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Sleep Stage Estimation by Non-invasive Bio-measurement

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Abstract: Sleep age and sleep index are defined based on heartbeat and body movement measured noninvasively by the pneumatic method for a person sleeping in bed. Sleep age indicates the quality of sleep, and sleep index shows the temporal changes in sleep conditions, by which the sleep stage of the R-K method can be estimated. The overall sleep stages estimated by the proposed method show similar sleep characteristics to those obtained by the R-K method and show reasonable sleep transition.

Keywords: Noninvasive biomeasurement, sleep quality, sleep index, sleep age, R-K method

1. INTRODUCTION

Safety and health are important for maintaining a high quality of life[1],[2]. Good sleep is a prerequisite for good health[3]-[6], and people have recently become more interested in the quality of their sleep. If we can monitor our sleep in a noninvasive manner by ourselves at home, then we might be able to use the obtained information to more effectively manage our daily routine to improve our sleep.

Various sleep-monitoring methods exist. The simplest is sleep-time monitoring that simply records the bedtime and wake-up time. The most accurate is the Rechtschaffen and Kales method[7], or R-K method, which is an international standard that categorizes the sleep depth and sleep conditions in six sleep stages, including the wake stage, as judged from biosignals such as EEG data, eye movements, and EMG data of the jaw. The R-K method, however, poses a problem in that the number of sleep categories (six) is not sufficient for expressing the various sleep conditions, and judgments made schematically from the biosignals lead to subjective error, even by medical specialists[8]. Another serious problem with the R-K method is its invasiveness and the necessity for subjects to be restrained during monitoring. Thus, it is rarely used at home. Sleep-monitoring methods that may be equally or less informative, but must be less invasive than the R-K method, are required for home sleep monitoring.

The proposed method is an extension of these conventional methods[9]-[16], whereby we employ the same pneumatic biomeasurement method[16]. Here, we use the measured heartbeat and body movements and define two sleep indices: the sleep age, which determines the sleep quality, and the sleep index, from which the sleep stage of the R-K method is estimated. The sleep age and sleep index can be simply calculated from the spectrum of a heartbeat signal, including artifacts due to body movement.

2. PROBLEM DESCRIPTION

2.1 Noninvasive biomeasurement

Figure 1 shows a person relaxing in bed with no restraints. An air cushion 5 mm thick is placed under the bed mattress and the change in pressure due to the vital motions of the person is detected by a pressure sensor having a gain of –35 dB (0 dB = 1 V/Pa) for the frequency range of 0.1 Hz to 10 kHz.

The sensor output is band-pass-filtered with a frequency band of 5–10 Hz and the envelope is detected. The output shown in Fig. 1 is the signal obtained during 40-s intervals for a specific sampling time. The signal during the period from 0 to 7 s shows the heartbeat without body movement and is periodic, and that during the period from 17 to 35 s shows the heartbeat corrupted by body movement artifacts and includes a low-frequency component with a large amplitude. The amplitude and distortion rate of the signal are influenced by the type of bed mattress, the subject and the sleep posture.

If the subject is a healthy sleeper, he experiences six sleep stages, including the wake stage. After going to bed, the subject passes from the shallow sleep stage to the deepest sleep stage within a short period. After the deepest stage, the subject's sleep transitions to REM sleep via several non-REM stages. This sleep cycle is repeated approximately every 90 minutes, and the sleep gradually shallows toward morning.

The following symbols, variables and constants are used for sleep and the measurement system shown in Fig. 1:

W: Wake
R: REM sleep
NRi: Non-REM sleep I (i = 1, 2, 3, 4)
k: Discrete time with sampling interval of 1 min (60 s)
$P(k)$: Peak spectrum of the heartbeat
$B(k)$: Average spectrum excluding heartbeat
$S(k)$: Sleep index
$\bar{S}(k)$: Sleep index movement averaged with the 2n+1 samples
σ_s : Standard deviation of sleep index of an entire night's sleep
f_x : Occurrence rate of sleep stage x (x = W, R, NR1, NR2, NR3, NR4)
Δf_x: Range of occurrence rate of sleep stage x (x = W, R, NR1, NR2, NR3, NR4)

