A study of sleep staging based on a sample entropy analysis of electroencephalogram

Hui Li, Cheng Peng and Datian Ye[*]
Department of Biomedical Engineering, Graduate School at Shenzhen, Tsinghua University, Shenzhen, 518055, China

Abstract. In this paper we report a detection method for different sleep stages and it is based on a single-channel electroencephalogram (EEG) system. The system is simple and can be easily setup in homes to perform sleep EEG recording, overnight sleep EEG automatic staging, and sleep quality evaluation. EEG data of 14 sleeping subjects were recorded through the entire night. All subjects were within the age group of 20-30 years and having no significant sleep disorders. To analyze the EEG data, it is segmented into equal time intervals. This is followed by calculation of Sample Entropy (SampEn) for each section, and the SampEn's statistical characteristics, such as the median, upper quartile, lower quartile and inter-quartile range. The sleep data were divided into training group (7 cases) and test group (7 cases). Sleep stages' quantitative ranges of training group referring to ZEO results were extracted and the quantization range used to sleep staging EEG data. Both the training group and test group results were close to ZEO results. It suggested that the statistical characteristics of Sample Entropy could be used as a criterion for sleep staging and evaluation.

Keyword: Electroencephalogram (EEG), sleep staging, sample entropy (SampEn), median, inter-quartile range (IQR)

1. Introduction

Sleep is an essential physiological function, and it is required for maintaining physical and mental well-being. In order to measure sleep, several sleep staging criteria have been developed by the international communities. The most important is "A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subject", which is also called Rechtschaffen & Kales (R & K) Standard [1]. Most of the clinical sleep tests use polysomnography (PSG) method [2, 3]. PSG is a technique that records and analyzes physiological indicators of sleep simultaneously and is not suitable for using at home. Sample Entropy (SampEn) is an embedding entropy that quantifies the irregularity (or complexity) of data [4, 5]. It is used to estimate the probability of generating new EEG models when the dimension changes [6]. In this paper, a single-lead, long-term monitoring system for utilization at household is proposed that is able to perform sleep staging and could evaluate sleep quality automatically. Researchers have focused to automate EEG-based sleep-staging problem experimentally as well as clinically [7-9].

---

    [*] Address for corresponding author: Datian Ye, Department of Biomedical Engineering, Graduate School at Shenzhen, Tsinghua University, Shenzhen, China, 518055. Tel.: 13718525904; Fax: 0755-26036353; E-mail: yedt6386@sz.tsinghua.edu.cn.
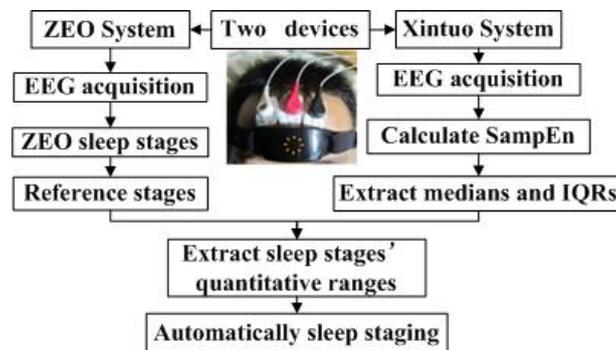
Fig. 1. Technical procedure.

2. Methods

2.1. Subjects and equipment

In order to ensure data's consistency and credibility, the subjects selected were of age 20 through 30 with no significant sleep disorders. Two detecting electrodes were fixed in Fp1 and Fp2 positions of the bipolar recording system. Two sets of equipments were used to record EEG signals simultaneously. One is Beijing Xintuo bioelectricity amplifier with a laptop, and the other is ZEO that is manufactured in U.S.A. Xintuo bioelectricity amplifier is a bipolar, single-lead system, and could obtain raw EEG signals. The sampling rate and sensitivity of Xintuo bioelectricity amplifier were 1000 Hz and 0.5 V respectively. ZEO could not provide raw EEG signals, but its results were used as a reference providing priori knowledge in the sleep stages' duration and sleep quality score in our study. The subjects needed to wear ZEO headband and Xintuo electrodes at the same time, as shown in Figure 1.

