Analysis of Phase Shifts in Clinical EEG Evoked by ECT

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Abstract

We propose a new strategy for studying the phase shifts of electroencephalography (EEG) after electroconvulsive therapy (ECT) to patients with major depression. We divide each ECT EEG time series into four phases and calculate the power spectrum and coherence of left and right prefrontal EEGs for each phase. Previously, we have qualitatively demonstrated certain ECT EEG dynamical patterns by using a neo-cortical neural network model. Now we quantitatively analyze the dynamical phase shifts of the ECT EEG data. Our results are suggestive for a deeper understanding of the ECT EEG patterns and for building more realistic cortical models.

Keywords: Electroconvulsive therapy, EEG frequency bands, neurodynamics, power spectrum, phase shift.

1. Introduction

One of the most successful treatments of depression and other mental disorders is ECT. Treatments and their effects on the patients are monitored with EEG. Some basic oscillation patterns and features of ECT EEG have been obtained in clinical practice. Clinical data show that the dynamics of ECT EEG time series changes with time. Because of the complexity of these time series, little work on the analysis has been done, with some exceptions. Andrew D. Krystal and his coworkers have divided EEG into 12 consecutive segments, with each segment beginning 1 s after the start of the previous segment, in order to calculate the largest Lyapunov exponent for each segment [1]. No post-ictal EEG data were included in their analysis. In a previous work of our group the frequency distribution of each entire ictal ECT EEG time series was analyzed in subgroups of major depressed [2]. The complex dynamical features of ECT EEG remain to be elucidated.

In general, the EEG after ECT stimulation exhibits a specific pattern of seizure in the central nervous system (CNS), but there are differences between individuals, depending on seizure threshold, stimulus doses and sub-diagnosis of major depressed [2]. This implies that ECT stimulation can induce synchronous oscillations of neuronal populations over large parts of the brain, and that the oscillatory patterns depend on intrinsic properties, the external input and the treatment procedure. The dynamics of a recorded ictal EEG time series shifts between several phases. Generally, in the clinical data one can find phases, such as preictal, polyspike (tonic), polyspike and slow- wave (clonic), termination and postictal from the beginning to the end [3]. The anatomic and physiological mechanisms behind such dynamical patterns are poorly known.

We have previously used neural network models of neo-cortical structure to describe possible mechanisms underlying the EEG-signal, how ECT-like input might influence the dynamics of the system, and qualitatively simulated certain ECT EEG patterns [4]. Considering the characteristic of dynamical phase shift of ECT EEG between several phases, in the present report we propose a new strategy to analyze its dynamical features. We divide the time series of clinical EEG into four phases, in accordance with the changing oscillatory patterns along the series and calculate the power spectrum and coherence of the left and right prefrontal EEG signals in phase. We speculate that the dynamical phase shifts are related to the intrinsic local and global network properties and physiological parameters of the cortex of patients and the external ECT stimulus. We believe that the combination of computational analysis and modeling methods of this kind can be used as complementary tools to clinical and experimental methods in furthering our understanding of EEG and the underlying neurodynamics, as well as for improving ECT efficiency.

2. Subjects, ECT Administration and EEG Recordings

The subjects consisted of seven patients with the diagnosis of severe recurrent depression. All subjects were right motor dominant and had not received ECT in the last three months. Neither had they shown any evidence of active cerebral disease in their neurological history. Most of the subjects received unilateral electrode placement according to the d'Elia method [5]. The patients received bi-directional pulse ECT (MECTA 5000Q ECT device; Mecta, Lake Oswego, OK). The stimulus intensity, measured as mC, was predetermined according to sex and age [6]. Two channels of EEG of left and right prefrontal-to-ipsilateral (Fp1, Fp2 according to the 10-20 system) were recorded. The digitalized data from the digital port of the MECTA equipment were simultaneously recorded and transferred to computer hard disc. The continuous EEG signals were digitalized at a sampling frequency of 128 Hz.

3. Theories and Methods

3.1 EEG Frequency Bands

Brain wave EEG has a complex pattern of frequencies. Experimentally, it has been established that there are several frequency bands that are associated with particular states (or processes) in the brain. Delta waves (0.1 to 4Hz) might be generated in the thalamo-cortical circuit and are the most dominant waves in sleep stages 3 and 4. Theta waves (4 to 8Hz) are believed to reflect activity from the limbic system (hippocampus, cingulate gyrus, dentate gyrus, and amygdala), which is important in memory and emotion. Alpha waves (8 to 13Hz) are reported to be generated from the thalamo-cortical circuit during wakefulness and related to relaxed, conscious and inactive state. Beta (13 to 36Hz) and gamma (above 36Hz) waves may occur in e.g. the neocortex, the hippocampus and the olfactory cortex and are associated with attention, perception, and cognition. Data suggest that gamma rhythms are associated with relatively local computations, whereas beta rhythms are associated with higher level interactions, involving more distant structures [7]. Generally, it is believed that lower frequency bands are generated by global circuits, while higher frequency bands are derived from local connections.

