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Research paper

Entrainment of chaotic activities in brain and heart during MBSR mindfulness training

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HIGHLIGHTS

- Wavelet entropy is used to measure the chaotic activities.
- Coordination between electronic activities of brain and heart.
- MBSR meditation can reduce the chaotic activity of brain waves.

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ABSTRACT

The activities of the brain and the heart are dynamic, chaotic, and possibly intrinsically coordinated. This study aims to investigate the effect of Mindfulness-Based Stress Reduction (MBSR) program on the chaoticity of electronic activities of the brain and the heart, and to explore their potential correlation. Electroencephalogram (EEG) and electrocardiogram (ECG) were recorded at the beginning of an 8-week standard MBSR training course and after the course. EEG spectrum analysis was carried out, wavelet entropies (WE) of EEG (together with reconstructed cortical sources) and heart rate were calculated, and their correlation was investigated. We found enhancement of EEG power of alpha and beta waves and lowering of delta waves power during MBSR training state as compared to normal resting state. Wavelet entropy analysis indicated that MBSR mindfulness meditation could reduce the chaotic activities of both EEG and heart rate as a change of state. However, longitudinal change of trait may need more long-term training. For the first time, our data demonstrated that the chaotic activities of the brain and the heart became more coordinated during MBSR training, suggesting that mindfulness training may increase the entrainment between mind and body. The 3D brain regions involved in the change in mental states were identified.

1. Introduction

Living organisms are nonlinear, complex systems, with certain degree of chaoticity in their physiological variables. For example, the electroencephatholography (EEG) waves are known for their dynamic activity with brain networks operating between order and chaos [1]. Likewise, heart rate variability (HRV) is non-zero for a living subject. However, chaotic degree must be maintained at a certain yet not well-known limiting level. The lyapunov exponent (LE) of EEG can be considered as a measure of chaotic behavior. Previously, we strived to apply the LE of EEG as a parameter to predict epilepsy [2]. Similarly, we also analyzed the chaotic features of electrocardiogram (ECG) waves to look for a parameter characterizing ECG signals that would likely lead to pre-matured ventricular contractions [3]. Since the advent of high-resolution EEG machine (with ~100 or more channels), a number of methods have been developed to measure objectively the chaotic nature of signals. In particular, the concept of entropy has been applied to study the chaotic nature of various signals. Entropy describes the distribution probability of molecules in a fluid system in physics. During

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the evolution of a system of many signals, the degree of disorderness, which is measured by entropy, increases in general [4]. Since different EEG waveforms represent different states of the electrical activity of the brain, the entropy of EEG signals signifies the chaotic degree of such activity as a whole, which cannot be measured by the traditional spectrum analysis. Particularly, it measures the chaotic level over different scales and hence is more applicable and convenient for analyzing EEG data [4]. Entropy measures have been employed to study AD, epilepsy and anaesthesia in clinical settings [5].

Neurocardiology in medicine suggests a close interplay between the heart and the brain, and cardiac afferent information can affect emotion processing in the brain [6]. There is evidence of meditation-related change in the heart rate variability, when compared to pre-meditation states [7]. Another study found that during mindfulness meditation, there is also quantitative change of EEG and respiration signals [8]. However, previous studies mainly investigate the effect of meditation on the brain or the heart separately. Only a few studies report on better coordination of body and mind after meditation training and mindfulness practices [9,10]. For example, it has been shown that integrative body-mind training (IBMT) increased the correlation between frontal midline theta wave and heart rate variability (HRV), suggesting that a better regulation of autonomic nervous system by midfrontal brain region [10].

The main aims of this investigation are: (i) to measure the power of the 5 standard bands of EEG waveforms, in order to see the changes brought by MBSR. (ii) to measure the wavelet entropy of EEG before and after an eight-week MBSR program, in order to find the difference in chaotic degree as compared to the rest (control) state. (iii) to find out the 3D source positions related to the entropy changes, based on a source analysis of the EEG activity. (iv) to measure wavelet entropy of the heart rate concurrently in order to find the chaotic change, similar to (ii). (v) to find if there is correlation of the entropy changes in the two variables above, in order to see if there is heart–brain entrainment.

