Fuzzy entropy as a measure of EEG complexity during Rajayoga practice in long-term meditators

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***Abstract*— Effects of meditation on electroencephalographic (EEG) activity are still being investigated despite decades of research. Neurophysiological correlation during meditation has been empirically postulated using different time and frequency domain entropy features of EEG. EEG has been recorded from fifteen Rajayoga meditators practiced by Prajapita Brahmakumaris World Spiritual University. Most of the meditators have shown increase in time domain fuzzy based entropy in frontal region during meditation. We have compared the data recorded during the peace and angelic meditation practices. The mean of the entropy values in each state is used to study the meditation and non-meditation states. Analysis has been carried out region wise. The frontal region shows significant increase in the entropy values during the meditative states.**

Keywords—Entropy, fuzzy entropy, meditation, Rajayoga, EEG

I. Introduction

Not much is known about the process and impact of meditation on the brain. Previous studies show that wavelets are effective in analyzing EEG data. Wavelet based analysis of EEG is employed in [1] to study the effects of meditation and in [2], for epileptic seizure detection. Wavelet packet log entropy is used in [3] for epileptic and normal EEG classification. The analysis of meditation EEG is discussed in [1], [4] and [5]. A great amount of work has already been published using spectral analysis of EEG in meditators. Alzheimer’s disease, epilepsy and anesthesia have been studied using entropy measures [7]. It is suggested that entropy is suppressed in normal waking consciousness, meaning that the brain operates just below criticality [7]. This further indicates that the elevated states of consciousness, in which metacognitive functions and self-awareness are above normal, are associated with high entropy.

Brain activation in many networks in terms of low alpha and delta frequency was reported by Sharma et. al [8] during seed stage meditation under Rajayoga practice. Higher parietal and frontal cortical asymmetry and increased band power in theta and alpha frequencies was observed in the study conducted by Sharma et. al [9]. Cardiosympathetic activation during Rajayoga meditation practice resulting in increased heart rate which is a psychophysiological arousal sign was reported by Telles et. al [10]. However, study conducted by Sukhsohale et. al [11] reported decrease in heart rate along with decrease in diastolic and systolic blood pressure and respiratory rate suggesting improved cardiovascular parameters due to arousal in sympathetic system during Rajayoga practice. Study by Telles et. al [12] on Rajayoga practice showed peak latency decrease in a negative component of the middle latency auditory evoked potentials during meditation. Enhanced white matter integrity in corpus callosum segments was observed by Sharma et. al [13] in meditators as compared to controls in a neuroimaging study. Interrelationships between the channels in the frontal lobe have been observed to be uniform during meditation resulting in decreased mean and variance of the distance between covariance matrices of successive epochs of the EEG [14]. In the current work, EEG recorded during meditation under Rajayoga practice has been analyzed. The meditation is practiced with eyes open, which makes Rajayoga practice unique among other meditation techniques. An attempt is made to understand the changes in the neural activity of the brain during meditative states by extracting time-domain features based on entropy. The entropy features have been used to compare the meditating with the non-meditating states.

II. Dataset Descripion

A. *Subject Selection*

EEG data collected from fifteen healthy right-handed subjects [15] practicing Rajayoga meditation regularly for a period of more than 10 years (age 30-52 years, mean 43.9 (SD=3.96) years) is used in this study. With a record of regular practice, these meditators have spent 11-17 years in practicing this technique after learning the same. At the time of recording the EEG data, the total number of hours spent in meditation ranged from 4000-7200 hours throughout their life. The subjects did not have any history of cardiac, pulmonary and other nervous system dysfunctions. The experimental procedures were explained to the subjects. Written information consent was obtained from each subject. It was confirmed that the subjects did not consume alcohol, cigarette or any therapeutics within the last six months.

B. *Experiment Protocol*

EEG data was recorded using ANT Neuro amplifier and EEGO software employing the 64-channel waveguard cap. The electrode placement in waveguard cap follows the international 10-10 system. The signal was recorded at a sampling frequency of 1024 Hz. EEG signals were later digitally filtered at 0.5-75 Hz. The subjects were asked to sit straight on a floor mat, making sure that the body was not touching the ground during the whole recording session.

