Artificial Realization of Decision Making for Sleep Stage of EEG Contaminated with Artifacts: Conditional Probability of Knowledge-Base of Expert Visual Inspection

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Abstract

An artificial realization of decision making for sleep stages of EEG (electroencephalograph) contaminated with artifacts was developed in order to construct a reliable sleep stage recognition system for clinics. The methodology was based on the conditional probability of knowledge-base of expert visual inspection. Expert visual inspection was the manual scoring result of sleep stages by a qualified EEGer (F.K.). Knowledge-base was constructed in terms of probability density functions of characteristic parameters with each sleep stage, according to the expert visual inspection. Artificial realization of decision making for sleep stage was based on the value of conditional probability. Totally, the overnight sleep EEG recordings of four subjects were analyzed. The results showed a close agreement with the expert visual inspection by EEGer.

Key words: sleep EEG, artifacts, decision making for sleep stage, conditional probability, knowledge-base of expert visual inspection

1. Introduction

In human sleep, there are several types of sleep stages. Sleep stage determination has clinical importance for the inspection of sleep related disorders. As one's overnight sleep EEG is long-term recording, it is inevitably contaminated by variance artifacts under usual recording conditions in most hospitals and sleep laboratories (P. Anderer et al [1], D. P. Brunner et al [2]).

In many other studies, waveform detection technique (first applied by Smith et al. [3]) could be found for the computerized sleep stage scoring. When sleep EEG was recorded under the usual recording condition, it had limitation to detect the characteristic waveforms from artifacts.

In this study, we investigated on the artificial realization of decision making for sleep stages of EEG contaminated with artifacts in order to construct a reliable sleep stage recognition system for clinics. The methodology was in the field of statistics by using conditional probability of knowledge-base of expert visual inspection, based on our previous study (M. Nakamura and T. Sugi [4]). Expert visual inspection was the manual scoring result of sleep stages by a qualified EEGer (F.K.). Knowledge base was constructed in terms of probability density functions of characteristic parameters, according to the expert visual inspection. The EEGer made visual inspection of sleep stages and artifact contamination for one's overnight sleep recordings. The artificial realization of decision making for sleep stage or artifact was based on the value of conditional probability.

2. Method

2.1 Subjects and Data Acquisition

The overnight sleep of four subjects after the treatment of Continuous Positive Airway Pressure were recorded in the Department of Clinical Physiology, Toranomon Hospital, Japan. Sleep EEGs were recorded at four sites C3/A2, C4/A1, O1/A2 and O2/A1, according to the International 10-20 System (H. H. Jasper [5]). EOGs (electrooculogram) were derived near the eyes, LOC/A1 and ROC/A1. Chin-EMG (electromyogram) was obtained from muscle areas on and beneath chin. Sleep EEGs and EOGs were recorded under a sampling rate of 100 Hz, Chin-EMG under a sampling rate of 200Hz.

Table 1: Classification of sleep stages and artifact contaminated stage A.

Stages	Characteristics
Awake	
with eyes opened	predominant rhythmic alpha activity (8-13Hz) in EEG
with eyes closed	eye blinks in EOG
REM	relatively low-voltage, mixed-frequency activity in EEG, episodic REM in EOG and low-amplitude EMG
NREM	
Stage 1	relatively low-voltage, mixed-frequency activity in EEG, without rapid eye movement in EOG
Stage 2	relatively low-voltage, mixed-frequency activity with sleep spindles (12-14Hz) and K complexes in EEG
Stage 3	moderate amounts of high-amplitude, slow-wave activity (0.5-2Hz) in EEG
Stage 4	large amounts of high-amplitude, slow-wave activity (0.5-2Hz) in EEG
Stage A	with artifact contamination, accompanied with body movement or tonic activity in EEG

2.2 Expert Visual Inspection

A qualified EEGer (F.K.), who is one of the co-author, made visual inspection on the sleep EEG recordings of four subjects. Their overnight sleep recordings were separated into consecutive 30-second segments, which is called epoch. Each epoch was assigned with a single stage or artifact contamination by the EEGer based on the well-known Rechtschaffen and Kales criteria [6] and her clinical experience.