2. Materials and methods

2.1. Participants

The research was approved by the local Institutional Review Board (IRB). All participants provided their written informed consent prior to participate in this study. Eleven healthy participants (6 males, 5 females; mean age 35.7 year; 7 Asians and 4 Caucasians) from a local MBSR course voluntarily participated in this study. Each participant was paid 200HKD for transportation fee. All participants were above the undergraduate level. Six of them had some experience of mental exercises such as Yoga, Qigong, or other meditation methods. Nonetheless, they all did not have experience in MBSR and during the experiment, they were requested to only practice mindfulness breathing learned from the MBSR course. The course were taught following the standard MBSR program consisting of one pre-program orientation session, eight weekly classes and one all-day class when the teacher gave direct instructions. Participants also needed to make strong commitment to practice 45 min of MBSR training each day as home assignments for 8 weeks individually, including body scanning and mindful breathing.

Beck Depression Inventory (BDI) was used to exclude participants with depression [11]. The effectiveness of MBSR was measured by Five Facets Mindfulness Questionnaire (FFMQ) [12]. These five facets included non-judging, describing, non-reacting, acting with awareness, and observing. The sub-scores of each facet and a total score were calculated for each participant. The FFMQ was used to measure the subjective experience of mindfulness, and in the following we also used EEG to measure relatively objective brain waves associated with mindfulness practice.

2.2. Experiment procedure

Ten minutes of eye-closed normal rest EEG was collected for each participant in a quiet room and participants were requested not to ruminate too much or fall asleep. They were also asked to practice mindful breathing for 10 min, following the teaching of the MBSR course. Participants were requested not to ruminate too much or fall asleep, and a post-experiment dialog showed that they could largely follow the procedures. EEG data were recorded at the beginning of the MBSR training (within two weeks), and less than one month after the MBSR course, resulting in two data sets and two conditions. The early-stage MBSR condition was not set before MBSR training but within two-weeks training time. It was to ensure that the trainees knew the right way to practice the MBSR mindful breathing at the time of EEG recording. The sequence of mindfulness state and normal rest state was counter-balanced, with half of the participants did the mindfulness condition first and half did rest condition first, randomly.

2.3. Data acquisition and analysis

The data were acquired by a 128-channel NeuroSCAN system in a quiet room. The sampling rate was 1000 Hz. The original reference point was at left mastoid, and re-referenced to both mastoids when processing the data. The ECG electrodes were placed at the left and right infraclavicular fossae.

The data was processed by EEGlab (see Supplementary materials for details). The spectra of EEG were computed using fast Fourier transform (FFT) and the log powers (dB) of delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–80 Hz) waves were obtained. In order to evaluate the chaotic degree, wavelet entropy, an entropy of the energies under different scales given by discrete wavelet transform, of the EEG (as well as their estimated cortical sources) and heart rate were then calculated (see Supplementary materials for details on how to calculate wavelet entropy). To explore the relationship between brain and heart during the MBSR practice and normal rest states, we calculated the linear correlation coefficient (Pearson coefficient) between the EEG's and the heart rate's wavelet entropies.

3. Results

All the participants were not depressed according to their BDI scores (<13). The FFMQ data was shown in Supplementary Table 1. No significant change was found between early-stage MBSR and post-stage MBSR stages except for the facet of nonreacting ($p < 0.05$).

There were enhanced Alpha (8–12 Hz) and Beta (12–30 Hz), and reduced delta waves (1–4 Hz) during MBSR practice than during normal rest. The increase of alpha waves was globally significant, especially in the frontal and occipital lobes. The increase of beta wave was mainly in the frontal lobe. Decreased delta wave was at central-parietal areas. However, we did not find significant change between the early-stage and post-stage MBSR training. See Fig. 1 and Supplementary Table 2.