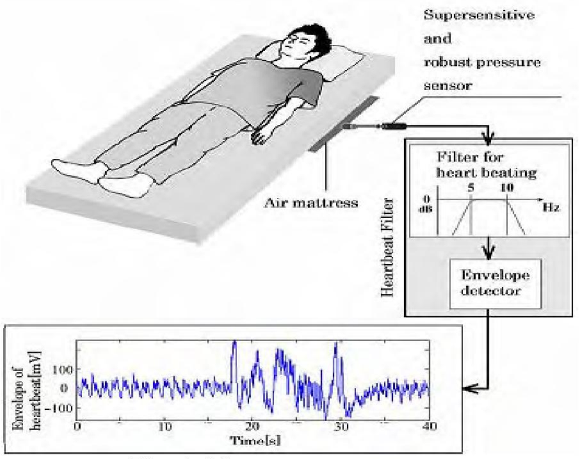


Fig. 1 Measurement system

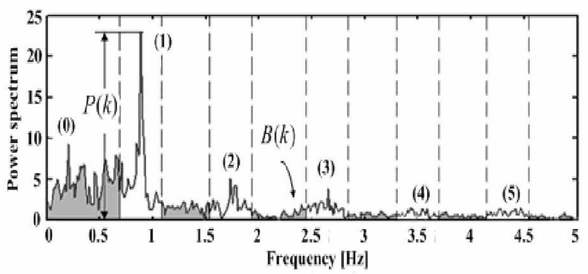


Fig. 2 Power spectrum of heartbeat measured by the system shown in Fig. 1

y : Actual age

y_s: Sleep age judged by the occurrence rate of NR4

$\hat{y}_s$: Sleep age estimated by the sleep index

2.2 Definition of sleep index and sleep age

Figure 2 shows the spectrum of a heartbeat signal having a period of 51.2 s with a sampling interval of 0.1 s in discrete time k. In Fig. 2, Peak (0) is the spectrum of respiration, Peak (1) is the fundamental component of the heartbeat, and Peaks (2) to (5) are the harmonics of the heartbeat. From the peak spectrum $P(k)$ of the heartbeat and the average spectrum $B(k)$ shown by the gray area, excluding the heartbeat components, we define the sleep index:

$$S(k) = -20\log_{10}\frac{P(k)}{B(k)} = 20\log_{10}\frac{B(k)}{P(k)} \qquad (1)$$

We calculate moving average as follows:

$$\bar{S}(k) = \frac{\sum_{i=-n}^{n} S(k+i)}{2n+1} \qquad (2)$$

The spectrum $P(k)$ in Fig. 2 is a signal component for heartbeat measurement. The gray spectra $B(k)$, even if they are the spectra of respiration and body movement, are nothing more than noises with respect to the heartbeat measurement. Thus, the sleep index defined by (1) is the N/S ratio for the heartbeat measurement. Because the sleep index $S(k)$ is given by the ratio of $P(k)$ and $B(k)$, the influence from differences in measurement gain due to different bed mattresses, subjects and sleep postures can be compensated. Furthermore, the influence from distortion of the heartbeat signal is also small because the harmonics are not used.

Table 1 Qualitative relationship between sleep depth, body movement, heart rate and sleep index

Sleep depth	Body movement	Heart rate	Index $S(k)$
Shallower sleep (W,R,NR1)	Bigger and higher frequency	Higher and random	Greater
Deeper sleep (NR2,NR3,NR4)	Smaller and lower frequency	Lower and constant	Less

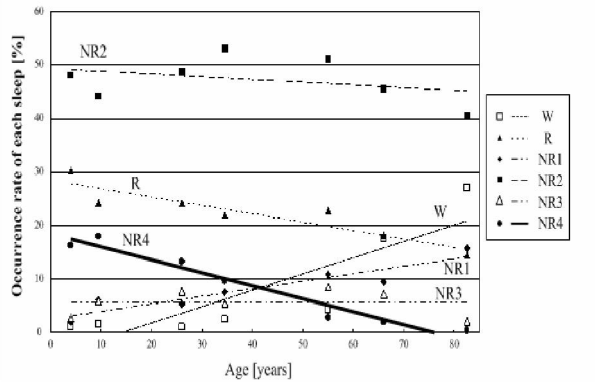


Fig. 3 Frequency of sleep stage occurrence, and age

Table 2 Subjects for estimating sleep age

Subject	Age	Trial number	f_{NR4}	Sleep age
E	22	1	9.6	36.8
M	22	2	2.3	67.1
			3.6	61.7
K	21	2	6.1	51.3
			4.6	57.5
A	21	2	1.4	70.8
			3.3	62.9
R	18	1	4.9	56.3
S	23	1	6.9	48.0
O	23	3	6.4	50.0
			4.3	58.8
			6.0	51.7
W	24	5	5.8	52.5
			3.1	63.7
			6.1	51.3
			4.6	57.5
			3.2	63.3
I	22	2	1.3	71.2
			1.8	69.1
H	24	1	7.2	46.7

