# For Children's Sleep Assessment: Can we trace the change of sleep depth based on ECG data measured at their respective home with a wearable device?

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# 1. Necessity of the development of a convenient sleep measuring system

## *What short sleep duration causes*

Short sleep duration and poor sleep quality may negatively affect physical health, such as obesity, diabetes, cardiovascular disease and hypertension, and psychological health, such as anxiety symptoms, depressed mood, concentration, performance, behavior, emotional instability .

A cohort study about the effect of longitudinal sleep duration patterns to the obesity reported persistently short sleep duration (<10 h) during early childhood (from 2.5 to 6 years old (y.o.)) significantly increases the risk of excess weight or obesity at age 6 y.o.

A cross-sectional study of the relationship between short sleep duration and obesity-related variables in children (5-10 y.o.) reported that when compared to children reporting12–13 h of sleep per day, the adjusted odds ratio for childhood overweight/obesity was 1.42 for those with 10.5–11.5 h of sleep and 3.45 for those with 8–10 h of sleep.

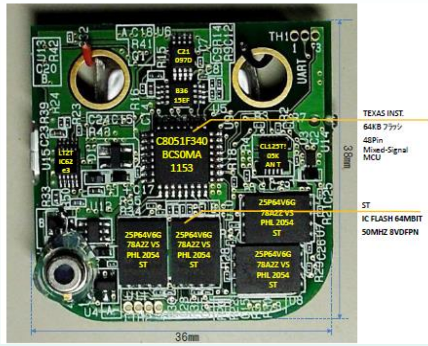
## *Three methods for sleep assessment*

Sleep durations used in these important studies were parental reports (PARD) , i.e., times in bed of their children.

Also, many reports of actigraphic sleep duration (ACTD) , and comparisons of sleep durations for children around 4 y.o. indicated that 10-11 h by PARD corresponded to 8-9 h by ACTD.

On the other hands, several polysomnographic (PSG) sleep-disordered breathing (SDB) studies of children also reports sleep duration of normal children as 7.6 h (mean 4.4 y.o.) , 6.6 h (mean 9.8 y.o.) and 7.6 h (mean 6.5 y.o.) . Sleep durations with PSG examinations (PSGDs) were shorter than ACTDs.

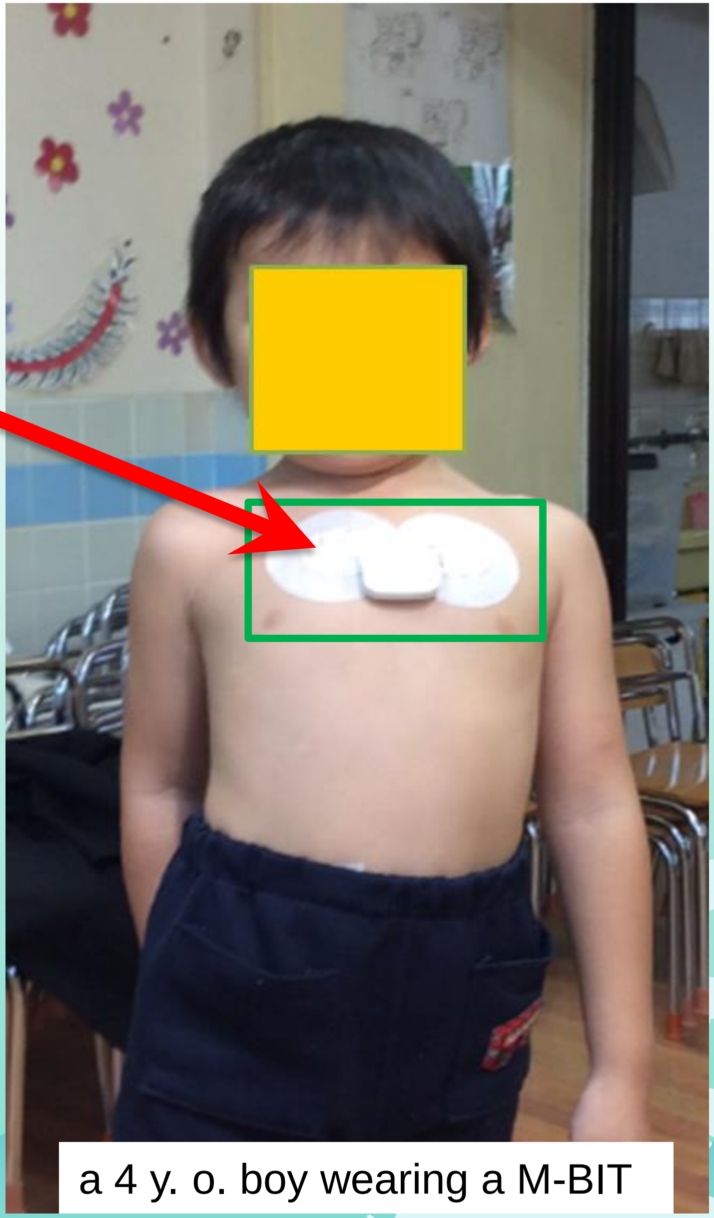
# 2. 25 hours measurement of ECG and Acceleration with M-BIT





a 56 y. o. male wearing a M-BIT

size: 40×39×8mm,
weight: 14g,
measuring duration: 25 hours
sampling frequency:128 Hz (ECG)
1Hz (ACC)
nickel-cadmium rechargeable battery
*three 25-hour measurements are possible by one charge.*



a 4 y. o. boy wearing a M-BIT

They can do anything they wants, and can enter sleep without paying attention to M-BIT.