2.2. Experimental procedure

In order to diminish the impact of environmental variation, the first night sleep EEG recorded by ZEO is scored without processing. The ZEO score and the subject's feelings were together used to decide whether there were sleep disorders and also if the subject adapted to the new environment. If the answer is no, then the above procedure is repeated. If the subject failed to pass the test for the first two consecutive nights, the experiment had to be terminated. Otherwise, Xintuo system and ZEO system were used simultaneously in the following two nights for data recording and processing.

2.3. Technical procedure

The technical procedure is shown in Figure 1. Two kinds of equipments were utilized to acquire sleep EEG simultaneously. ZEO provided sleep stages results and sleep quality score. It is used as a reference to extract the characteristic parameters of different sleep stages. Xintuo system is used to achieve the following functions: 1) Obtain raw sleep EEG signals; 2) Calculate SampEn; 3) Calculate medians and inter-quartile ranges of SampEn, and get sleep box-figure sequences; 4) Extract sleep stages' SampEn quantitative ranges referred to ZEO results; 5) Use the quantitative range for automatic sleep staging.

2.4. Principle of SampEn

For a data sequence x(1), x(2),…, x(N), where N indicates the length of sequence, SampEn computation is shown in the following steps:

(1) N-m vectors and each of size m is composed as follows:

$$X_m(i) = [x(i), x(i+1), \cdots, x(i+m-1)](i = 1 \sim N-m) \tag{1}$$

(2) The distance d[Xm(i), Xm(j)] between each vector and the other vector (not including itself) is computed as:

$$d[X_m(i), X_m(j)] = \max_{k=0, m=1}(| X_m(i+k) - X_m(j+k) |)(i, j = 1 \sim N-m; j \neq i) \tag{2}$$

(3) Let Nm be the number of d[Xm(i), Xm(j)] within r (the given tolerance). The function is defined as:

$$C_r^m(i) = N^m(i)/(N-m-1) \tag{3}$$

Average over i:

$$C^m(r) = (N-m)^{-1} \sum_{i=1}^{N-m} C_r^m(i) \tag{4}$$

(4) The dimension is increased to (m+1) and the previous steps are repeated. Sample Entropy is defined as:

$$SampEn(m, r, N) = -\ln[\frac{C^{m+1}}{C^m}] \tag{5}$$

The parameters' selection principle of SampEn can be found in the literature [10]. This paper selected m=2, r=0.2*SD (m: embedding dimension of the vector to be formed; r: tolerance that functions as a noise filter; SD: standard deviation of the data). The EEG data sequence is selected by the sliding rectangular window method. The sliding window length is 60 seconds and sliding step is 30 seconds.

2.5. Statistical parameter selection

To analyze the sleep EEG SampEn' central tendency and dispersion tendency, a set of four statistical parameters including the median, the upper quartile, the lower quartile and the inter-quartile range (IQR) were chosen. This is due to the fact that the medians had good stability with the respect to anti-extreme values.

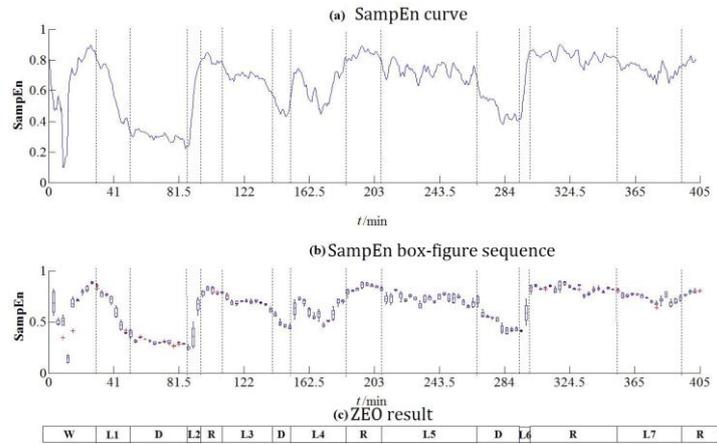## 2.6. SampEn curve and overnight sleep box-figure sequence

Fig. 2. Each sleep stage's SampEn characteristic.

The SampEn medians and inter-quartile ranges of every time interval (3 minutes) were calculated, as shown in Figure 2. In each sleep stage's SampEn characteristic is as follows.

