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Relationships Among Wake Episode Lengths, Contiguous Sleep Episode Lengths, and Electroencephalographic Delta Waves in Rats with Suprachiasmatic Nuclei Lesions

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Summary: The lengths of sleep and wake episodes during 2 consecutive days of recording were measured in five rats lacking circadian rhythms owing to lesions of the suprachiasmatic nuclei. Total sleep (TS) episode lengths and the amount of NREM sleep and paradoxical sleep (PS) within each episode were examined in relationship to the lengths of the immediately preceding and the immediately following wake episodes. As putative measures of sleep intensity, average and maximum delta wave (1–4 Hz) incidence and amplitude within NREM were also examined in relation to adjacent wake episode lengths. For sleep episodes longer than 50 min (78% of daily sleep), TS episode lengths and amount of NREM within these episodes showed significant positive correlations with both prior and subsequent wake episode lengths. PS durations within sleep episodes also showed significant positive correlations with subsequent wake episode lengths, but little correlation with prior wake episode lengths. The results suggest that in the absence of sleep-wake circadian rhythms, sleep time is subject to short-term homeostatic regulation. Amounts of PS within sleep episodes were highly correlated ($r = 0.84$) with amounts of NREM. NREM delta wave incidence and amplitude showed no significant relationships with the lengths of prior or subsequent wake episodes, suggesting that variations in sleep intensity may not play a prominent role in the short-term homeostatic regulation of ad lib sleep. Delta wave incidence and amplitude were also not correlated with the duration of NREM episodes, but incidence during wake was positively correlated with wake episode duration, suggesting that delta density during wake may be an electrophysiological indicator of the propensity to sleep. **Key Words:** Rat sleep—Electroencephalographic waveform analysis—Sleep homeostasis—Circadian rhythms—Suprachiasmatic nucleus lesions.

Sleep deprivation is followed by apparently compensatory increases in several parameters of sleep, including subsequent sleep time and/or sleep stages (for review, see

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1), electroencephalography (EEG) amplitude and delta wave incidence in NREM sleep (2,3), and auditory arousal thresholds (4,5). These compensatory responses suggest that sleep quotas are homeostatically regulated. Homeostatic regulation could be manifest in two ways. There could be immediate short-term homeostatic regulation, in which case the length of individual sleep bouts would be positively correlated with the length of the preceding wake bout. Alternatively, there could be a more temporally extended regulation, in which case positive correlations between sleep and prior wake durations might emerge only over extended temporal intervals such as a day or longer.

Studies bearing on this issue have produced mixed results. Webb and Friedmann (6) found that the duration of individual sleep bouts in rats did not correlate significantly with the duration of the immediately preceding wake bout, suggesting that there is no short-term regulation of sleep time. Mitler et al. (7) further showed in hamsters free-running under constant lighting that the daily amounts of sleep and wake within each circadian sleep-wake cycle were negatively correlated; evidently, the periodicity of the free-running sleep-wake cycle was preserved at the expense of homeostatic regulation of sleep-wake quotas. Similar negative correlations between sleep and wake have been observed in free-running birds (8) and humans (9). Wever (9) reported that while wake time within a given circadian cycle is negatively correlated with sleep time in that cycle, it is positively correlated with the amount of sleep in the next two cycles. Apparently, in humans the control of ad lib sleep time by prior ad lib wake time emerges only over successive circadian cycles.

The lack of evidence for short-term homeostatic regulation of sleep time in the rat is subject to two qualifications. First, since sleep seems to vary in intensity, as indicated by increased arousal thresholds and altered electrophysiological parameters following sleep loss, it is conceivable that a short-term regulation of sleep is accomplished by changes in its intensity rather than its duration. Second, it is possible that short-term control of sleep may be obscured in organisms such as the rat whose strong circadian rhythms restrict most sleep to one part of the day and most wakefulness to the other. An appropriate test for short-term control of sleep by prior wake time would require that this overriding circadian control be removed.

In the present study, we looked for short-term relationships between wake and sleep durations or intensity measures in rats whose circadian sleep-wake rhythms were destroyed by suprachiasmatic nuclei (SCN) lesions (10–13). Such rats do show normal amounts of daily sleep as well as sleep rebound phenomena after sleep deprivation (14,15), indicating that neural mechanisms mediating recovery responses are preserved. Correlations will be presented here between durations of contiguous wake and sleep episodes in five SCN-lesioned rats, with separate analyses for NREM sleep, paradoxical sleep (PS), and total sleep (TS). As putative measures of sleep intensity, the incidence and amplitude of EEG waves in the delta band (1–4 Hz) during selected NREM episodes in three rats were correlated with prior and subsequent wake durations.

