measured by SSPT) on the relationship between pre-post change in HRV (LF/HF ratio) on emotional regulation (informant report).

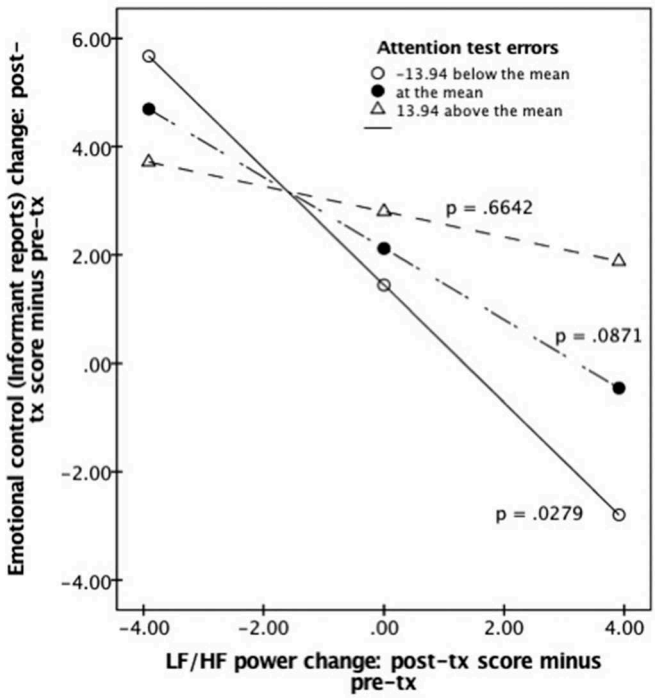

Figure 2. Moderation effect of attention.

A visualization of attention's (speech sound perception test's [SSPT]) moderating (conditional) effect on the relation (regression coefficient slope) between emotional control and HRV resonance. When SSPT error is one *SD* above the mean (13.94), increases in HRV resonance lead to a non-significant increase in the outcome ($b = -.2344$, $p = .66$). The relationship between HRV resonance and emotional control is negative (lower emotional control is better) but still non-significant, when SSPT is at its mean ($b = -.6581$, $p = .09$). However, the relationship is negative and significant when SSPT error is one SD below the mean ($b = -1.0818$, $p = .03$).

prefrontal, posterior insular, and middle temporal cortices) (42,44,71–73). Damage to areas within the prefrontal cortex has also been linked to problems with emotion regulation following brain injury (74).

The emotional, behavioural and interpersonal challenges that confront a person with a brain injury have sharpened the rehabilitative focus on socio-emotional adjustment, specifically the importance of learning to regulate emotion (75). But teaching individuals with severe, chronic brain injury how to regulate emotions has remained a challenge, simply because impaired cognition disrupts a person's ability to learn and apply new skills (76); and many current treatment programs rely primarily on cognitive cues and cognitive awareness. For persons with ABI, learning is acquired through sensory and perceptual experiences. Explicit learning (the process of consciously encoding, consolidating, storing and retrieving factual knowledge) is more impaired than implicit learning, a process of unconsciously acquiring or modifying behaviour through experience (77). Implicit learning refers to learning without awareness and how such learning can be manifest in behaviors that are automatic (78).

This paper proposes that psychophysiological interventions that rely on implicit learning, through physical cues and body awareness offer an alternative treatment of emotion dysregulation following brain injury, especially for those with severe brain injuries. Such interventions are based on the principle that the body and emotions are connected so that changes in the body will spur changes in emotion, and changes in emotions will spur changes in the body. Implicit emotion regulation strategies do not rely on the involvement of "higher" brain regions like the prefrontal or cortical brain systems, but rather on what has been described as "bottom-up" regulation processes which are influenced instead by input from the peripheral sensory, visceral, cardiovascular and autonomic systems (79). Recognizing emotional dysregulation as a physiological symptom can be particularly useful for those with brain injury because such individuals often lack self-awareness, and they may reject or contest feedback from others on their emotional behaviour (60,80).

ANS, attention, and emotions

The results of this current re-analysis reinforce the relation between psychophysiology and neuropsychology and furthermore, these results show that how we measure emotional regulation makes a difference. For example, inferences were the same for five versus ten minute HRV epochs. But they were different (significant versus not) for LF versus LF/HF. The initial analysis was performed using repeated measures and found no change in emotional control (1). However, in this current analysis of the data, linear regression was conducted – with change in emotional control from pre-to-post treatment as the dependent variable and change in HRV from pre-to-post treatment as the independent variable. Change scores obtained in pretest-posttest designs are viewed as more sensitive measures for evaluating treatment effectiveness (53). They control for between-subjects differences, which makes them more powerful. The results show a non-significant linear association with large effect size between improvements in HRV resonance (pre-to-post-treatment) and improvements in the participants' emotional control, according to informants' ratings. When the participant's attention score was added as a moderator, the relationship between improvements in HRV resonance and emotional regulation became significant.

