Sleep, 18(10):880–889

EEG Analyses and Transition from Wake

Topographical and Temporal Patterns of Brain Activity During the Transition From Wakefulness to Sleep

*Kenneth P. Wright Jr., *Pietro Badia and †Albert Wauquier

*Department of Psychology, Bowling Green State University, Bowling Green, Ohio, U.S.A.; and
†Department of Neurology, Texas Tech University Health Sciences Center, Lubbock, Texas, U.S.A.

Summary: Changes in electroencephalographic (EEG) spectral power, coherence and frequency were examined for the last minute of wakefulness and the first minute of sleep via topographical mapping. Data were also analyzed across sequential 1-minute samples of wake, stage 1 and stage 2 sleep. Not all brain regions exhibited the same EEG changes during the transition and not all brain regions were found to change at the same time. Brain sites closest to the midline (e.g. F4, C4, P4, O2) showed significant changes in EEG power (increases in theta and decreases in alpha power) during the transition to sleep, whereas brain sites most lateral to the midline (e.g. Fp2, F8, T4) showed little change. Decreases in alpha coherence were observed from wakefulness to sleep for brain site comparisons furthest away from each other (e.g. T3 vs. T4, T5 vs. T6, F7 vs. F8, F3 vs. O1, F4 vs. O2). Spectral analysis of EEG activity revealed that the time of significant change in EEG power varies among brain regions. Decreases in alpha power continued to occur later into the transition period for the posterior regions of the brain (O2, P4). **Key Words:** Sleep onset—Brain mapping—EEG—Hemispheric differences—FFT.

Considerable effort has been directed to identifying physiological and behavioral changes that occur during the transition from wakefulness to sleep. A better understanding of these changes may lead to new insights concerning brain function during wakefulness and sleep. The research here focuses on changes in brain activity during the transition from wakefulness to sleep using quantitative electroencephalographic analyses (QEEG).

Among the measures used to describe differences between wakefulness and sleep, the electroencephalograph (EEG) is the most common. Investigators have provided descriptions of electrophysiological activity for wakefulness and sleep based on visual scoring of EEG records (1–6). In general, these studies report decreases in alpha activity and increases in theta activity during the transition.

Others have used computer analysis of the EEG to examine changes in brain activity during the transition period. Computer-based techniques are more sensitive than visual scoring because they allow for the full range of EEG activity to be examined. Such studies have corroborated visual scoring reports (7–11). However, these studies also report increases in delta and decreases in beta activity (10,12). Unfortunately, even with computer analysis techniques the aforementioned experiments do not agree upon the precise moment of change in theta and alpha activity.

Some studies also report brain site differences in EEG activity during the transition period. For example, increases in theta are observed to be largest in the central region of the brain, and decreases in alpha are largest at the occipit. In addition, these studies show that frontal and central sites show changes earlier than occipital brain sites (3,8–10).

Although the above studies are informative, they are limited in that only a small number of brain sites were recorded, and typically only one QEEG technique was used. The use of a small number of brain sites does not allow for the examination of how the brain as a whole changes during the transition. In this regard, it remains to be determined whether all brain regions show similar changes at similar times. In addition, whether hemispheric differences exist during the transition needs additional research.

The present study used topographical mapping (21 sites) to examine EEG changes during the transition from wakefulness to sleep. In addition, multiple QEEG techniques were used (i.e. spectral power, coherence, frequency).

Accepted for publication July 1995.
Address correspondence and reprint requests to Kenneth P. Wright, Jr., Department of Psychology, Bowling Green State University, Bowling Green, OH 43403, U.S.A.

METHODS

Subjects

There were 12 healthy female subjects (mean age 21 years; range 18–28 years old). Two subjects were excluded from analysis because they did not fall asleep. Subjects were instructed to refrain from alcohol and drugs for 24 hours prior to the experimental session and not to drink any caffeine the day of the study. Subjects were tested during the follicular phase of their menstrual cycle. Only right-handed subjects [mean laterality score of 85.05 on the Endinburgh Handedness Inventory (13)] were tested.

