Original Article

Heart–brain Rhythmic Synchronization during Meditation: A Nonlinear Signal Analysis

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Abstract

Background: Heart–brain synchronization is the integration of mind, body, and spirit. It occurs when the electrical activity of the heart and brain is synchronized. In recent years, there has been mounting curiosity to investigate the effects of meditation on heart–brain synchronization with respect to mental and emotional health and well-being. The current investigation aims to explore the rhythmic synchronicity between the brain and the heart during heartfulness meditation (HM) practice. **Materials and Methods:** The study was performed on 45 healthy volunteers who were categorized into three equal groups: long-term meditators (LTMs), short-term meditators (STMs), and nonmeditators (NMs). The electroencephalogram (EEG) signals were recorded to measure the prefrontal activity, and electrocardiogram (ECG) signals were recorded to measure the cardiac activity. The data were recorded in four states: baseline, meditation, transmission, and posttransmission. The detrended fluctuation analysis (DFA) method was used for the analysis of EEG and ECG signals. **Results:** The result indicates that DFA values of EEG and ECG declined during meditation and transmission states as compared to pre- and postmeditation states. Significant results were obtained for the LTM group in all the states. A positive correlation was also observed between DFA of the heart and brain for the LTM group and no significant correlations were observed for the STM and NM groups. **Conclusion:** The shreds of evidence suggest that heart–brain synchronization facilitates mental and emotional stability. HM practice has the potential to regulate the fluctuation of the mind. Regular meditation practice may result in physiological synchrony between cardiac and neural behavior, which can be considered a quality index for meditation practice.

Keywords: *Detrended fluctuation analysis, electrocardiogram, electroencephalogram, heart–brain synchronization, heartfulness meditation*

Introduction

Meditation helps to improve quality of life and is now considered alternative and complementary treatments for different illnesses and disorders.[1] Recent studies revealed positive effects of meditation on encountering disorders such as stress, anxiety, and depression.[2] Furthermore, meditation practice may have a significant effect on the autonomic nervous system.[3] Among all meditation practices known throughout the world, heartfulness meditation (HM) has a unique feature of "*Pranahuti* or yogic transmission" to access the deeper levels of meditation.[4] It is a guided form of meditation where subtle energy is transmitted to the aspirant from the trainer.[5] Previous studies on HM reveal that it lowers depression, anger, and stress and enhances sleep quality and overall mood.[6,7] HM practice is also helpful in regulating cardiac parameters: heart rate (HR) and blood pressure (BP).[8] There are very few studies have shown the effect of HM practice on brain signals. The most conventional and well-established techniques for accessing heart and brain functionality are electrocardiogram (ECG) and electroencephalogram (EEG) signals, which are popular among researchers due to their low cost and portability and involve noninvasive procedures for data acquisition.[9,10] There are various physiological parameters that can be measured with the help of ECG (HR, BP, fibrillation and defibrillation of arteries and veins, diabetes, etc.) and EEG signals (stress level, fatigue, etc.).[11-13] There are also some disorders related to the heart (heart arrhythmia, sleep disorder, etc.) and brain (epilepsy, sleep disorder, etc.) that can be accessed through ECG and EEG signals.[14-17] ECG and EEG are

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nonstationary and nonlinear signals that record variations in electromagnetic signals from the heart and brain; there are previous studies employing linear techniques for the analysis of EEG and ECG signals which may not capture complex dynamics of signals.[18,19] Therefore, to study such complexity of nonstationary signals, nonlinear techniques can be employed. There are various known nonlinear techniques that can be employed for stationary signals such as EEG and ECG. Among such techniques, one of the most prominent methods is detrended fluctuation analysis (DFA) which can be successfully implemented in meditation-based studies.[20] DFA can be considered an index to represent long-range temporal correlation. The studies reveal that the value of DFA reduces postmeditation as compared to premeditation.[21] The DFA method can quantify the complexity of nonstationary signals using the modified root mean square method.[22] Meditation practices can improve heart and brain coordination. There are only a few studies that highlight the coordination between the heart and brain during meditation. A positive correlation has been obtained between cardiac index and EEG parameters during the meditation state as compared to baseline.[23-25] Meditation is related to relaxation and attention, as EEG alpha frontal oscillations increase during focused meditation, reflecting thalamocortical and cortico-cortical activities.[26,27] Therefore, in this study, coordination between heart and brain was investigated using DFA of EEG (alpha band) and ECG signals.