(1) Deep sleep (D): SampEn had the lowest values and a small inter-quartile range. This is due to the fact that EEG has characteristics such as high amplitudes, slow waves, low complexity and good stability.

(2) REM sleep (R): SampEn had the highest values and a small inter-quartile range. This is due to the fact that the brain is dreaming, adjusting and repairing memory. During this stage, EEG is fast waves, low amplitudes, high complexity and stable.

(3) Light sleep (L): There were two modes in light sleep. There are different types of light sleep, so digital numbers followed by L were used to distinguish each other as can be seen in Figure 2.

a) Gradual transition mode. Light sleep transitioned between deep sleep and REM sleep. The SampEn increased or decreased monotonically, but did not exceed the SmapEn values of deep sleep and REM sleep. This process could be fast or slow. The IQR is small when SampEn changed slowly as shown by L1 and L3 in Figure 1, and the IQR is large when SampEn changed fast as shown by L2 and L6 in Figure 2.

b) Repeated adjustment mode. SampEn hopped several times between deep sleep and REM sleep with the hopping period, very short at first, and then stabilizing gradually at one stage. Multiple medians of SampEn were not continuous and did not exceed the medians of deep sleep and REM sleep. The inter-quartile ranges of SampEn were large. This is shown as L4, L5 and L7 in Figure 2.

(4) Awakening (W): Due to the irregular and random EEG activities, it has higher inter-quartile ranges than any other stages. SampEn medians are discontinuous and non-monotonic.

2.7. Quantization range of SampEn for sleep staging

To perform EEG sleep staging automatically, we needed to search for a suitable quantization range of SampEn. Based on the qualitative characteristics of SampEn given in the previous section, we used quartiles and inter-quartile ranges of SampEn to determine the numerical ranges. The sleep data were divided into training group (7 cases) and test group (7 cases). The upper margins' medians, inter-quartiles and differences between the adjacent medians of different sleep stages of the training group were also counted. The numerical results intuitively reflected the mainstream values and
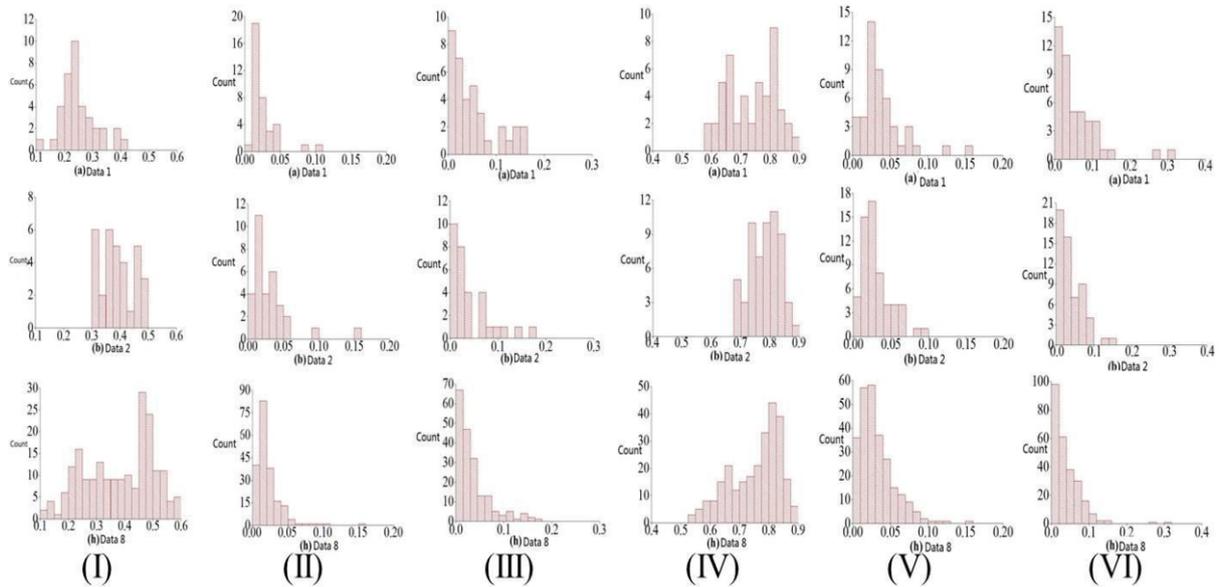
Fig. 3. The training group result.