## 3. Purpose:  improve sleep analysis software

We performed simultaneous measurement of M-BIT and polygraph, and verified the validity of our ACC-based sleep/awake identification method.

We studied the relationships between parameters that were obtained through the time frequency analysis of RR interval variations (RRIV) of M-BIT ECG,

para-sympathetic (PSNS), and
sympathetic nervous system's activity (SNS),
coefficients of variation of RR intervals (CVRR),
RRIV-based respiration frequency (RFRE),
its variation width within an epoch (VRFRE),
heart rate (HR),

⇕ relationships

and polygraph sleep depth.

# 4. Subjects and PSG measurements

*Subjects*

volunteer
students of Hosei University
staff members of the Ota memorial sleep center. (Kawasaki, Kanagawa).

8 subjects (male: 5, female: 3, age: 22.1±1.9, BMI: 23.4±3.4).

*PSG measurement*
EEG (C3, C4, O1, and O2),
musculus-mentalis EMG,
right and left ocular movement.

sleep stage were scored by medical experts at Ota Memorial Sleep Center.

depth of sleep
*shallow sleep (sleep stages I and II)*
*slow sleep (stages III and IV)*
*REM sleep.*

## 5. Sleep/awake identification by body movement

*1) Upper body posture*

At first, we decided in bed time area from subjects upper body posture.

*2) Body movement detection*

As to each sampling, we selected “sampling difference” as its maximum value among 3-axe difference of acceleration with previous sampling, and put “epoch difference (EPD)” as the epoch maximum of sampling difference.

We set a threshold for EPDs with or without movement based on the average of EPD within the whole analyzed area, and judged epoch without movement (ENMV) when EPD was less than the threshold.

Then, we searched “in active areas (IAAs)”, an areas where ENMV was ongoing, and we combined two successive IAAs if the duration of separation was one epoch or the average of ENMV during separation was less than four times the threshold.

# 6. Sleep/awake identification by body movement 2

Finally, we searched these IAAs in order of the time, and obtained the sleep area. We determined the beginning of the sleep area by searching for all the IAAs based on the following four rules.

1) An IAA shorter than 20 minutes and followed by active area (AA) longer than 21 minutes is not the beginning of the sleep area.
2) An IAA shorter than 15 minutes and followed by AA longer than 16 minutes is not the beginning of the sleep area.
3) An IAA shorter than 10 minutes and followed by AA longer than 11 minutes is not the beginning of the sleep area.
4) An IAA shorter than 6 minutes and followed by AA longer than 6minutes is not the beginning of the sleep area.

After determining the beginning of a sleep area, we lengthened the sleep area by repeating the protocol processes that combines the sleep area and following area if distance from sleep area to following IAA was shorter than 30 minutes and if average EPD of this area was smaller than two times of above threshold.

# 7. Extraction of RR intervals

We detected time locations of the R wave on the ECG signal based on well-known robust real time QRS detection algorithm [9].

In this algorithm, ECG row data’s 5 to 11 Hz, a frequency band of most information about QRS peaks, of were extracted by way of a band pass filter. Then, they were differentiated, converted to absolute values and averaged with 80-millisecond’s window. Thus, QRS peaks converted to a hill like waveforms, and the location of R wave is a point where the waveform exceeds a certain defined threshold level.

[9] P. S. Hamilton and W. J. Tompkins, “Quantitative investigation of QRS detection rules using the MIT/BIH arrhythmia database,” *IEEE Trans Biomed Eng.*, vol.33, pp.1157-1164,1986.

# 8. Extraction of RR intervals, our improved points

*Two weak points of used algorithm.*

1) obtained points did not correspond to peak points of the original ECG waveform.

after detecting a candidate point, we checked the original ECG data, and searched the nearest R wave peak,

2) ECG data with smaller R wave and larger T wave

we used the difference of the sharpness between R wave and T wave.

*Removing False RR intervals*

1) False RR intervals

The ECG signal areas in inferior quality due to body movement or deterioration of contact between the skin surface and electrode, or the superimposition of power line alternating-current noise, however, may generate a false RR interval (RRI) and affect the results of the RRIV analysis.

2) two different approaches for classifying false RRIs and removing them.

A: we calculated the RRI duration distribution of all the RRIs, and removed isolated outliers of abnormally large or small length.