Materials and Methods

The study has been conducted in four steps: data acquisition, preprocessing, estimation of DFA, and finally investigating the correlation between heart and brain. The flow diagram of the study is represented in Figure 1.

Participants

A total of 45 (30 males and 15 females) participants were recruited from Heartfulness Institute, Bangalore. Out of that, the data of 15 participants were excluded due to inconsistency or poor signal in data. The participants selected have an age range of 20–45 years and do not have any physical or medical issues. Further, they were categorized into three groups: long-term meditator (LTM), short-term meditator (STM), and nonmeditator (NM). The study was approved by the Institutional Ethics Committee, SVYASA, Bengaluru, India. Furthermore, the participants selected are nonsmokers, nonalcoholic, and not under any type of medication.

Data acquisition and preprocessing of electroencephalogram and electrocardiogram

The EEG and ECG recordings were carried out at the Cognitive Neuroscience Lab, SVYASA, Bangalore, India. First, after the arrival of participants at 7:00 AM, their sociodemographic information was recorded.

ECG data collection was done using Acknowledge 3.9 version Biopac Acquisition software (MP 100 BIOPAC, Inc., U.S.A.). The room temperature and humidity were maintained at 24.0°C ± 1.0°C and 56%, respectively, on the day of recording. The ECG signals were recorded using a standard bipolar limb lead II configuration, and an amplifier with settings of a lower cutoff frequency of 1.5 Hz and a high cutoff frequency of 100 Hz has been employed. The ECG was then applied to a 12-bit analog-to-digital converter with a sampling rate of 1024 Hz. The entire session was performed with closed eyes in a single sitting. The recorded data were visually inspected offline, and only noise-free data were included for analysis. The ECG data were extracted using Kubios (Version 2.0, Biomedical Signal Analysis Group, Department of Physics, University of Kuopio, Finland). The HR in beats per minute (bpm) was calculated by continuous the R waves of the QRS complex in the ECG in 60 s epochs, continuously. The ECG data were segmented in four stages, i.e., baselines, mediation, transmission, and post. The data were epoch for 5 min at each stage, and the DFA, a nonlinear parameter of heart rate variability (HRV), was obtained using fast Fourier transformation.

The EEG recording was done using a 128-channel EEG system (EGI, GSN300) and Net Station (version 4.5.8) software with a sampling frequency of 250 Hz. The EEG recording captures four states: baseline (5 min), meditation (10 min), in this state, participants initiate HM practice, and transmission (10 min), in these states, HM practice was carried out by participants and is aided by an expert meditator (guru), and the final state was posttransmission (5 min) were participants were instructed to relax for 5 min after ending HM practice. Preprocessing of the EEG signal was carried out using EEGLABa toolbox. The direct current noise and muscular, ocular, and head movement were removed by clean line and independent component analysis, respectively. After preprocessing, EEG signals were extracted from different lobes. Each lobe is further divided into the left and right hemispheres. In this study, the prefrontal cortex of the brain is selected for

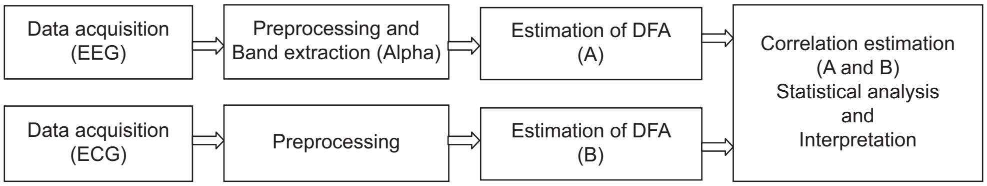

Figure 1: Flow diagram of the study

the analysis whose electrodes are given in Figure 2. The EEG bands were extracted using a bandpass filter: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz).

