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Heart rate dynamics during three forms of meditation

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Abstract

Objective: This study was designed to quantify and compare the instantaneous heart rate dynamics and cardiopulmonary interactions during sequential performance of three meditation protocols with different breathing patterns. *Background:* We analyzed beat-to-beat heart rate and continuous breathing signals from 10 experienced meditators (4 females; 6 males; mean age 42 years; range 29–55 years) during three traditional interventions: relaxation response, breath of fire, and segmented breathing. *Results:* Heart rate and respiratory dynamics were generally similar during the relaxation response and segmented breathing. We observed high amplitude, low frequency (~ 0.05–0.1 Hz) oscillations due to respiratory sinus arrhythmia during both the relaxation response and segmented breathing, along with a significantly ($p < 0.05$) increased coherence between heart rate and breathing during these two maneuvers when compared to baseline. The third technique, breath of fire, was associated with a different pattern of response, marked by a significant increase in mean heart rate with respect to baseline ($p < 0.01$), and a significant decrease in coherence between heart rate and breathing ($p < 0.05$). *Conclusions:* These findings suggest that different meditative/breathing protocols may evoke common heart rate effects, as well as specific responses. The results support the concept of a "meditation paradox," since a variety of relaxation and meditative techniques may produce active rather than quiescent cardiac dynamics, associated with prominent low frequency heart rate oscillations or increases in mean resting heart rate. These findings also underscore the need to critically assess traditional frequency domain heart rate variability parameters in making inferences about autonomic alterations during meditation with slow breathing.

Keywords: Autonomic nervous system; Heart rate variability; Meditation; Relaxation response; Vagal tone; Yoga

There has been an explosion of popular and scientific interest in the potential health benefits of various types of meditative protocols. However, the comparative physiologic effects of different forms of meditation remain incompletely explored. Available data suggest important cardiopulmonary interactions during different types of meditation [1–12]. In a previous study, we observed very prominent low frequency (~ 0.1 Hz) oscillations in heart rate during specific forms of Chinese Chi and Kundalini yoga meditation in two groups of healthy young adults [6]. These cardiac interbeat interval oscillations, associated with marked sinus arrhythmia, appeared to correlate with slow breathing. Similar dynamics were apparent in Zen monks performing Zazen meditation [7], and in practitioners of rosary prayer and yoga mantras [8] in other studies. The detection of large excursions in heart rate appears to contradict the conventional notion that meditation is primarily a psychologically and physiologically quiescent (homeostatic) state. Instead, subjects may show a paradoxical increase in the dynamical range of their heartbeat during a state subjectively perceived as one of profound relaxation [6].

The present study was designed to further characterize beat-to-beat heart rate dynamics during the performance of different forms of meditation and to compare their effects on cardiopulmonary dynamics. In particular, we sought to address the following interrelated questions: How does heart rate variability change when the same subjects perform

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meditative protocols with different breathing patterns? Are certain types of dynamics common to different protocols? How do these heart rate dynamics relate to cardiopulmonary interactions?

To help compare physiologic commonalities and unique features of different protocols, we studied heart rate and pulmonary dynamics as subjects performed three meditation/breathing approaches: the relaxation response, breath of fire and segmented breathing.

1. Methods

1.1. Subjects

Volunteers ($n = 11$) were recruited from a group of practitioners of Kundalini yoga as presented by Yogi Bhajan, emphasizing the integration of breath, sound, movement and attention [13]. Subjects had 3–15 years experience and practiced up to 5 or more times/week. Subjects filled out a brief health questionnaire. All subjects rated their health as excellent or good. No subject was taking any medication reported to affect heart rate variability. One subject had type 1 diabetes mellitus and was taking low dose insulin. As reported below, his results were similar to those of the other subjects and did not significantly alter the results or conclusions. For one other subject, the signal quality was not adequate for analysis. This report is based on data from the remaining 10 subjects (6 males; 4 females; mean age 42 years; range 29–55). All subjects provided written informed consent in accord with a protocol approved by the Beth Israel Deaconess Medical Center Institutional Review Board.

1.2. Meditation protocols

Subjects were seated in a quiet room. The protocol included three meditation/relaxation approaches with different breathing patterns performed in the following order: the relaxation response [11,12], breath of fire [13], and segmented breathing [13]. Each meditation period lasted approximately 10 min and was preceded by a baseline (control) period of equal duration, during which time the subjects were instructed to rest quietly without meditating. To perform the three meditation protocols, subjects were instructed as follows.

(1) Relaxation response: Sit comfortably. Let your breath relax. Let your mind dwell naturally on the mantra: Sat Nam, Whahe Guru. Do not fight other thoughts. Simply focus without effort on the mantra as the breath goes naturally in and out. Focus is at the center of the brow.