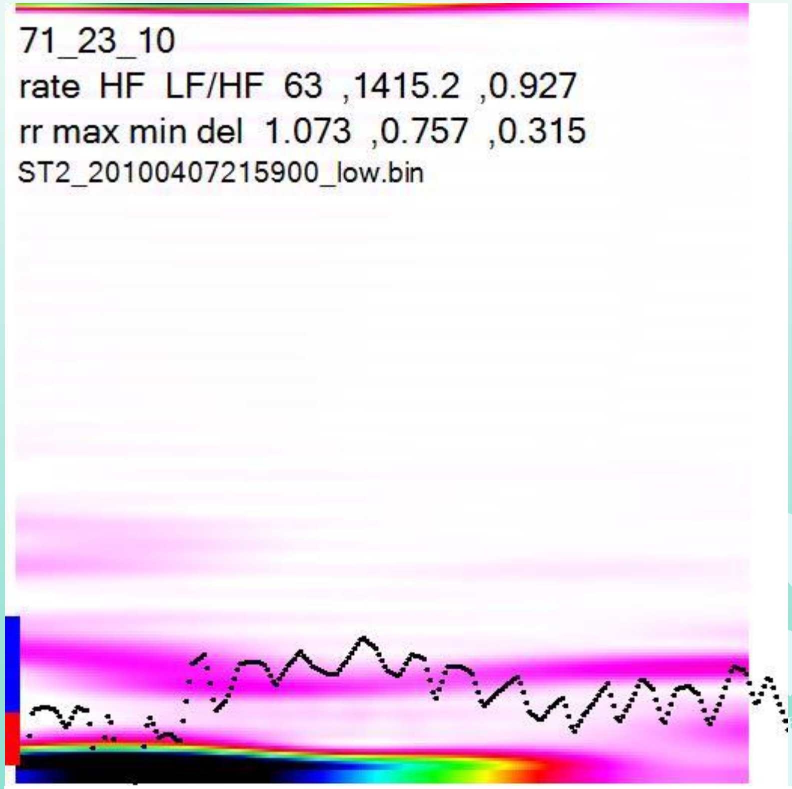
B: we focused on RRIs with “jumped out” duration in successive RRIs for a period of tens of seconds.

# 9. Time Frequency Analysis and Index of the Autonomic Nervous Systems Activity

We performed time/frequency analysis of RRIV using the SPWV (Smoothed Pseudo Wigner-Ville) method with the highest available frequency resolution setting for each epoch (1 minutes duration), and obtained time/frequency MAPs (the results of time/frequency analysis) . Assuming that 180bpm (3Hz) is the maximum daily heart rate of ordinal subjects, we used a re-sampling frequency of 4Hz..

For the index of the autonomic nervous systems activity of the epoch, we calculated LF, HF (low and high frequency components) as the sum of the absolutes of mapped values of corresponding frequency bands along the frequency axis and their average along the time over the map, and we set HF and LF/HF as the indexes of PSNS and SNS of the epoch, together with HR.

We also calculated average value and standard deviation of RRI durations belongs to each epoch, and defined CVRR values as the ratio of standard deviation to the average value.