Detrended fluctuation analysis

DFA estimation of EEG and ECG can be done using the following steps:

- Read preprocessed signal x(t) of length N
- Calculate mean of the signal <x>
- Calculate cumulative profile Y (n) through equation

$$\mathrm{Y}(\mathrm{n}) = \sum_{t=1}^{n}\left(\mathrm{x}(\mathrm{t}) - < x >\right),\ \mathrm{n} = 1, 2 \ldots..\mathrm{N} \tag{1}$$

- Divide Y (n) into equal windows of length k each
- Calculate least square fit that represents the trend line F (*n*)
- Calculate fluctuation

$$f^2(k) = \frac{1}{N}\sum_{n=1}^{N}\left(Y(n) - F(n)\right)^2 \tag{2}$$

- Repeat this process for different window size
- Calculate square root of average fluctuation of overall window F_{DFA} (k).

The power law is expressed by $F_{DFA}(k) = k^{\alpha}$, where α represents the nature of fluctuation. $\alpha < 0.5$ represents long-range anticorrelated signal, $\alpha = 0.5$ represents white noise noncorrelated signal, and $\alpha > 0.5$ represents long-range correlated signal.[21]

Results

A quantitative analysis was performed in this study. The main aim is to analyze the coordination between the heart verses brain during different states of HM. The nonlinear method, DFA, was used to analyze EEG and ECG signals.

Detrended fluctuation analysis of electroencephalogram

The EEG results of the LTM group showed lower values during baseline, meditation, transmission, and posttransmission as compared to the baseline state. Repeated measure analysis of variance (ANOVA) results of DFA of the EEG showed hemispheric effect ($F_{(1,28)} = 5.32$, $P < 0.05$, $\eta^2P = 0.16$), state effect ($F_{(3,84)} = 5.36$, $P < 0.05$, $\eta^2P = 0.16$), and group effect ($F_{(2,28)} = 1.2$, $P > 0.05$, $\eta^2P = 0.08$).

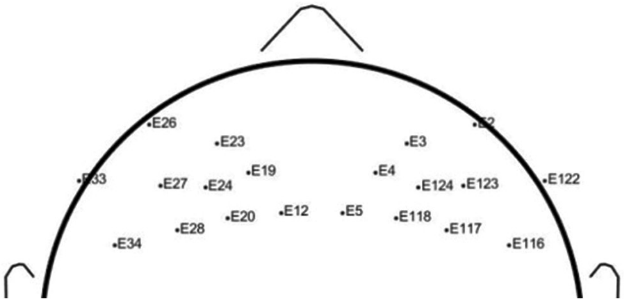

Figure 2: Frontal lobe electrode locations

The *post hoc* analysis with Bonferroni adjustment was applied for all the states for EEG (alpha band) and showed a decrement in DFA values in both hemispheres during meditation, transmission, and posttransmission as compared to the baseline state, also DFA values of LTM were found lower as compared to STM and NM.

The DFA of EEG results of the right frontal showed a significant difference in LTM during baseline ($P > 0.05$; $P < 0.05$), meditation ($P < 0.05$; $P < 0.001$), transmission ($P < 0.05$; $P < 0.01$), and post ($P > 0.05$; $P < 0.01$) compared to STM and NM. Similarly, the left frontal of the LTM group showed significant differences during meditation ($P < 0.05$) and transmission ($P < 0.05$) compared to NM.

Within-group analysis, LTM group showed a significant change during meditation ($P < 0.01$; $P < 0.05$) and transmission ($P > 0.05$; $P < 0.05$) compared to baseline, and during transmission ($P < 0.01$; $P > 0.05$) compared to transmission in the right and left frontal, respectively, whereas the STM group showed significant changes during post ($P < 0.05$; $P < 0.01$) compared to transmission in the right and left frontal, respectively, as shown in Tables 1 and 2.