Note: (I~III): The upper margins' median\IQR\differences between the adjacent medians statistical results of deep sleep. (IV~VI): The upper margins' median\IQR\differences between the adjacent medians statistical results of REM sleep.

common fluctuation range of different cases as shown in Figure 3. In each panel, from data 1 to 7 is 7 case results; and Data 8 is the total numerical range result of the 7 samples that represented the logical relationship "or".

From the study of the numerical results of different sleep stages,the following can be inferred. For deep sleep, the median range is defined as (DM1 ~ DM2), the maximum inter-quartile is DI, and the maximum difference between adjacent medians is DD. For REM sleep, the median range is defined as (RM1 ~ RM2), the maximum inter-quartile is RI, the maximum difference between adjacent medians is RD. From Figure 3, all the values that reflected the mainstream numerical range distribution were extracted. The mainstream numerical ranges mean the peak decreased by 2 variances (2). It covered 95% of 7 cases histograms' qualitative characteristics. DM1, DM2, DI, DD were integrated to judge deep sleep. RM1, RM2, RI, RD were integrated to judge REM sleep.

(1) Deep sleep: SampEn of deep sleep had the lowest medians and a small inter-quartile range. Moreover, there is a small change in the adjacent medians. Here, DM1 and DM2 took the sum of the 7 cases' ranges, DI chose the max values of its mainstream, and DD selected the max value of its mainstream. DM1 and DM2 were responsible for screening the approximate range, while DI and DD were responsible for the numerical range. Based on these ranges, the results were accurate. Here, DM1 is 0.10, DM2 is 0.60, DI is 0.07, and DD is 0.12.

(2) REM sleep: SampEn of REM sleep had the highest medians, small inter-quartile ranges. In addition, the changes between adjacent medians were small. Here, RM1 and RM2 took the sum of the 7 cases' ranges, RI chose the max values of its mainstream, and RD selected the max value of its mainstream. RM1 and RM2 were responsible for screening the approximate range, while RI and RD were responsible for the numerical range. Based on these ranges, the results were accurate. Here, RM1 is 0.60, RM2 is 0.90, RI is 0.07, and RD is 0.12.

(3) Light sleep: Light sleep is considered as transitional and adjustable sleep. Except for awakening stage, REM sleep and deep sleep and rest is grouped into light sleep. The SampEn medians were

constrained between those of deep sleep and REM sleep. The median variations were monotonic and continuous. The inter-quartile ranges and the differences between adjacent medians were larger than those of deep sleep as well as REM sleep.

(4) Awakening: In awakening stage, the SampEn medians were discontinuous and non-monotonic, the inter-quartile ranges had larger fluctuations, EEG waves performed without regularity.

2.8. Sleep quality evaluation

Upon completion of the above listed steps, sleep quality evaluations would be performed. The duration before sleep, awakening duration, light sleep duration, deep sleep duration, and REM sleep duration were defined as T_{tz}, T_w, T_l, T_d and T_r respectively. The sleep quality score is annotated by S. Sleep stages' contribution coefficients were annotated as k_{tz}, k_w, k_l, k_d and k_r, and all of them were supposed to be positive. The contributions were the multiplication of the durations and contribution coefficients, such as $T_{tz} * k_{tz}$, $T_w * k_w$, $T_l * k_l$, $T_d * k_d$ and $T_r * k_r$. Regardless of sleep depth and dreams, light sleep, deep sleep, and REM sleep apparently had positive contributions to the score, while the duration before sleep or the occasional awakening duration during sleep had negative impact on the sleep quality. The total duration of overnight valid sleep is defined as $(T_l + T_d + T_r)$. The best sleep quality is scored 100. ZEO results that were shown in Table 1 and Table 2 (in brackets) were used as priori knowledge for determining the coefficients of the score equation. The data is fitted by the least squares method and the score equation is:

Table 1

Comparative results of training group: SampEn algorithm *vs* ZEO system

No.	Total sleep duration (min)	Duration before sleep (min)	Deep sleep duration (min)	REM sleep duration (min)	Light sleep duration (min)	Awakening duration (min)	Score
1	399(400)	11(26)	108(108)	153(149)	138(143)	15(19)	88(86)
2	378(380)	35(50)	69(46)	132(98)	177(236)	15(19)	77(66)
3	375(373)	37(52)	93(93)	96(85)	186(195)	15(20)	82(73)
4	405(405)	33(42)	108(98)	96(101)	195(206)	9(16)	85(82)
5	405(408)	32(41)	99(100)	126(128)	174(180)	9(0)	85(88)
6	417(416)	61(76)	96(100)	150(179)	171(137)	15(16)	83(87)
7	405(421)	27(36)	81(59)	123(82)	201(280)	9(13)	80(72)

Table 2

Comparative results of test group: SampEn algorithm *vs* ZEO system

| No.	Total sleep duration (min)	Duration before sleep (min)	Deep sleep duration (min)	REM sleep duration (min)	Light sleep duration (min)	Awakening duration (min)	Score
1	396(393)	40(55)	102(47)	138(157)	156(189)	15(31)	85(68)
2	387(386)	21(36)	96(54)	90(185)	201(147)	15(28)	81(74)
3	429(430)	18(27)	90(83)	117(114)	222(233)	9(9)	80(83)
4	378(377)	30(45)	48(92)	117(112)	213(173)	15(63)	71(73)
5	396(394)	51(60)	75(86)	123(93)	198(215)	9(1)	79(81)
6	369(369)	37(52)	72(58)	126(129)	171(182)	15(28)	78(69)
7	366(366)	3(3)	57(64)	111(135)	198(167)	9(27)	76(71)
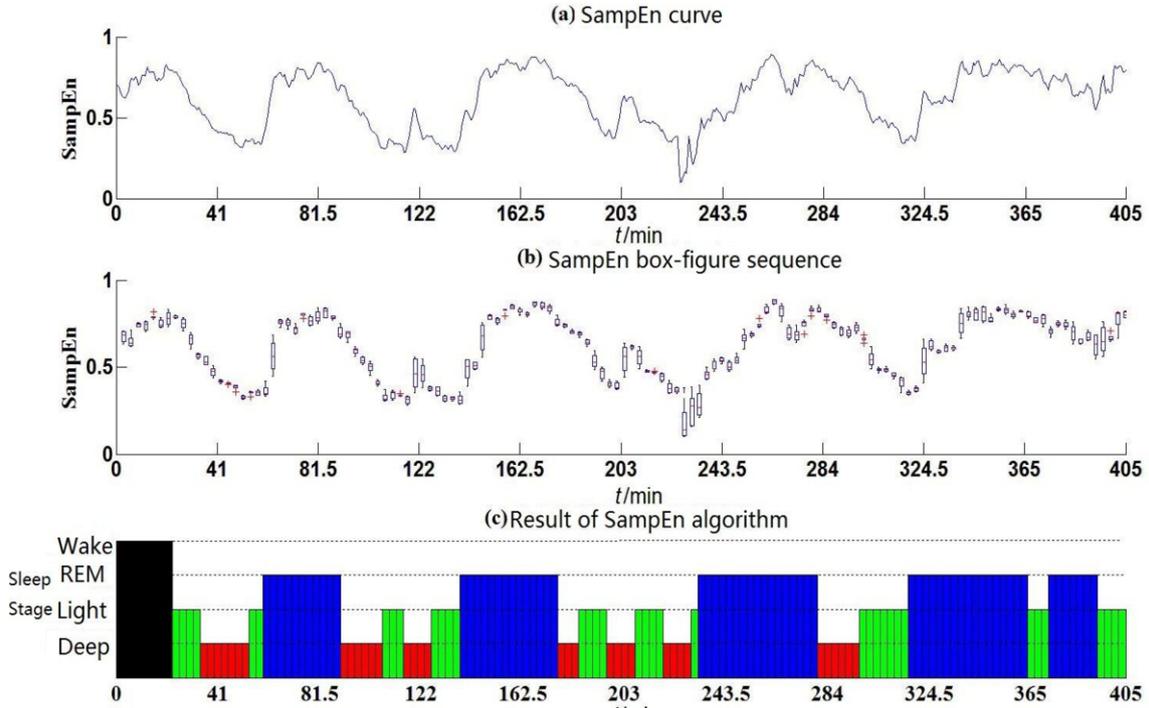
Fig. 4. Sleep stages result. From top to bottom, there were SampEn curve, ZEO result, box-figure sequence and sleep stages.