Similar to previous studies [13,14], several regions of interest (ROI) were selected to represent the occipital lobe, the middle frontal lobe and the middle parietal lobe (see Supplementary material for channels defined for these ROIs). Analysis on these ROIs showed that the increase of alpha wave and decrease of delta wave were prominent all the three ROIs, while the increase of beta was mainly in the frontal lobe. See Supplementary Table 2.

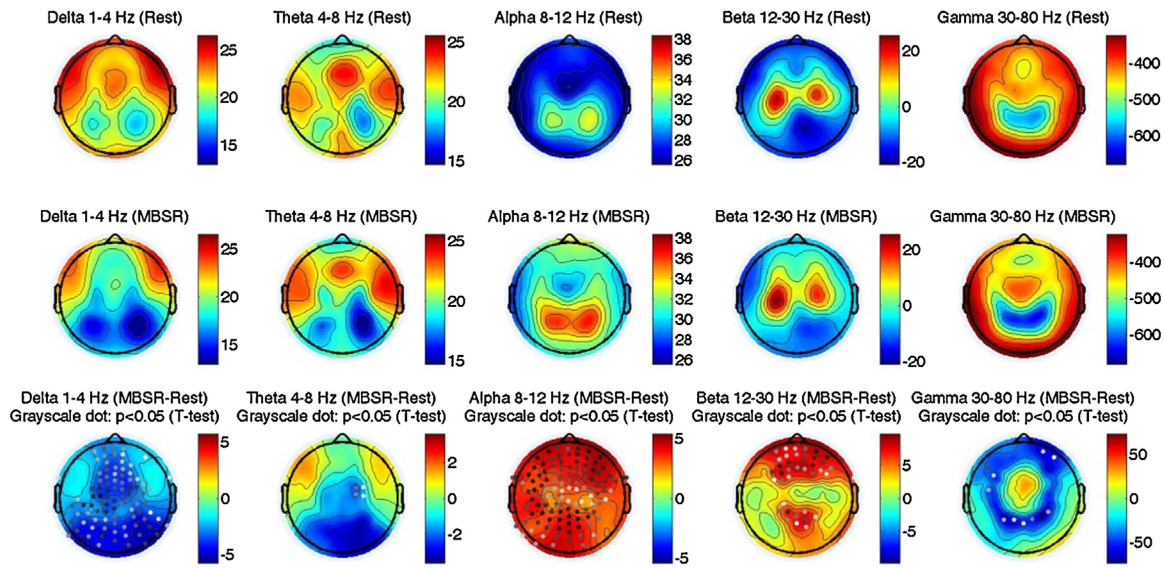

Fig. 1. Power analysis on different spectrum. The bottom row is the difference between the two states (first row is Normal-Rest, second row is MBSR practice) and the corresponding *T*-test results, where the small dots indicate channels with significant difference between two states. The *p*-value is set at <0.05, and darker dot implies smaller *p*-value (more significant difference).