(2) Breath of fire: This pattern involves a rapid (~ 140/min) breath through the nose. The breath is equal in and out, not labored, powered from the navel point and solar plexus/diaphragm, not a belly pump. Most of the air moved is dead air space. It must be smooth and not erratic. The chest is lifted slightly and moves little during the breath. The head is perched in a balanced manner. Focus is at the center of the brow.

(3) Bilateral segmented breathing: This pattern is simply the breath divided into eight equal steps on inhalation and eight equal steps on exhalation. You may put a mental mantra on the steps: Sa Ta Na Ma. Each step is distinct, but equal in duration.

1.3. Signal acquisition and analysis

Two electrocardiogram (ECG) signals (bipolar chest leads) and two respiration signals (abdominal and chest elastic transducer bands) were recorded at 200 Hz using a DigiTrace 1800 SL recorder (SleepMed, Boston, MA). Automated QRS detection, with visual review, was performed using both ECG channels [14]. For respiration, we report results using the signal from the abdominal band only, since comparable results were obtained with the chest band signal. The heart rate was calculated by taking the inverse of each interbeat interval to create an instantaneous heart rate time series. We then computed the mean heart rate for each segment, and its Fourier spectrum using the Lomb technique for unevenly sampled data points [15,16]. Spectral powers were computed in three frequency bands [17]: total power (0–0.4 Hz); high frequency (0.15–0.4 Hz), and low frequency (0.04–0.15 Hz). The ratio of high/low power was also calculated.

1.4. Heart rate oscillation amplitude

To quantify the amplitude of heart rate oscillations in the frequency range of respiration, we applied Hilbert transform analysis to extract the magnitude of the oscillations in the heart rate time series [6,18,19]. The Hilbert transform was employed for two reasons: (i) it does not require stationarity of the signal; and (ii) it measures the instantaneous amplitude and frequency of the dominant oscillation in the signal [19]. However, the Hilbert transform requires that the signal be evenly sampled and restricted to a limited frequency range. Therefore, we resampled the instantaneous heart rate signal at 2 Hz using a cubic spline algorithm, and bandpass-filtered the resampled signal to 0.025–0.35 Hz, to ensure that all respiratory-related heart rate oscillations were included. The magnitude of the dominant heart rate oscillation in this band was quantified for each segment by finding the median values of the Hilbert transform amplitudes of the filtered heart rate signal, as previously described [6].

1.5. Respiratory rate

To determine respiratory rate during each segment, the chest and abdomen band signals were downsampled from 200 to 20 Hz (by extracting every 10th point) and a 0.025–5.0 Hz bandpass filter was applied. The upper cut-off of 5 Hz was chosen so as to include the 2–2.5 Hz (120–150 breaths/min) respiratory rate during the breath of fire maneuver. For each segment, we then calculated the Fourier power spectrum of the filtered signals and used the frequency at maximum power as a measure of the dominant respiratory frequency during that segment (Figs. 1 and 2).

1.6. Cardiopulmonary interactions

The interaction between heart rate and respiratory dynamics was quantified using cross-spectral and coherence analysis. For this type of analysis, both heart rate and

