A Behavioral and Electrophysiological Assessment of Activity States Defined by Using the Static Charge Sensitive Bed (SCSB) Method

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Activity states based on static charge sensitive bed (SCSB) recording were assessed as indicators of sleep depth. Twelve subjects' instructed responses to auditory stimuli were studied in relation to the sleep stages and to three categories of SCSB activity, quiet (QS), intermediate (IS), and active state (AS), which were automatically defined according to the variability of motor, respiratory, and cardiac parameters. The differences in responsiveness during sleep stages were consistent with earlier findings. The response rates (without polygraphic signs of awakening) were as follows: stage 1, 52.8%; stage 2, 11.0%; stage REM, 8.5%; slow wave sleep, 0.5%. The lacking of responses in wakefulness occurred mostly during trials after the initial sleep onset. In the SCSD data responsiveness was lowest in QS and highest in AS. After the first hour in bed the response rates were 3.9% in QS, 13.3% in IS, and 30.3 % during AS (for most subjects even lower in QS and IS). QS seems to reflect a behaviorally deep sleep and IS and AS appear as lighter states respectively. The results suggest that the SCSB activity states are useful measures of sleep quality, QS providing an approximate estimate of deep sleep. **(Sleep and Hypnosis 2003;5(3):136-144)**

Key words: *static charge sensitive bed (SCSB), behavioral responses, depth of sleep, sleep stages*

INTRODUCTION

There is an obvious need in some fields of sleep research for objective methods which are less expensive and complicated than the standard procedure for defining sleep stages (1) or than the modern polysomnography (PSG) in which even more physiological parameters are used in addition to the EEG, EOG, and EMG recordings. The static charge sensitive bed (SCSB) is a movement sensor, also capable of registering respiratory movements and those caused by the recoil power of the pumping action of the heart (ballistocardiography, BCG) (2,3). SCSB signals have been compared with the standard sleep stages (4,5), and there have been efforts to identify sleep stages by using different combinations of the SCSB parameters (6-10). Even though SCSB activity classified into quiet (QS), intermediate (IS), and active (AS) states according to the variability of

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respiration, BCG, and motility, cannot be regarded as sleep staging proper, SCSB analysis appears as a potential method for evaluating the cyclic changes during sleep and thus as a measure of sleep quality (4,5).

The continuum of sleep depth can be seen as ”a convenient abstraction” (11) without real empirical reference, as the changes in behavioral, physiological, and subjective measures of sleep do not entirely coincide. It does, however, have everyday meaning and it is also useful scientifically, at least as regards non-REM sleep. The relationship between the SCSB analysis and sleep depth has been previously studied by comparing SCSB activity with electroencephalic delta activity during one cycle of daytime sleep (12). Snyder and Scott (13) decades ago pointed out that any method suggested as an indicator of the depth of sleep should be behaviorally tested. In this vein, the aim of the present experiment was to assess whether SCSB-based activity, automatically scored as QS, IS, AS could be used as a rough measure of the changes in the depth of sleep. Behavioral responsiveness, electrophysiological measures of sleep, and the SCSB states were compared with each other during nocturnal sleep.

According to different behavioral methods utilizing responses to auditory stimuli (arousal thresholds or probability and latency of responding with/without awakening) the depth of the standard non-REM sleep stages 1-4 are unambiguous. Probability of responding (11,14-18), response latencies (16,18-20) and stimulus intensities (14,21-23) refer to slow wave sleep (SWS, stages 3 and 4) as deep sleep, stage 2 (S2) as lighter, and stage 1 (S1) as the lightest stage of sleep. The results concerning REM sleep have been inconsistent referring to either deep (14,17,24) or light (11,23,25,26) sleep comparable to SWS and S2 respectively or something in between these stages (18,19,21,22) on a hypothetical depth continuum. The REM sleep has been reported to be even lighter than S2 (27).