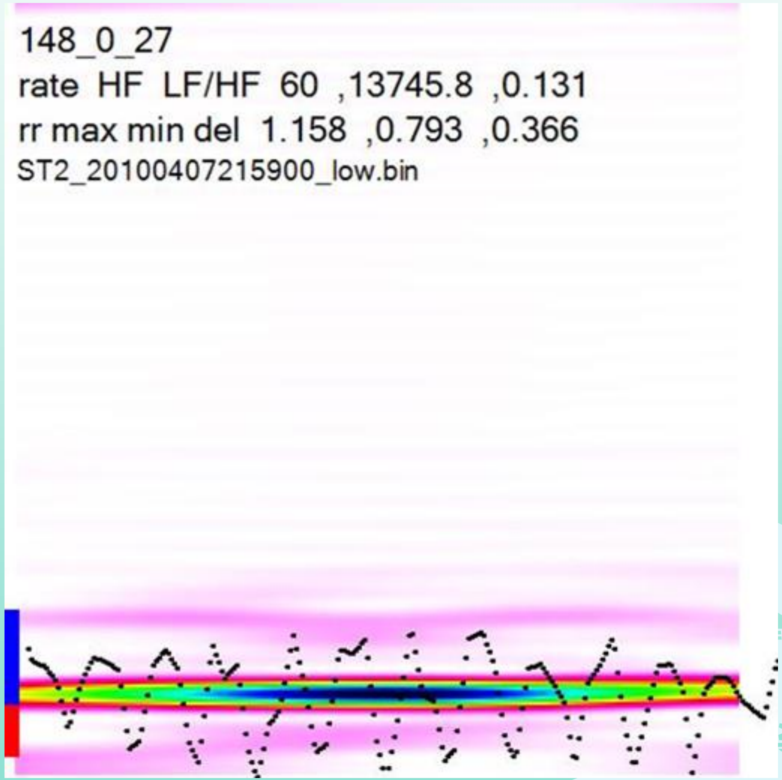



Example of time-frequency map at awake

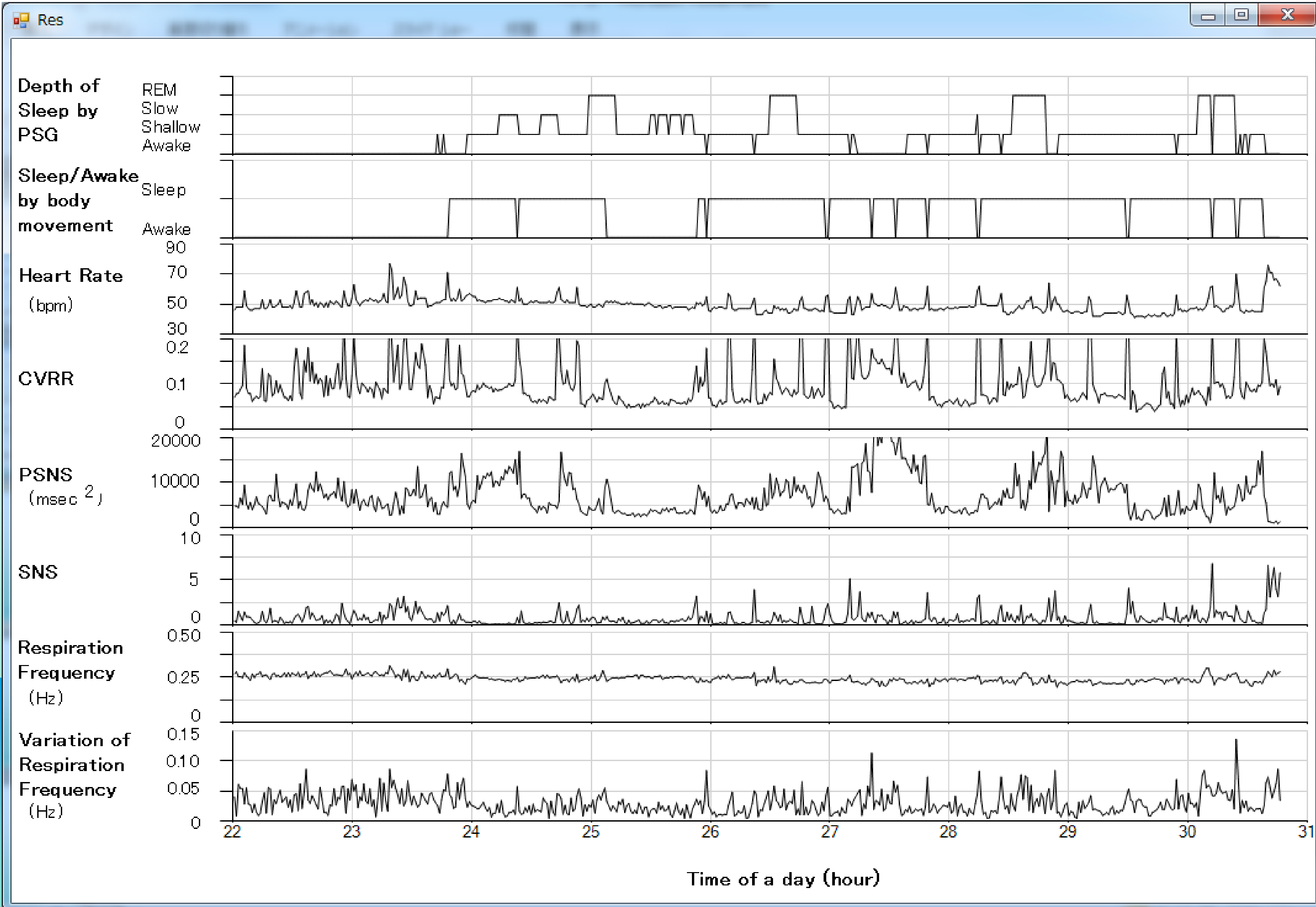
# 10. Respiration Frequency (RFRE) and its variation (VRFRE)

Since high frequency (> 0.15Hz) variations of RRI are caused by the mechanism whereby the output of the para-sympathetic nervous system is intercepted during inspiration, and only works during expiration, higher frequencies of the RRI variation is the frequency of respiration.

Through extending the method of Jasson et al. [12], we calculated an instantaneous central frequency (CFR) from 0.15Hz to the half frequency of the average heart rate of each epoch. We defined the raw respiration frequency as a 10- second average of these CFRs, and obtained RFRE, and the VRFRE, as the average values, and the difference of the maximum and the minimum values of raw respiration frequency, respectively.




Example of time-frequency map at NREM sleep



Res
Depth of Sleep by PSG
REM
Slow
Shallow
Awake
Sleep/Awake by body movement
Sleep
Awake
Heart Rate (bpm)
90
70
50
30
CVRR
0.2
0.1
0
PSNS (msec 2)
20000
10000
0
SNS
10
5
0
Respiration Frequency (Hz)
0.50
0.25
0
Variation of Respiration Frequency (Hz)
0.15
0.10
0.05
0
22
23
24
25
26
27
28
29
30
31
Time of a day (hour)

## 12. Sleep parameters

| | | PSG | | M-BIT | |
|---|---|---|---|---|---|
| | | Mean | S.D. | Mean | S.D. |
| Sleep latency | min | 13.2 | 6.7 | 5.1 | 8.1 |
| Sleep start time | | 23:40:00 | 0:23:00 | 23:32:00 | 0:26:34 |
| Sleep end time | | 6:30:40 | 0:11:17 | 6:29:45 | 0:11:28 |
| Sleep duration | min | 410.7 | 16.6 | 417.8 | 20.9 |
| Sleep effeciency | | 0.893 | 0.061 | 0.894 | 0.063 |

Sleep latency, sleep start time, sleep end time, sleep duration, and sleep efficiency obtained polygraph sleep scoring (PSG) and M-BIT sleep/awake estimation (M-BIT) were compared in TABLE I. A significant difference ($F(1,7)=4.677$, $p<0.05$) existed in sleep latency, which was a period from the light off time to the sleep start time for polygraph, and a period from the start of bed in area to the sleep start time for M-BIT, only.

# 13. VRFRE, the most expectable parameter

| Awake | | Shallow sleep | | Slow sleep | | REM sleep | |
|---|---|---|---|---|---|---|---|
| Mean | S.D. | Mean | S.D. | Mean | S.D. | Mean | S.D. |
| 0.050 | 0.028 | 0.029 | 0.019 | 0.024 | 0.016 | 0.044 | 0.024 |

As anticipated from Fig.1, each of VRFRE values was largely different in values of Shallow sleep, Slow sleep and Awake, and REM sleep. As shown in Fig.1, we cut out data portion from 22:00 for an analysis work, and obtained Mean and S.D. of Awake from Awake epochs within this time area. One way ANOVA with the factor of sleep depth showed the existence of significance ($F_{(3,1440.2)}$ =254.8, $p<0.05$), and multiple comparisons indicated that there were significant differences in the values Awake, Shallow sleep, Slow sleep, and REM sleep.