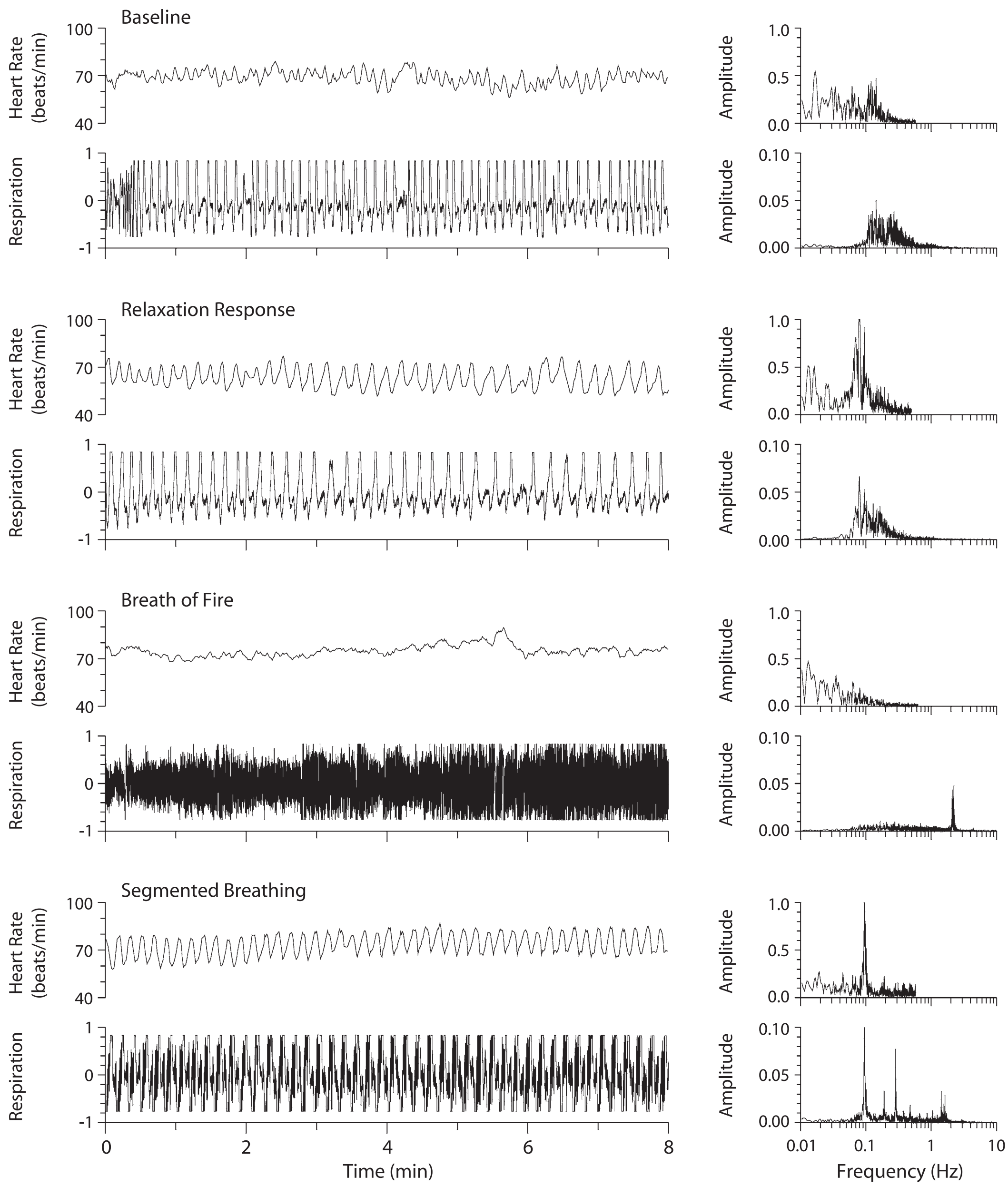

Fig. 1. Effects of three meditation practices on heart rate and breathing dynamics from a representative subject. The simultaneous heart rate and respiratory time series are shown on the left and their respective Fourier spectra (Lomb periodogram method) on the right. Respiration (abdominal band) is plotted in arbitrary units, with inspiration indicated by positive values. For the spectral amplitudes, the *x*-axis (frequency in Hz) is on a logarithmic scale; the *y*-axis is on a linear scale (beats/min) for heart rate. The units and time scales for the *x*-axes of the time series and spectra are the same for all four panels given as indicated under the left and right bottom (segmented breathing) panels, respectively. The baseline (second baseline period) is a control recording taken at quiet rest. Note the similarity in heart rate variability during the relaxation response and segmented breathing. Both interventions induced prominent, relatively low frequency oscillations in heart rate (~ 0.1 Hz), associated with slow breathing at the same slow frequency (~ 6 breaths/min). Compared to baseline, for both the relaxation response and segmented breathing, there is an increase in dynamic range, with up to 20 beats/min change in heart rate occurring over 10 s. The respiration spectrum during segmented breathing shows a dominant peak at the mean breathing rate, as well as higher harmonics due to the nonlinearity of the signal. In contrast, during breath of fire, the respiratory rate is markedly increased (~ 2.2 Hz = 132 breaths/min). A slight increase in mean heart rate is seen compared to baseline, and overall variability is diminished. Compare this response with the atypical pattern noted in one of the subjects (Fig. 2), where breath of fire was associated with low-frequency heart rate oscillations.

respiratory signals must be sampled at the same rate. Therefore, the original abdominal and chest band signals were downsampled from 200 to 2 Hz by extracting every 100th point, then bandpass-filtered over the frequency range 0.025–0.35 Hz to match the filtered heart rate signal used to calculate the heart rate oscillations, as described above. We then computed the cross-spectral power and coherence between the filtered heart rate and respiration signals for each segment of the protocol. We measured the coherence value at the maximum cross-spectral power as an index of coupling between heart rate and breathing dynamics.