In addition to the stage differences, responsiveness, especially during S2 and REM sleep, depends on the meaningfulness of the stimuli (15,27,28) and on the ongoing cognitive activity (25,29). A decrease in the rate of responsiveness or an increase in response latencies as a function of time-of-night have often been reported (14,23,30,31). Responsiveness appears quite stable across non-consecutive nights (21) but has been found to decrease across consecutive experimental nights (18,31-33). The type of response can have a great effect on the response probabilities. While the percentages of responses have been relatively low in S2, REM sleep, and SWS in studies using a microswitch closure as a behavioral criterion (14-17), considerably higher response rates have been reported when a deep breath has been used as an instructed response (18,20,31,32).

The main hypothesis of the present experiment was that while using a light hand movement as a behavioral response, QS defined by using SCSB method which is characterized by immobility and regular autonomic nervous system functions would appear as a deeper state as compared with IS and AS. According to earlier findings it was also assumed that the probability of responding in QS, IS, and AS would reflect the response rates in SWS, S2, and S1/wakefulness, respectively.

METHOD

Twelve healthy volunteers (mean age 26.75 years; 5 females/7 males) served as subjects for one night. Because all of them had previously participated in psychophysiological sleep studies no adaptation night was used. The subjects were told to abstain from alcohol for 24 hours before the experiment. They were asked to attend the laboratory about 2 hours before their usual bed time. The subjects were instructed to switch off an auditory signal with a pressure transducer whenever they heard the stimuli during the night. In order to avoid the possible effects of body position or changes in hand preference (34) on the rate of responses, similar transducers were attached to both hands. The device consisted of an oval rubber balloon (diameter 33 mm, length 60 mm) which was taped diagonally on to the middle of the palm (at a 45o angle from the wrist, the air tube on the hypothenar side) and a SenSym SCX01 pressure/voltage transducer (size about 4 cm3) taped on the palmar side of the wrist. A light flexion of the fingers or the palm produced a pulse sufficient to switch off the stimuli. The pressure signals from both hands and from the SCSB movement channel were digitized at a 50 Hz sampling rate in 20 sec epochs starting from 10 sec before the stimuli onset.

The auditory signal was composed of a sequence of 1200 Hz/50 msec tones (10 msec rise and fall time, 30 msec plateau) with a 625 msec interstimulus interval and a fixed intensity of 45 dB. These sounds have been used as standard stimuli in studies on nocturnal event-related potentials with an oddball setting (35). The time between sequences varied pseudorandomly from 20 to 150 sec. The stimuli were presented through the night via a loudspeaker 50 cm behind the subject's head (midline). The signal was interrupted automatically after the 11th stimulus (6800 msec) if no response took place before it. If subjects had difficulties in falling asleep, the rate of stimulus sequences was decreased or the stimuli were switched off until unambiguous S2 was present.

EEG, EMG, and EOG were registered from the standard sites and digitized at sampling rates of 100 Hz (EEG), 200 Hz (EMG), and 50 Hz (EOG) in 20 sec epochs that started from 10 sec before the stimuli onset. These epochs were scored by the second author according to the standard criteria (1). S3 and S4 were combined as SWS. If there were polygraphic phenomena during the second half of the epochs which could affect the staging, the stage score was given according to the first 10 sec. In order to check the scoring reliability the data of four subjects were scored also by the first author. The agreement was 92% indicating reasonably high reliability.

Body motility was registered with the SCSB sensor and respiration movements and BCG were filtered from the raw signal by a BR CPA8 preamplifier. The three SCSB signals and a marker showing the stimulus onset were recorded using a Hewlett-Packard 3960 Instrumentation Recorder. The data were digitized by a Data Translations DT2801 A/D converter and automatically analyzed in 3 min epochs by a BR01 program (4,12) and categorized into QS, IS, and AS according to respiratory amplitude variation, slow BCG amplitude variation and the frequency of small body movements. The BR01 analysis yields eight variability parameters but these three have been found to have the highest correlations with the principal sleep stages (SWS, S2, REM sleep) (4).

Behavioral responses, sleep stages, and SCSB activity states were compared with each other. As the behavioral data and EEG, EMG, and EOG signals were collected in 20 sec trials related to each stimuli sequence, and the continuous SCSB signals were analyzed in 3 min epochs by the BR01 software, the former were used as units in the analyses. EEG alpha-activity after stimulus onset can be regarded as a sign of momentary arousal and therefore the data were analysed with and without the trials containing>1 sec EEG alpha after stimulus onset. Inter-individual differences and time-of-night effects on responsiveness were also examined. Separate analyses were performed for the body movements related to auditory stimuli, because the response type presupposed a slight movement of either hand and because the frequency of small movements was one of the parameters used in the SCSB analysis.