The relationship between index $S(k)$ and depth of sleep is considered. As shown in Table 1, the depth of sleep is related to body movement and heart rate. During shallow sleep, the average value of the gray area $B(k)$ increases and the spectrum $P(k)$ decreases, and therefore the value of the sleep index $S(k)$ increases. Conversely, during deeper sleep, body movement level and heartbeat fluctuations decrease, i.e., the value $B(k)$ decreases and the spectrum $P(k)$ increases, and therefore the value of the sleep index $S(k)$ decreases. The index $S(k)$ shows the sleep depth quantitatively.

Figure 3 shows the relationship between the average occurrence rate of sleep stages W, R, NR1, NR2, NR3, and NR4 and actual ages. The plots shown in Fig. 3 are experimental data from the Handbook of Sleep Science and Sleep Medicine[6]. Assuming these plots are on lines, we estimate linear regression models that relate the occurrence rate of each sleep stage and the actual age y under the constraint $f_{\mathrm{W}}+f_{\mathrm{R}}+f_{\mathrm{NR1}}+f_{\mathrm{NR2}}+f_{\mathrm{NR3}}+f_{\mathrm{NR4}}=100\%$:

$$\begin{aligned} f_{\mathrm{W}} &= 0.307\, y - 4.39 \\ f_{\mathrm{R}} &= -0.157\, y + 28.49 \\ f_{\mathrm{NR1}} &= 0.141\, y + 2.53 \\ f_{\mathrm{NR2}} &= -0.051\, y + 49.32 \\ f_{\mathrm{NR3}} &= 0.001\, y + 5.59 \\ f_{\mathrm{NR4}} &= -0.241\, y + 18.46 \end{aligned} \qquad (3)$$

Since the plots in Fig. 3 are experimental data, they include errors. Among the plots, the occurrence rate includes the least error and fluctuations with respect to age. Furthermore, the NR4 stage is judged mainly by the percentage of clear delta waves, and the number of mistakes in judgment is the lowest. Thus, to relate age and sleep, the occurrence rate f_{NR4} is the most reasonable. From (3), the age y_s estimated from f_{NR4} is given by

$$y_s = -4.15\, f_{\mathrm{NR4}} + 76.6 \qquad (4)$$

Equation (4) gives the sleep age, which indicates the degree of sleep degradation. If, for example, the sleep age given by (4) is greater than the actual age, then the quality of the sleep is degraded.

2.3 Problem description

From the definitions of sleep index in (1) or (2) and of sleep age in (3), the present paper treats the following problems:

P1) Estimate the sleep age from the sleep index.

P2) Estimate the sleep stages from the sleep age and sleep index according to the R-K method.

P3) Verify experimentally the sleep age, sleep index and sleep stage.

3. SLEEP INDEX AND SLEEP AGE

3.1 Sleep experiment

Problem P1) is considered in this section, specifically the quantitative relationship between sleep age and sleep index $S(k)$. The sleep depth was calculated from the heartbeat data obtained experimentally using the system shown in Fig. 1. Simultaneously, the sleep stage was obtained using the software SLEEP SIGN (Kissei Co. Ltd., Default) based on the R-K method from EEG data and EMG data from jaw and eye movements measured by a polygraph (NEC Co. Ltd.). Table 2 shows the occurrence rate of f_{NR4} and the sleep ages calculated from (4) for 20 trials with 10 subjects. Figure 4 shows an example of the sleep index movement averaged by (2) with n = 2 and the sleep stage obtained by the R-K method for the second trial with Subject O.