1.7. Statistical analysis

Group values are summarized as mean ± SD. To compare the three meditation protocols, we applied the non-parametric equivalent of repeated measures analysis of variance (Friedman's test) to determine if the measured and derived parameters of heart rate and respiration were

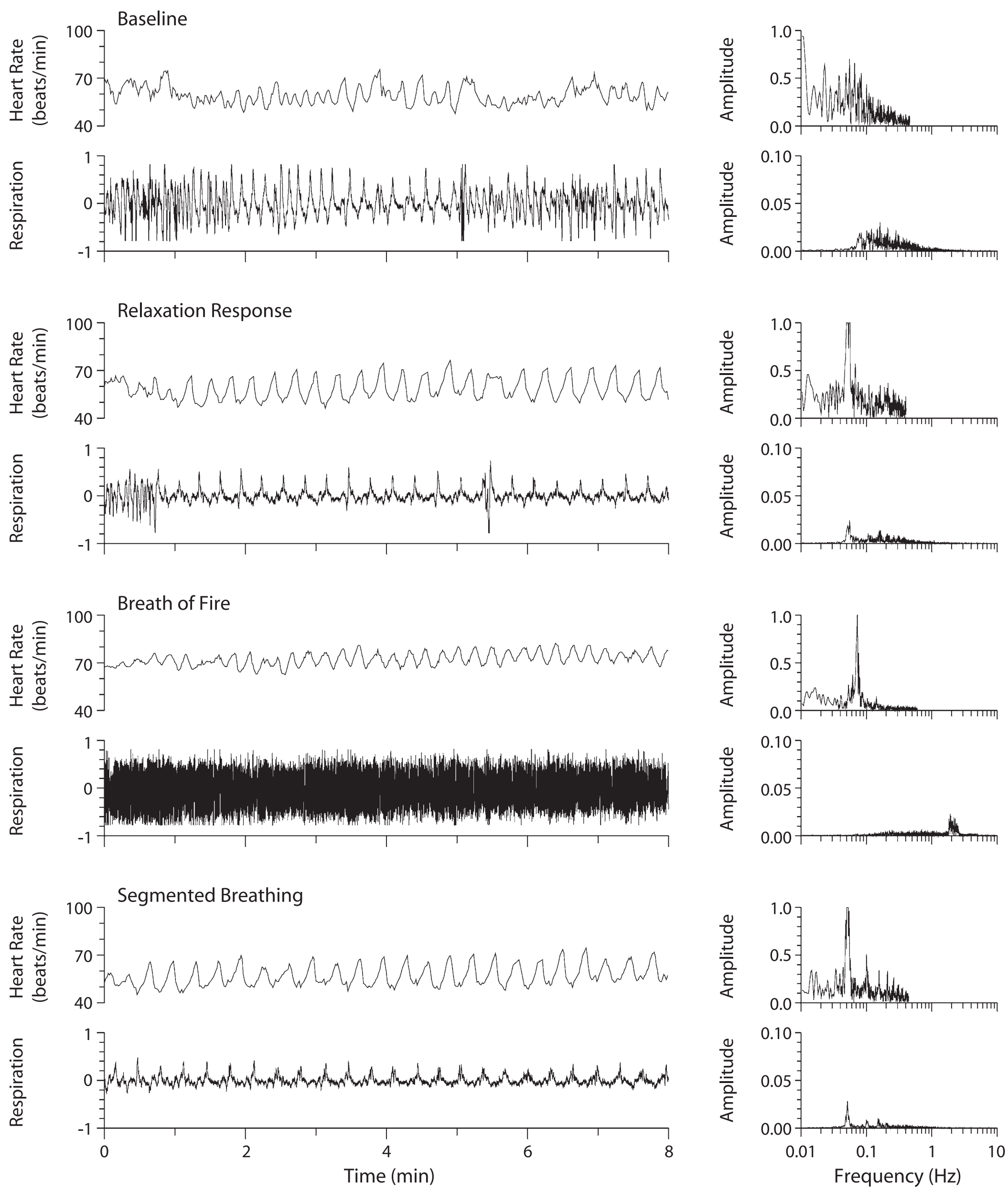

Fig. 2. Effects of three meditation practices on heart rate and breathing dynamics. Shown are recordings from the one subject with an atypical heart rate response during breath of fire. The plots are the same format with the same units as in Fig. 1. Heart rate and respiration changes during the relaxation response and segmented breathing are very similar to those of the subject in Fig. 1. In both cases, prominent low-frequency (~ 0.1 Hz) oscillations in heart rate are associated with slow breathing at about the same frequency. However, in contrast to the patterns in Fig. 1, during breath of fire, this subject showed relatively low-frequency oscillations in heart rate, despite very rapid breathing. The mechanism of this atypical response is uncertain.