Table 1: *Post hoc* analysis of detrended fluctuation analysis values in the alpha band of electroencephalogram signal (right hemisphere)

Groups	Meditation states (mean±SD)			
	Baseline	Meditation	Transmission	Post
LTM	9.63±2.17*	8.23±1.73$^{***,\#,aa}$	8.05±1.69$^{**,\#}$	9.49±2.17^{**,cc}
STM	13.2±6.04	12.27±2.23	11.45±4.31	13.14±4.73^{c}
NM	14.36±2.23	14.63±2.94	13.97±2.53^{bb}	14.9±2.9^{ccc}

$^{*,\#,c}P<0.05$, $^{**,aa,bb,cc}P<0.01$, and $^{***,ccc}P<0.001$. In between group comparison – *Compares NM and $^{\#}$Compares STM. Whereas, within-group comparison – compares baseline, ^{b}compares meditation, and ^{c}compares transmission. LTM: Long-term meditator, STM: Short-term meditator, SD: Standard deviation, NM: non-meditator

Table 2: *Post hoc* analysis of detrended fluctuation analysis values in alpha band of electroencephalogram signal (left hemisphere)

Groups	Meditation states (mean±SD)			
	Baseline	Meditation	Transmission	Post
LTM	10.96±2.87	9.52±2.26^{*,aa}	9.26±2.21^{*,a}	10.34±3.48
STM	14.19±5.95	13.23±5.88	12.55±4.75	13.94±5.42^{c}
NM	14.62±2.64	14.79±3.47	14.21±3.67	14.61±3.24

$^{*,a,c}P<0.05$, $^{aa}P<0.01$, In between group comparison – *compares NM. Whereas within-group comparison- ^{a}compares baseline, and ^{c}compares transmission. LTM: Long-term meditator, STM: Short-term meditators, SD: Standard deviation, NM: non-meditator

The log–log plot between the logarithmic value of DFA of the EEG signal alpha band and window size for the LTM group is shown in Figure 3; the slope is represented by the exponent α which represents the rate of change of intrinsic fluctuation. It is evident from the figure that the slope of the graph α reduces in meditation and transmission states as compared to baseline and postmeditation. Although the values are not significant, the reduction in the value of α represents a reduction in DFA values.

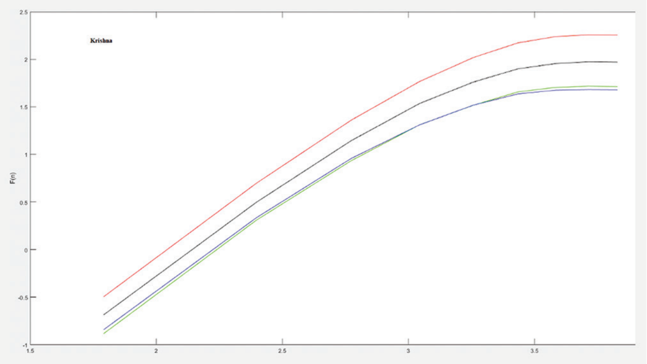

Figure 3: Log–log plot between intrinsic fluctuation and window size for α values of electroencephalogram signal for long-term meditators group during different states

Detrended fluctuation analysis of electrocardiogram

The results for ECG also showed a decrement in values during meditation, transmission, and posttransmission as compared to a baseline state. Repeated measure ANOVA results of DFA of the ECG neither showed any significant difference between group nor within-group effect ($F_{(2,28)} = 0.47$, $P > 0.05$, $\eta^2P = 0.032$ and $F_{(3,84)} = 0.996$, $P > 0.05$, $\eta^2P = 0.034$), respectively.

Log–log plot for electrocardiogram

The log–log plot between the logarithmic value of DFA of EEG signal alpha band and window size for the LTM group is shown in Figure 4. Here, the exponent α decreases during meditation and transmission state as compared to the baseline and transmission states.

Pearson's correlation among DFA values of EEG (left and right frontal lobe) and ECG signals is given in Figures 5-7. Positive correlation was found during meditation ($r = 0.59$; $P < 0.05$, $r = 0.52$; $P > 0.05$) and transmission ($r = 0.59$; $P < 0.05$, $r = 0.45$; $P > 0.05$) in the right and left frontal in the LTM group. Whereas during transmission in the STM group showed a positive correlation ($r = 0.78$; $P < 0.05$) in the right frontal, other states of STM and NM did show any correlation.

