Novel Polygraphic Observations in High Frequency Range during Rapid Eye Movement Sleep

Mitsuaki YAMAMOTO, Ken SUZUKI, Kazuhiro NAKAMURA, Mitsuyuki NAKAO, Norihiro KATAYAMA and Takashi UENO*

Lab of Neurophysiology and Bioinformatics Graduate School of Information Sciences
Dept of Human Development and Disabilities Faculty of Education Tohoku University, Sendai 980-8579, Japan

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EEG activities in the higher frequency range rather than the conventionally used was hypothesized to be more directly related to neurogenic activities which are expected to construct EEG activities. According to this hypothesis, EEG activities up to 90 Hz were measured and analyzed during REM sleep. REM sleep is considered to be only a physiological state which allows one to measure the high frequency EEG activities without contamination of EMG due to muscle atonia except for twitches. The study found that the rhythmic activities with different frequencies randomly appeared one after another in the frequency range up to at least 90 Hz. This result suggests that the rivalry among small neural assemblies activated synchronously is realized during REM sleep, which might be understood within our hypothesized framework of disinhibition and activation associated with REM sleep. In addition, the extremely wide bandwidth of 500 Hz analyzed here disclosed the phasic potentials related to the rapid eye movements which had the consistent topographic pattern, i.e., frontal positive and occipital negative, which suggests the dipole located deep in the brain. This phasic event may be related to a neurogenic potential generating ponto-geniculo-occipital (PGO) wave observed in cats during REM sleep. Therefore, our finding potentially discloses novel aspects of human neurophysiology.

KEYWORDS: high frequency EEG, rapid eye movement (REM), REM sleep, REM-related phasic events, ponto-geniculo-occipital (PGO) wave

1 Introduction

Conventionally, electroencephalogram (EEG) is observed in the four special frequency ranges of 0.5–4.0 Hz (δ-band), 4.0–8.0 Hz (θ-band), 8.0–13.0 Hz (α-band), and 13.0–30.0 Hz (β-band). This is supposed to be due to a common belief that EEG in the lower frequency range reflects ensembles of slow processes such as synaptic potentials, but EEG in the higher frequency range includes only noise. In addition, electromyogram (EMG) contaminating the recorded signals is another major factor confining the concerned frequency range of EEG to the lower. This should be seriously considered in studies of the γ band (about 40 Hz) EEG [1,2]. Since EMG has wide band width up to several kilo Hz, EEG recording needs preventing this EMG contamination. Therefore, such a limitation of the concerned band width comes from the difficulty in recording EEG rather than its physiological significance.

Actually, neurons are generating action potentials continuously with some rate, whose durations are about 1 msec and amplitudes 100 mV. Considering synchronous firings recently found [3], the possibility is not completely denied that the collective neuronal activities appear in the higher frequency band of EEG above the standard band width. Actually, γ band EEG activities have been investigated in the context of cognitive functions [4]. That is, the EMG contamination might hide the fast neuronal activities which are supposed to appear on the surface of the skull. However, signal processing techniques could not completely exclude the contamination due to the overlap of the concerned band width between EEG and EMG.

In this paper, in order to investigate the high frequency polygraphic signals beyond the conventionally concerned frequency range, we focus on a rapid eye movement (REM) sleep, where anti-gravity muscles are completely relaxed (muscle atonia) [5] as shown in Fig. 1. This recording condition is expected to disclose the high frequency phenomena in the polygraphic signals.

2 Measurement and Analysis of Polygraphic Signals

Nocturnal sleep of four young male adults aged 24 was recorded. The study was approved by the local ethics committee, and informed consent was obtained from the subjects. The electroencephalograms (EEG; Fp1, Fp2, C3, C4, O1, O2, and A1, following the international 10–20 method), the submental electromyogram (EMG), the electrooculogram (EOG(L) and EOG(R); left and right) were recorded against A2 on a paper chart of the polygraph (EE2000, NEC Corp.) and subject to A/D conversion with 12 bits resolution (NI Corp.). The record-

E-mail: mituaki@yamamoto.ecei.tohoku.ac.jp  TEL&FAX: 022-217-7177
ed bandwidth was from 0.5 Hz to 500 Hz. The sampling frequency was 1 kHz.