RESULTS

The number of auditory signals presented to each subject, the response percentages during the stages, and the distribution of stimulation across the sleep stages are shown in Table1. The mean percentages of responding showed a decrease in responsiveness from wakefulness (W) to SWS. The probability of behavioral responses was high but not perfect during W (81.3%) and lower in S1 (62.2%). Responses were still present during S2 (11.7%) and REM sleep (9.5%), but practically absent in SWS (0.6%). When the trials with alpha activity were excluded the mean values during S1, S2, REM, and SWS were somewhat lower (52.8%, 11.0%, 8.5%, 0.5%, respectively) indicating that some of the responses were related to a brief cortical arousal. There were considerable inter-individual differences in responsiveness. Three subjects (#7, #8, and #11, "low responsivity group") had rather low response percentages even during stage W trials. Three other subjects (#3, #5, #10, "high responsivity group") showed extraordinary high response rates in either or both S2 and REM sleep. Figure 1 presents the responsiveness in W, S1, and S2 (after alpha exclusion) during the first hour in bed and during the subsequent hours (hours 2-8) separately for subjects with high, moderate, and low responsivity. Even though there were some lapses in responsiveness among the "low responsivity group" in W during the first hour, the low percentages for these subjects were for the most part due to the decreased responsiveness during W episodes after initial sleep onset. Response rates in S1 and S2 after the first hour also showed a sharp decrease. A similar but not as prominent tendency was obvious for the subjects with moderate and high responsivity. For the high responsivity subjects the response failures in W were infrequent throughout the night and the responsiveness in S2 remained at an elevated level. REM sleep did not appear during the first hour in any subject. The mean percentages of responses in REM sleep during subsequent hours for the subjects showing low, moderate, and high responsivity were 2.6%, 4.5%, and 24.5%, respectively. The three subjects with high responsivity accounted for 47.0% of all behavioral responses during S2 and 65.6% of those during REM sleep.

Table 1. Response rates in percents during different polygraphic stages for each subject and for the data as a whole.

Subject	Number of trials	Percentages of responding W	S1	S2	SWS	REM
1	537	92.3	67.6	12.6	0.0	13.2
2	639	96.5	73.3	12.7	1.5	2.4
3	455	100.0	93.8	42.1	0.0	10.3
4	560	86.4	59.3	7.6	0.0	6.0
5	415	97.8	84.3	22.4	3.3	24.1
6	594	75.9	47.8	7.5	0.0	3.6
7	620	56.5	36.9	1.3	0.0	0.0
8	559	58.7	38.0	4.1	0.0	8.1
9	470	88.1	37.7	5.5	0.0	0.8
10	350	87.5	69.7	28.2	0.0	44.9
11	483	55.0	46.7	4.2	1.3	0.8
12	455	81.3	91.7	11.0	1.0	0.0
Total	6137	84.7	61.2	11.7	0.7	9.5
Mean	511	81.3	62.2	13.3	0.6	9.5
SD	88	16.3	21.0	12.0	1.0	13.2
Mean-a	485	81.3	52.8	11.0	0.5	8.5
Tot % trials		7.7	10.4	47.9	11.8	22.3

Mean-a = trials with EEG alpha after stimulus onset excluded.
Tot % trials = the mean distribution of the trials across the stages.

