Combined Recurrence and Cross Recurrence Quantification of MCI EEG

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Abstract—The present study is aimed at characterizing the EEG dynamics of the Mild cognitive impairment (MCI) subjects compared to that of normal controls using Recurrence Quantification Analysis (RQA) and Cross Recurrence Quantification Analysis (CRQA). EEG from MCI and control subjects are recorded under resting eyes closed (EC) condition. Recurrence rate of RQA and CRQA are calculated for the signals from both groups. RQA method quantifies the regularity/complexity signals and CRQA method quantifies the similarities between the two signals. The CRQA analysis of EEG is carried out for signals between the channels from different lobes. These two measures are combined in a feature space. The clear distinction of the two groups is obtained using this method of combined RQA and CRQA measures.

Keywords—Alzheimer’s Disease; Mild Cognitive Impairment; EEG; Cross Recurrence Quantification Analysis.

I. INTRODUCTION

Dementia is one of the major disorders that affect a majority of the geriatric population in any society. Alzheimer’s Disease (AD) is the most common form of dementia and is characterized by the progressive impairments in memory and cognition. Mild cognitive impairment (MCI), is a condition usually presented with memory problems greater than what is expected for that age, but not serious enough to disturb daily activities [1]. Generally, MCI is considered as the early stage of AD. Hence preclinical discrimination of MCI and normal subjects is of crucial importance for prevention of further disease progression. AD and MCI are cortical disorders, and hence are expected to be associated with changes in electrical activities of the brain. The most general and simple technique of studying these electrical activities is the electroencephalogram (EEG). The simplicity of administration, noninvasiveness and commercial viability of EEG attracts much attention towards use of this technique for the clinical detection of AD and MCI. Such studies have gained much importance in the past few decades [2], [3].

Conventional linear analysis of AD EEG have identified the characteristic features of a shift to low frequency regime and decrease in coherence between signals of different cortical region [4], [5]. Significant difference in theta power of EEG is observed between MCI and control subject [6]. Altered functional connectivity between different cortical regions of MCI subjects are also indicated by the reduced coherence during resting as well as working memory state [7].

Nonlinear dynamical systems are also characterised by EEG analysis and has been successfully applied to different pathological conditions [2]. Reduced complexity of AD EEG compared to that of controls is identified using conventional nonlinear measures like correlation dimension and Lyapunov exponent [8], [9]. Such conventional nonlinear measures are sensitive to nonstationarity, noise contamination and short data length and reduce their applicability for the analysis of real world signals.

Recurrence plot based analysis are found to be highly efficient for the study of nonlinear systems, and are found to be suitable for short nonstationary signals [10]. An extension of the method of recurrence plots to cross recurrence plots enables the investigation of the time dependent behaviour of two processes. Recurrence quantification analysis (RQA) provides various measures for the characterisation of complex system dynamics from the time series of its variables. Similarly cross recurrence quantification analysis (CRQA) provides quantitative measures for the interrelation between two systems as inferred from their time series.

Both RQA and CRQA methods are widely applied for dynamical characterisation and synchronisation studies of different real world systems [11], [12]. Both linear and nonlinear approaches of EEG analysis of AD and MCI are generally carried out either based on the complexity information or that of synchronisation. Here we propose to study both these aspects of MCI EEG using a common platform of recurrence based analysis.

II. METHODS

A. RQA and CRQA techniques

Recurrence and cross recurrence analysis are carried out on the reconstructed trajectory of a given dynamical system. Reconstruction of trajectory is performed on the basis of delayed embedding and the analysis is carried out for obtaining the dynamical characteristics. RQA provides several quantitative measures of dynamical complexity from a given signal. Among these, the recurrence rate (RR) provides a direct measure of self similarity of the system. It measures the percentage of recurrence points falling within a specified radius in the state space and value can range from 0 to 1 indicating 0 to 100% of recurrence points. The CRQA is a bivariate extension of RQA and measures the recurrence of state points between the trajectories of any given systems where in both time series are to be embedded in the same phase space.

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The CRQA also provides several quantitative measures for the interdependence of two systems. The recurrence rate of CRQA measures the percentage of recurrent points between the two trajectories falling within a specified radius.

\[
RR(t) = \frac{1}{N-t} \sum_{l=1}^{N-t} P_r(l)
\]  

(1)

where \(P_r(l)\) is the probability of occurrence of similar states in both systems with a given delay \(t\).

