Artificial Realization of an Adaptive Expert Knowledge Database for Automatic Sleep Stage Determination in Clinical Practice

Bei Wang[1, 4], Takenao Sugi[2], Fusae Kawana[3], Xingyu Wang[1] and Masatoshi Nakamura[4]

[1]*Department of Automation, East China University of Science and Technology, Shanghai 200237, China*
(Tel: +86-2164253581; wangbeish@gmail.com)
[2]*Department of Electrical and Electronic Engineering, Saga University, Saga 840-8502, Japan*
(Tel: +81-952-288643; sugi@cntl.ee.saga-u.ac.jp)
[3]*Department of Clinical Physiology, Toranomon Hospital, Tokyo 105-8470, Japan*
(Tel: +81-3-3588-1111; kawana@toranomon.gr.jp)
[4]*Department of Advanced Systems Control Engineering, Saga University, Saga 840-8502, Japan*
(Tel: +81-952-288644; nakamura@cntl.ee.saga-u.ac.jp)

***Abstract*:** Artificial realization of an adaptive expert knowledge database for the sleep data from clinics was investigated. The ultimate purpose is to develop automatic sleep stage determination technique for variable cases of sleep data in hospitals. The automatic sleep stage determination algorithm is designed by using probabilistic method based on conditional probability. In order to make algorithm flexible for variable sleep data, an adaptive expert knowledge database is constructed based on a set of fundamental and optional parameters. The parameters, which can improve the accuracy of sleep stage recognition for the training data, are selected. The adaptive expert knowledge database is consisting of the probability density functions of fundamental parameters and selected optional parameters. The overnight sleep data of 4 subjects from Toranomon hospital, Tokyo, Japan were utilized for analysis. The automatic sleep stage determination results were compared with the visual inspection by clinician. Finally, satisfied results of close agreement with the visual inspection were obtained. The developed automatic sleep stage determination by adaptive expert knowledge database can be an effective tool for clinical practice.

Keywords: Adaptive expert knowledge database, Parameter selection, Conditional probability, Automatic sleep stage determination

I. INTRODUCTION

Sleep can be described by awake stage, rapid eye movement stage (REM) and non rapid eye movement (NREM) stage of I, II, III and IV. The sleep data recorded from real clinics is complex and variable. The staging criteria containing typical waveforms for healthy persons are insufficient to deal with the various cases of sleep data in hospitals and institutions [1], [2]. The conventional rule-based automatic sleep stage determination methods, which have been designed according to the staging criteria, have the similar limitation for clinical practice [3], [4]. An expert knowledge-based method was developed in our previous study which can overcome the limitations of rule-based methods [5]. The expert knowledge is the visual inspection by qualified clinician, which considers the actual surrounding circumstances in hospitals. The expert knowledge database includes probability density functions of parameters for various sleep stages. However, the probability density function of defined parameters may not be efficient enough for the variable sleep data in real clinics. Therefore, an adaptive expert knowledge database is necessary to be developed.

In this study, we are investigating on the artificial realization of adaptive expert knowledge database. The ultimate purpose is to develop an effective automatic sleep stage determination technique for clinical practice. In order to make an adaptive expert knowledge database, an automatic parameter selection algorithm is developed. A set of fundamental parameters and optional parameters are defined. The optional parameters, which can improve the accuracy of sleep stage recognition for training data, are selected. The adaptive expert knowledge database is consisting of the probability density functions of the selected parameters together with the fundamental parameters. The sleep stage is determined based on the conditional probability.