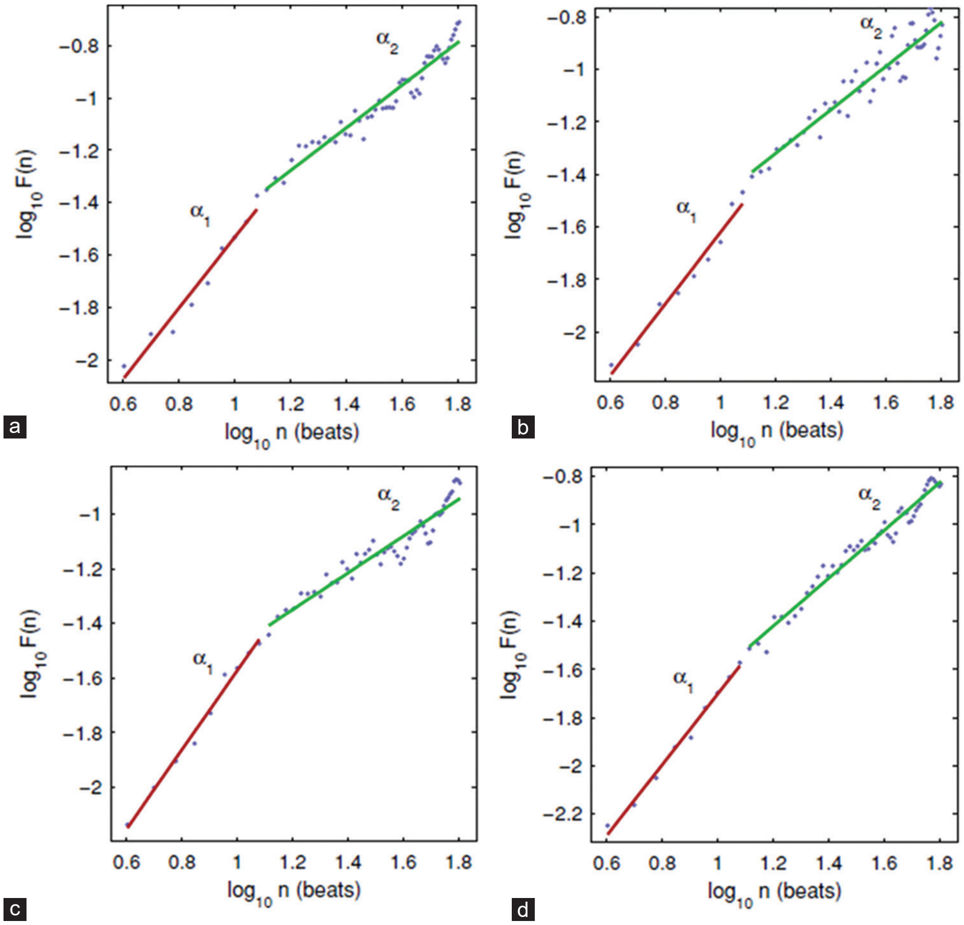

Figure 4: Log–log plot between intrinsic fluctuation and window size for α values of electrocardiogram signal for the long-term meditators group during different states: (a) baseline $\alpha_2 = 0.840$, (b) meditation $\alpha_2 = 0.783$, (c) transmission $\alpha_2 = 0.672$, and (d) posttransmission $\alpha_2 = 0.992$