METHODS

Subjects and surgical preparations

Five male Sprague-Dawley rats weighing 280–320 g at surgery were used. The rats were anesthetized and placed in a stereotaxic instrument with the mouthpiece set at 5 mm above the interaural line. Bilateral monopolar radio frequency lesions of the SCN

were made by passing a 1.8-mA current for 15 s from a Grass lesion maker through a 00 insect pin insulated with Epoxylite (Epoxylite Corp.) to within 0.4 mm of its tip. The stereotaxic coordinates were 1.4 mm anterior to bregma, ±0.3 mm lateral to the sagittal suture, and 9.3 mm ventral to the dura (16).

For EEG recording, two pairs of stainless-steel jeweler screws were threaded into holes drilled through the skull. Lateral EEG was recorded from one screw positioned 1.0 mm posterior and 2.5 mm lateral to bregma and a second ipsilateral screw 1 mm anterior and 3.5 mm lateral to lambda. Midline theta waves were recorded from two screws within 1 mm of the midline, with one screw 2–3 mm anterior to bregma and the other midway between lambda and bregma. Electromyogram (EMG) was recorded from two silver plates cemented to the back of the occipital bone beneath the nuchal muscles. All electrodes were soldered to a miniature 9-pin Amphenol connector cemented to the skull.

Experimental procedures

After surgery the rats were placed in a sound-attenuated recording cage and permitted to recover for 2 weeks in constant dim light (2.8 lux) with ad lib access to food and water. A flexible recording cable was attached to one end to the electrode connector and at the other to a commutator and counterbalanced boom assembly that permitted unrestricted movement within the cage. Rats that showed no sleep-wake rhythms in periodogram analysis and inspection of "running wheel" style charts over the 2-week period were transferred to a second chamber with an identical cable and boom assembly and the same lighting. Habituation to the chamber and stabilization of EEG recordings were permitted for 3–4 days. Two undisturbed baseline days were then recorded, from which the data for this experiment were obtained. During the second baseline day, EEGs from three of the rats were stored on magnetic tape.

Sleep recording

Amplification, filtering, and ink recordings of electrophysiological signals were made with a Beckman type R polygraph. The EEG was band pass filtered from 1 to 20 Hz (20 dB/oct). Theta (the signal from the skull midline) was narrow band filtered with a notch pass filter centered at 7 Hz (14 dB/oct). EMB was high pass filtered at 22.5 Hz (12 dB/oct) and notch reject filtered at 60 Hz. The signals were digitized with resetting integrators, which reset when the rectified signal voltage reached a preset level. Thus, the number of resets per 30-s epoch was proportional to the mean signal amplitude for that epoch. Reset counts for each epoch were collected by a PDP 11 minicomputer. Every 24 h the reset count data were transferred to floppy disks for storage.

Stage scoring was performed automatically by the Parametric Animal State Scoring (PASS) system developed in our laboratory (17). This system makes use of the observation that the mean amplitudes (reset counts) of the EEG, theta, and EMG signals for a day's epochs tend to group into four clusters: low-EEG, low-theta, high-EMG cluster (wake); low-EEG, low-theta, low-EMG cluster (low-amplitude NREM); high-EEG, high-theta, low-EMG cluster (high-amplitude NREM); and low-EEG, high-theta, low-EMG cluster (PS). Each day the computer produced frequency distributions of the integrated amplitudes for the three signals for the 2,880 epochs. From these distributions the modes for each signal that corresponded to each of the four clusters were identified. Then, by a decision-making process, the computer assigned each epoch to the cluster (and stage score) whose modes were closest to the epoch's EEG, theta, and EMG mean amplitudes (reset counts). Low-voltage NREM appears primarily at sleep

onset, after body movements in sleep, and following PS episodes. For most analyses, low- and high-amplitude NREMs were combined as total NREM, since the two stages normally have similar behavior, response thresholds, and paucity of ponto-geniculo-occipital (PGO) spike activity (18,19). PASS has been validated against both visual scoring of polygraph records and direct observation of rats' wake, PS, and NREM behavior (17).