B. Subjects

Fourteen MCI patients with mean age 67.07 ± 7.2 years, participated in the study. Fourteen age matched elderly subjects with mean age 65.07 ± 5.6 years formed the control group. Control and MCI groups consisted of three and five females respectively. All participants were right handed and native language speakers and had normal or corrected to normal vision. The mean Mini Mental State Examination (MMSE) score of the MCI group is 26.21 ± 1.4 and that of the control group is 30. All control and MCI subjects were volunteers. All the control subjects gave informed written consent to participate in the study. Care-givers of MCI patients also gave informed written consent of participation of their wards in the study with full knowledge of the nature of the procedure. The Medical Ethical Committee of Welcare Hospital approved the study.

Diagnostic testing of MCI was performed by clinical evaluation, biochemical screening, radiological and neuropsychological testing. The MCI subjects enrolled for the study were affected only in the memory domains while attention, language and other cognitive functions were normal. None of the MCI or control subjects were on psychoactive drugs.

Inclusion criteria for the patient group were (i) subjective memory complaint as per medical history (ii) independent activities of daily living as per the information provided by the care-givers (iii) normal general cognitive performance other than memory loss (iv) no dementia according to DSM IV (Diagnostic and statistical manual of mental disorders, IVed.) criteria (v) absence of psychiatric history (vi) a cut off of MMSE ≥ 24. Exclusion criteria were (i) history of head trauma (ii) substance abuse (iii) seizure/epilepsy (iv) delirium (v) dementia (vi) clinical signs of anxiety or depressive illness (vii) focal lesions in gray or white matter on radiological evaluation.

C. Experimental protocol

EEG was recorded under eyes closed (EC) resting condition. Five minutes of EEG recording were closed when the subjects are in resting EC state. The subjects were seated in an armchair in a semi reclined position. EEG were recorded from 19 electrode sites according to the international 10-20 system and separate ear electrodes A1 and A2, with electrodes referenced to linked ear lobes. EEG was recorded using Neurocare Digital Wingraph EEG system with sampling frequency of 128 Hz and 16 bit A to D conversion. The recorded EEG was digitally filtered with a band pass filter of cut-off frequencies at 0.4 and 60Hz

All EEG were visually inspected by a specialist physician for eye movement and muscle artifacts. Artifact free epochs of 10s duration are chosen and stored in a pc for further off-line analysis using RQA and CRQA. RQA RR of each of the artifact free epochs is calculated for each of the channels F3,F4,F7,F8 from frontal, T3,T4,T5,T6 from temporal, C3,C4,P3,P4 from parietal and O1, O2 from occipital lobes. As the fronto-polar channels FP1 and FP2 are the most affected ones by even eye-ball movements, these two channels are not included in the study and only artifact free epochs from other channels are used for analysis. Average value of RQA RR of all the epochs for each of these channels are calculated for the analysis.

Cross recurrence rate (CRQA RR) between corresponding epochs of every pair of channels is calculated. For every pair of channels, these values are averaged over all the epochs. The synchronisation analysis using cross RR is carried out on inter lobar level. To analyse the synchronisation properties between the different lobes, the cross recurrence rate is averaged for all the pairs of the electrodes between all pairs of lobes viz. frontal, temporal, parietal and occipital. The cross RR values are averaged for every pair of channels between the chosen pair of lobes. For example, in the case of frontal-temporal inter lobar analysis the cross RR is averaged over all the pairs of channels from frontal (F3, F4, F7, F8) and temporal (T3, T4, T5, T6). This is repeated for all pairs of lobes: Frontal-Temporal (FT), Frontal-Parietal (FP), Frontal-Occipital (FO), Temporal-Parietal (TP), Temporal-Occipital (TO), Parietal-Occipital (PO).

D. Statistical Analysis

SPSS for windows is used for statistical analysis. Multivariate ANOVA is applied to RQA RR different electrodes of RQA RR and CRQA RR for different pairs of lobes. RQA RR of each electrode and inter lobar CRQA RR of measure was used for further analysis and the statistical analysis is carried out on the RR of RQA and CRQA of EEG from the resting eyes closed (EC) condition.