For the analysis of high frequency EEG activities up to 90 Hz, the recorded EEG from the electrodes P3-A2 were only analyzed. The EEG data during REM sleep were extracted for power spectral analysis and also for wavelet analysis with a Gabor function\(^1\) (\(\sigma = 4\), unless otherwise stated) [6]. The analyzed results were investigated for three separate frequency ranges, 1–15 Hz, 15–45 Hz, and 60–90 Hz, which are called low, mid, and high frequency ranges here, respectively. On the other hand, for the analysis of fast phasic potentials in the polygraphic signals, the raw digitized data were used. MATLAB (MathWorks, Inc.) was used for the analyses.

3 Results

3.1 High frequency electroencephalogram during REM sleep

The low frequency range contains the conventional EEG frequency bands such as \(\delta\), \(\alpha\), and \(\theta\) bands. Figure 2 shows a typical time series of one minute EEG (P3-A2) picked up from 15 min data together with the corresponding spectrogram in the low frequency range obtained every minute as well as the scalogram obtained every 10 sec during the first 5 min. Among the conventional rhythmic components, \(\alpha\) waves can be detected discontinuously, which is clearly recognized as the concentration of spectral power around 8 Hz in the spectrogram and the randomly discontinuous appearance of ridges around 8 Hz in the scalogram. Other than the \(\alpha\) waves, small periodic waves with different frequencies can be seen in the time series. These components are observed as scattered small peaks in the spectrogram. Such a structure of EEG during REM sleep presumably corresponds to the observation that Rechtschaffen and Kales stated as “the concomitant appearance of relatively low volt-

\[\psi(x) = (2\pi\sigma^2)^{-1/2} \exp\left(-\frac{x^2}{2\sigma^2}\right) \exp(-i\omega x)\]
Fig. 2  Typical times series of EEG activity (P3-A2) during REM sleep and the results of FFT and wavelet analyses in the low frequency range up to 15 Hz.
A: EEG activity for the first 1 min picked up from 15 min data. The arrows indicate $\alpha$ waves. B: Spectrogram obtained every minute during 15 min. C: Scalogram obtained every 10 sec during the first 5 min.
Fig. 3 Typical times series of EEG activity (P3-A2) over 15 Hz during REM sleep and the results of FFT and wavelet analyses in the mid frequency range 15–45 Hz.

A: EEG activity for the first 10 sec picked up from 15 min data. B: Spectrogram obtained every minute during 15 min. C: Scalogram obtained every 2 sec during the first 1 min.
Fig. 4  Typical times series of EEG activity (P3-A2) over 60 Hz during REM sleep and the results of FFT and wavelet analyses in the high frequency range 60–90 Hz.

A: EEG activity for the first 10 sec picked up from 15 min data. B: Spectrogram obtained every minute during 15 min. C: Scalogram obtained every 1 sec during the first 9 sec (wavelet parameter $\sigma = 10$).
age, mixed frequency EEG activity". A preliminary analysis suggests random occurrence of these rhythmic activities [7].

As shown in Figs. 3 and 4, similar features hold for the other two frequency ranges except for the dominant rhythmic components such as an α wave. Actually, amplitudes of the signals in the mid and high frequency ranges become smaller comparing with the low range. However, commonly in both frequency ranges, many periodic components with different frequencies are observed to occur one after another, which is clearly seen from the spectrogram and scalogram. The random occurrence of the rhythmic activities are also suggested. Therefore, this observation could well characterize the EEG activity during REM sleep over the different frequency ranges. This is commonly observed through the subjects.

Actually, the time series of EEG activity above 60 Hz has the comparable level with the measurement noise which was about 4 μV-p in the frequency range 60–500 Hz. However, since the noise exhibited purely random behavior, the rhythmic activities detected in Fig. 4A are supposed to have physiological origins. The spectral structure of the noise supports this supposition. The power spectral density of the noise was almost white up to 500 Hz, and its level in the frequency range 60–90 Hz was at most 3 μV²/Hz, which is well below the spectral power of EEG activity during REM sleep shown in Fig. 4B. Therefore, at least in the frequency range 60–90 Hz,

![Fig. 5 Polygraphic observation of phasic potentials. Dotted lines indicate the potentials.](image)

![Fig. 6 Typical polygraphic observation of a single phasic potential. Vertical ticks: every 50 μV. Horizontal ticks: every 10 msec.](image)
physiologically meaningful activities are suggested to exist, although further confirmation is needed.