These results suggest that the VRFRE value was a reliable discriminating parameter of REM and NREM sleep during the time point of Sleep area, and another parameter to detect sleep onset with.

## 14. Estimation of NREM sleep area and modification of body movement based sleep/awake estimation using VRFRE values

In principle, NREM sleep area is a low VRFRE area.

We started body movement based sleep area, and obtained average VRFRE value of whole sleep area.

**in some cases this sleep area contained awake areas or epochs.*

We performed preliminary NREM area detection with the trial threshold,

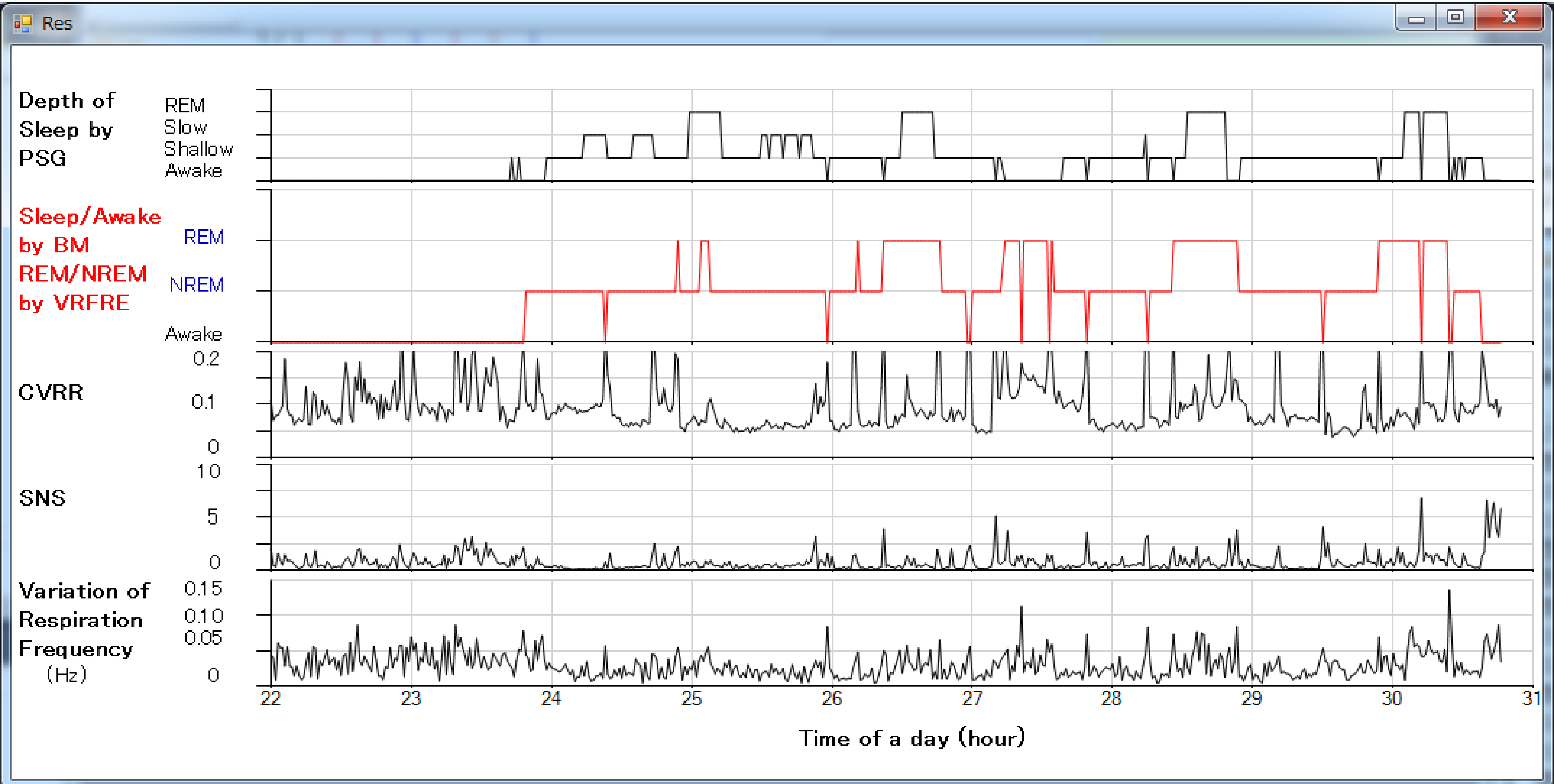
trial threshold =average VRFRE × 1.615+ 0.0045.

Then we searched NREM sleep areas (NSAs) where more than 15 NREM epochs were successively continue, and obtained averages of VRFRE values of each NSA.

We set the real threshold as the 90% value of the maximum value of average NSA VRFRE values. We performed classification and NSA search again with this real threshold.

Awake epochs within sleep area were reassigned to sleep epochs (and NREM sleep epochs) if their VRFRE values were below the real threshold.