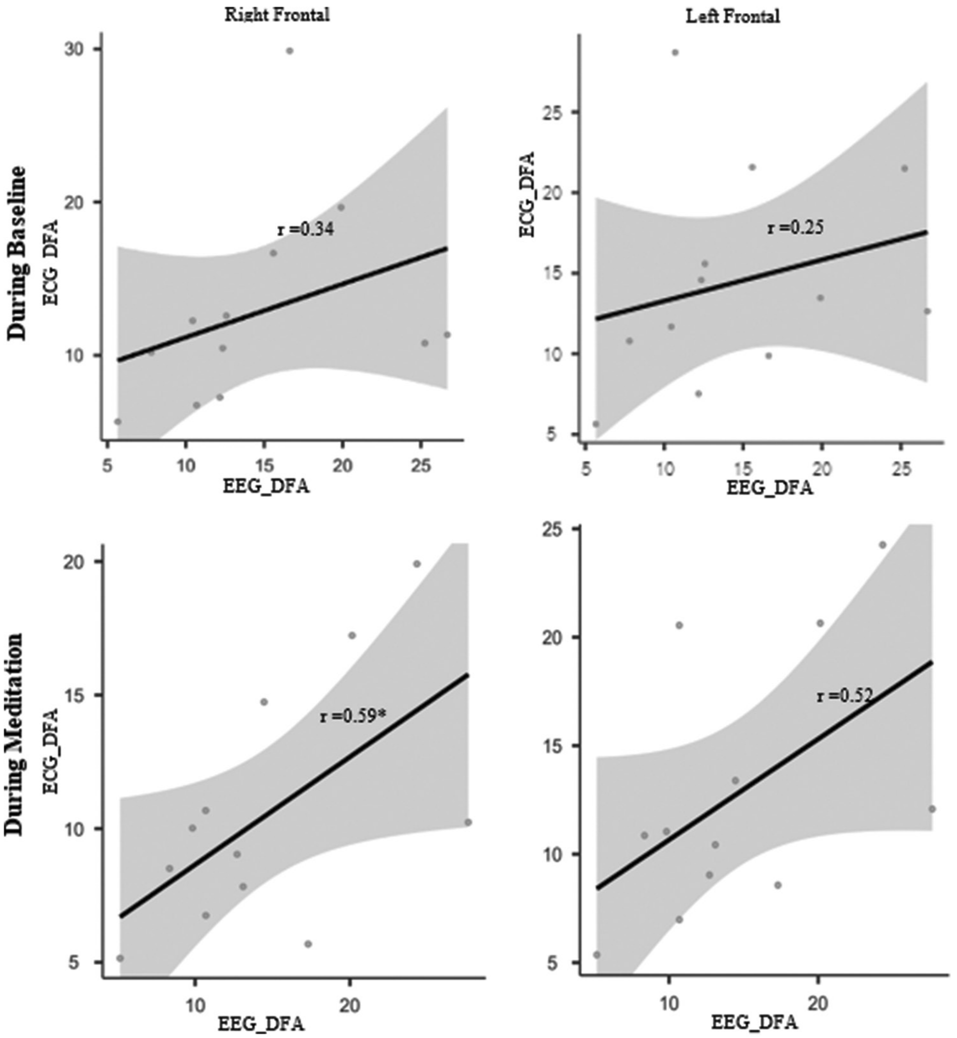

Figure 5: Correlation between detrended fluctuation analysis of electrocardiogram and electroencephalogram during baseline and meditation states in the long-term meditators group. DFA: Detrended fluctuation analysis, ECG: Electrocardiogram EEG: Electroencephalogram, LTM: Long-term meditators

The result shows an increment in correlation values in meditation, transmission, and posttransmission states as compared to baseline in the LTM group in both the hemispheres of the brain with a significance level of $P < 0.05$ in meditation, transmission, and posttransmission states in the right hemisphere. The STM group shows a slight increment in the correlation values which is not significant, whereas there is no correlation observed in the NM group.

Discussion

Last few decades, nonlinear parameters have been performed in meditation studies, but this is the first study that has achieved nonlinear parameters of ECG and EEG in HM. The present study found significant differences in the DFA values of ECG and EEG signals.

The within-group comparison showed that the significant reduction in the proficient meditators that indicates meditation has the potential to reduce the fluctuation of the frontal (right and left) lobe activities. Due to fewer inherent fluctuations in the EEG, the DFA values decrease, demonstrating the deeper intricacy of the physiological rhythms and improvement in the brain activity of meditators.[21] As expected, the control group did not show any significant changes during meditation.