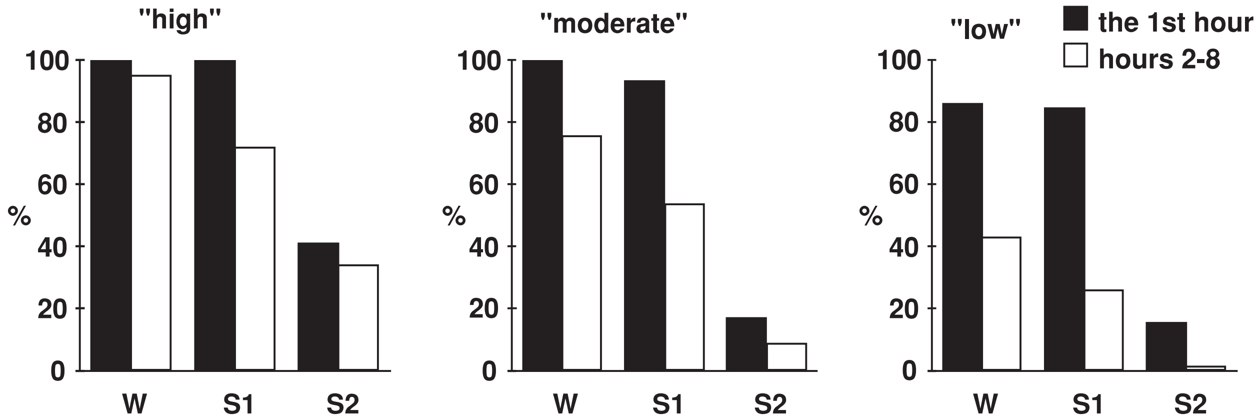

Figure 1. The response percentages of "high", "moderate", and "low" responsive subjects in wakefulness (W), stage 1 (S1), and stage 2 (S2) during the first hour in bed and during the subsequent hours.

QS is characterized by immobility, regular respiration, and regular BCG, whereas considerable variations in the autonomic signals together with small movements are typical during AS. In the data as a whole the behavioral responses were most frequent during AS (37.2%), clearly less common in IS (16.9%), and rare in QS (5.6%). The changes in responsiveness during the SCSB activity states are presented for all subjects and trials in Figure 2 (left side) as a function of time in bed. There was a decline in responsiveness during the course of the night in all states, but the most obvious change for QS and IS was found between the first and the second hour. If the three subjects with high responsivity are not taken into account (Figure 2, right side) behavioral responses during QS and IS were even more infrequent. The percentages of behavioral responses during the SCSB activity states during and after the first hour are shown in Table 2 for all subjects and without the high responsive subjects. Even though the response rates were relatively high during the first hour, there were already differences in behavioral responsiveness between QS, IS, and AS. The percentages after the first hour in bed show a low responsiveness during QS (3.9%). Behavioral responses during IS (13.3%) were also rare, but quite common during AS (30.3%). Naturally, the percents for the moderate and low responsive subjects were even lower, especially during QS (1.2%) and IS (6.1%).

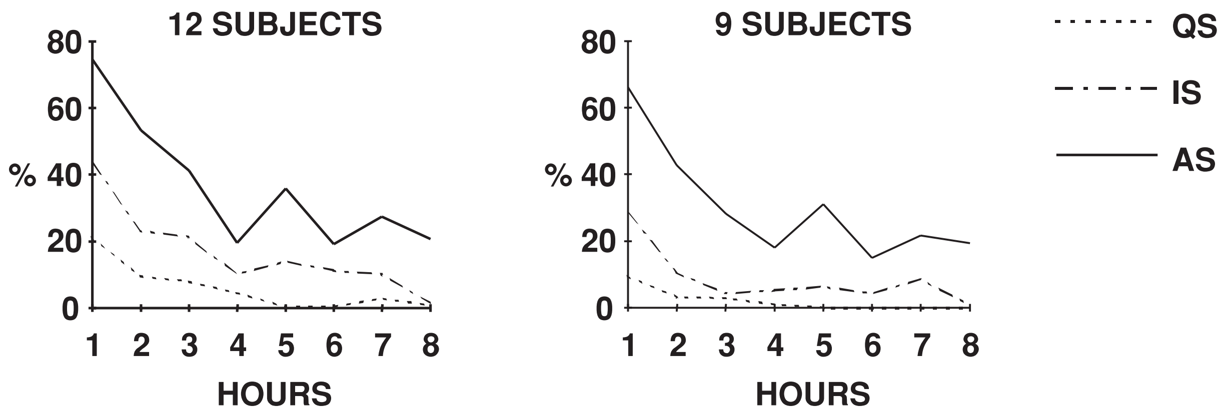

Figure 2. The changes in responsiveness during QS, IS, and AS as a function of time. The left part represents all subjects and the right one stands for those nine after the exclusion of the three with high responsivity.