# 15. Example of estimated results



# 16. Sensitivity, false negative and false positive of sleep depth estimation

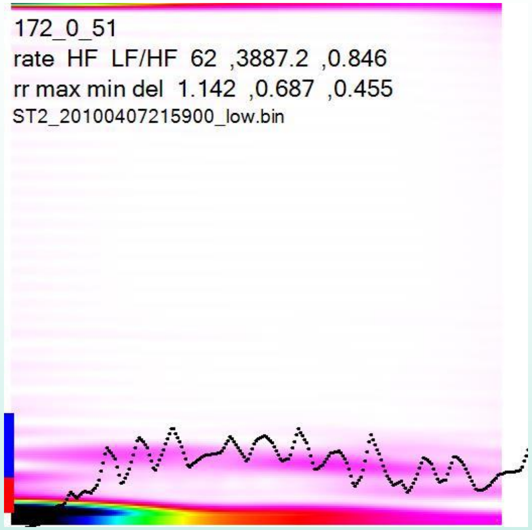
| | Awake | | | NREM Sleep | | | REM Sleep | | |
|---|---|---|---|---|---|---|---|---|---|
| | sensitivity | false negative | false positive | sensitivity | false negative | false positive | sensitivity | false negative | false positive |
| subject1 | 0.838 | 0.162 | 0.132 | 0.745 | 0.255 | 0.208 | 0.595 | 0.405 | 0.543 |
| subject2 | 0.843 | 0.157 | 0.164 | 0.791 | 0.209 | 0.115 | 0.773 | 0.227 | 0.560 |
| subject3 | 0.735 | 0.265 | 0.042 | 0.885 | 0.115 | 0.091 | 0.841 | 0.159 | 0.857 |
| subject4 | 0.893 | 0.107 | 0.029 | 0.893 | 0.107 | 0.107 | 0.625 | 0.375 | 0.475 |
| subject5 | 0.698 | 0.302 | 0.023 | 0.741 | 0.259 | 0.082 | 0.922 | 0.078 | 2.039 |
| subject6 | 0.790 | 0.210 | 0.042 | 0.928 | 0.072 | 0.244 | 0.580 | 0.420 | 0.168 |
| subject7 | 0.392 | 0.608 | 0.013 | 0.915 | 0.085 | 0.185 | 0.636 | 0.364 | 2.242 |
| subject8 | 0.676 | 0.324 | 0.039 | 0.759 | 0.241 | 0.323 | 0.342 | 0.658 | 0.703 |
| mean | 0.733 | 0.267 | 0.061 | 0.832 | 0.168 | 0.170 | 0.664 | 0.336 | 0.948 |
| S.D. | 0.147 | 0.147 | 0.052 | 0.075 | 0.075 | 0.080 | 0.169 | 0.169 | 0.714 |

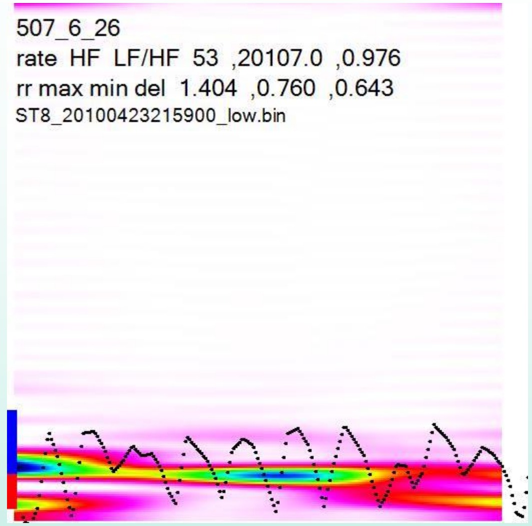
# 17. Large false positives in REM sleep

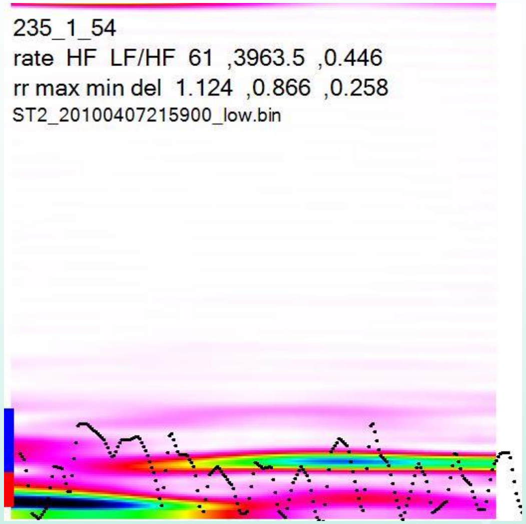

Many awake epochs were observed during sleep, and we could not distinguish awake and REM sleep epochs based on RRIV.