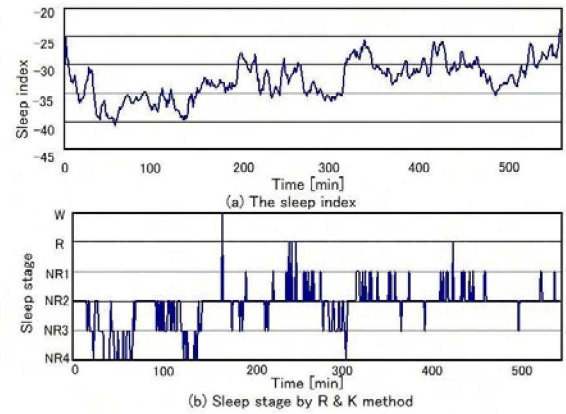


Fig. 4 Sleep index and sleep stages for Subject M (First trial)

Table 3 Correlation between f_{NR4} and sleep index statistics

Sleep index statistics	Correlation between statistics and f_{NR4}
Mean	-0.14
Variance	0.82
Standard deviation	0.81
Log(Variance)	0.80
Variance/Mean	-0.78
Standard deviation/Mean	-0.67

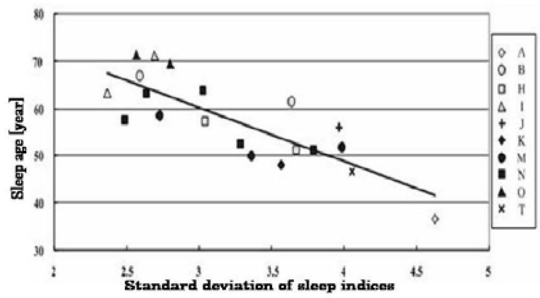


Fig. 5 Standard deviation of sleep index vs. sleep age

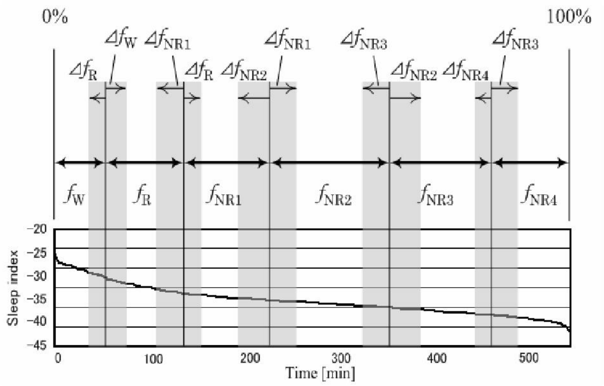


Fig. 6 Sleep stage occurrence rate

3.2 Sleep age and statistics of sleep index

In this section, we determine the relationship between sleep age, listed in Table 2, and sleep index. Table 3 shows the correlation coefficients between the sleep age and several statistics of the sleep index for 20 sleep trials shown in Table 2. Since the standard deviation has the same dimension as the sleep index, we use the standard deviation as the variable for estimating sleep age. Figure 5 shows plots of standard deviation $\hat{\sigma}_s$ with respect to sleep age y_s. The sleep age becomes younger as the standard deviation increases because young sleepers experience a wide range of sleep depth, i.e., from wake W to deepest sleep NR4, during the entire night's sleep, whereas older sleepers experience a narrow range of sleep, i.e., from W to shallow sleep stages, such as NR2 and NR3. From the plots in Fig. 5, we can obtain a relationship by which to estimate the sleep age from the standard deviation of the sleep index as follows:

$$\hat{y}_s = -11.4\sigma_s + 94.4(\pm 6.4) \qquad (5)$$

4. SLEEP INDEX AND SLEEP STAGE

Problem P2) is considered in this section. The setting of thresholds to discriminate the sleep stage from the sleep index is a simple method by which to convert the sleep index to the sleep stage. The difficulty is in selecting the proper threshold. Here, we present a method for determining the threshold from the estimated sleep age and the sleep index $S(k)$. The algorithm for estimating the sleep stage is as follows:

< Calculation of sleep index $S(k)$, sleep age $\hat{y}_s$ and the occurrence rate and its range for the sleep stages >

(S1) Obtain the sleep index $S(k)$ from (1)

(S2) Obtain the smoothed sleep index $\overline{S}(k)$ from (2)

(S3) Calculate the sleep age $\hat{y}_s$ from the standard deviations $\hat{\sigma}_s$ of sleep index $S(k)$ from (5)

(S4) Calculate the occurrence rate and its range for the sleep stages by substituting the sleep age $\hat{y}_s \pm 6.4$ into (3), as shown in Fig. 6.

< Calculation of sleep stages >

(S5) Order the sleep index $\overline{S}(k)$ from maximum to minimum and find the critical points in the ranges $f_x \pm \Delta f_x, x = W, R, NR1, NR2, NR3, NR4$. Divide the sleep index into six zones that correspond to the six sleep stages.

(S6) Reorder the six stages of the sleep index into temporal order.