$$\frac{-T_{tz} * 0.0787 - T_w * 0.9965 + T_l * 0.5347 + T_d * 1.5699 + T_r * 0.8155}{T_l + T_d + T_r} = S\% \qquad (6)$$

3. Results

Figure 4 shows an example of SampEn algorithm. Table 1 shows the automatic staging results of the training group and the ZEO system results are shown in brackets. Deep sleep and REM sleep had a great impact on the quality of sleep. Therefore in this paper we focused on the degree of match statistics of these two sleep periods. Table 1, shows that the maximum error of deep sleep time is 23 minutes and the error percentage of the total sleep time period is not more than 6.05%. Further the maximum error of REM sleep is 41 minutes and the error percentage of the total sleep time period is not more than 9.74%. The automatic staging results of the test group and ZEO system results (in brackets) are shown in Table 2, with the exception of samples 1 and 2. The other results and ZEO results were close. These five samples were studied, and the maximum error of deep sleep time is estimated to be 44 minutes and the error percentage of their total sleep time period is not more than 11.67%, while the maximum error of REM sleep is 30 minutes and the error percentage of their total sleep time period is not more than 7.61%. Therefore, it is suggested that SampEn could be used as a criterion to discriminate different sleep stages.

4. Discussion and conclusions

It is suggested that SampEn could be used as sleep EEG staging criteria. However the current work had some limitations. The 14 cases studied were too small to build a classification standard. More samples are required to improve the accuracy and the stability of the proposed method. In addition to the above constraint, the main objects of this paper were in a narrow range, so a further expansion of the sampled population is needed.

This paper analyzed 14 cases sleep EEG data by SampEn method. It is found that different sleep stages have different SampEn features. 14 cases of overnight sleep EEG data were staged automatically. The results were close to ZEO results. Finally, it is suggested that SampEn could be used as a criterion to discriminate different sleep stages.

Acknowledgments

References

[1] A. Rechtschaffen and A. Kales, A manual of standardized terminology, techniques and scoring system for sleep stages of human subject, Brain Information Service⁄Brain Research Institute, University of California, Los Angeles, 1968.
[2] K. Šušmáková, Human sleep and sleep EEG, Measurement Science Review **4** (2004), 16.
[3] N.J. Douglas, S. Thomas and M.A. Jan, Clinical value of polysomnography, Lancet **339** (1992), 347-350.
[4] J.S. Richman, D.E. Lake and J.R. Moorman, Sample entropy, Methods in Enzymology **384** (2004), 172-184.
[5] D. Zhang, Cerebral development/injury in neonates: EEG study, Ph.D. Dissertation, Tsinghua University, 2010.
[6] J.R. Shambroom, S.E. Fabregas and J. Johnstone, Validation of an automated wireless system to monitor sleep in healthy adults, Journal of Sleep Research **21** (2012), 221–230.
[7] F. Yaghouby, P. Modur and S. Sunderam, Naive scoring of human sleep based on a hidden Markov model of the electroencephalogram, IEEE Engineering in Medicine and Biology **8** (2014), 5028-5031.
[8] F. Yaghouby, C.J. Schildt, K.D. Donohue, B.F. O'Hara and S. Sunderam, Validation of a closed-loop sensory stimulation technique for selective sleep restriction in mice, 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Chicago, Illinois, USA, August 26-30, 2014, 3771-3774.
[9] F. Yaghouby and S. Sunderam, Quasi-supervised scoring of human sleep in polysomnograms using augmented input variables, Computers in Biology and Medicine **59** (2015), 54-63.
[10] J.S. Richman and J.R. Moorman, Physiological time-series analysis using approximate entropy and sample entropy, American Journal of Physiology-heart and Circulatory Physiology **278** (2000), H2039-H2049.