3.2 Dividing ECT EEG Time Series into Four Different Phases

According to the phase shift feature of ECT EEG, we divide each EEG series into four phases as follows: 1) the preictal and polyspike phase, 2) the polyspike and slow-wave phase, 3) the slow-wave and termination phase, and 4) the postictal phase (see Fig.1).

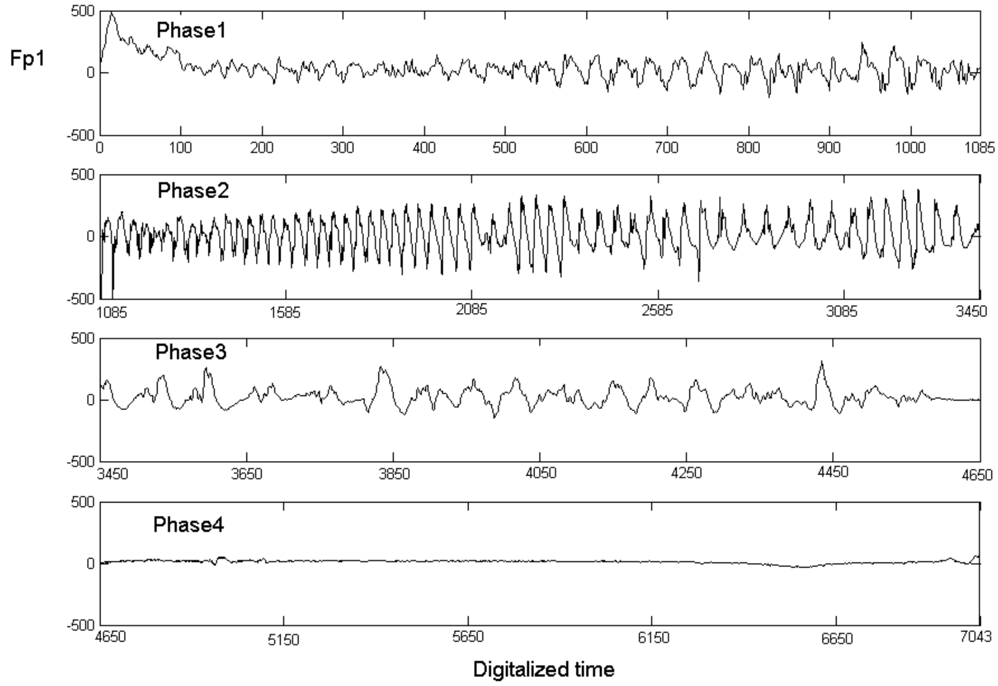

Figure 1. The four phases of Fp1 of a patient during the second ECT

3.3 Power Spectrum

Power spectra are calculated by means of Fast Fourier Transformation (FFT). Power spectrum analysis shows the distribution of the magnitude of signals within particular frequency bands. The behavior of the original EEG signals at one instant appears to depend on what happened before; they had very long-range temporal dependencies and presented global, as well as local trends. Therefore, in order to avoid any bias in the spectral estimates due to the presence of such trends, we filtered the series by taking the first difference, thus obtaining the signals, $x_t = (1 - B)y_t$, where B is the usual back shift operator and y_t the original EEG signal at time t [2]. After this preliminary operation the power spectrum of EEG were computed by using the signal processing toolbox in Matlab.

3.4 EEG Coherence

Coherence is a specific quantitative measure of functional relations between paired locations. Mathematically, EEG coherence is defined as the squared correlation coefficient in the frequency domain:

$$C_{xy}(f) = \frac{\left|\Gamma_{xy}(f)\right|^2}{\Gamma_{xx}(f)\Gamma_{yy}(f)} \quad ,$$

where $|\Gamma_{xy}(f)|^2$ is the square of the cross power spectral density at a given frequency f, and $\Gamma_{xx}(f)$ and $\Gamma_{yy}(f)$ are the respective auto power spectral densities at that same frequency f [8,9]. Coherence measures phase consistency recorded at paired locations, for each frequency component in the EEG [10]. Coherence can be computed by using signal processing toolbox in Matlab.