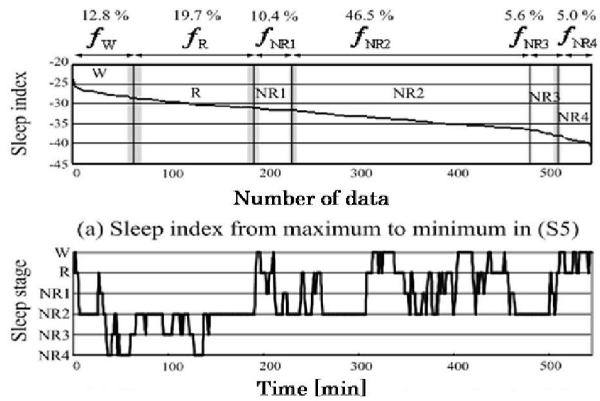
In Step (S4), the sleep age and occurrence rate of each sleep stage are given with the range due to the fluctuation in plots in Fig. 5 or (5). Furthermore, in Step (S5), the critical point is selected as the border of adjoining sleep stages because we follow the inherent assumption of the R-K method in which the number of sleep stages is six and the subjects maintain constant biological conditions during each stage. Figure 7 shows an example of how the algorithm is implemented. In the example, Subject O is shown in Fig. 4. The standard deviation of sleep index is given as 3.36. Thus, the sleep age estimated from (5) is $56.1(\pm 6.4)$ years, and the range of occurrence rate of sleep stages from (3) is as follows:

W-R:[11.8, 14.8], R-N1:[31.6, 33.5], NR1-NR2:[42.6, 43.9]
NR2-NR3:[89.4, 89.7], NR4[93.5, 95.5]

From the critical point, the following occurrence rates were calculated:

$f_w = 12.8\%$, $f_R = 19.7\%$, $f_{NR1} = 10.4\%$,
$f_{NR2} = 46.5\%$, $f_{NR3} = 5.6\%$, $f_{NR4} = 5.0\%$

Using these occurrence rates, Fig. 7(a) shows the process in Step (S5), and Fig. 7(b) shows the final results obtained by the process in Step (S6).



(a) Sleep index from maximum to minimum in (S5)

(b) Sleep stages estimated from sleep index in (S6)

Fig. 7 Estimation of sleep stages from sleep age and sleep index

Table 4 Subjects for evaluating proposed method

Subject	Age	Number of trials	f_{NR4} [%]	Sleep age by f_{NR4} [years]
M	22	2	5.6	53.4
			3.6	61.7
N	21	1	2.2	67.5
L	24	1	4.3	58.8
H	24	1	7.4	45.9

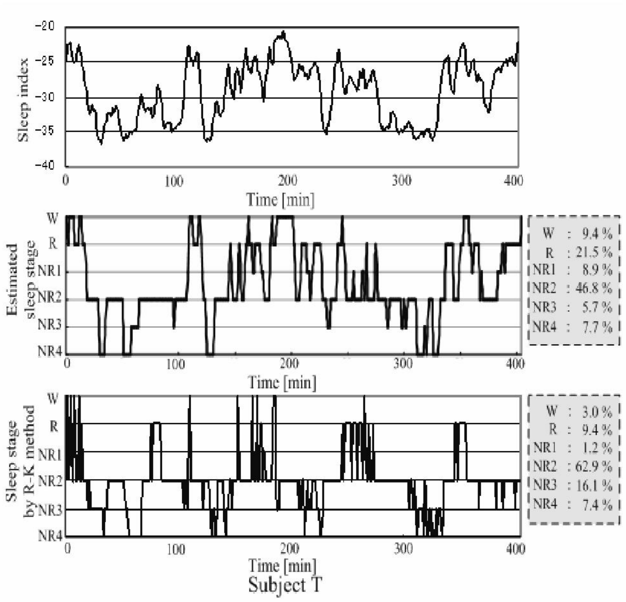


Fig. 8 Changes in sleep stages estimated by the proposed method and the R-K method

Table 5 Errors between sleep stages estimated by the proposed method and the R-K method

Subject	σ_s	Sleep age by σ_s	Difference in ages	SQRM of stage error	Agreement [%]
M	3.56	53.8	-0.4	1.28	32.6
N	3.78	51.3	16.3	1.08	39
L	3.96	49.3	9.5	1.14	37.9
H	4.33	45	0.9	1.13	36.1