Table 2. Percentages of responses/number of trials during different levels of SCSB activity during the first hour in bed and during the subsequent hours. N=12 refers to all subjects and N=9 indicates the data after the exclusion of the three highly responding subjects.

		QS/trials	IS/trials	AS/trials
1 st hour,	N = 12	21.2/ 198	43.2/ 243	74.6/ 334[a]
	N = 9	9.4/ 160	28.3/ 184	66.1/ 251[b]
hours 2-8,	N = 12	3.9/1769	13.3/1791	30.3/1802[c]
	N = 9	1.2/1458	6.1/1415	24.9/1449[d]

Responding (yes/no) crosstabulated (2 x 3) with the SCSB states: [a]x^2=150.3, [b]x^2=480.0, [c]x^2=145.4, [d]x^2=475.3; df=3 and p<.001 for each.

Most of the trials without responses during QS (85.5%) and IS (65.1%) were scored as either S2 or SWS. In turn, approximately 90% of SWS non-response trials and more than 75% of those in S2 were found during QS or IS. Non-response AS trials occurred mainly (82.1%) during S2 and REM epochs. These percentages are in concordance with the relationship between sleep stages and SCSB activity during undisturbed sleep in adults (4-7,9).

The sleep stage scores of the trials with a response across the SCSB activity states are presented in Table 3. During the first hour in bed the behavioral responses mainly occurred during W or S1 trials (QS: 85.8%, IS: 89.5%, AS: 85.5%). After the first hour S2 trials accounted for approximately a half and S1 trials for a quarter of the responses in QS and IS. The majority of the AS responses were evenly distributed between W (28.0%), S1 (29.9%), and S2 (27.3%) trials. During each SCSB state approximately 15% of the responses took place during REM trials. Exclusion of the high responsivity subjects would not have markedly affected the results concerning AS, but for QS and IS the role of S1 trials would have increased instead of those of S2.

Table 3. Sleep stage scores of response trials (percentages) in QS, IS, and AS during and after the first hour in bed. All subjects. # trials = the number of trials.

	1st hour			hours 2-8		
	QS	IS	AS	QS	IS	AS
W %	42.9	58.1	53.4	4.3	10.5	28.0
S1 %	42.9	31.4	32.1	26.1	25.5	29.9
S2 %	14.3	10.5	14.1	55.1	46.9	27.3
SWS %	0.0	0.0	0.4	0.0	0.8	0.4
REM %	0.0	0.0	0.0	14.5	16.3	14.5
Total %	100	100	100	100	100	100
# trials	42	105	249	69	239	546
% trials	10.6	26.5	62.9	8.1	28.0	63.9

The body movements during the 10 sec periods before and after stimulus onset were analysed in order to examine whether some amount of IS or AS was caused by the instructed hand responses. Movements were slightly more common after the signal onset (4.2%) than prior to them (2.6%) during the non-response trials. Among the instructed responses, movements were more than twice as frequent after the stimulus onset (21.6%) as before the stimuli (9.6%). A majority (58.1%) of the former occurred within 1000 msec before or after the response proper. At least those movements could be considered as response related. When all SCSB epochs containing one movement or more during the 10 sec period after stimulus onset were abandoned, the rates of responding during the SCSB activity states after the first hour in bed were 3.6% (QS), 11.1% (IS), and 17.7 (AS). While the percentages in QS and IS were practically intact as compared with those above, an evident change could be found in responsivity during AS. According to this some of the SCSB activity was apparently caused by the behavioral responses. This finding, however, does not change the results as regards the role of QS and IS.

DISCUSSION

The experiment was carried out in order to study whether activity states which are based on a SCSB body movement recording could be used as rough indicators of the depth of sleep. A behavioral approach was applied together with electrophysiological measures of sleep stages. Previous studies have shown that instructed behavioral responses can occur during all stages of sleep. According to behavioral criteria SWS is regarded as deep sleep, S2 as a lighter stage, and S1 as the lightest (if sleep at all). The results concerning the role of REM sleep have been more incoherent but in most studies the responsiveness during the REM stage have been approximately the same as in S2 or lower.