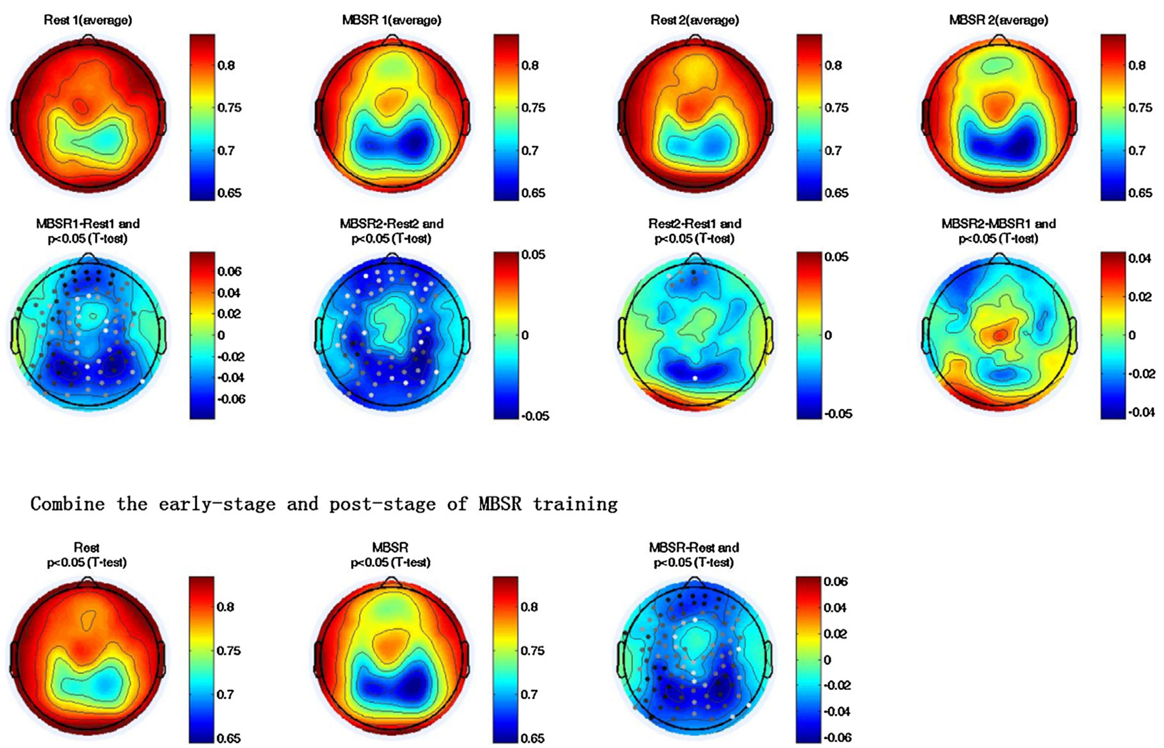

Fig. 2. The wavelet entropy analysis in the early-stage and post-stage of MBSR versus normal-rest conditions. Since there were no difference between the early-stage and post-stage MBSR, they were merged together for comparison in the third row for average maps. The small dots indicate channels with significant difference between two states. The *p*-value is set at <0.05, and darker dot implies smaller *p*-value (more significant difference).

The wavelet entropy of EEG was decreased during MBSR practice as compared to that during normal rest, both in the early-stage and post-stage of MBSR training. Since there was no difference between the two stages, they were merged together for an averaged map in the third row in Fig. 2. The main areas with decreased entropy were in the frontal lobe and the parietal-occipital lobe.

Source analysis on the EEG entropy improved the spatial resolution by deconvolving the scalp EEG into electrical activity over the cortical surface [15]. It showed that major brain regions affected by MBSR mindfulness training were the left middle occipital lobe, the precuneus, superior temporal lobe, and the right middle cingulate cortex. See Fig. 3 and Supplementary Table 3.

Analysis showed no difference in average heart rate but the heart rate entropy was lower during MBSR training, both at the beginning and after MBSR training, compared with the control. See Supplementary Table 4.

Our data showed that wavelet entropy of the brain and heart signals were significantly correlated during MBSR practice but not during normal rest. See Fig. 4. The upper figure shows the significance of entropy of EEG in each channel and heart rate entropy.