Table 1 showed the expert visual inspection of sleep stages and the corresponding characteristics. In Rechtschaffen and Kales criteria, sleep is consisted of stage awake, rapid eye movement (REM) and non-REM (NREM) sleep which is further divided into stage 1, stage 2, stage 3 and stage 4. The EEGer inspected the sleep stages based on the corresponding characteristics of a certain frequency bands as in Table 1. In addition, stage awake was separated into open and close eyes awake. Because alpha activity is predominant when subjects closed eyes and was relaxed, significantly attenuates when subjects opened eyes or became tension. The EEGer also inspected the artifacts accompanied with tonic activity in sleep EEG. Stage A was defined as an extra stage of artifacts besides the other sleep stages.

2.3 Knowledge-base

Knowledge-base is in terms of probability density functions of characteristic parameters corresponding to each stage. Based on the manual scoring result of expert visual inspection, the epochs of ones overnight sleep recording can be classified into different stages. For each stage, a set of characteristic parameters (Table 2) are calculated to make the probability density functions in Cauchy distribution.

Based on the definition of Cauchy distribution, the probability density function of parameter y in stage ζ can be mathematically expressed by Eq. 1,

$$f(y \mid \zeta) = \frac{b}{\pi((y-a)^2 + b^2)} \qquad (1)$$

where a is the location parameter and b is the scale parameter. The values of a and b are determined by applying least square method on the histograms.

Table 2: Parameter Definition

EEG	Duration of alpha activity (α: 8-13Hz) in O1/A2 or O2/A1 Duration of slow wave activity (s1: 0.5-2Hz) in C3/A2 or C4/A1 Amplitude of mixed requency activity (s2: 2-7Hz) in C3/A2 or C4/A1 Amplitude of high frequency activity (h: 25-50Hz) in C3/A2 or C4/A1
EOG	Amount of eye movement (LOC: 2-10Hz) in LOC/A1 Amount of eye movement (ROC: 2-10Hz) in ROC/A1 Amount of eye movement (L-R: 2-10Hz) in LOC/ROC
chin-EMG	Amount of tonic activity (chin-EMG: 50-100Hz) in chin-EMG

2.4 Artificial Realization of Decision Making

Sleep stage determination can be considered as decision making problem. Artificial realization of decision making is proposed to solve the multiple decision making problem (M. Nakamura and T. Sugi [4]). It is carried out based on the value of conditional probability,

$$P_{k|k}(\zeta^{i}) = \frac{f(y_k \mid \zeta^{i}) P_{k|k-1}(\zeta^{i})}{\sum_{j=1}^{n} f(y_k \mid \zeta^{j}) P_{k|k-1}(\zeta_{j})}, \qquad (2)$$

where $P_{k|k-1}(\zeta^{i})$ is the predicted probability of previous segment. The decision of sleep stage or artifact contamination is made by choosing the stage which has the maximum value of conditional probability, as

$$\zeta^{*} : \max(P_{k|k}(\zeta^{i})). \qquad (3)$$

Then predicted probability is calculated by

$$P_{k+1|k}(\zeta^{i}) = \sum_{j=1}^{n} t_{ij} P_{k|k}(\zeta^{j}), \qquad (4)$$

where t_{ij} corresponds to the transitional probability between every two stages.

3. Result

3.1 Knowledge-base of probability density functions

The overnight sleep recordings of two subjects were utilized to obtain knowledge-base. The probability density functions of each characteristic parameter and stage were shown in Figure 1. In Fig.1, black dots were the location parameter of Cauchy distribution and white dots the scale parameter. Stage awake with eyes closed had the largest location value in the distribution of the duration of alpha activity (8-13Hz). In the amplitude of high frequency (25-50Hz), stage A of artifact contamination had the largest location value, discriminated from other sleep stages. Stage REM was separated from other stages with lowest location value in the amount of chin-EMG (25-100Hz). Stage 3 and 4 shared the largest location value in the duration of s1 (0.5-2Hz), which corresponding to the slow wave activity.