Period-amplitude analysis

The filtered lateral EEG signal was recorded on a Hewlitt Packard model 3900 FM tape recorder along with an epoch identification signal. Tapes were played back through a Kron-Hite model 3700 band pass filter set at 0.2–20 Hz, 3 dB, 24 dB/oct (real time) into an eight-bit A/D converter attached to a PDP 11 computer that sampled at 500 Hz (real time). Temporal resolution was thus 2 ms, and amplitude resolution was 0.4% full scale. The digitized signal was reconverted to an analog display, and gain was adjusted to keep the highest waves in NREM from clipping. This approach maximized amplitude resolution and signal/noise ratio at the expense of an amplitude calibration. An assembly language program performed the period-amplitude analyses at twice real time.

The program detected and measured half-waves, defined as the portion of the EEG signal lying between successive zero crossings. Starting at a zero crossing, the program counted the number of samples (timing) and summed the absolute values of these samples until the next zero crossing was reached. The summed amplitude was then divided by the number of samples to give the mean amplitude for the half-wave. This procedure gave an amplitude measure that was independent of wavelength and, since it represented the amplitude of a square wave having the same area as the wave measured, to some extent independent of wave shape also. It also meant that waves were treated as objects: That is, a long wave would contribute the same amount to amplitude statistics as a short wave.

Half-waves with wavelengths corresponding to 0.125–0.5 s, i.e., 1–4 Hz, were selected as corresponding to the "delta" range. We have reported elsewhere (3,20) that waves at all wavelengths in this range respond to the diurnal cycle in intact rats and to prior sleep deprivation in both intact and SCN-lesioned rats similarly to delta waves in human EEG. Delta wave incidence was calculated as the sum of all the half-waves in the delta range per 30-s epoch; delta wave amplitude was calculated as the sum of the corresponding mean wave amplitude divided by the number of waves.

Sleep-wake episode analysis

Plots of wake percentage of total time in 30-min blocks in SCN-lesioned rats revealed a distinct ultradian variation of sleep and wake time, with a period of ~1–4 h (Fig. 1). Rather than use the standard 1- or 2-min criterion for defining sleep and wake bouts in the rat (2,6), we attempted to tailor our bout criteria in accordance with this longer physiological time span. By visually scanning printouts of coded stage scores for the 2,880 daily 30-s epochs in pilot animals, we found that major sleep and wake times were readily blocked off. Specific criteria for defining these times were established post hoc. For purposes of this study, sleep and wake "episodes" were defined as follow: Wake episodes were initiated by at least 5 consecutive min (10 30-s epochs) of wake. Wake episodes were terminated and sleep episodes initiated if 20 consecutive epochs passed without at least 3 consecutive epochs of wake. Sleep epochs occurring within wake episodes were not included in calculating wake episode durations. Wake