# 18. Example of time frequency maps of false case (VRFRE:PSG)

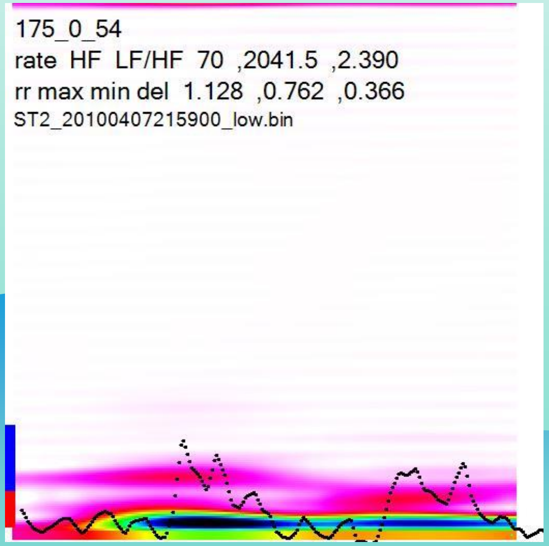
*(Awake:NREM) 171 epochs*

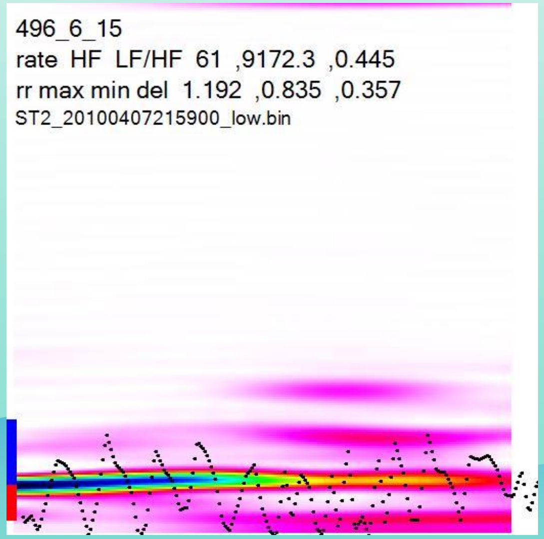


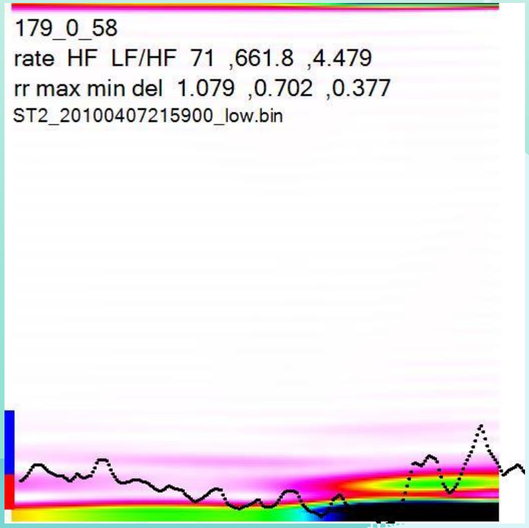




*(Awake:REM) 137epochs*

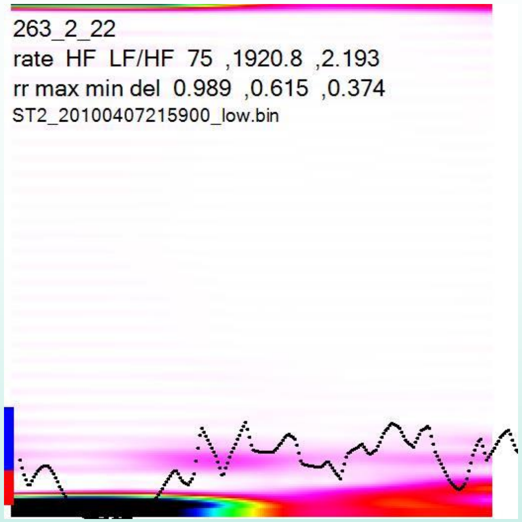


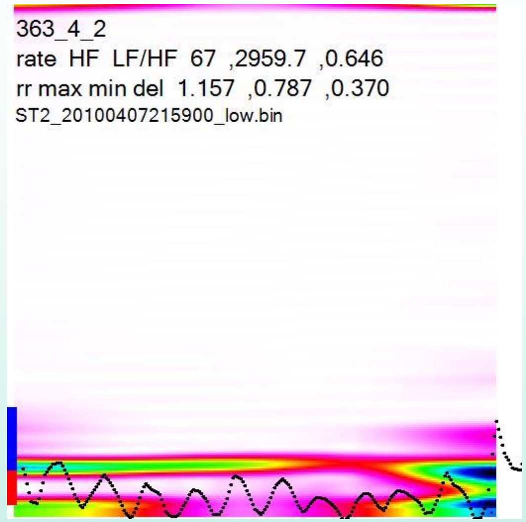



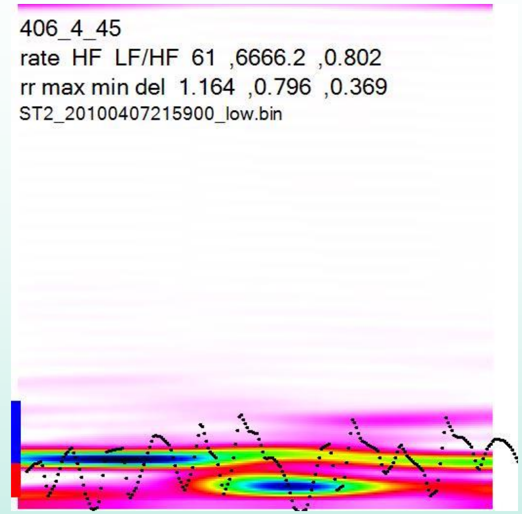



# 19. Example of time frequency maps of false case (VRFRE:PSG) 2

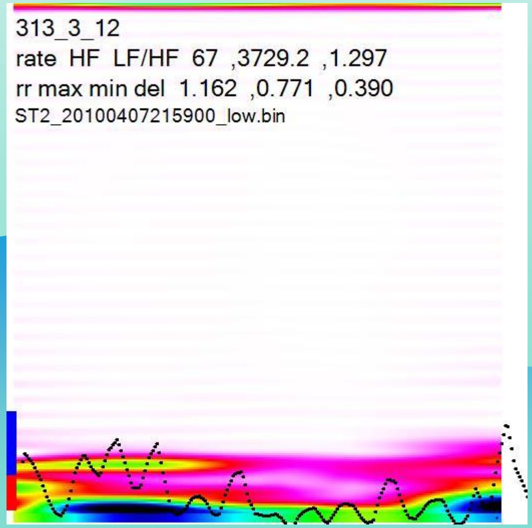