Electrode placements

Electroencephalographic data were acquired over 21 brain sites using an electrode cap (Electro-Cap International, Eaton, OH) configured according to the International 10/20 system. Specific locations were as follows: Fp2, Fp1, Fpz, F4, F3, F8, F7, Fz, C4, C3, Cz, T4, T3, T6, T5, P4, P3, Pz, O2, O1, Oz. Linked-ear electrodes were used as references for EEG activity. Standard mentalis electromyogram (EMG) and electrooculogram (EOG) activities were also recorded to assist in sleep stage scoring.

Apparatus and recording procedure

Recordings were made with a Cadwell Neuroscan 32 Brain Mapping System, Kennewick, WA. Each EEG amplifier was set at a sensitivity of 5 μV/mm and used a frequency bandwidth (filter settings) of 0.53–35 Hz. A 60-Hz notch filter was used to attenuate electrical interference noise. A 50-μV sine wave signal was used for calibration. Impedances for the EEG electrodes were all <10 kohms. Data were stored and displayed at a rate of 200 samples per second per channel with a 12-bit Data Translations 2821 A-D board.

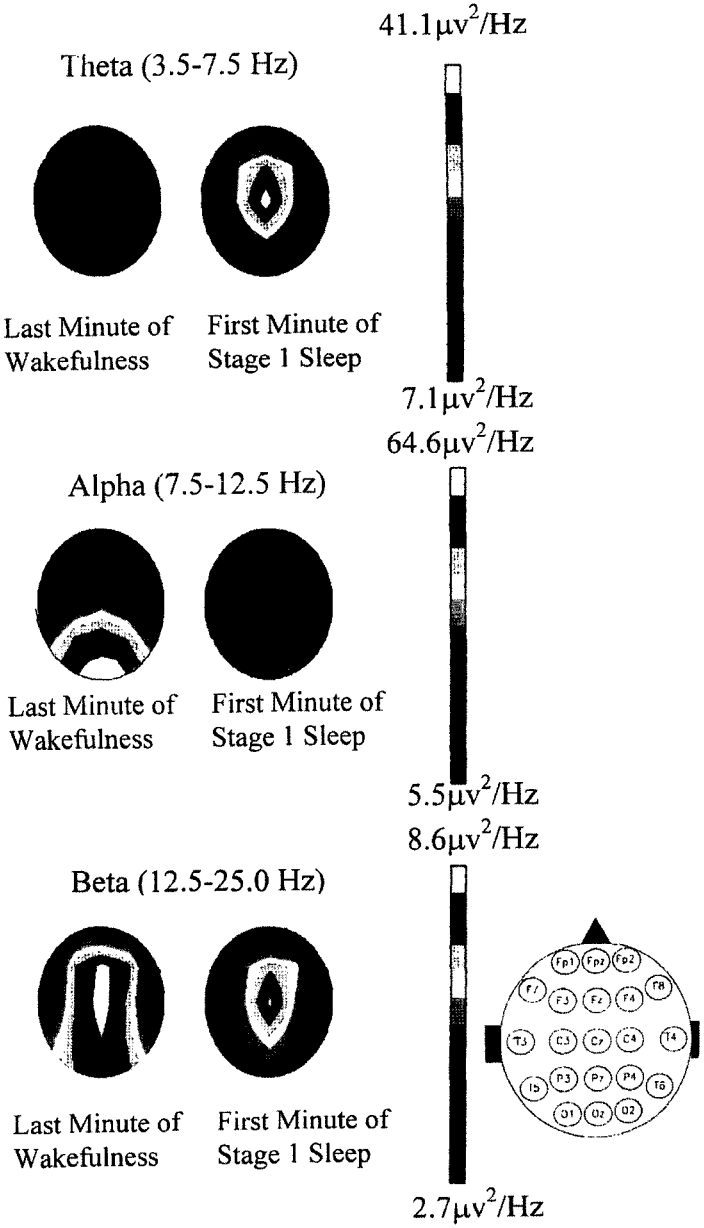
Brain maps for the subjects' averaged data (in 1-minute epochs) were created using "Whole Head Graphics"—a 19-channel EEG graphical display program (average interpolation) developed by The Psychoneurophysiology Laboratory, Psychology Department, University of Arizona, (Tucson, AZ). Microvolt scales for the brain map displays were chosen by the Whole Head Graphics program.