Baseline (BL) recording was carried out for approximately 3 minutes, when the subjects were asked to relax with their eyes open before meditation. BL was followed by the peaceful soul consciousness state of meditation (PM), wherein the subjects meditated by focusing their attention on the positive thought about themselves as peaceful souls. This lasted for around 10 minutes. This was followed by another intermediate baseline (IBL) for 3 minutes. After IBL, subjects were asked to delve themselves into angelic state of meditation (AM) for 10 minutes, where they are supposed to attain a blissful state. A final baseline (FBL) was recorded for 3 minutes as given in Fig 1. Soul conscious state is aimed to be attained during peace meditation, while the progression of soul conscious state is aimed to be attained during the angelic meditation. The fundamental difference between these two states is believed to be due to self-observing experience in PM and the state of being detached from the physical body, its sensual pleasures, relationships, and material assets [16].

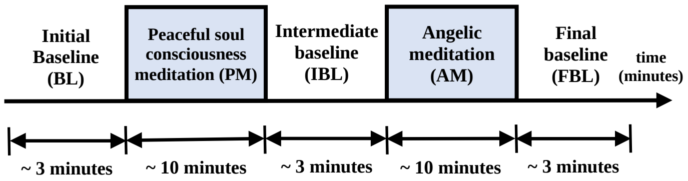

Fig. 1. Experimental Protocol: 3 minutes of initial baseline (BL) followed by 10 minutes of peaceful soul consciousness state meditation (PM), 3 minutes of intermediate baseline (IBL), 10 minutes of angelic state meditation (AM) and 3 minutes of final baseline (FBL).

C. Preprocesing

The collected EEG data was subjected to line noise (50 Hz) removal using a notch filter. Further, a band pass filter (0.5 – 45 Hz) was used and independent component analysis (ICA) was performed using runica algorithm in EEGLAB v 13.4 [17]. Components with eye movements, muscle artifacts and electrode popping were removed to make the data artifact-free. After preprocessing, data from only 14 subjects was considered for further analysis. One subject data was dropped out of final analysis due to excessive eye movement and bad quality. Data of each subject is grouped into broader groups namely frontal, frontocentral, centroparietal, occipital and temporal (see Fig. 2). Both temporal right and left are grouped as temporal.

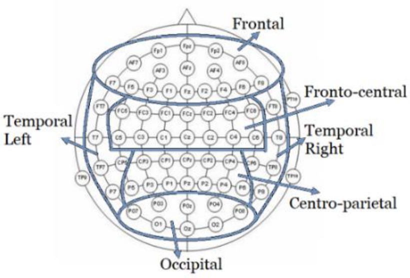

Fig. 2. 10-10 system electrode placement of 64 channels and grouping of the electrodes to form broader regions considered for the proposed analysis.

III. Methodology

In the statistical sense, entropy of EEG in the time domain quantifies the amount of randomness or uncertainty in the signal pattern, also equivalent to the amount of information available in the signal. Time domain measurement of entropy involves dividing the signal into smaller segments that are compared for similarity. The measurement of entropy has some implicit assumptions on what aspect of the signal is important to quantify or is meaningful. The distance between vectors formed in each segment in the time domain has also been used by some researchers as entropy measures. In our work, fuzzy entropy is used to analyze the amount of randomness in EEG across different meditating and non-meditating states.