Table 1
Heart rate and respiration during three meditation techniques

	Baseline[a]	RR	BF	SB	p-Value for comparison of		
					RR vs. SB	RR vs. BF	BF vs. SB
Mean HR (beats/min)	68.5 ± 8.6	68.3 ± 10.2	77.8 ± 8.5	72.8 ± 10.4	0.01	0.01	NS
HR oscillation amplitude (beats/min)	4.7 ± 1.2	6.8 ± 2.4	2.5 ± 0.9	7.1 ± 2.8	NS	0.005	0.005
Respiration (breaths/min)	12.2 ± 5.3	8.3 ± 5.4	145 ± 16.9	6.6 ± 2.0	NS	0.005	0.005
Coherence	0.74 ± 0.17	0.92 ± 0.04	0.51 ± 0.13	0.96 ± 0.03	NS	0.005	0.005
Total HR power (beats/min)^2	43.0 ± 27.1	42.3 ± 21.2	21.4 ± 21.2	40.5 ± 15.3	NS	NS	NS
Low frequency power (beats/min)^2	13.0 ± 5.4	23.3 ± 11.4	4.3 ± 2.9	24.0 ± 13.2	NS	0.005	0.005
High frequency power (beats/min)^2	4.1 ± 2.9	5.3 ± 4.0	48 ± 0.26	4.7 ± 4.1	NS	0.005	0.005
High/Low ratio	0.32 ± 0.16	0.23 ± 0.12	0.15 ± 0.11	0.19 ± 0.09	NS	NS	NS

HR = heart rate; RR = relaxation response; BF = breath of fire; SB = segmented breathing; NS = not significant (p>0.013).
[a] Values are averaged over all four baseline periods.

significantly different during any of the three meditation techniques. If repeated measures analysis of variance indicated a state-dependent effect ($p < 0.05$), post hoc tests were then performed using the Wilcoxon signed rank test to evaluate differences between pairs of variables in the three states. A Bonferroni adjusted p-value of 0.05/3 or 0.0166 (two-tailed) was used as the level of significance in these pair-wise comparisons. In a secondary analysis, we