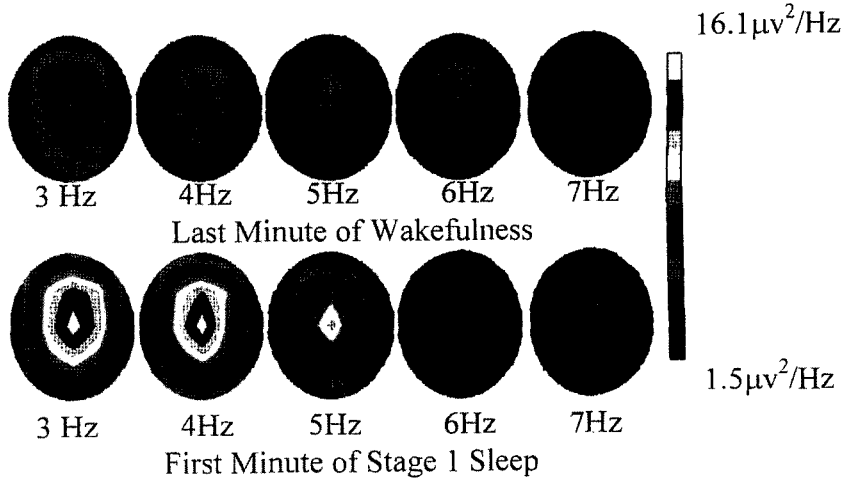
Experimental routine

Subjects arrived at the laboratory at either 1000 or 1300 hours. They were instructed the night before to decrease their sleep time by 2 hours to help speed the transition to sleep and to minimize fluctuations between wake and sleep. Prior to entering the laboratory, a consent form was signed, and background questionnaires were completed. The questionnaires related to their sleep–wake habits, handedness, and general medical health. Subjects reclined in a hospital bed in a sound- and light-attenuated room and were instructed to simply go to sleep. For present purposes sleep was defined as the first minute of stage 2 sleep. The experimenter awakened subjects 1 minute after the first K-complex or sleep spindle. If a subject did not fall asleep within 20 minutes after lights out, the nap was ended and after 5 minutes a second nap attempt was permitted. If subjects did not fall asleep within 20 minutes a second time, the session was concluded, electrodes were removed and subjects were free to leave. Data from only one successful nap attempt per subject were analyzed.

Scoring

Data were assessed for changes in amplitude, phase and frequency by submitting the digitized EEG data to a Fast Fourier Transform (FFT) in manually selected 2.5-second epochs. The EEG data were then accumulated in power, coherence and frequency units, over a frequency bandwidth of 2.5–25 Hz, in 2.5-second bins. EEG activity was then averaged across six 2.5-second bins, providing 15-second epochs to be examined. Artifacts were removed from data prior to analysis. Spectra of epochs with EEG artifacts (e.g. muscle artifact, amplifier blocking) were eliminated on the basis of visual inspection. If fewer than three artifact-free 2.5-second epochs were available, the 15-second epochs of wake and the first four 15-second epochs of sleep, data were averaged into 1-minute epochs for statistical analysis. The final data for each brain site were computed for theta (3.5–7.5 Hz), alpha (7.5–12.5 Hz) and beta (12.5–25 Hz) in 1-minute epochs (the last minute of wakefulness and the first minute of sleep—all eyes closed). Data were also analyzed across sequential 1-minute samples of wake, stage 1 and stage 2 sleep (eyes closed). Sleep scoring (except for stage 2) was based on Rechtschaffen and Kales (5) criteria and were scored from the C3 lead. The delta band (0.75–2.5 Hz) was not examined due to concern over eye movement artifacts. Coburn and Moreno (14) reported that eye movement artifacts can be easily overlooked by both artifact rejection programs and visual examination of the EEG record. Power spectral analysis (absolute power), EEG coherence [both interhemispheric and intrahemispheric (15)] and EEG frequency analysis (mean, median and peak frequency between 3 and 25 Hz) were computed.