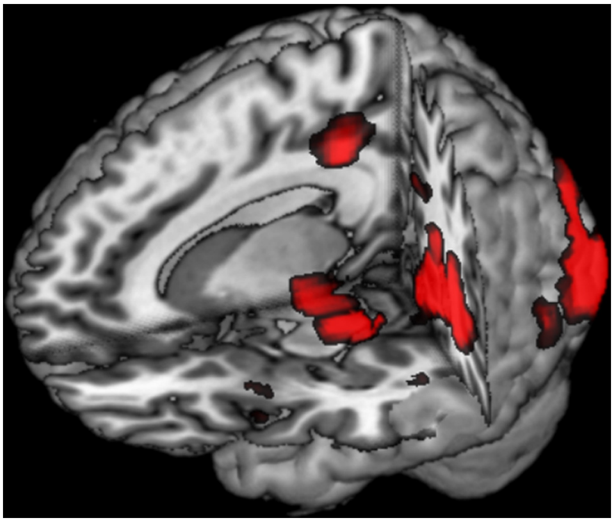

Fig. 3. Source analysis on entropy showed that the difference in EEG source entropy between two states of MBSR practice and normal rest ($p < 0.001$, *T*-test, uncorrected).

The significance of correlation is most prominent in the central part of the brain. The lower figure shows the correlation between the average of brain EEG entropy of all EEG channels and the heart rate entropy.

4. Discussion

Spectrum analysis showed that as compared to normal rest, the alpha wave power in the frontal and occipital lobe increased in both early-stage and post stage of MBSR training, while no significant difference existed between the two stages. Alpha waves appear when the brain is free from significant sensory input or specific cognitive processing, and they attenuate when the mind is engaged in mental tasks [16]. This result is in line with a majority of meditation reports of an increased alpha wave during meditation, especially in beginners [17].

The beta waves increased during MBSR practice, mainly in the frontal lobe. Beta waves usually represent active concentration and alertness. They are linked to wakefulness in daily mental activity, which usually consists of ongoing cognitive and motorsensory activities [18]. On the other hand, delta waves were found to decrease more during MBSR practice than during normal rest, mainly in the occipital and the frontal lobe. Delta waves commonly appear during non-eye movement sleep, and may locally increase in some special cases such as brain tumor [19]. The results did not show significant theta or gamma wave change.

Wavelet entropy analysis on EEG showed that during MBSR practice, the chaotic electronic activity decreased when compared to that during the normal rest state. The decreased areas cover both the anterior and posterior regions of the brain, and the difference was prominent in both the early-stage and post-stage of the training. Since no difference existed between the data from the two stages, they were merged together to get an average map of MBSR state versus the normal rest state, resulting in decreased entropy in mainly the occipital and frontal lobes. The temporal lobe and central regions were less affected. Given the relatively poor spatial resolution in EEG mapping, we applied source analysis to further explore the core regions with the decreased entropy [20]. It turned out that the main difference between MBSR and normal rest conditions was at the left occipital and precuneus regions. Also, the right temporal and middle cingulate areas were involved.