III. RESULTS AND DISCUSSION

MANOVA (Table I) revealed statistically significant difference between RQA RR of MCI and controls in all channel except C3, P3 and P4. Fig. 1a and 1b show the scalp maps of RQA RR of MCI and Control groups for all the electrodes. From the figure it can be clearly observed that the RQA RR values of MCI group are globally higher than the control group.

RQA RR is a measure of probability of recurrence of particular state of a given system. Hence higher values of RR indicate that similar states are repeated more often in the reconstructed trajectory. This further indicates the increased regularity in the underlying dynamics. Statistically significant higher values of MCI group confirm the increased regularity or lowered complexity of the cortical dynamics of the MCI group. The results are in agreement with earlier finding of lowered complexity in the cortical dynamics of MCI which is suggestive of inactivation of previously active networks and/or loss of connectivity of cortical networks [2], [3].
MANOVA (Table I) revealed statistically significant difference between CRQA RR of MCI and controls in all pairs of lobes. Fig. 2 shows the cross RR values for the inter lobar CRQA analysis of MCI group for the different lobes. Fig. 2a shows the inter lobar CRQA RR for the frontal lobe with all other lobes. Similarly Fig. 2b-d shows the inter lobar CRQA RR for temporal, parietal and occipital lobes. Fig. 3a-d shows the cross RR values for the inter lobar CRQA analysis of control group for frontal, temporal, parietal and occipital lobes with all other lobes.

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<tr>
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<th>RQA RR</th>
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<tr>
<td>P &lt; 0.05</td>
<td>P &lt; 0.005</td>
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<td>F3</td>
<td>F7</td>
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Fig. 2. The inter lobar CRQA RR of MCI group for a) frontal lobe b) temporal c) parietal and d) occipital lobes with all other lobes

Fig. 1. Scalp maps of RQA RR of (a) MCI and (b) control groups for all the electrodes

CRQA RR quantifies the similarity between the phase space trajectories reconstructed from two signals. It is a measure of probability of the occurrence of similar states in two systems. This indicates the level of synchronization between a given pair of signals. Higher values of CRQA RR indicate higher probability of occurrence of similar states between a given pair of systems. Thus significantly higher values of inter lobar CRQA RR of MCI group indicates increased similarity between the dynamics of any two given cortical regions.

Fig. 3. The inter lobar CRQA RR of control group for a) frontal lobe b) temporal c) parietal and d) occipital lobes with all other lobes.

Fig. 4a-c shows the feature space of RQA RR of frontal region with the CRQA RR of frontal-temporal, frontal-parietal and frontal-occipital lobe pairs respectively. Fig. 5a-c shows the feature space of RQA RR of temporal lobe with the corresponding CRQA RR values. Similarly fig. 6a-c and fig. 7a-c shows the feature space for RQA RR and CRQA RR for parietal and occipital lobes respectively.

Fig. 4-7 show clear separation between the control and MCI subjects in each of these feature spaces.
Fig. 4. The feature space of RQA RR of frontal lobe with the CRQA RR of a) frontal-temporal, b) frontal-parietal and c) frontal-occipital lobe pairs respectively.

Fig. 5. The feature space of RQA RR of temporal lobe with the CRQA RR of a) temporal-frontal, b) temporal-parietal and c) temporal-occipital lobe pairs respectively.

Fig. 6. The feature space of RQA RR of parietal lobe with the CRQA RR of a) parietal-frontal, b) parietal-temporal and c) parietal-occipital lobe pairs respectively.
Fig. 7. The feature space of RQA RR of occipital lobe with the CRQA RR of a) occipital-frontal, b) occipital-temporal, c) occipital-parietal lobe pairs respectively.

IV. CONCLUSION

In conclusion, the above investigation shows that the MCI group can be clearly distinguished from that of control using RQA and CRQA variables. These variables classify the two groups based on predictability and synchronization levels. MCI EEG is characterized by the lowered complexity indicated by the increased RQA RR and increased synchronization level indicated by increased cross recurrence rate. The feature space based on these two measures shows clear separation between MCI and control groups. These results suggest that the combination of RQA and CRQA RR can be effectively used for the characterization and distinction of MCI EEG. For a deeper understanding of the dynamical information that can be extracted from the proposed method, further studies on EEG of different groups under different cognitive states including memory activation are necessary. Investigations in this direction are under progress.

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