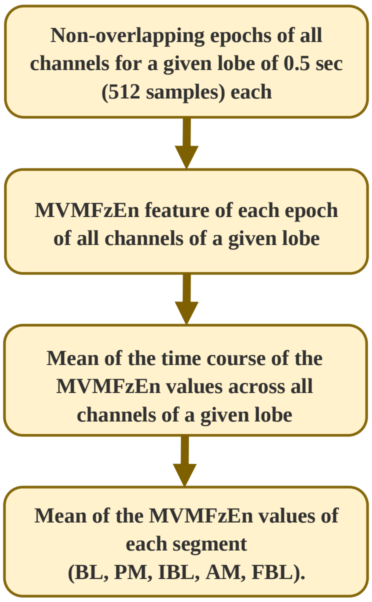

Fig. 3. The flowchart for calculating MVMFzEn features. Non-overlapping epochs of 512 samples each were extracted from all the channels and MVMFzEn values were calculated. Average of the time course values of entropy was obtained across all the channels for a given lobe. Mean of the averaged time course entropy values was calculated.

A. Modified Fuzzy Entropy (MFzEn)

Figure 3 shows the flowchart of the processing carried out to extract the features desired. Modified fuzzy entropy was calculated for every channel of each segment. The resulting time course of the entropy values of all the channels is given below [18][19]. The artifact-free multichannel EEG is divided into non-overlapping epochs of 0.5 sec each as

$$X^k = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,N} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,N} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ x_{M,1} & x_{M,2} & \cdots & x_{M,N} \end{bmatrix}$$

Here, k is the epoch number, M is the number of channels, and N is the number of samples. Relative energy function given in (1) is used to obtain Ψ^k.

$$\Psi^k = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,N} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,N} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ p_{M,1} & p_{M,2} & \cdots & p_{M,N} \end{bmatrix}$$

$$p_{i,j} = \frac{|x_{i,j}|^2}{\sum_{j=1}^{N} |x_{i,j}|^2} \quad (1)$$

Equation (1) maps the finite set of samples $x_{i,j}$ values between 0 and 1.

The MFzEn vector denoted as h^k is obtained using the relative energy as a new membership function as given below.

$$h_i^k = -C \sum_{j=1}^{N} \{p_{i,j}\, log(\, p_{i,j}) + (1 - p_{i,j})\, log(\, 1 - p_{i,j})\} \quad (2)$$

resulting in a vector of length equal to number of channels for each epoch. The C value was chosen as 1 rather than $\frac{1}{N}$ to avoid precision error.

B. *Minimum Variance Modified Fuzzy Entropy (MVMFzEn)*

After estimation of MFzEn (h^k), a scaling operation is introduced to increase the difference between meditative and non-meditative states, referred as MVMFzEn by concatenating all the vectors h^k of K epochs to form a matrix H for each segment namely BL, PM, IBL, AM and FBL as given below.

$$H = \begin{bmatrix} h_1^1 & h_1^2 & \ldots. & h_1^K \\ h_2^1 & h_2^2 & \ldots. & h_2^K \\ : & : & & : \\ : & : & \ldots. & : \\ h_M^1 & h_M^2 & \ldots. & h_M^K \end{bmatrix}$$

$$H_{new} = \begin{bmatrix} h_{1new}^1 & h_{1new}^2 & \ldots. & h_{1new}^K \\ h_{2new}^1 & h_{2new}^2 & \ldots. & h_{2new}^K \\ : & : & & : \\ : & : & \ldots. & : \\ h_{Mnew}^1 & h_{Mnew}^2 & \ldots. & h_{Mnew}^K \end{bmatrix} \quad \text{where}$$

$$h_{inew}^k = \frac{h_i^k}{min(h_i^1, h_i^2, \ldots, h_i^K)} \quad (3)$$

and MVMFzEn is calculated as defined in (4)

$$H_{MVMFzEn} = \begin{bmatrix} z_1^1 & z_1^2 & \ldots. & z_1^K \\ z_2^1 & z_2^2 & \ldots. & z_2^K \\ : & : & & : \\ : & : & \ldots. & : \\ z_M^1 & z_M^2 & \ldots. & z_M^K \end{bmatrix} \quad \text{where}$$

$$z_i^k = \frac{|h_{inew}^k|^2}{var(h_{inew}^1, h_{inew}^2, \ldots, h_{inew}^K)} \quad (4)$$

The time course MVMFzEn values are averaged across all the channels to obtain a row vector for which the mean is calculated for a given subject.