II. METHODS

1. Subjects and data acquisition

All the sleep data were recorded at the department of Clinical Physiology, Toranomon Hospital in Tokyo,

©ISAROB 2009

Japan. Totally four subjects were participated, having an average age of 50 years old. They were suffered by breathing disorders during sleep (Sleep Apnea Syndrome). Their overnight sleeping data were recorded after the treatment of Continuous Positive Airway Pressure (CPAP) based on the polysomnographic (PSG) measurement. The PSG measurement at Toranomon Hospital includes four EEG recordings, two EOG recordings and one EMG recording. EEGs were recorded on central lobes and occipital lobes with reference to opposite earlobe electrode (C3/A2, C4/A1, O1/A2 and O2/A1) according to the International 10-20 system. EOGs were derived on Right Outer Canthus and Left Outer Canthus with reference to earlobe electrode A1 (LOC/A1 and ROC/A1). EMG was obtained from muscle areas on and beneath chin which was termed as chin-EMG. Initially, EEGs and EOGs were recorded under a sampling rate of 100 Hz. Chin-EMG was recorded under a sampling rate of 200Hz.

2. Probabilistic method by conditional probability

Sleep stage scoring was considered as a multi-valued decision making problem in the field of clinics. The automatic sleep stage determination algorithm was designed by probabilistic method based on conditional probability.

Sleep data were divided into 30-second epochs and each epoch was subdivided into 5-second segments for sleep stage determination. The automatic sleep stage determination is carried out based on conditional probability as,

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

where $f(y_k|\zeta^i)$ is the probability density function of parameters y_k for sleep stage ζ^i and $P_{k|k-1}\ (\zeta^i)$ is the predicted probability of previous segment. The conditional probability indicates the possibility of the occurrence of sleep stage ζ^i for current segment k. The sleep stage which has the maximum value of conditional probabilities was decided as the result for current segment k.

The predicted probability of first segment for various sleep stages shared the probability equally with a value of $1/n$, where n is the number of the types of sleep stages. The calculation algorithm was repeated by conditional probability and predicted probability among the consecutive segments. The sleep stage for an epoch is determined by choosing the stage which takes up the major portion among the consisting segments within one epoch.

3. Adaptive expert knowledge database

In order to realize the automatic sleep stage determination algorithm, probability density functions of parameters were required. The adaptive expert knowledge database construction was a learning process to obtain the probability density function of parameters for various sleep stages.

A.Visual inspection

A qualified clinician made visual inspection of sleep stage scoring on the training data. The overnight sleep recording was divided into consecutive 30-scond epochs. The clinician made visual inspection through an epoch-by-epoch approach. Totally, seven types of sleep stages were visually inspected, including awake with eyes closed, awake with eyes opened, REM sleep and non-REM sleep of stage I, II, III and IV. Stage awake was classified into open eyes state and close eyes state according to the alpha activity (8-13Hz) on EEGs of O1/A2 and O2/A1 channels and the existence of eye movements on EOGs. Stage I and II were identified as light sleep. Deep sleep of stage III and IV were scored based on a relatively different presence of slow wave activity within an epoch.

B.Probability density function

The epochs were classified into sleep stage groups according to the visual inspection. Each epoch was assigned to a single sleep stage based on the visual inspection of clinician and described by a set of parameters values. For each sleep stage, the values of parameters are counted to make the histograms.

The probability density function is approximately evaluated using histograms with Cauchy distribution as

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

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.

In addition, a transitional probability matrix of sleep stage change was calculated. The transitional probability between sleep stages designated the probabilities of sleep stage transition between two conjoint segments.

C.Parameter selection

Since the sleep data may be variable from hospitals and institutions, a set of fundamental parameters and optional parameters were extracted from the periodogram of sleep EEGs, EOGs and EMG.

According to the sampling rate, the periodogram was derived by taking 512-point FFT (Fast Fourier Transform) for EEGs and EOGs, whereas 1024-point FFT for EMG. The parameters were defined by certain frequency bands of ratio, amplitude and amount. The equations of parameters were given in Table 1. The parameter type of "F" indicates fundamental parameters and "O" indicates optional parameters. The corresponding frequency bands were listed in the notation under Table 1.

The automatic sleep stage determination algorithm was firstly applied on the fundamental parameters. The accuracy was evaluated comparing with the visual inspection by clinician as,

$$ACC_f = \frac{n_f}{N}, \tag{3}$$

where n_f is the number of epochs which have the consistent determination result with visual inspection and N is the total number of epochs.