Furthermore, group analysis showed significant differences in the LTM group that align with previous findings. Reduced DFA alpha of EEG shows that healthy brain activity is considered by long-term temporal correlations across cortical regions, facilitating decision-making and memory functions.[28] Previous scientific research has revealed the frontal lobe's decreased DFA alpha has been linked to neuromodulators, thalamic effects, and cingulate cortex activities.[29]

Neuromodulators are chemicals in the brain that influence the synaptic dynamics or intrinsic excitability of a neuron.[30,31] It balances the excitatory and inhibitory processes within the signal. Serotonin increases the

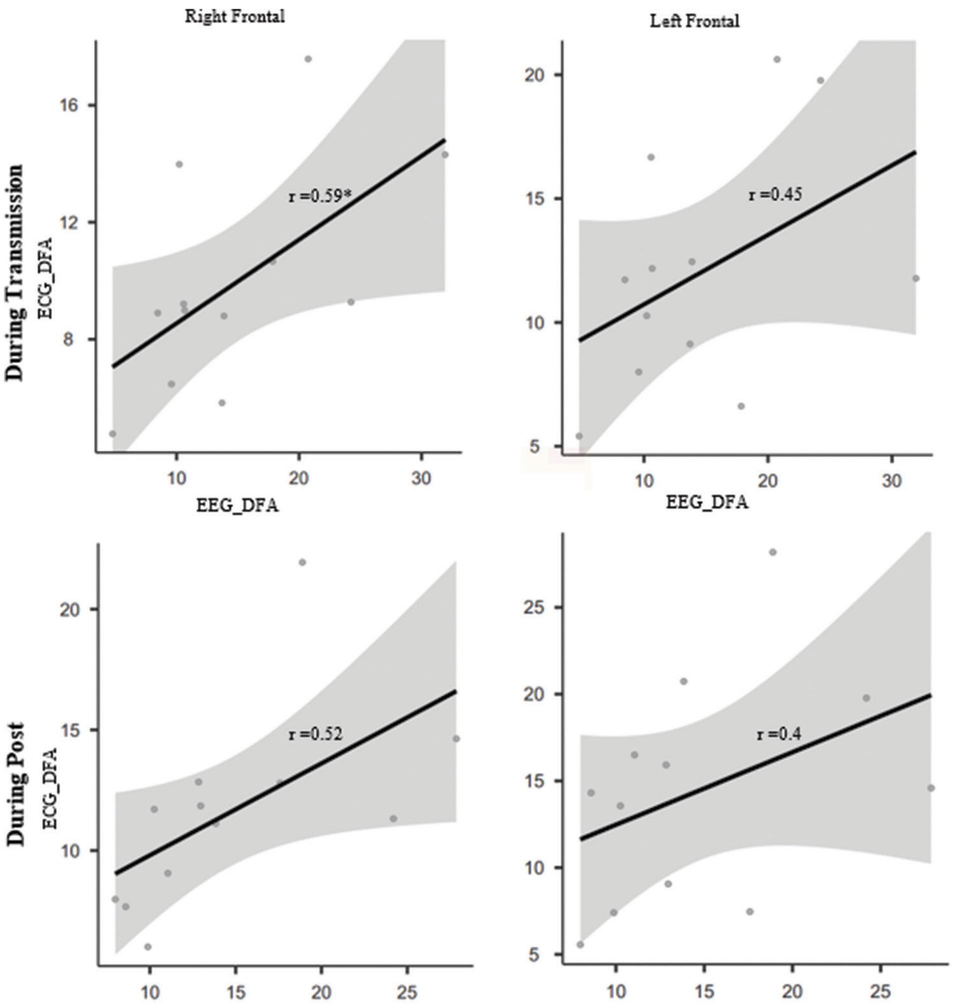

Figure 6: Correlation between detrended fluctuation analysis of electrocardiogram and electroencephalogram during transmission and post in the long-term meditators group. DFA: Detrended fluctuation analysis, ECG: Electrocardiogram EEG: Electroencephalogram

excitatory process has been observed during Zen practice, and gamma-aminobutyric acid (GABA) increases the inhibitory process as seen after mindfulness, vipassana meditation, and yoga practices.[32-35] Since GABA is elevated during meditation, neuronal dynamics are driven toward a subcritical domain with lower DFA alpha of EEG.