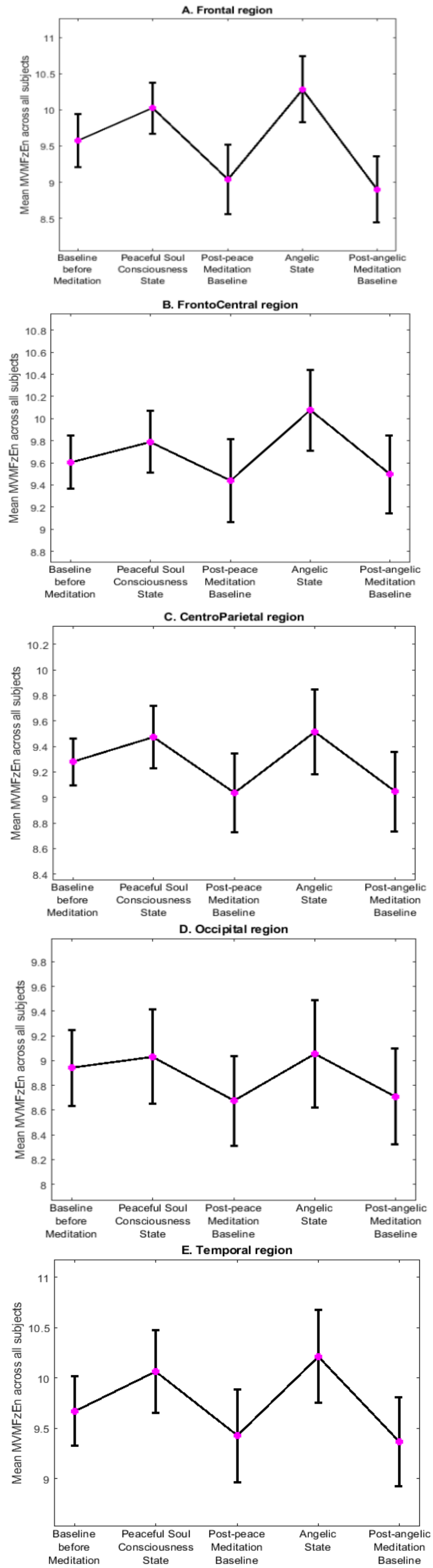

Fig. 4. Mean MVMFzEn values across the subjects with standard error of mean (SEM). (A) Frontal region, (B) Frontocentral region, (C) Centroparietal region, (D) Occipital region, (E)Temporal region.

IV. Results

The modified fuzzy entropy analysis showed higher irregularity during meditative states than during the non-meditating states, which may imply an increase in the signal complexity during meditation as shown in Fig 4. Changes in the entropy values in the frontal region were more statistically significant than in other regions and hence the statistical significance results of the frontal region only are reported here. The study conducted by Vivot et.al [20] has reported increase in the entropy during Vipassana meditation in alpha and gamma bands. Another study by Venugopala et.al. [21] has reported decrease in the permutation entropy during insight meditation. The frontal lobe is involved in the execution of behavioral responses and complex mental responses to environmental challenges. It is also considered to represent the internal states and accumulate external information [22][23]. As compared to other lobes, higher significance in frontal lobe to be investigated in future.

Comparing the results reported in the present work with the available literature is difficult, given that there are very few antecedents of scientific papers investigating the fuzzy entropy measures for meditation data. A primary source of confusion is the difference in the traditions of meditation types that are investigated. Also, the neuronal activity during meditation is confounded by many factors and hence the results may not be consistent with other meditation methods.

The non-parametric Wilcoxon tests revealed that the proposed entropy increased in the frontal lobe during the meditative states as given in Table I with z-values and Table II with p-values.

TABLE I. z-values of frontal lobe compared with all the meditating and non-meditating states.

	PM	IBL	AM	FBL
BL	-1.6008	-1.538	-2.103	-2.668
PM		-3.0447	-0.9103	-2.7936
IBL			-2.668	-0.6592
AM				-2.7936

TABLE II. p-values of frontal lobe compared with all the meditating and non-meditating states.