Attentional control, especially the ability to sustain or shift our attention, has been identified as a prerequisite for higher-level cognitive processes such as cognitive flexibility, self-regulatory behaviours and working memory (81). Self-

regulation is a process of control achieved by intact attentional skills at multiple levels. Attentional problems and related regulation deficits arise in the context of higher level conceptual processing. What the mind attends to can shape experiences, good or bad. How successful individuals are at controlling their attention can determine their subsequent affective experience and behaviour.

The role of attention in the successful regulation of emotions is consistent with the various models of emotional regulation (82,83), and consistent with the moderating role attention played in this current analysis. In the literature on self-regulation, the role that attentional skills play in self-regulation has significant implications for treating individuals with brain injuries. Emotion regulation and specific patterns – sinusoidal oscillations – of an individual's HRV have also been associated with the ability to control attention (84–87). If attention can be controlled, then it may be used to actively guide individuals' emotion regulation processes and thereby ultimately enhance subjective well-being. That is, people could learn to selectively attend to specific types of information in controlling their emotional experience.

Conclusion and future direction

The results of this current analysis provide stronger evidence and thereby confirms that HRV biofeedback is a tool that can teach individuals with severe brain injury to become more aware of the connection between changes in their emotions and changes in their body. HRV biofeedback was associated with large increases in HRV, and thereby suggests increased baroreflex sensitivity. Furthermore, the study's findings showed that individuals with severe brain injury can be taught to enhance or achieve resonance of their HRV and thereby improve their emotional self-regulation through the practice of HRV biofeedback (88,89). HRV has been found to be an objective marker of an individual's capacity for emotional self-regulation in other populations (14,32,90–92), and can serve as an index of an individual's capacity to regulate emotional responses (14,32,90–92). Addressing autonomic dysfunction and improving HRV in individuals with ABI can have significant consequences for their physiological, emotional and cognitive health (44,93–95).

The results of this current analysis are limited by the study's small sample size and the lack of a control group. Another limitation is that some of the participants may have had intellectual disability (ID). Individuals with ID are not admitted into the site from which we recruited participants. Nevertheless, there is a possibility that these individuals might have been misdiagnosed and included given the low IQs of some of the participants and since no additional testing was done by the study team to confirm the accuracy of their ABI diagnosis. However, given the promise of these preliminary findings, a study with a control group engaged in another process could provide more information to determine the extent of a causal relation between HRV patterns and self-regulation. Future studies should also compare varying HRV indices to help design better ways to measure treatment effects in individuals with brain injury. In this regard, investigation into what constitutes the "low frequency band" would clarify what innervates HRV and how. Studies show that the low frequency power of the HRV predominantly reflects vagal activity and approximates baroreflex function (96,97). This finding is consistent with the results of this current re-analysis. Increases in low frequency/high frequency ratio and increases in the power of low frequency band were both associated with improved emotional control. Gaining a better understanding of the physiological basis that contributes to both LF and LF/HF measures, or the associations between baroreflex modulation and vagal control, would help elucidate how these two physiological functions are linked to emotional reactivity and regulation. It would also be important to test other possible mechanisms for improvements in emotional self-regulation, such as placebo effects, or baroreceptor training vs. relaxation effects, etc. An improved understanding of these mechanisms could be used to test hypotheses on how treatment to manage emotional reactivity and its negative effects works. Additional studies on the role of the baroreflex on improving emotional regulation should also examine if and how training the baroreflex would also improve attention and how such improved attention would impact the emotional control. Ultimately, these efforts could shed light on the physiological basis of emotional reactivity and regulation, and could be used to enhance the quality of life for people with brain injury.

Note

1. When people breathe slowly at the frequency of the Meyer wave (cyclic changes or *waves* in arterial blood pressure brought about by oscillations in baroreceptor function, about 6 breaths/min), two waves, e.g., the Meyer wave and the respiratory sinus arrhythmia, resonate with each other, producing very high amplitudes of sinusoidal oscillations in the LF range.

Declaration of interest statement

The authors have no conflict of interests to disclose.

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