## *(NREM:awake) 52 epochs*

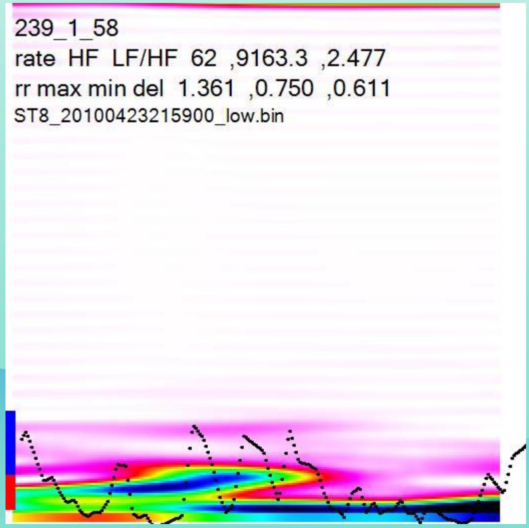


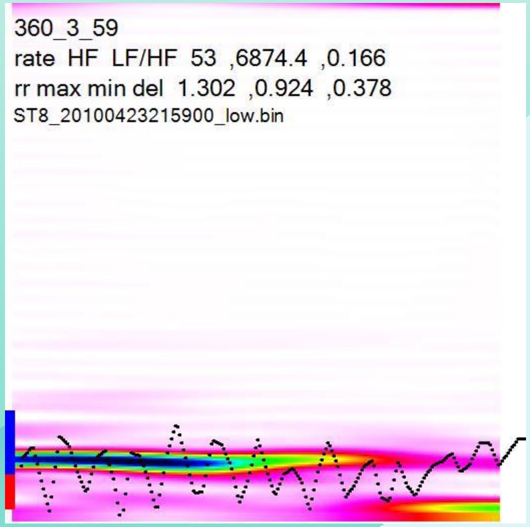




## *(NREM:REM) 336 epochs*

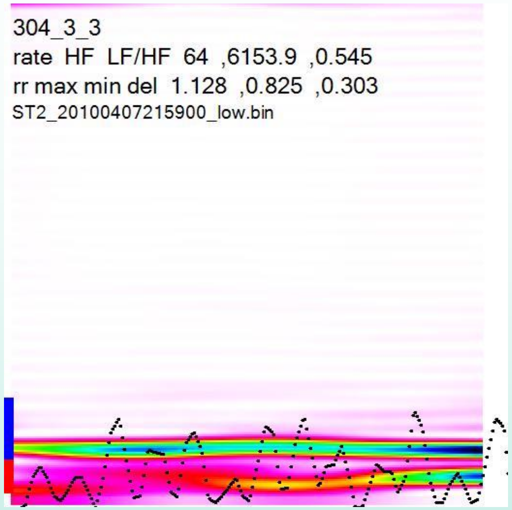


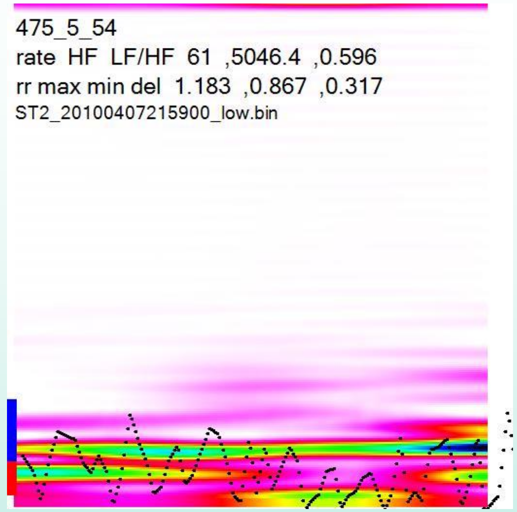



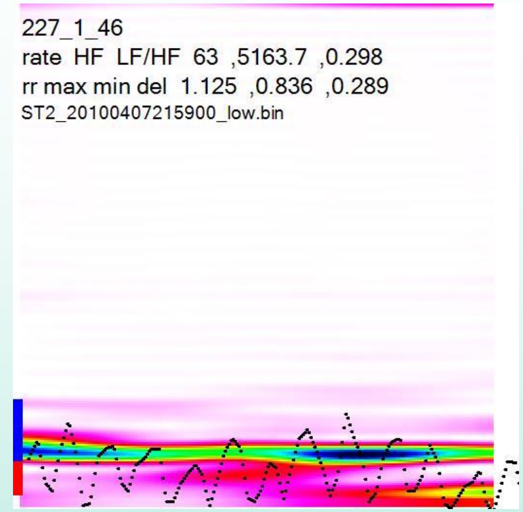



# 20. Example of time frequency maps of false case (VRFRE:PSG) 3

## *(REM:awake) 17 epochs*




## *(REM:NREM) 226 epochs*