The thalamus is a crucial structure that controls information flow to brain regions involved in cognitive functions, including the neocortex, the hippocampus, and the basal ganglia.[36] Slow oscillations of thalamic activity have been found during focused meditation that may contribute to the reduction of DFA alpha of EEG.

The cingulate cortex comprises the anterior and posterior cortex where the anterior cortex is associated with emotion,[37,38] and the posterior cingulate cortex is involved in internalized attention and metabolically active brain region.[39] Numerous research has shown that practicing meditation increases cingulate cortex activity, which helps to regulate neuronal fluctuations and balance emotions.[40,41] Previous studies reported that contemplating the heat is to reduce anxiety and deepens meditation with relaxation.[42,43]

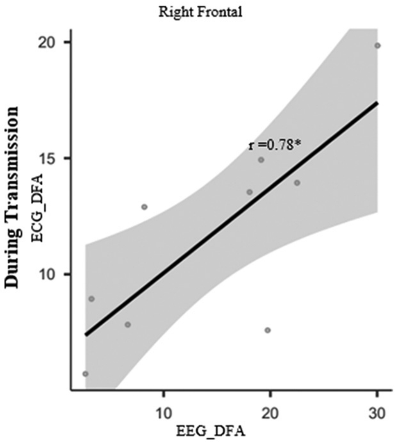

Figure 7: Correlation between detrended fluctuation analysis of electrocardiogram and electroencephalogram during transmission in the short-term meditators group. DFA: Detrended fluctuation analysis, ECG: Electrocardiogram EEG: Electroencephalogram

The DFA alpha of ECG was found to be lower in meditation and transmission. However, the statistical analysis did not show any significance. Ancient Indian Literature claims that the mind recedes in the heart and regulates the brain functions. The results of the present study claim that contemplating on the heart can regulate the brain wave fluctuations. It also showed a positive synchronization between heart and brain during meditation and transmission which indicates meditation improves synchronicity of heart and brain activities. Synchronized heart–brain may facilitate emotional stability, attention, memory, learning capacity, comprehension, and overall well-being.[44,45] The present study outcomes align with the previous study's report that meditation regulates the chaotic activities of the heart and brain.[25] Meditation influences both the autonomic and central nervous systems and enhances body–mind coordination. It might be due to the vagal nerve which plays a central role in brain–heart synchronization.[46] Scientific research has also highlighted the importance of central nuclei, which are located in the brainstem and include the nucleus of the solitary tract. These nuclei are involved in processing respiratory and cardiovascular data, which helps to synchronize heart and brain activity.[45,47] These scraps of evidence show that HM practice has the potential to influence the heart and brain to maintain practitioners' health. Heart–brain rhythmic synchronization illustrates the complex relationship between the cardiovascular and central neurological systems. This phenomenon has the potential to improve our understanding of human physiology, mental health, and prospective therapies. As research progresses, we will certainly get a better understanding of the mechanisms driving this synchronization and its larger implications for human well-being.

However, the present study has certain limitations also; the sample under consideration was small which limits the generalization. Other nonlinear techniques such as correlation dimension, entropy, and Hurst exponent can be employed to support the findings of the study. Other limitations are discomfort caused to the meditators due to EEG setup, clinical history of participants, and heterogeneity in practice, which were not considered in this study.

Conclusion

According to the examination of the ECG and EEG data, it is clear that long-term HM practice may lead to a decreased value of DFA in the ECG and EEG signals, which denotes a decrease in intrinsic fluctuation and an improvement in the function of the brain and heart. In comparison to NM, continued HM practice may lead to improved heart and brain coordination. All groups of meditators (LTM, STM, and NM) were found to benefit from the yogic transmission component of HM practice. Therefore, it may be inferred from the results of the current study that DFA, a nonlinear parameter, can be used to measure meditation practice. This study also demonstrates the beneficial effects of HM practice on cardiac and brain function, which can be further investigated using other nonlinear factors.

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Ethical clearance

The institutional ethics committee of Swami Vivekananda Yoga Anusandhana Samasthana, Bangalore, approved the study "RES/IEC-SVYASA/164/1/2020."

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Conflicts of interest

There are no conflicts of interest.

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