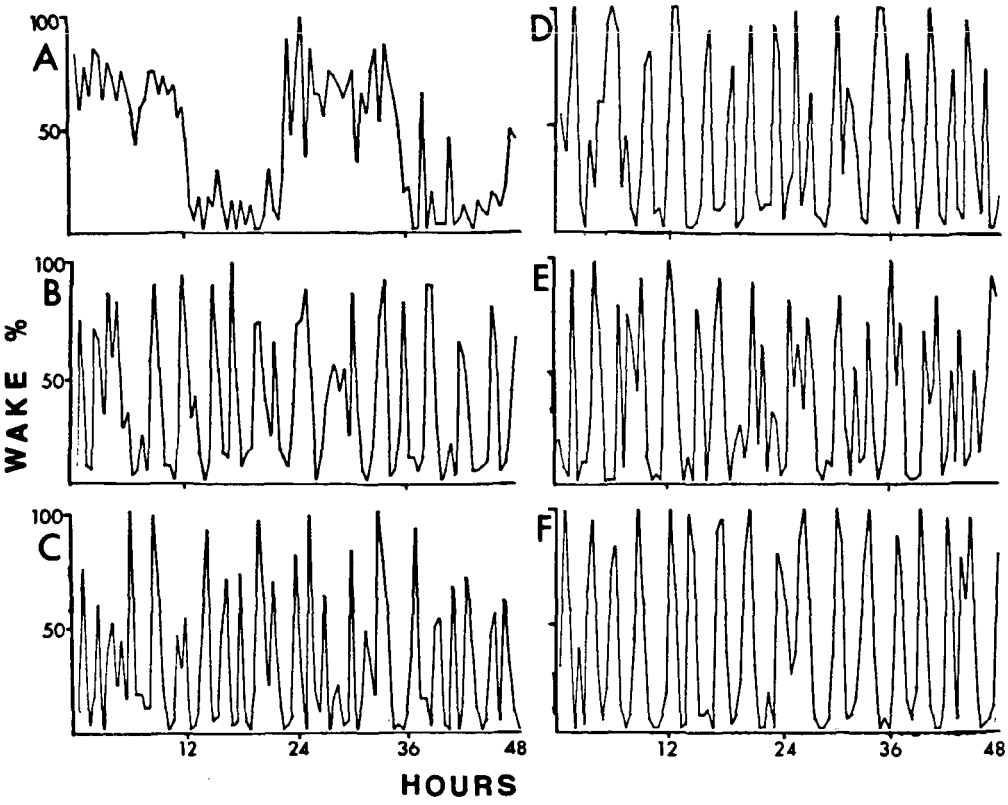

FIG. 1. Wake percentage for each 30 min of the 2 recording days for the five suprachiasmatic nuclei–lesioned rats (B–F) and an intact rat (A).

epochs were included in sleep episodes, since these often represent brief postural shifts, with sleep resuming within the epoch.

For each rat, Pearson product-moment correlation coefficients were calculated for all successive sleep-wake episode combinations over the 2-day recording period. There were six combinations; TS episode length and following wake (TS → wake), wake → TS, NREM → wake, wake → NREM, PS → wake, wake → PS. The amounts of NREM and PS within sleep episodes were also correlated. Group correlations were obtained by pooling the data for all rats and subtracting from each episode duration the mean episode duration for that rat, thus eliminating its potential contribution to the correlations. Probabilities were found by performing an *r*-to-*t* conversion and finding the appropriate p levels for two-tailed *t* tests.

Delta wave incidence and wave amplitude were quantified within some of the longer sleep and wake episodes in three rats. NREM delta within sleep episodes was averaged over 15-min blocks. Wake delta was averaged over 10-min blocks. The following parameters were calculated: the mean amplitude within episodes, the peak (maximum) wave incidence per block and its location within each episode, and the peak amplitude per block and its location.

Histology

After all recordings were completed, the rats were killed with an overdose of ketamine hydrochloride and perfused intracardially with saline followed by 10% formalin.

The brains were removed, stored in 10% formalin, and later sectioned at 60-μm intervals with a freezing microtome. Sections corresponding to the SCN and the lesion were mounted and stained with cresyl violet.

RESULTS

Histology and sleep-wake rhythms

Sleep-wake circadian rhythms were severely disrupted in all rats. Figure 1 illustrates the diurnal distribution of wake time in 0.5-h blocks over the 2 experimental days for the five lesioned rats and, for comparison, one representative intact rat from a separate study. Ultradian variation of wake time is prominent in the lesioned rats, but circadian variations were minimal or absent. This apparent attenuation of the sleep-wake circadian rhythm was substantiated by periodogram analysis of TS and PS over 5-day intervals for each rat using the method of Dorrscheidt and Beck (21). The periodograms produced were all at noise level for periods between 20 and 33 h.

Histological analysis revealed that two of the rats (L3 and L5) had complete SCN lesions that were relatively confined to the SCN area. The lesions in the remaining rats were 70–90% complete, with fragments of rostral or lateral SCN evident. Representative examples of a total and a partial lesion are provided in Fig. 2. Whether sleep-wake circadian rhythms might eventually reappear in rats with incomplete lesions (13) is not critical for this study, since these rats showed no circadian sleep-wake rhythms at the time of the study, and their data were indistinguishable from those of rats with complete lesions. All rats showed some damage to the optic chiasm immediately ventral to the SCN.

Sleep and wake duration distributions

The frequency distribution of all sleep durations (consecutive epochs) over the 10 recorded days was bimodal, with a prominent mode at 0–10 min and a second mode at 60–80 min (Fig. 3). The distribution of wake durations also showed two major peaks, including a prominent peak below 10 min and a lesser peak at 30 min. When we invoked the "episode" criteria described earlier, the mean number of sleep and wake