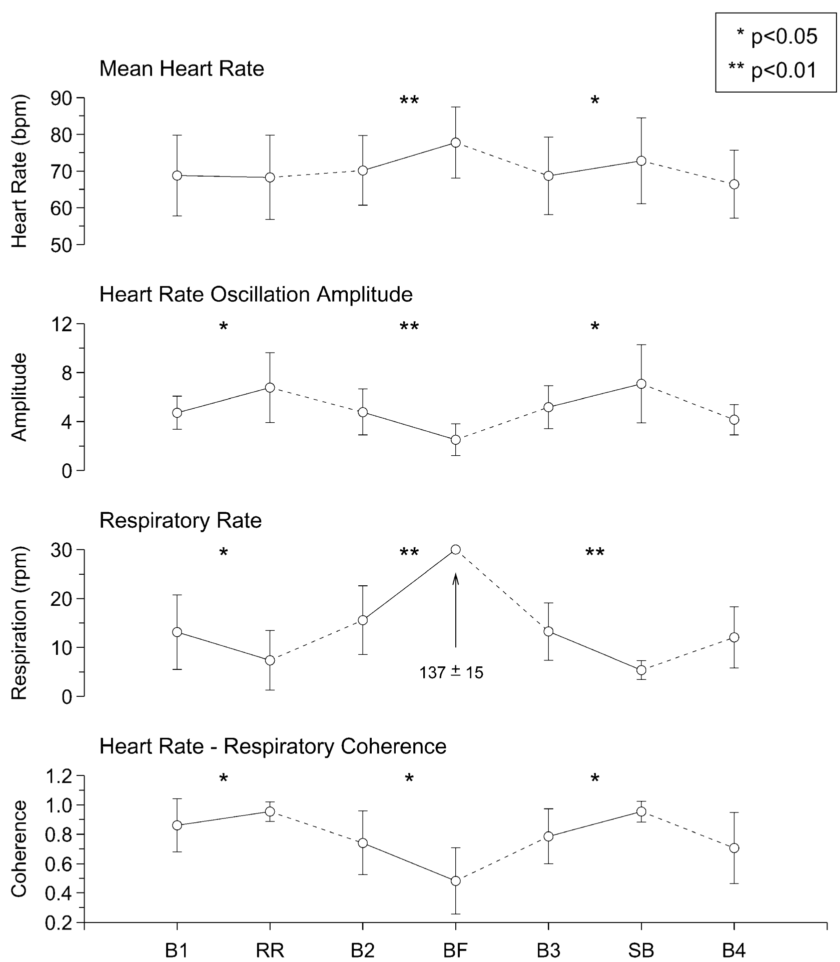

Fig. 3. Selective measurements of heart rate and respiratory dynamics. These measurements are plotted by baseline (control) and meditation periods, in their sequential order. Top panel shows the mean heart rate. Second panel shows amplitude of heart rate oscillations measured by the Hilbert transform technique (see text for details). The respiratory rate is shown in the third panel. The bottom panel shows the coherence measurement between heart rate and respiration. Values are given as means (small circles) ± standard deviation (brackets). The solid line segments indicated comparisons of each meditation period to its preceding baseline. Significant changes are noted by * (for $p < 0.05$) and ** (for $p < 0.01$). The four baseline periods are indicated as B1, B2, B3, and B4, respectively. RR = relaxation response, BF = breath of fire, and SB = segmented breathing.

examined the effects of each protocol on heart rate variability by comparing measured parameters during each meditation state with those during the immediately preceding baseline period using the Wilcoxon signed rank test. Statistical significance was defined as $p<0.05$ for these comparisons. Statistical analysis was performed using SPSS for Windows (version 10.1) and the R package [20].

2. Results

The typical effects of the three meditation practices on heart rate and respiratory dynamics are shown in Fig. 1. The relaxation response and segmented breathing both induced high amplitude, low frequency (~ 0.05–0.1 Hz) oscillations in heart rate with excursions up to 20 beats/min. These low-frequency heart rate oscillations were associated with slow breathing at the same frequency during these two forms of meditation (Fig. 1). One subject (Fig. 2) had an atypical response during breath of fire associated with similar low frequency heart rate oscillations. Quantitative results are summarized in Table 1 and Fig. 3, as discussed below.

2.1. Comparison among different meditation approaches

Table 1 summarizes comparison of cardiopulmonary measurements among the three meditation protocols. Mean heart rate was significantly higher ($p<0.01$) during both segmented breathing and breath of fire compared to the relaxation response. Total power and high/low spectral power ratios were not significantly different among the three meditation protocols. For all other spectral and coherence measurements, the breath of fire period showed significantly lower values when compared to the relaxation response and segmented breathing periods (Table 1).

2.2. Comparison of meditation with baseline

We also compared each meditation period to the immediately preceding baseline period (Figs. 3 and 4). The three meditation protocols had different effects on the mean heart

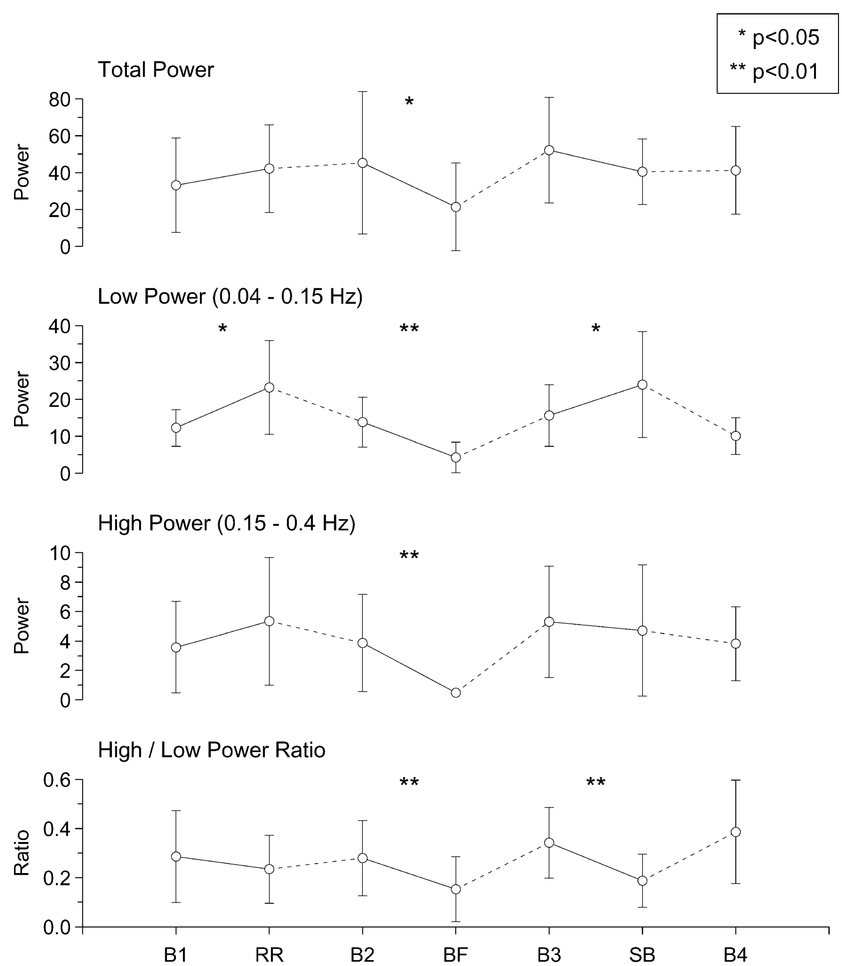

Fig. 4. Summary of results of Fourier analysis of heart rate time series. Abbreviations are the same as in Fig. 3. Values are given as means (small circles) ± standard deviation (brackets).