5. EXPERIMENTAL VERIFICATION

Problem P3) is considered in this section. Table 4 shows the subjects, their actual ages, the number of trials, the occurrence rate of f_{NR4} and the sleep age obtained from (4). The subjects or trials differ from those used for developing the estimation formula of (5). Figure 8 shows the sleep index when n = 2 in (2), sleep stages estimated by the proposed method and sleep stages judged by the R-K method for Subject H, whose actual age is 24 years. The occurrence rate of NR4 f_{NR4}=7.4% is less than that of 24-year-old sleepers. The sleep age from (4) is 45.9 years. The sleep depth decreased to the deepest value when the subject fell into a deep sleep approximately 30 min after going to bed. After the deep sleep, the sleep depth gradually decreased, i.e., the sleep became shallow toward morning, with some oscillating rhythms of REM occurrence periods. This is the tendency of a normal sleeper. The standard deviation of the sleep index was 4.33, and from (5), the subject's sleep age was estimated to be 45.0 years. The estimated sleep stage shows slower changes in stage, due to the selection of n = 2, than the results given by the R-K method. The details of the estimated stages include differences but are similar to the entire night's sleep pattern. The coincidence rate of the stages obtained by the proposed method and the R-K method was 36.1%. Under the assumption that the sleep stages W, R, NR1, NR2, NR3, and NR4 are on a linear scale with respect to sleep depth, and if we assign the numbers 6, 5, 4, 3, 2, and 1, respectively, to each sleep stage, then the SQRM error is 1.13, i.e., one stage.

Table 5 shows the standard deviation, the sleep age estimated by the standard deviation, the difference in the ages, the SQRM error of the stages, and the agreement percentage of the sleep stages. The standard deviation of sleep ages was 7.8 years. The average agreement percentage of the sleep stages was 36.4%, and the SQRM error of the sleep stages was 1.16, i.e., one stage.

6. DISCUSSION

We investigated how sleep index and estimated sleep stage can be used in the field of psychoneurosis by means of a questionnaire given to four psychoneurologists. We received the following comments from the psychoneurologists:

C1) The R-K method using the polygraph restrains the subjects and is so invasive that the method is used only in experiments. The pneumatic method is noninvasive and so has the potentiality to be used in hospitals as well as at home.

C2) Sleep states can be estimated from only the transition of sleep depth, as follows:

- Sleep gradually shallows toward morning.
- Sleep latency is clearly observed.
- The period of REM sleep is observed.

C3) The R-K method is used to investigate the effect of sleeping pills and the degree of sleep disorders by observing the characteristics of sleep latency and the period of REM sleep.

The sleep stage estimated by the proposed method has sufficient accuracy for these observations.

C4) For the proposed method to be used in the field of psychoneurosis and sleep disorders, more clinical trials should be conducted, not only by comparison with the R-K method, but also by comparison with the results of apnea, stress foot syndrome and other sleep-related diseases.

The pneumatic method can measure respiration and body movement and so has high potentiality for application to various diseases.

7. CONCLUSIONS

A novel method by which to measure the sleep index from the heartbeat is presented. The measurement principle is based on the pneumatic method. A new index that gives the sleep depth quantitatively, in dB, is defined by the ratio of the peak spectrum of the heartbeat and the average spectrum of the body movement. The occurrence rate of non-REM4 sleep is given by a linear relationship with age from a previous study. From this relationship, we further define the sleep age as determined by the occurrence rate of non-REM4 sleep. The standard deviation of the sleep index of an entire night's sleep has a correlation of 0.81 with the occurrence rate of non-REM4 sleep and so the sleep age can be estimated from the standard deviation of the sleep index. Using the estimated sleep age and based on the sleep index, a method by which to estimate the sleep stage with six sleep categories, in the manner of the R-K method, is proposed.

The average estimated error of sleep age defined by the occurrence rate was 7.8 years. The average coincidence rate of sleep stages between the R-K method and the proposed method was 36.4%, and the SQRM error of the sleep stage was one stage. The coincidence rate of the sleep stage for each minute was not high, but the overall characteristics of the entire night's sleep obtained by the proposed method were similar to those obtained by the R-K method. The changes in sleep index and the estimated sleep stage show the essential sleep characteristics.

The proposed method presents the sleep quality, i.e., the sleep age, the changes in sleep index and sleep stage, which are not as accurate as the results given by the R-K method but will be useful in sleep diagnosis in hospitals, and are noninvasive, requiring no restraints, which will allow the method to be used for sleep monitoring not only in hospitals but also at home.

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