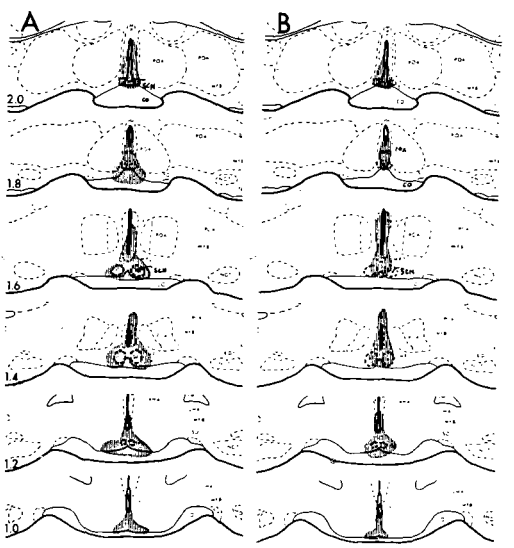

FIG. 2. Reconstructions of representative complete (A) and partial (B) suprachiasmatic nuclei (SCN) lesions. Schematics were traced from Pellegrino and Cushman (1967).

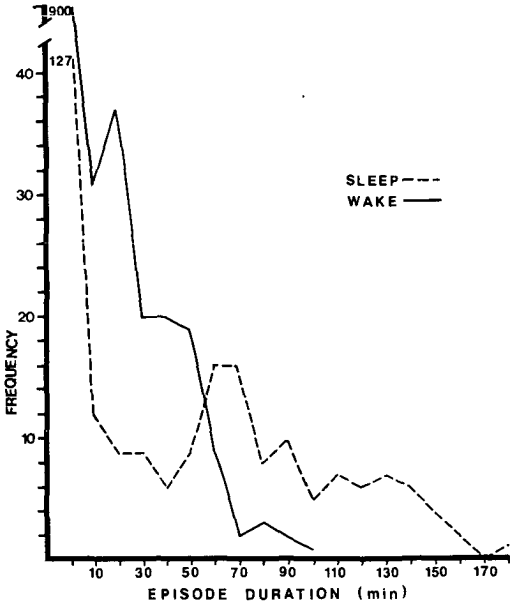

FIG. 3. Distributions of sleep episode durations (dashed lines) and wake episode durations (solid lines) for the five suprachiasmatic nuclei–lesioned rats. Episodes of <5 (wake) or 10 (sleep) min were not considered as episodes elsewhere in this article.

episodes per 24 h was 11.1 ± 2.5 and 11.5 ± 2.6, respectively. Their mean lengths were 77.5 ± 13.7 and 39.5 ± 8.3 min, respectively. Two-thirds of the sleep episodes were >50 min long, which lends support to our sleep episode onset criteria, since they usually signaled the onset of long sleep episodes.

Episode correlations

Pilot data indicated that sleep episodes longer than ~50 min and sleep episodes shorter than ~50 min were related differently to wake episodes. This separation corresponded roughly to the point in the sleep episode frequency distribution just prior to the rise of the second mode (Fig. 3). Accordingly, sleep episodes longer than 50 min ("long" episodes) were analyzed separately from episodes of <50 min ("short" episodes). Individual and group mean correlation coefficients are summarized in Table 1.

Wake → sleep. Correlations between wake episode durations and the duration of the following sleep episode (TS) showed considerable intersubject variability. For long sleep episodes (mean length 100 ± 30 min), all rats showed positive correlations with preceding wake (43 ± 22 min), which were significant for two rats ($p < 0.05$) and for the group correlation ($p < 0.002$). NREM within long sleep episodes (79 ± 24 min) was also positively correlated with prior wake, significantly in two rats ($p < 0.05$) and for the group ($p < 0.002$). In contrast, PS (13 ± 5 min) within long sleep episodes was not strongly related to prior wake: Three rats showed nonsignificant negative correlations and one rat a significant positive correlation ($p < 0.05$).

For short sleep episodes, TS (28 ± 11 min) and PS (3.2 ± 2.5 min) showed negative correlations with prior wake (31 ± 19 min) in three of five rats and NREM (22 ± 8 min) in four of five rats. The negative correlations for TS and PS were significant for one rat ($p < 0.05$) and the PS group ($p < 0.05$).