4. Results

In this section, power spectrum and coherence analysis was carried out for left and right prefrontal ECT EEG traces (Fp1 and Fp2) in the four phases of 41 ECT EEGs of seven patients. In the statistical analysis we regard the 41 series to be independently distributed.

4.1 Power Spectrum changes with phase shifting

Results of power spectrum analysis show that the dominant frequency varies with the EEG dynamics shifting from phase 1 to phase 4. In phase 1 the dominant frequency is mostly in theta or higher delta bands, some times in alpha, beta or gamma bands. In phase 2 the dominant frequency usually changes into lower delta. In phase 3 the dominant frequency may be in delta, theta, alpha, beta or gamma bands. In phase 4 the dominant frequency is mostly in the gamma band. In many cases, we can see clear peaks around 46 Hz or 51 Hz in the power spectrum of phase 4. Figure 2 is an example of the power spectrum of the four phases of Fp1.

The mean power in each frequency band for the four phases of each EEG trace is calculated. Then, the mean relative power of a band is calculated as the mean power of this band divided by the sum of the mean power of all bands. After that, the mean relative power is averaged over the 41 ECT EEG traces from the seven patients. The averaged mean relative power strength of each frequency band in each phase is shown in table 1. From table 1 we can see how the power distribution changes from phase 1 to phase 4. In phase 1 the mean relative power of delta and theta is relatively much higher than that of the other bands and theta frequencies are almost the dominant rhythms. In phase 2, it is clearly seen that the delta power (of both Fp1 and Fp2) is the highest, and the power of theta decreased and the power of beta increased relative to phase 1. In phase 3, theta frequencies become the almost dominant rhythms again, the power of delta decreased relative to phase 2 and the power of alpha increased relative to phase 1 and 2. In phase 4, the power of alpha and gamma is higher; gamma power increased relative to the previous three phases and is almost the dominant rhythms.

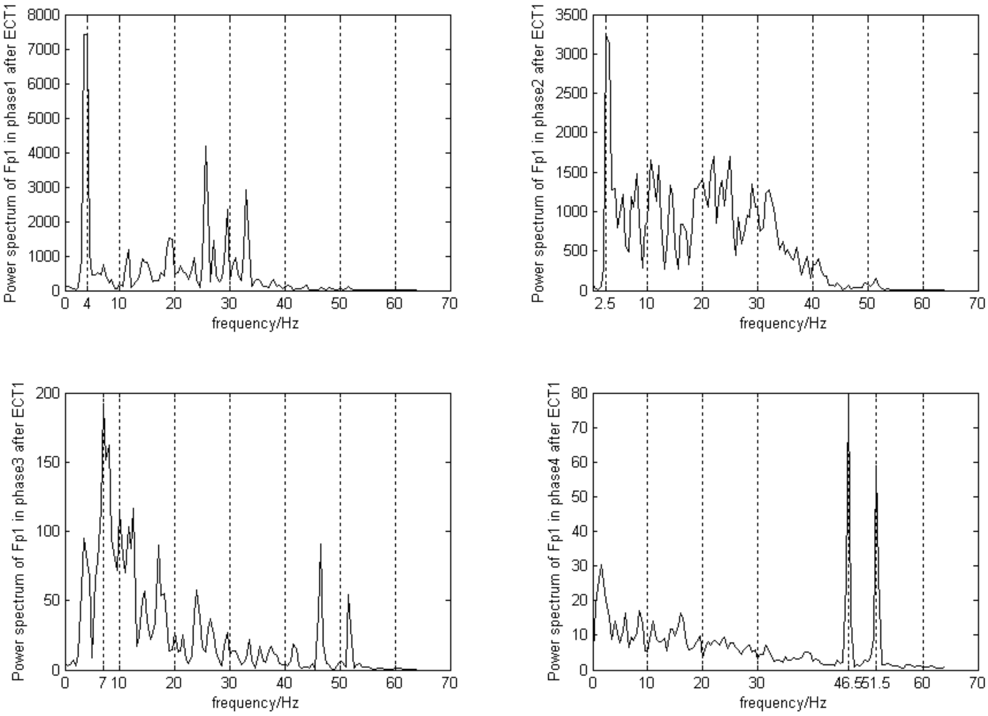

Figure 2. Power spectrum of the four phases

Table 1. Mean relative power ±SEM of frequency bands in the four phases.