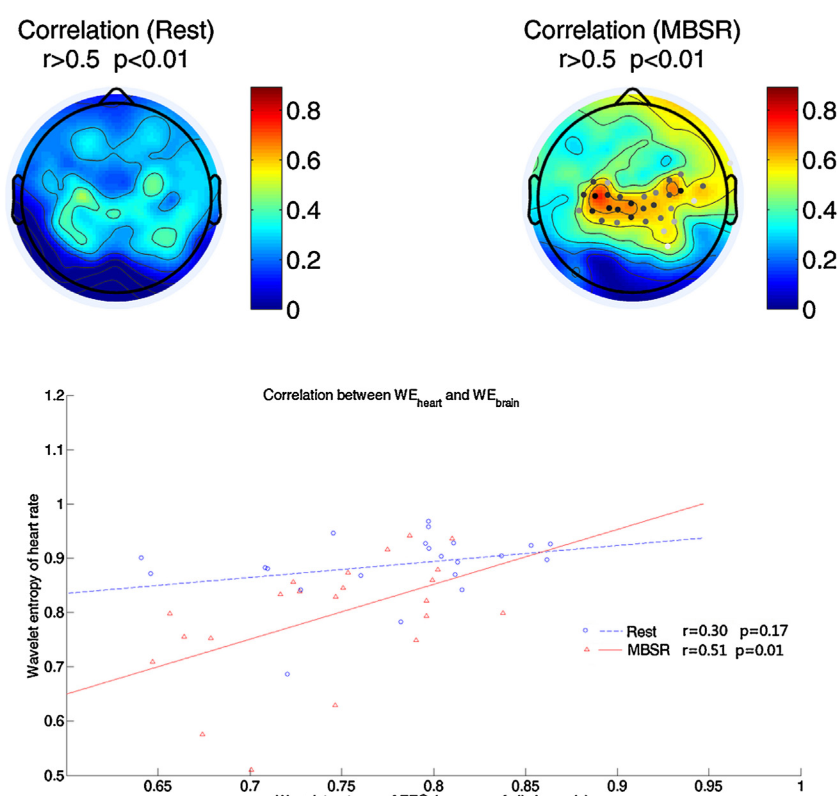

Fig. 4. The entropy of whole brain EEG is correlated with the entropy of heart rate during MBSR practice (red line), while no such correlation is observed during normal-rest (blue line). The small dots indicate channels with significant correlation between HR entropy and each EEG channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The occipital lobe and parieto-occipital area are related to the trait of advanced meditators [21]. For example, for long-term Vipassana meditator, increased gamma power was found in the occipital lobe. This increased gamma power may contribute to the enhanced sensory awareness in those advanced practitioners [22]. The occipital lobe engages in processing visual stimuli, while the precuneus area helps to judge the familiarity and usefulness of perceived information. The precuneus also aids internally represented visual images. It plays an important role not only in perception, memory retrieval, but also in working memory and attention [23].

The general guide of MBSR instructs the participants to be less reactive to or judgmental of external or internal stimuli, and to stabilize the habitually wandering mind. We did find that the participants had an increased score in non-reacting facet. The decrease in entropy in these two areas may indicate a detachment from visual information pursuit, expectation and non-judgment during MBSR training [24].

The entropy of heart rate was lower during MBSR training than during the normal rest state. The difference was significant both at the beginning of MBSR and after MBSR. The heart beat is regulated by two competing autonomic nervous systems, the parasympathetic and sympathetic nervous system. Less irregularity of heart rate implies more refined balance of autonomic nervous system; i.e., a relatively unwavering interaction between parasympathetic tone and sympathetic tone. The advanced meditators were found to have reduced ECG complexity, as measured by Shannon entropy, while this reduction was not observed in novice meditators [25]. Another study on Chi and Kundalini meditation found less chaotic cardiac activity during meditation, and it was suggested that nonlinear chaotic indices can quantitatively measure meditative states [26].

The reduction of entropy in the brain and the heart activities was somehow correlated during mindful breathing, but not in the normal rest state. The correlation is most obvious in the central region of the brain which consists of bilateral somatosensory regions. This finding is in line with a previous report that mindfulness training could increase the activities of viscerosomatic areas, including the somatosensory area, the insula and parietal lobe [27]. Our result suggests that MBSR training may influence both the autonomic and central nervous systems, and improve the coordination of body and mind. This processed could be mediated by the vagal nerve, which plays a central role in brain–heart coordination [28].

As the heart rate did not change significantly, it implies that MBSR practices may not specifically strengthen the sympathetic or parasympathetic nervous system. Instead, MBSR training may incorporate a refined balance in the regulatory processes of feedback and feedforward between the autonomic nerves, the brain stem and limbic systems, so that heart rate becomes less chaotic under two competing systems [29].

There are several limitations in this research. First the participant number could be increased. Although the effect of MBSR training on EEG is significant, with more participants, the early- vs. post-stages effect might be more significant in both behavior and EEG data. Another limitation is that EEG source analysis was not as accurate as other functional neuroimaging scanners. Future resting-state functional magnetic resonance imaging (fMRI) may be helpful. However, one major disadvantage of fMRI study is its noisy interference on meditation.

Conflicts of interest

There are no conflicts of interest including any financial, personal, or other relationships with persons or organizations for any author related to the work described in this article.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neulet.2016.01.001.

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