Sleep → wake. All rats showed positive correlations between the duration of long sleep episodes (100 ± 31 min) and the immediately following wake episode (43 ± 20 min), significant for one rat ($p < 0.05$) and for the group correlation ($p < 0.002$). Corre-

TABLE 1. *Individual and group correlation coefficients for adjacent sleep-wake episode durations*

	Wake → sleep				Sleep → wake			
Rat	No. of pairs	TS	NREM	PS	No. of pairs	TS	NREM	PS
Long sleep episodes (>50 min)								
L1	15	0.35	0.41	−0.13	15	0.57[a]	0.44	0.50[a]
L2	15	0.47	0.59[a]	−0.17	14	0.46	0.33	0.06
L3	16	0.09	0.14	−0.28	16	0.26	0.17	0.55[a]
L4	14	0.37	0.25	0.31	14	0.42	0.50[a]	0.53[a]
L5	14	0.61[a]	0.60[a]	0.61[a]	14	0.49	0.47	0.49
Group	74	0.33[b]	0.40[b]	0.07	73	0.41[b]	0.38[b]	0.47[b]
Short sleep episodes (<50 min)								
L1	5	−0.17	−0.18	0.25	5	−0.89[a]	−0.90[a]	−0.77
L2	11	−0.44	−0.48	−0.52	11	−0.28	−0.31	−0.28
L3	8	0.19	0.12	−0.33	8	−0.51	−0.38	−0.46
L4	9	−0.72[a]	−0.59	−0.84[a]	9	−0.08	−0.05	−0.15
L5	3	−0.32	−0.51	0.59	2	—	—	—
Group	36	−0.21	−0.23	−0.35[a]	35	−0.29	−0.21	−0.37[a]

TS, total sleep; PS, paradoxical sleep.
[a] $p < 0.05$.
[b] $p < 0.002$.

lations for NREM (79 ± 24 min) were positive in all rats and significant for one rat ($p < 0.05$) and for the group correlation ($p < 0.002$). PS (13 ± 6 min) within long sleep episodes was also positively correlated in all rats. The correlations were significant for three rats ($p < 0.05$) and for the group correlation ($p < 0.002$).

Correlations between short sleep episodes (27 ± 10 min) and following wake (31 ± 24 min) were negative in all rats for TS, NREM (22 ± 8 min), and PS (3.1 ± 2.5 min), but only one rat achieved significance at $p < 0.05$ for TS and NREM. The group correlation for PS reached significance at $p < 0.05$, and the TS value was near significance at $p < 0.10$.

PS - NREM. The amounts of PS and NREM within sleep episodes were highly correlated in all rats. The overall group correlation was 0.84; the long and short episode correlations were 0.59 and 0.58, respectively (all $p < 0.001$).

Delta activity during NREM and wake episodes

Delta wave incidence and wave amplitude were averaged for each 15-min segment of NREM within 15 sleep episodes and for each 10-min segment of 11 wake episodes in three rats. The sleep episodes ranged from 63 to 127 min (mean 95 min) and the wake episodes from 31 to 67 min (mean 49.4 min). Table 2 summarizes the correlations between NREM delta and wake episode durations for each rat. For all but one comparison, one rat showed a correlation in the direction opposite for the other two. The only comparison that produced a consistent group result was between peak delta wave incidence and prior wave duration, which did not reach significance.

The timing of peak delta wave incidence and amplitude within sleep bouts did not appear to be strongly related to the duration of the immediately preceding wake episode. There was a tendency for peak delta wave incidence to occur earlier within sleep

TABLE 2. *Individual and group correlations between NREM delta wave incidence and amplitude and duration of adjacent wake episodes*

Rat	No. of pairs	Mean incidence	Mean amplitude	Peak incidence	Peak amplitude
Wake → NREM					
L1	5	−0.39	−0.02	0.41	0.40
L3	5	0.34	−0.50	0.37	−0.64
L4	5	−0.54	0.17	0.59	0.73
Group	15	−0.28	−0.06	0.38	0.28
NREM → Wake					
L1	5	−0.07	−0.16	−0.56	−0.44
L3	5	0.39	−0.53	0.63	−0.49
L4	5	−0.38	0.45	−0.89	0.09
Group	15	−0.09	−0.18	−0.34	−0.26

episodes that followed long wake episodes ($r = -0.35$), but this was not significant for the group or for individual rats. The group correlation for peak amplitude was only −0.03, and again there were no significant correlations with prior wake for individual rats.

Correlations were also examined between delta activity within sleep and wake episodes and the duration of the episode (Table 3). For sleep episodes all comparisons produced mixed positive and negative correlation across the three rats. For wake episodes there were strong positive correlations between episode length and both peak ($p < 0.01$) and mean ($p < 0.02$) delta wave incidence, but comparisons with delta wave amplitude produced mixed positive and negative correlations.