3.2 Decision Making of Sleep Stages

Another two subjects were analyzed as test data. The calculation processing of conditional probability and predicted probability was illustrated in Fig.2 with time series of an epoch. The later part of this epoch was contaminated by artifacts and detected by the artificial decision making method. The stage determination for this epoch was stage awake because half of sleep EEG was contaminated by tonic artifacts. The stage scoring result of expert visual inspection was also stage awake.

The evaluation of sleep stage determination for two test subjects were given in Table 3. Stage 1 and 2 were combined as light sleep of NREM, stage 3 and 4 were deep sleep of NREM. The number in Table 3 showed the agreement between artificial decision making of sleep stages and expert visual inspection for each subject respectively. Average accuracy was also evaluated in Table 3.

Table 3: Evaluation of sleep stage determination

	Subject A	Subject B	Average
Awake	92.8%	84.4%	88.6%
REM	63.8%	72.3%	68.1%
Stage 1/2	82.6%	82.2%	82.4%
Stage 3/4	94.6%	98.0%	96.3%

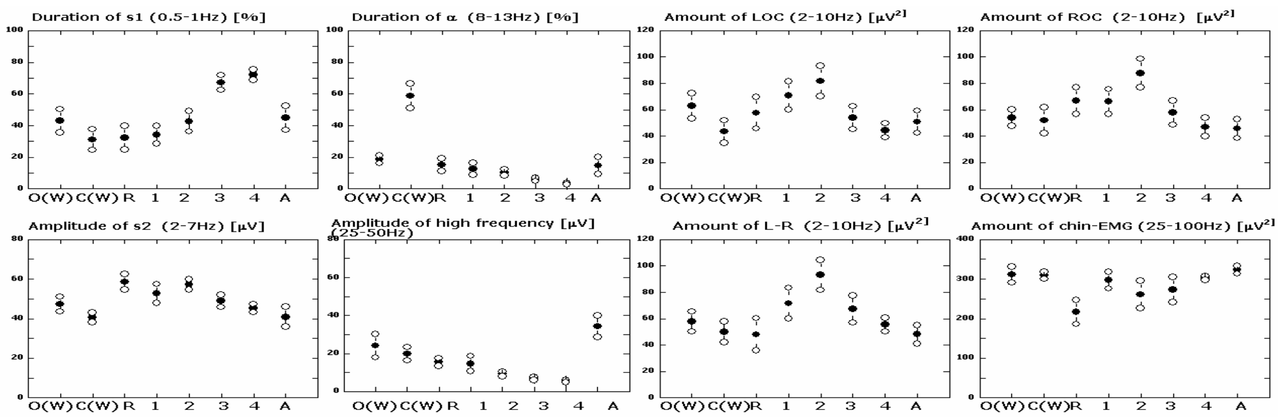
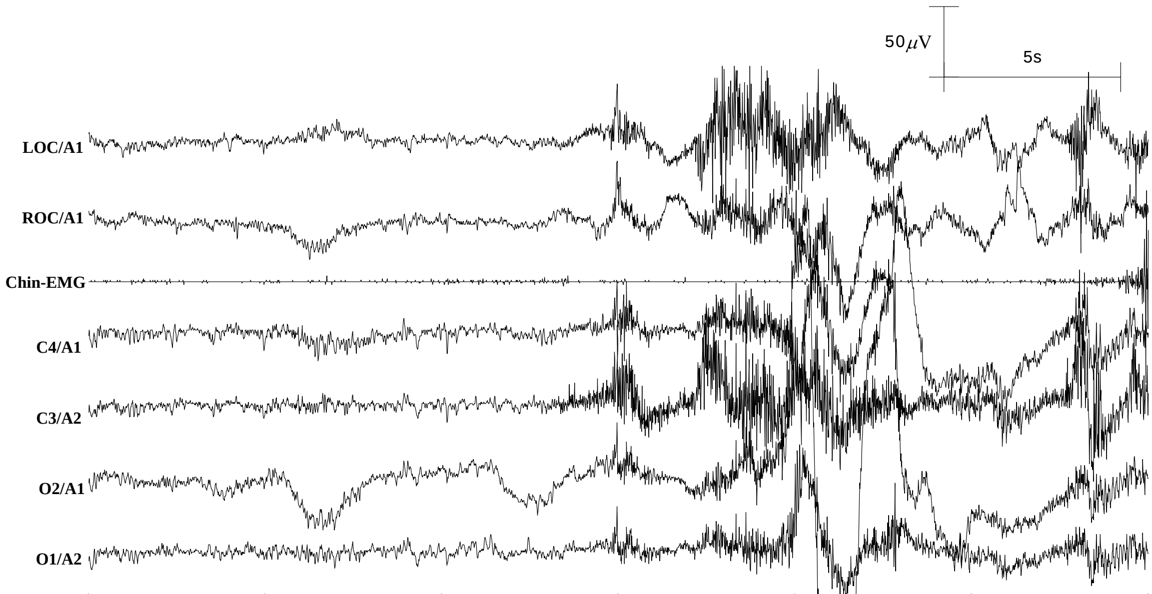