3.2 Phasic potentials related rapid eye movements during REM sleep

General features of the wide band EEG activity during REM sleep are described in the previous section. Here, specific potentials related rapid eye movements are reported, which cannot be discovered without observation of extremely wide bandwidth of 500 Hz. Figure 5 shows the record of EEG activities, EMG, and EOGs during 2 sec. One can clearly see the phasic potentials in all signals at every moment when the rapid eye movement is initiated. The small phasic potentials in EOG signals are associated with those in EEG signals. A closer look at this potential finds a consistent topographic relation among the polygraphic signals (Fig. 6): in the frontal area (Fp1, Fp2, EOG(L), and EOG(R)) positive, and in the parietal and occipital areas (C3, C4, O1, and O2) negative. This topographic pattern suggests an underlying dipole deep in the brain. Considering its topographic pattern and tight phase-locking to initiation of REM, this potential is easily known to be free from any possible artifacts such as leak of electrocardiogram, overshoot caused by dynamics of amplifier and filters, and phasic muscular activities under EOG electrodes.

In order to detect the potential systematically, a wavelet closely fitted to the potential waveform ('mexican hat', a second derivative of Gauss function [6]) is applied to EOG(L) signal of which phasic potentials are usually larger than the others. The potential is detected by the magnitude of the wavelet coefficient exceeding a certain threshold. Figure 7 shows 80 msec segments of polygraphic signals containing the detected phasic potential of which peak is located centrally. In the respective segments, the topographic pattern of the phasic potential described above is found to be held.
In order to examine the above description of the topographic pattern of the potential, statistical analysis is carried out. Table 1 shows the coefficient of correlations between peak amplitudes of the phasic potentials observed in the different locations. Forty events extracted from the 1 min polygraphic data during REM sleep are subject to the analysis. For convenience of comparison, the polygraphic signals are divided into two groups regarding the locations of electrodes: group I (EOG(L), EOG(R), EMG, Fp1, and Fp2) and group II (C3, C4, O1, and O2). Within the same group, positive significant or weak correlation is obtained. In contrast, between the different groups, significant negative or weak correlation is obtained. Therefore, the results of the statistical analysis support the topographic observation described above. The properties of the phasic potential are commonly recognized through the subjects.

4 Discussion

Here, EEG activity in the higher frequency range rather than conventionally concerned one was hypothesized to be related directly to neuronal activities which are expected to construct EEG activities. According to this hypothesis, the EEG activities up to 90 Hz were measured and analyzed during REM sleep. REM sleep is considered to be only a physiological state which allows one to measure the high frequency EEG activities without contamination of EMG due to muscle atonia except for twitches. The study disclosed that the rhythmic activities with different frequencies appeared one after another in the frequency range up to at least 90 Hz. This result implies that the features in EEG activity during REM sleep which Rechtschaffen and Kales reported concerning the low frequency range are still valid for characterizing the EEG activities in the mid and high frequency ranges. In addition, the extremely wide bandwidth of 500 Hz analyzed here disclosed the phasic potentials related to the rapid eye movements which had the consistent topographic pattern. The pattern, frontal positive and occipital negative, suggests the dipole located deep in the brain. The size of the phasic potentials in EOGs tended to be larger than those in EEG. The phasic potential in EOG might be neurogenic one which was led through electrotonic potential of the brain.

The guidelines of EEG analysis state that the frequency range concerned is at most from 0 to 30 Hz, and low and high pass filters are recommended to be set at 0.1 Hz and 60–70 Hz, respectively [1,2]. On the other hand, γ band (36–44 Hz and sometimes higher) EEG activity has been attracting many researchers. However, because this frequency range substantially overlaps with EMG, a certain elaborate technique should be developed to extract the true neurogenic activity from the contaminated signal by EMG [8,1]. Therefore, our idea using the muscle atonia during REM sleep provides a novel approach to the high frequency analysis of EEG activity, although their origin still remains to be explored.