To determine the course of change of delta parameters within episodes, the positions of the peak incidence and amplitude measures for the 11 wake and 15 NREM episodes were categorized according to the third of the episode in which they were found. Results are given in Fig. 4. NREM delta wave incidence and amplitude both tended to

TABLE 3. *Individual and group correlations between delta wave incidence and amplitude and episode duration*

Rat	No. of episodes	Mean incidence	Mean amplitude	Peak incidence	Peak amplitude
Sleep episode length versus NREM delta					
L1	5	0.42	0.90	−0.37	0.90
L3	5	−0.75	−0.40	−0.40	−0.06
L4	5	−0.86	0.94	0.97	0.96
Group	15	−0.18	0.28	−0.35	0.29
Wake episode length versus wake delta					
L1	4	0.15	0.81	0.69	0.79
L3	4	0.99	0.35	0.82	−0.002
L4	3	0.95	−0.39	0.84	−0.46
Group	11	0.69[a]	0.15	0.75[b]	0.24

[a] $p < 0.02$.
[b] $p < 0.01$.

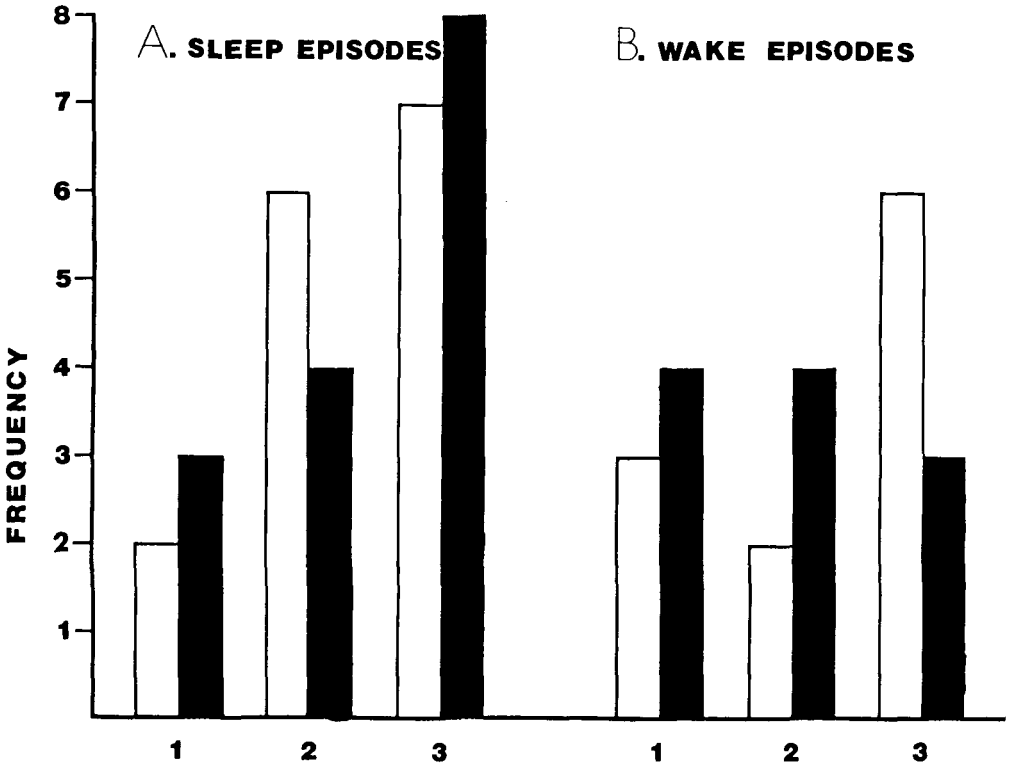

FIG. 4. Frequency histograms for time of peak delta wave incidence (filled bars) and wave amplitude (open bars) within 15 sleep (A) and 11 wake (B) episodes. Each episode was divided into thirds, represented by numbers 1, 2, and 3.

peak near the end of NREM episodes (both different from random at $p < 0.10$, by chi-square). Wake incidence showed a slight trend toward a peak in the final third, whereas wake wave amplitude showed no trend. These data parallel the finding that NREM wave incidence and amplitude were positively correlated (group $r = 0.66$, $p < 0.001$), whereas wake incidence and amplitude were not (group $r = -0.03$).