EEG Traces	Power / Bands	Phase 1	Phase 2	Phase 3	Phase 4
Fp1	Delta	0.27±0.024	0.39±0.029	0.28±0.019	0.13±0.019
Fp2		0.31±0.029	0.39±0.027	0.28±0.019	0.14±0.017
Fp1	Theta	0.35±0.023	0.23±0.015	0.32±0.013	0.19±0.011
Fp2		0.33±0.022	0.23±0.014	0.30±0.015	0.17±0.015
Fp1	Alpha	0.20±0.015	0.19±0.013	0.23±0.014	0.25±0.019
Fp2		0.18±0.013	0.20±0.012	0.22±0.013	0.21±0.020
Fp1	Beta	0.14±0.011	0.17±0.015	0.13±0.009	0.17±0.014
Fp2		0.14±0.011	0.16±0.015	0.14±0.010	0.15±0.014
Fp1	Gamma	0.04±0.009	0.02±0.003	0.04±0.014	0.26±0.034
Fp2		0.05±0.015	0.02±0.003	0.06±0.017	0.33±0.040

4.2 Fp1 and Fp2 coherence changes with phase shifting

The results of coherence computation show that the coherence of Fp1 and Fp2 also varies significantly (Wilcoxon one-sample test, 5%) with the EEG dynamics, shifting from phase 1 to phase 4. In order to study how the coherence changes with phase shifting, we computed the mean coherence in each frequency band for the four phases, after which we took the average over 41 ECT EEG of the seven patients. The results are shown in Table 2. We can see that in phase 1 the beta coherence is the highest, theta and alpha coherence is lower than beta coherence and higher than delta coherence, and gamma coherence is the lowest. In phase 2 and phase 3, delta coherence is the highest, then theta, alpha, beta and gamma, in turn. In phase 4, alpha coherence is the highest.

Table 2. Mean coherence ±SEM of Fp1 and Fp2 in frequency bands in four phases

Coherence / Bands	Phase 1	Phase 2	Phase 3	Phase 4
Delta	0.56±0.028	0.65±0.028	0.69±0.029	0.28±0.027
Theta	0.59±0.023	0.64±0.027	0.65±0.027	0.27±0.024
Alpha	0.59±0.023	0.61±0.023	0.61±0.027	0.31±0.030
Beta	0.62±0.018	0.59±0.020	0.55±0.023	0.25±0.024
Gamma	0.52±0.013	0.45±0.018	0.41±0.022	0.24±0.013

All the findings in table 1 and table 2 are statistically confirmed at a 5% level with a one-sample Wilcoxon test for paired differences.

5. Discussion

Our analytical results show that ECT EEG involves every brain wave band, from delta to gamma. We found that the distribution of relative power and coherence of Fp1 and Fp2 in each frequency band changes with the dynamics shifting from one phase to another. It is worth noting that the dominant frequency also shifts from one phase to another. It is also worth noting that we found two specific gamma frequencies around 46 Hz and 51 Hz, one or both of which usually dominates in phase 4.

In this work, we obtained some common dynamical features of ECT EEG, as discussed above. This finding indicates that the basic mechanisms of ECT effects are the same for different patients. However, there are variations in the detailed oscillatory patterns of the EEG traces between individuals and treatments. We also found a few special cases in which the first phase and second phase altered.

Based on the EEG frequency bands theory in section 3.1 and our results, we conclude that the ECT EEG dynamics experience complex phase shifting, between macroscopic, mesoscopic, and microscopic scales. We speculate that the dynamics of phase 1 is generated by macroscopic (thalamo-cortical) circuits competing with mesoscopic (cortio-cortical, limbic-cortical) circuits, because the relative power of theta and delta is stronger while the beta coherence is the strongest. In phase 2, the fact that the mean relative power distribution coincides with the mean coherence distribution of Fp1 and Fp2 and delta rhythms dominate, indicates that the dynamics should be dominated by macroscopic (thalamo-cortical) loops. In phase 3, the delta coherence is still the highest, however, delta rhythms no longer dominate, which implies that the mesoscopic (limbic-cortical, cortico-cortical) and microscopic (introcortical) connections compete with macroscopic (thalamo-cortical) connections. In phase 4, the mean coherence of Fp1 and Fp2 of each band is much smaller, implying that the dynamics should be dominated by microscopic/local circuits. The complex oscillatory patterns of EEG after ECT stimulation provide a challenge in revealing the relationship between the neurodynamics and the underlying concert of various cellular/network mechanisms, and external stimulation. In light of recent published imaging studies, where subcortical hyperintensities were associated with dysfunction in the fronto-temporal cortical structures, modeling of these structures becomes even more interesting and important for the understanding of functional and dysfunctional neural loops [11]. In future work, we will continue employing modeling and analysis approaches, to propose optimal ECT levels and frequencies for improving treatment and aiding diagnosis.

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