In the present experiment the response rates during the polygraphic stages were consistent with earlier findings. Responsiveness in NREM sleep was highest in S1, lower in S2 and almost absent in SWS. The mean response percentage during REM sleep was to some extent lower than in S2. The exclusion of trials with EEG alpha activity after stimulus onset showed that instructed behavioral responses can be performed while electrophysiologically asleep. Some responses were lacking during stage W, but the lapses occurred for the most part during W trials after the initial sleep onset. Nevertheless, this indicates that response failures can be found during episodes which are scored as awake. The latter were found in all but one subject, but they were more common among some subjects than in others. The observed inter-individual differences in responding were at least partly caused by the fixed intensity of the stimuli used. Adjusting of the sounds according to individual thresholds would have obviously affected the results in some degree, but it would not have changed the main findings concerning the relative roles of the three SCSB activity states.

Respiratory movements, ballistocardiogram (BCG), and body motility were registered using the SCSB method and the signals were classified into three categories. QS, in general, refers to immobility with regular respiratory and BCG signals. AS is characterized by considerable variations in autonomic signals often together with short body movements. IS refers to a moderate amount of variability between QS and AS. In general the relationship between sleep stages and SCSB activity was in concordance with earlier findings in adults (4-7,9,12), even though SCSB analyses have been performed in various ways in different studies.

The rate of behavioral responses was related to the level of SCSB activity in all subjects. Responsiveness during each SCSB state was relatively common during the first hour in bed, mainly because of wakefulness before sleep onset. Even then, however, the lowest response percentages were found in QS and the highest in AS. During the subsequent hours responsiveness decreased to a clearly lower level, especially in QS and IS, but it was still rather high in AS as compared with the other SCSB activity states. The infrequency of behavioral responses during QS trials after the first hour indicates that it is also a behaviorally quiet state, in addition to immobility and regular autonomic activity. Furthermore, it can be suggested that the result was partly biased by the three subjects who showed especially high response rates during sleep. Without their data the probability of responding during QS appeared close to that in SWS. Even with all subjects included, the responses during QS were rare as compared with those during S2. In fact the responsiveness in IS closely resembled the response rate in S2. QS seems to reflect a behaviorally deep sleep whereas IS appears to be a lighter state to some degree. The role of AS was more complicated both on a behavioral basis and in the light of the sleep stages. Response trials in AS occurred evenly during W, S1, and S2, and to a lower extent in REM sleep. Moreover, a further analysis of the trials with a behavioral response revealed that some of the SCSB activity scored as AS was perhaps due to movements related to responses. The roles of QS and IS remained in essence intact.

The SCSB was originally designed and used as a movement detector (2,36) but it is also regarded as a useful method for screening sleep related respiratory dysfunctions (37-40). Various systems have been developed for both visual and automatic scoring of the general activity in SCSB analysis (4-10,12). The potential advantage of the SCSB method over the pure movement recordings is in that the registering of respiratory and cardiac functions is simultaneously available. It has been known for a long time that different autonomic and motor phenomena reflect the cyclic changes which can be seen in sleep stages (41-43). There are a few reports concerning the application of SCSB activity states (44-47) but their infrequency is most probably due to the inadequate validation of the method.

The present study could be seen as one in a series of experiments which are necessary to test the validity of the SCSB activity analysis. The behavioral responding during the SCSB activity states indicates differences comparable to those found between the sleep stages. Even though QS, IS, and AS must not be regarded as sleep stages, the results suggest that nocturnal distribution of them can be used as a simple objective measure of sleep quality, and especially the amount of QS as an estimate of deep sleep.

As a simple and low cost method the SCSB seems to be especially useful for assessing sleep quality in follow-up studies when the effects of some kind of intervention are examined using a large sample of subjects. Because the movements from all parts of the body can be registered simultaneously together with those movements caused by respiration and the heart pumping function, it is evident that the SCSB can provide a more powerful tool than, for example, the recording of the movements of one limb only.

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