Figure 1: Probability density functions of characteristic parameters corresponding to each stage.



	K		K+1		K+2		K+3		K+4		K+5	
Stage	$P_{k\mid k-1}$	$P_{k\mid k}$	$P_{k+1\mid k}$	$P_{k+1\mid k+1}$	$P_{k+2\mid k+1}$	$P_{k+2\mid k+2}$	$P_{k+3\mid k+2}$	$P_{k+3\mid k+3}$	$P_{k+4\mid k+3}$	$P_{k+4\mid k+4}$	$P_{k+5\mid k+4}$	$P_{k+5\mid k+5}$
A	0.61	3.50e-3	9.51e-2	6.08e-7	8.61e-2	0.02	0.02	0.94	0.86	0.99	0.91	0.99
O(W)	0.32	0.27	0.27	0.02	0.02	7.60e-2	7.99e-2	0.01	0.03	1.06e-2	0.02	2.68e-3
C(W)	0.01	4.86e-5	5.30e-2	9.24e-7	6.47e-2	5.04e-5	6.88e-2	6.05e-3	0.02	1.54e-3	0.02	4.04e-5
R	8.94e-2	1.97e-5	1.46e-2	2.34e-3	2.17e-2	1.90e-3	2.12e-2	6.95e-5	1.68e-3	9.55e-6	1.26e-5	1.13e-6
1	0.04	0.72	0.68	0.96	0.92	0.97	0.92	0.04	0.07	1.53e-2	0.03	2.99e-6
2	6.88e-2	1.03e-3	0.03	0.01	0.05	3.20e-2	0.04	3.35e-6	0.01	3.81e-5	0.01	7.06e-9
3	5.65e-9	2.4e-127	2.98e-7	2.11e-11	3.51e-5	7.31e-9	9.27e-6	3.60e-10	1.00e-8	2.24e-8	1.31e-7	8.90e-12
4	5.18e-14	1.37e-20	2.88e-14	2.31e-22	2.22e-13	2.30e-18	7.67e-11	6.59e-16	3.78e-12	1.38e-13	2.35e-10	1.56e-15
Result	Stage 1		Stage 1		Stage 1		Stage A		Stage A		Stage A	
Automatic determination:	Stage awake											
Visual inspection:	Stage awake											

Figure 2: Artificial realization of decision making for sleep stage of EEG contaminated with artifact.

4. Conclusion

In this study, method of conditional probability of knowledge-base of expert visual inspection was utilized for sleep stage determination. The results showed a close agreement with expert visual inspection by EEGer. Artifact contamination can also be detected in sleep EEG. Compare with other sleep stages, REM was in low accuracy and need to be improved. With the knowledge-base of expert visual inspection, the proposed artificial realization system of decision making for sleep stage has strong performance in the clinical practice.

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