When one of the optional parameters brought best determination accuracy together with the fundamental parameters, this parameter would be selected. The selected parameter was added into the fundamental parameter set for next selection. The selection process was repeated until there was no parameter can improve the accuracy comparing with the current fundamental parameter set. The adaptive expert knowledge database was constructed to include the probability density functions of those parameters.

Table 1. Parameter description

Parameter		Type
Ratio (%)	$R_{s1} = max\left\{\frac{S_{s1}(C3)}{S_T(C3)} \times 100\%, \frac{S_{s1}(C4)}{S_T(C4)} \times 100\%\right\}$	F
	$R_{s2} = max\left\{\frac{S_{s2}(C3)}{S_T(C3)} \times 100\%, \frac{S_{s2}(C4)}{S_T(C4)} \times 100\%\right\}$	O
	$R_{s3} = max\left\{\frac{S_{s3}(O1)}{S_T(O1)} \times 100\%, \frac{S_{s3}(O2)}{S_T(O2)} \times 100\%\right\}$	F
	$R_{s4} = max\left\{\frac{S_{s4}(C3)}{S_T(C3)} \times 100\%, \frac{S_{s4}(C4)}{S_T(C4)} \times 100\%\right\}$	O
	$R_{s5} = max\left\{\frac{S_{s5}(C3)}{S_T(C3)} \times 100\%, \frac{S_{s5}(C4)}{S_T(C4)} \times 100\%\right\}$	O
Amplitude (μV)	$A_{s1} = max\left\{6 \times \sqrt{S_h(C3)}, 6 \times \sqrt{S_h(C4)}\right\}$	O
	$A_{s2} = max\left\{6 \times \sqrt{S_h(C3)}, 6 \times \sqrt{S_h(C4)}\right\}$	F
	$A_{s3} = max\left\{6 \times \sqrt{S_h(O1)}, 6 \times \sqrt{S_h(O2)}\right\}$	O
	$A_{s4} = max\left\{6 \times \sqrt{S_h(C3)}, 6 \times \sqrt{S_h(C4)}\right\}$	O
	$A_{s5} = max\left\{6 \times \sqrt{S_h(C3)}, 6 \times \sqrt{S_h(C4)}\right\}$	O
Amount (μV^2)	$S_{LOC}(LOC)$	F
	$S_{ROC}(ROC)$	F
	$S_{L-R}(LOC - ROC)$	O
	$S_{chin-EMG}(Chin - EMG)$	F

*EEG: *s1* (0.5-2 Hz); *s2* (2-7 Hz); *s3* (8-13 Hz); *s4* (13-25 Hz); *s5* (25-50 Hz). EOG: *LOC, ROC, L-R* (2-10 Hz). EMG: *chin-EMG* (50-100 Hz).

III. RESULTS

The overnight sleep recording of 2 subjects were utilized as the training data. The parameter selection process is illustrated in Table 2. (A) is for fundamental parameters. The number of the fundamental parameters was increased during the parameter selection process. The accuracy value indicates the agreement epochs between the sleep stage determination and visual inspection by clinician. (B) is for the optional parameters. The accuracy value indicates the determination result by using each optional parameter together with the fundamental parameters. For each column, those accuracies in (B) were compared with the accuracy by fundamental parameters in (A). "↑" indicates increased accuracy and "↓" indicates decreased accuracy. The optional parameter which had the highest increased accuracy was selected and added into the fundamental parameter set for next comparison. Finally, three optional parameters were selected. Those were R_{s5}, S_{LR}, and R_{s4}. The combination of the fundamental parameters and those selected optional parameters was utilized for automatic sleep stage determination.