	PM	IBL	AM	FBL
BL	.0548	.06178	.01786	.00379
PM		.00118	.18141	.00264
IBL			.00379	.25463
AM				.00264

Non-linear analysis study by Aftanas et. al [24] reported the changes in midline frontal and central regions during Sahaja Yoga meditation. In our study, centroparietal region was observed to be the next statistically significant after frontal region as shown by Fig 5.

V. Conclusion

In summary, peace and angelic meditations, practices under the tradition of Rajayoga meditation, resulted in increased time domain entropy of the EEG recorded from the frontal region of the brain. Consistent with the work reported by Vivot et. al. [20], our study provides an example of a non-pharmacologically induced brain state of high entropy. Future research should include frequency band-wise entropy analysis and address whether these 'endogenous' increases in EEG entropy are due to the long-term positive effects that certain meditative traditions can have on mental and physical health.

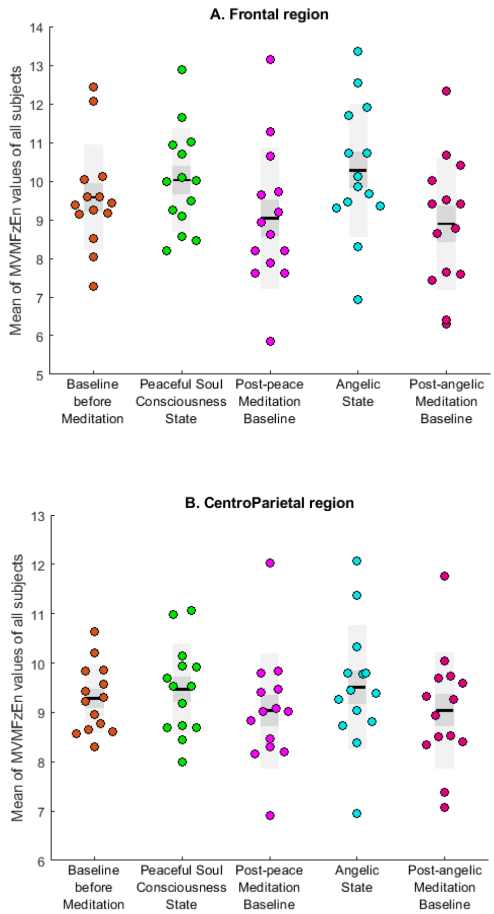

Fig. 5. Univariate scatter plot of all the meditative and non-meditative states of all the subjects (14 points in each state). Black horizontal line represents the mean, dark grey box represents the SEM and light grey box indicates the standard deviation. (A) Frontal region (B) Centroparietal region.

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REFERENCES

[1] Chang, K. M., & Lo, P. C. "Meditation EEG interpretation based on novel fuzzy-merging strategies and wavelet features. Biomedical Engineering: Applications", *Basis and Communications*, 17(04), 167-175, 2005.

[2] Adeli, H., Zhou, Z., & Dadmehr, N. "Analysis of EEG records in an epileptic patient using wavelet transform". *Journal of neuroscience methods*, 123(1), 69-87, 2003.

[3] Raghu, S., Sriraam, N., & Kumar, G. P. "Classification of epileptic seizures using wavelet packet log energy and norm entropies with recurrent Elman neural network classifier". *Cognitive neurodynamics*, *11*(1), 51-66, 2017.

[4] Banquet, Jean-Paul. "Spectral analysis of the EEG in meditation." *Electroencephalography and clinical neurophysiology* 35.2, 143-151, 1973.

[5] Takahashi, Tetsuya, et al. "Changes in EEG and autonomic nervous activity during meditation and their association with personality traits." *International Journal of Psychophysiology* 55.2, 199-207, 2005.

[6] Giannakakis, G., Sakkalis, V., Pediaditis, M., Farmaki, C., Vorgia, P., & Tsiknakis, M. "An approach to absence epileptic seizures detection using approximate entropy". *35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 413-416). IEEE., 2013.