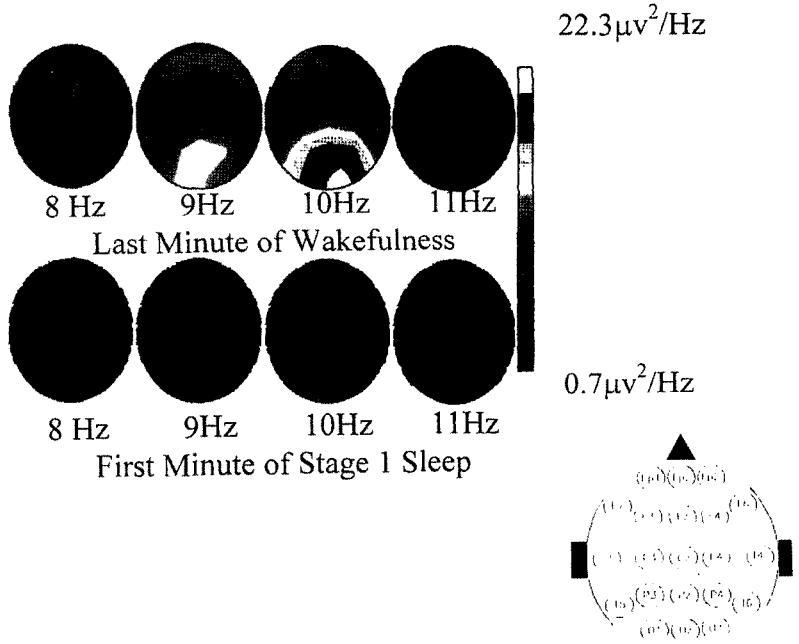


FIG. 1. Topographical patterning of theta, alpha and beta during the last minute of wakefulness and first minute of stage 1 sleep (n = 10).

FIG. 2. Topographical patterning of single Hz activity (from 3 to 11 Hz) during the last minute of wakefulness and first minute of stage 1 sleep (n = 10).

To compensate for possible violations of repeated measure assumptions (e.g. sphericity, homoscedasticity) and to decrease type I error rate, Huynh Feldt Correction Factors were used in all analyses where appropriate. For interhemispheric power and frequency analyses, Bonferoni Correction Factors were used to correct for multiple comparisons. For all other analyses the standard significance level of $p < 0.05$ was used. Tukey LSD Post-Hoc tests were used to determine significant comparisons.

RESULTS

Topographical differences

Power analysis

The question of hemispheric differences in EEG power was examined for 8 homologous brain site comparisons (Fp2 vs. Fp1, F4 vs. F3, F8 vs. F7, C4 vs. C3, P4 vs. P3, T4 vs. T3, T6 vs. T5, O2 vs. O1). For each EEG bandwidth and brain site comparison, a two-way analysis of variance (ANOVA; homologous brain site and wake-sleep state) was computed, totaling 24 comparisons (eight brain site comparisons for three EEG bandwidths). A Bonferoni Correction Factor required a level of $p < 0.0063$ to be significant (16).

Figure 1 displays absolute EEG power in the theta, alpha and beta bands during the last minute of wakefulness and the first minute of stage 1 sleep. As shown, symmetry in EEG power for the theta, alpha and beta bands is observed between the hemispheres during the last minute of wakefulness and first minute of stage 1 sleep. In general, decreases in alpha and beta power and increases in theta power from wakefulness to sleep occurred. In addition to the broad band data, data for single Hz EEG activity from 3 to 11 Hz are presented in Fig. 2. As can be seen, the largest increases in EEG power are observed at 3 and 4 Hz (predominantly at the vertex) and the largest decreases at 9 and 10 Hz (predominantly at the occiput).

The interaction between brain sites and wake–sleep state was examined to determine whether differences in the magnitude of change in power existed when comparing homologous brain sites (e.g. did C3 show more, less or about the same change in EEG power compared to brain site C4 during the transition to sleep). ANOVA results yielded no significant interaction between homologous brain sites and wake–sleep state for the theta, alpha, or beta bands. Because no interhemispheric differences in EEG power were found during the transition to sleep, the right hemisphere was selected to examine intrahemispheric differences. The right hemisphere (arbitrarily chosen over the left) was selected instead of the midline so temporal brain sites (e.g. T4, T6) could be included in the analysis. Thus, eight brain sites on the right hemisphere (Fp2, F4, F8, C4, P4, T4, T6, O2) were examined.