Another two subjects different from the training subjects were tested and analyzed. The accuracy of stage awake, stage REM, light sleep (stage I and II) and deep sleep (III and IV) were calculated and evaluated. The average accuracy of stage awake was 92.41%, stage REM was 58.91%, light sleep was 80.90% and deep sleep was 94.96%. The results for stage awake, light sleep and deep sleep were satisfied. Stage REM showed lower accuracy comparing with other sleep stages.

©ISAROB 2009

Table 2. Parameter selection

(A) Fundamental parameters	**Accuracy**	**Accuracy** (+ R_{s5})	**Accuracy** (+ R_{s5} , S_{LR})	**Accuracy** (+ R_{s5} , S_{LR}, R_{s4})
R_{s1}, R_{s3}, A_{s2}, S_{LOC}, S_{ROC}, $S_{chin\text{-}EMG}$	80.69%	81.61%	82.62%	82.72%
(B) + Optional parameters	**Accuracy**	**Accuracy**	**Accuracy**	**Accuracy**
+ R_{s2}	79.27% ↓	80.08% ↓	81.81% ↓	81.91% ↓
+ R_{s4}	80.59% ↓	78.46% ↓	82.72% ↑	
+ R_{s5}	81.61% ↑			
+ A_{s1}	78.15% ↓	79.67% ↓	82.42% ↓	80.89% ↓
+ A_{s3}	80.96% ↑	79.27% ↓	82.22% ↓	79.78% ↓
+ A_{s4}	77.24% ↓	77.95% ↓	82.01% ↓	80.18% ↓
+ A_{s5}	81.10% ↑	79.17% ↓	82.11% ↓	80.18% ↓
+ S_{LR}	80.89% ↑	82.62% ↑		

IV. DISCUSSION

In real clinics, sleep data adopts long-term recording. It is inevitably being affected by various artifacts. Individual differences are also commonly existed, even under the same recording condition. For the patients with sleep-related disorders, their sleep data has particular characteristics. The conventional rule-based methods are insufficient to deal with the recorded sleep data which containing complex and stochastic factors. We adopt an expert knowledge-based method. The expert knowledge of visual inspection covered staging criteria and considered the actual circumstance in clinics.

The fundamental parameters were defined according to the traditional definition of sleep stages. The optional parameters were defined to cover the frequency bands of the periodogram of sleep EEGs (0.5-50 Hz) together with the fundamental parameters. Even the frequency characteristic is differed from the typical definition of fundamental parameters, the characteristics can be reflected by optional parameters. Additionally, the optional parameter can provide indicators for special cases of sleep disorder which are different from the requirements in hospitals and institutions.

VI. CONCLUSION

An adaptive expert knowledge database was developed by fundamental and optional parameters. The probability density functions of parameters for sleep stage determination were flexible to variable cases of sleep data. The developed automatic sleep stage determination by using adaptive expert knowledge database can be effective for clinical practice.

ACKNOWLEDGMENT

This study is partly supported by Nation Nature Science Foundation of China 60543005, 60674089, and Shanghai Leading Academic Discipline Project, Project number: B504.

REFERENCES

[1] Rechtschaffen A and Kales KK, Manual of standardized terminology, techniques and scoring system for sleep stages of human subject, *California Brain Information Service*, USA, 1968.

[2] Himanen SL, Hasan J (2000), "Limitations of Rechtschaffen and Kales". *Sleep Med Rev*. 4(2):149-167

[3] Smith JR, Karakan I and Yang M (1978), "Automated analysis of the human sleep EEG, waking and sleeping", *Electroenceph. clin. Neurophysiol*, 2:75-82

[4] Smith JR and Karakan I (1971), "EEG sleep stage scoring by an automatic hybrid system", *Electroencephalogr Clin Neurophysiol*, 31(3):231-237

[5] Wang B, Sugi T, Kawana F, Wang X and Nakamura M (2008), "Multi-Valued Decision Making of Sleep Stages Determination Based on Expert Knowledge", *Proceedings of International conference on Instrumentation, Control, and Information Technology*, SICE Annual Conference 2008, Chofu, Japan.

©ISAROB 2009