As described in the section 3, the dynamical features in the time series over 60 Hz should be confirmed by measurements reducing noise extremely. In addition, if non-REM sleep episodes with negligibly low EMG can be obtained, comparison between the EEG activities during REM and non-REM sleep might be able to demonstrate existence of physiologically meaningful EEG activities in the high frequency range during REM sleep.

Fig. 8 EEG in visual cortex (VC) and EOG associated with cat’s PGO waves during REM sleep. An arrow indicates the phasic potential which might be an analogue of the human’s associated with rapid eye movements. A broken line indicates the beginning of the potential.
Our preliminary study comparing them showed that the spectral power in the high frequency range during REM sleep significantly dominated that of non-REM sleep. This suggests that the high frequency EEG activity during REM sleep would be relevant to sleep state in spite of the contamination of measurement noise.

Biological significance of high frequency EEG activities has been investigated especially concerning the $\gamma$ band [4]. Most of the studies, in the context of cognitive functions, deal with task-related EEG activities in the $\gamma$ band. For natural sleep, a few studies reported more coherent and prominent $\gamma$ band MEG (magnetoencephalogram) and EEG activities during REM sleep comparing with the other sleep states [9,10]. Considering the suggested relationship between $\gamma$ band activities and cognitive processes, the high frequency EEG activities including the $\gamma$ band activities may subserve specific functions in REM sleep [10]. Concerning the generation mechanisms, because the high frequency rhythms were found to appear one after another with small amplitudes and various frequencies, the rhythms are supposed to manifest ‘rivalry’ among small neural assemblies activated synchronously rather than large assemblies generating distinct oscillations such as $\alpha$, $\beta$, and $\delta$ waves. We have been accumulating physiological evidence supporting the hypothesis that REM sleep is a peculiar state under the progress of disinhibition and activation [11], which is shared by other researchers [12]. According to this idea, the rivalry among small neural assemblies might be realized by the disinhibition and activation during REM sleep.

A possible origin of the phasic potentials is discussed here. In cats, PGO (ponto-geniculo-occipital) waves are well known as phasic potentials during REM sleep, which are initiated in the pons and delivered to wide-spread area in the cortex through the thalamus [13,14]. In addition, the PGO wave occurs in prior to the rapid eye movement [13]. The supposed analogue of PGO wave in human EEG activities were reported by a few researchers [15,16,17]. They found a positive potential with a duration up to 100 msec peaking nearly at the initiation of REM by averaging technique. The potentials were reported to be observed in the wide-spread area of the skull, which were largest in the occipital area. Their spatially uniform positive polarity and prominence in the occipital area is supposed to be plausible for PGO wave [14]. In this sense, they may be the surface potential reflecting the cortical activities evoked by the PGO wave delivered from the thalamus. However, considering their topographic properties and durations, these potentials seem to be different from ours, although direct comparison could not be done due to the difference in sampling rates, 1 msec in our case, 4 msec [15], 5 msec [16], and 8 msec [17], and/or the difference in reference-settings, i.e., A2 in our case and the linked ears in their case.

A preliminary simultaneous recording of field potential in the visual cortex and EOG suggests an alternate origin rather than the PGO wave. Figure 8 shows a polygraphic recording of the cat’s PGO waves during REM sleep. Superposed to the component related to REM, the phasic potentials can be observed in EOG at the moments when the PGO waves occur in the cortex, where the negative polarity of the EOG potential is probably due to the bipolar recording in the cat. Therefore, the similar phasic potential to ours is observed in the cat’s EOG, although different from the PGO wave itself in its time course. In our preliminary observations, the similar potential can be detected sometimes in human saccadic EOG, although the topograph cannot be obtained due to contamination of EMG. Therefore, the phasic potential concerned here may reflect neuronal corollary discharges [18] and/or activities of PGO-on cells and transferring neurons in the peribrachial area of the pons, which are activated in prior to the PGO wave generation in the LGN [19]. Although further study is required to explore the physiological origin of the phasic potential we found, our finding may be an important discovery in human neurophysiology. Pathological and ontogenetical analyses of REM sleep in humans are expected to be facilitated by making use of this potential. Finally, high frequency analysis of EEG will be useful not only during REM sleep but also during other states including wakefulness in space, where activities of anti-gravity muscles are expected to be significantly reduced.

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