rate and the amplitude of the heart rate oscillations. Compared to the baseline period, mean heart rate was not significantly changed during the relaxation response, but was significantly increased during breath of fire ($p<0.01$) and during segmented breathing ($p<0.05$) (Fig. 3). The amplitude of heart rate oscillation, as measured by the Hilbert transform analysis, was significantly increased during relaxation response ($p<0.05$) and segmented breathing ($p<0.05$), but was significantly decreased during the breath of fire ($p<0.01$) (Fig. 3). The three meditation protocols also had different effects on heart rate-respiratory coupling. Compared to the preceding baseline, the coherence measurements indicated a significant increase in heart rate-respiratory coupling during both the relaxation response ($p<0.05$) and segmented breathing ($p<0.05$) (Fig. 3). In contrast, coherence significantly decreased ($p<0.05$) with breath of fire (Fig. 3) where the respiration rate was substantially faster than the heart rate.

Consistent with results obtained using the Hilbert-transform method, spectral analysis revealed changes in total power (an index of overall heart rate variance) that were dependent on the specific meditation protocol (Fig. 4). Compared to the baseline just prior to each meditation period, total power significantly decreased during breath of fire ($p<0.05$) while there were no significant changes during either the relaxation response or segmented breathing (Fig. 4). Both low and high frequency power were significantly decreased during breath of fire ($p<0.01$ for each) (Fig. 4). Low-frequency power significantly increased during both the relaxation response ($p<0.05$) and segmented breathing ($p<0.05$). The high/low frequency power ratio was not significantly changed during the relaxation response, but significantly decreased during breath of fire ($p<0.01$) and segmented breathing ($p<0.01$) (Fig. 4) compared to the preceding baseline.

The 200 Hz ECG sampling frequency used here is lower than a suggested standard sampling rate of 250 Hz [17]. However, the digitization uncertainty introduced by the slightly lower sampling rate should not affect the analyses because it falls well below the level of intrinsic physiologic variability for healthy subjects. To confirm this assumption, all analyses were duplicated using heart rate signals requantized, by truncating the least significant digit, to simulate a 100 Hz ECG sampling frequency, thereby introducing additional digitization noise. For all heart rate variability measures, this added noise resulted in only slight variation from values reported above, and all statistical conclusions were unchanged.

3. Discussion

The results of this small observational study are of interest from a number of perspectives. First, we observed that two apparently distinct meditative practices, namely the relaxation response and segmented breathing, induce very similar heart rate dynamics in a group of experienced meditators. In particular, we observed prominent low frequency (0.05–0.1 Hz) oscillations in heart rate during both protocols. Further, these oscillations were tightly coupled to breathing at the same slow frequency, as confirmed by high coherence values (Table 1). These heart rate oscillations, representing a marked form of respiratory sinus arrhythmia, are similar to heart rate variability patterns reported with a number of other meditative protocols derived from Chinese Chi, yogic, and Zen traditions as well as rosary prayer [6–8]. This finding raises the intriguing possibility that apparently distinct meditative prescriptions may evoke certain common responses, and that slow breathing is a fundamental component of these interventions [6,8]. Not surprisingly, we found that another meditative protocol, namely, breath of fire, was typically associated with a very different pattern of response in the same subjects. This pattern was marked by a decreased overall heart rate variability, decreased high and low frequency power, decreased high/low spectral power ratio, and decreased heart rate-respiratory coherence (Table 1; Figs. 1, 3 and 4).

The prominent heart rate fluctuations (Fig. 1) observed during both the relaxation response and segmented breathing support the concept [6,21,22] that certain forms of meditation may, paradoxically, induce active, rather than quiescent (homeostatic) cardiac dynamics. The present study extends these earlier findings by showing that very prominent oscillations in the normal heartbeat are a characteristic feature of other forms of meditation (relaxation response and segmented breathing), and are associated with high coherence between heart rate and breathing dynamics.