DISCUSSION

The significant positive correlation between long sleep episodes and preceding wake in these SCN-lesioned rats supports a short-term restorative model of sleep: Waking causes the accumulation of a deficit that is reversed by some restorative process of sleep. The positive correlation between long sleep episodes and subsequent wake can be explained as an extension of the same model: A surplus of some sort is accumulated during sleep, which is then dissipated during the following wakefulness. Thus, sleep could be considered as having a short-term "preparative" function as well as a "restorative" function. NREM within these sleep episodes also showed significant positive forward and backward correlations that could be considered "preparative" and "restorative." PS, on the other hand, showed a significant positive correlation with

only following wake, i.e., a "preparative" but not a "restorative" relationship. It could be argued that the PS function was in positive balance, i.e., so near the top of its range that no deficit would occur within a wake period, but a surplus could occur during sleep. The strong correlation of NREM to PS for both long and short episodes suggests that PS and NREM have a common function, although the significant difference ($p < 0.005$) between the (highly significant) NREM and (near zero) PS correlations with prior wake would indicate that NREM has a separate function as well.

There were no sleep episodes between 37 and 47 min long, and this gap provided a natural division between "long" and "short" episodes. Both wake → sleep sequences and sleep → wake sequences included a concentration of sleep episodes 25–35 min long paired with short (5–25 min) wake episodes. For sleep episodes shorter than 25 min, wake → sleep sequences were quite different from sleep → wake sequences. In the former there were no preceding wake bouts shorter than 22 min, as if there were a minimum constraint of ~35 min on wake → sleep cycle time. This apparent minimum constraint corresponds to the negative correlations found between TS, NREM, and PS versus wake; i.e., when wake episodes were short, sleep episodes were necessarily longer, and vice versa. In the sleep → wake sequences, on the other hand, sleep episodes shorter than 25 min were accompanied by a wide range of following wake episode lengths, ranging from 6 to 103 min. Three of the seven longest wake episodes were found here, and these outlying episodes were the primary contributors to the negative correlations in short sleep → wake in Table 1. Four of the five rats had an outlying long wake episode following a short sleep episode. We could find no other common characteristic of preceding wake or sleep, following sleep (two of the outliers followed short episodes and substantially decreased the strength of short wake → sleep correlations), or drowsiness for these episodes, nor did they occur at any particular time of day. One might speculate that these outliers represent the results of some competing drive or external stimulus that causes a sleep episode that would otherwise have been a longer episode to be aborted at an early stage. However, such a model assumes that sleep and following wake episode lengths are somehow preplanned.

We have found that depriving intact rats of as little as 4 h sleep near the beginning of the lights-on (sleep) phase of their diurnal cycle produced dramatic increases above baseline in delta wave incidence (50%) and amplitude per wave (26%) during recovery sleep (22). It was therefore somewhat surprising to find that there were no significant correlations of any NREM delta parameters with preceding wake bout length or, for that matter, with following wake bout length. Thus, we found no evidence of short-term "restorative" or "preparative" regulation of delta. It is, of course, quite possible that with a larger range of episode lengths or a greater number of episodes, a relationship could be detected.

There are, however, several parallels between the delta in these episodes and the delta of the sleep-wake cycle of intact rats. The significant increase in delta incidence as wake episode length increases in these rats paralleled the increase in waking delta incidence in intact rats across the waking portion of the diurnal cycle. The (nonsignificant) trend toward decreasing NREM delta incidence with episode length in these rats paralleled the decrease in this parameter across the sleep portion of the diurnal cycle in intact rats (20). Similarly, the positive correlation between delta incidence and amplitude in the NREM episodes and the (nonsignificant) trend toward negative correlation of these parameters in wake episodes correspond to the correlations between incidence

and amplitude during the diurnal cycle in intact rats and during recovery from sleep deprivation in both SCN-lesioned and intact rats (3,20).

One finding that did not fit with other data was the tendency for the delta incidence and amplitude to peak near the end of NREM episodes. In humans stage 4 is maximal near the beginning of the sleep period under both entrained and free-running conditions (23). In the intact rat, delta is highest at the beginning of the diurnal sleep period (2,20). One could argue that in the intact subject, the appearance of delta early in the sleep period is an immediate response to the accumulation of some deficit during the circadian wake period, whereas the SCN-lesioned rat never has this degree of accumulation and remains therefore in "positive delta balance." This argument is supported by the (nonsignificant) tendency of the peak delta incidence to occur earlier in NREM episodes following long wake episodes. It is also a convenient explanation for our failure to find a strong relationship between NREM delta measures and preceding wake time.

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