[7] Carhart-Harris, R. L., Leech, R., Hellyer, P. J., Shanahan, M., Feilding, A., Tagliazucchi, E., Dante R L., Nutt, D. "The entropic brain: a theory of conscious states informed by neuroimaging research with psychedelic drugs". *Frontiers in human neuroscience*, *8*, 20, 2014.

[8] Sharma, K., Achermann, P., Panwar, B., Sahoo, S., AG Ramakrishnan, Pascual-Marqui, R. D., & Faber, P. "Brain-electric activity during eyes open Brahma Kumaris Rajayoga meditation", *mindrxiv.org*, 2020.

[9] Sharma, K., Chandra, S., & Dubey, A. K. "Exploration of lower frequency EEG dynamics and cortical alpha asymmetry in long-term rajyoga meditators", *International Journal of Yoga*, *11*(1), 30, 2018.

[10] Telles, S., & Desiraju, T. "Automatic changes in Brahmakumaris Raja yoga meditation", *International Journal of Psychophysiology*, *15*(2), 147-152, 1993.

[11] Sukhsohale, N. D., & Phatak, M. S. "Effect of short-term and long-term Brahmakumaris Raja Yoga meditation on physiological variables", *Indian J Physiol Pharmacol*, *56*(4), 388-92, 2012.

[12] Telles, S., & Naveen, K. V. "Changes in middle latency auditory evoked potentials during meditation", Psychological Reports, 94(2), 398-400, 2004.

[13] Sharma, K., Trivedi, R., Chandra, S., Kaur, P., Kumar, P., Singh, K. & Khushu, S. "Enhanced white matter integrity in corpus callosum of long-term Brahmakumaris Rajayoga meditators", *Brain connectivity*, *8*(1), 49-55, 2018.

[14] AG Ramakrishnan, KG Pradeep, Sharma K. "Characterization of meditation EEG based on consistency of covariance matrices over time", *Proc. IEEE 17th India Council International Conference (INDICON)*, Dec. 11-13, 2020, to be published.

[15] Sharma, K., "Attention networks in long term Rajayoga meditators". *Ph D thesis, University of Delhi*, 2019.

[16] Dadi Janki, "Attaining angelic attributes By Brahma Kumaris". Available:https://www.soulveda.com/spiritual-leader/attaining-angelic-attributes/

[17] Makeig, S., "Matlab toolbox for analysis of electrophysiological data", 1997.

[18] Raghu, S., Sriraam, N., Kumar, G. P., & Hegde, A. S. (2018). "A novel approach for real-time recognition of epileptic seizures using minimum variance modified fuzzy entropy". *IEEE Transactions on Biomedical Engineering*, 65(11), 2612-2621, 2018.

[19] Al-Sharhan, Salah,. "Fuzzy entropy: a brief survey." *10th IEEE International Conference on Fuzzy Systems.(Cat. No. 01CH37297)*. Vol. 3. IEEE, 2001.

[20] Vivot, R. M., Pallavicini, C., Zamberlan, F., Vigo, D., & Tagliazucchi, E., "Meditation increases the entropy of brain oscillatory activity". *Neuroscience*, *431*, 40-51, 2020.

[21] Venugopala RJ, Sasidharana A, Naira AK, Kutty BM, Ghosh PK "Permutation entropy as a complexity measure of EEG time series in Vipassana meditators". *23rd EEGLAB Workshop Jan 16–20 AIISH*. Mysuru, 2017.

[22] Case, R. The role of the frontal lobes in the regulation of cognitive development. Brain and cognition, 20(1), 51-73, 1992

[23] Fuster, J. M. Cognitive functions of the frontal lobes. In B. L. Miller & J. L. Cummings, (Eds.), The Human Frontal Lobes. New York: Guilford Press, 1999

[24] Aftanas. L. I & Golochekine. S. A. "Non-linear dynamic complexity of the human EEG during meditation". Neuroscience letter, 330(2), 143-46, 2002.