Second, we found that changes in mean heart rate were of very limited value in assessing the complex dynamics of meditation effects (Table 1; Fig. 3). Consistent with previous findings [11], we did not observe a substantial change in mean heart rate during the relaxation response, compared to resting baseline. Segmented breathing was associated with a slight (4.1 beats/min), but significant ($p<0.05$), increase in mean heart rate. The most marked (7.6 beats/min; $p<0.01$) increase was noted during breath of fire (Fig. 3). Overall heart rate variability (total power) was significantly decreased ($p<0.05$) only during the breath of fire period. These findings also indirectly support the conjecture that certain forms of meditation may be associated with activation of selected components of the heart rate variability response [6,18,20,22] and perhaps increased baroreflex sensitivity [8,23].

Third, we note that the prominent heart rate spectral peak at about 0.1 Hz during the relaxation response and segmented breathing protocols (Table 1) falls within the traditional "low frequency" spectral band (0.04–0.15 Hz) [17]. An increase in power in this band has been related to increased sympathetic tone and activation of the baroreflex. However, with slow breathing, an increase in power in this band appears to correlate with changes in respiratory sinus arrhythmia frequency, a physiologic parameter conventionally associated with vagal modulation [25,26]. Therefore, as described by Bernardi et al. [24], particular care must be exercised in inferring neuroautonomic mechanisms based on spectral power measurements using traditional frequency band parameters in the context of altered breathing dynamics.

3.1. Limitations and future directions

This study assessed meditation effects on selected cardiopulmonary variables in a small group of young to middle-aged men and women with training in yogic breathing during three specific protocols. Comparison with control group of subjects not practicing yoga was not available. (Experienced practitioners were selected in part because of their familiarity with segmented breathing and breath of fire protocols.) Measurements of other potentially relevant variables, including continuous blood pressure and CO_2 concentrations, were also not available. We did not attempt to control for tidal volume [24] or to do paced breathing during baseline periods. Further, by study design, subjects performed the three meditative interventions in the same order. Therefore, we cannot exclude the possibility that the responses to segmented breathing and breath of fire, in particular, were influenced by the preceding meditative exposures. However, given the intervening 10-min baseline (control) periods and the consistency of the findings, such interaction effects, to the extent that they occurred, are not likely to be large. Further, we note that heart rate and respiratory parameters were similar in the resting state before each meditation protocol (Figs. 3 and 4). Another potential limitation is that one subject had mild diabetes. All results and conclusions were similar when the analysis was repeated after excluding this subject.

Future studies should help to elucidate the effects of different forms of meditation and distinguish nonspecific breathing effects from more specific meditation-related changes. The use of autonomic blocking agents will be useful in determining whether the increase in power in the low-frequency band associated with segmented breathing, and to a lesser extent, with the relaxation response, is exclusively vagal in origin, or represents combined vagal and sympathetic effects, associated with baroreflex activation [23,27]. The possible role of other factors (e.g., mechanical or chemoreflex-related) affecting these cardiopulmonary oscillations also remains uncertain [28]. It will also be interesting to determine whether other meditative and relaxation protocols evoke patterns comparable to the ones observed here, which appear to fall into two distinct classes (relaxation response and segmented breathing, on the one hand, and breath of fire, on the other). For example, the prominent cardiopulmonary oscillations we observed were not described in studies of transcendental meditation [29,30]. However, the mean breathing rate in subjects in these two studies was about 11–12 per minute, substantially higher than the rate we observed during the relaxation response and segmented breathing. The relationship between these distinctive cardiopulmonary oscillations and central nervous system activity during specific forms of meditation and controlled breathing without explicit meditation interventions also warrants detailed study [21].

One of the subjects (Fig. 2), showed an unexpected, apparently atypical pattern of response during breath of fire, marked by relatively slow, prominent oscillations in heart rate (~ 0.1 Hz) during very rapid respiration (~ 2 Hz). This unanticipated response, although observed in only one of the ten individuals tested, raises the possibility that breath of fire may be capable of inducing activation of baroreflex-related oscillations in heart rate. Lehrer et al. [27] postulated that certain types of slow breathing may induce a resonance effect between respiratory and baroreflex-mediated heart rate oscillations. The importance of such an effect, and the intriguing possibility that it can be induced by certain rapid forms of yogic breathing, remains to be determined.

Finally, the finding that various forms of meditation appear to differentially alter specific components of heart rate variability may support their health benefits in conditions where such variability has been blunted by disease or aging. Future detailed studies of comparing the effects of meditation and controlled breathing without meditation [8] on cardiopulmonary dynamics, in conjunction with other physiologic responses in specific subsets of patients [33], as well as in healthy subjects across a wide age spectrum, will be of interest. Possible gender differences in physiologic response should also be investigated. Such studies will help define the uses and limitations of tailored meditation and breathing prescriptions in different physiologic and pathologic contexts [12,13,27,31–37].

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