TABLE 1. *Summary of effects during the last minute of wakefulness and first minute of stage 1 sleep for intrahemispheric EEG power, interhemispheric EEG coherence and intrahemispheric EEG coherence*

Effect	df	Intrahemispheric EEG power (*F*)	Interhemispheric EEG coherence (*F*)	Intrahemispheric EEG coherence (*F*)
Site				
Theta	7,63	12.04	91.56	200.99
Alpha	7,63	29.96	77.83	105.13
Beta	7,63	17.89	117.95	266.58
State				
Theta	1,9	15.24	1.67	2.55
Alpha	1,9	7.77	28.72	4.49
Beta	1,9	7.84	5.25	0.68
Site × state				
Theta	7,63	6.93	0.46	4.08
Alpha	7,63	6.31	5.63	11.52
Beta	7,63	2.85	2.32	13.41

Underline denotes significance at $p < 0.05$.

Figure 1 shows intrahemispheric differences for magnitude of increase in theta and magnitude of decrease in alpha and beta power during the transition to sleep. In general, brain regions closest to the midline (e.g. F4, C4, P4, O2) exhibited marked changes in brain activity, whereas brain sites more lateral (e.g. Fp1, F8, T4) showed little change. The interaction between brain sites and wake–sleep state was examined to test for brain site differences across wake–sleep state. ANOVA results (Table 1) revealed a significant interaction between brain sites and wake–sleep state for the theta and alpha bands and a marginal interaction for the beta band ($p = 0.085$). Tukey LSD post-hoc tests revealed significantly more theta power during sleep compared to wakefulness for brain sites F4, C4, P4 and O2 (all $p < 0.01$); significantly lower alpha power during sleep compared to wakefulness for brain sites F4, P4, O2 and T6 (all $p < 0.05$) and significantly less beta power during sleep compared to wakefulness for brain sites P4 and O2 (both $p < 0.05$). Brain regions most lateral on the right hemisphere (e.g. Fp2, F8, T4) exhibited nonsignificant changes in EEG power.

Brain site differences in EEG power at sleep onset

The main effect for site in the intrahemispheric analysis was examined to determine whether topographical differences in EEG power during wakefulness and during sleep were evident. The number of differences in power for theta and beta remained relatively stable across state [i.e. during the last minute of wakefulness

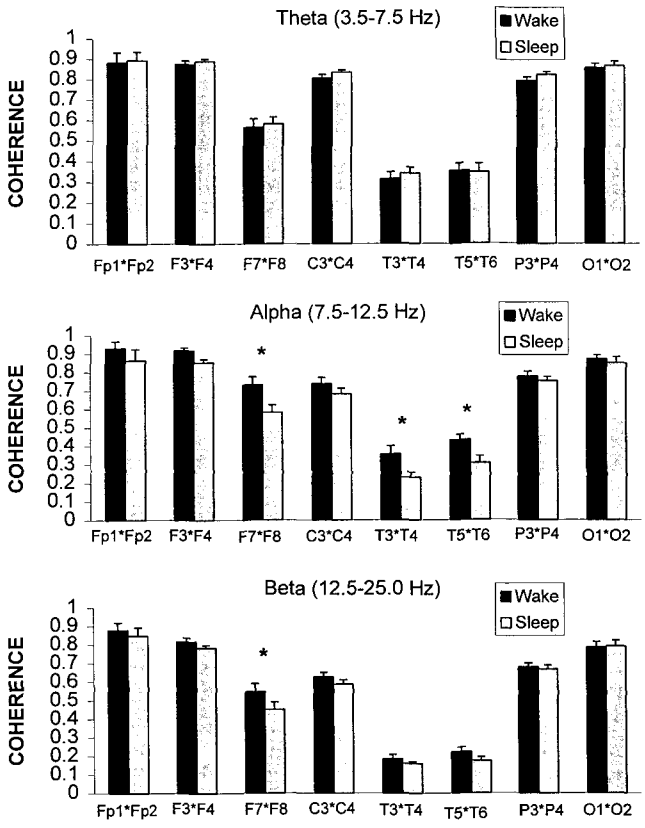


FIG. 3. Interhemispheric coherence data during the last minute of wakefulness and the first minute of stage 1 sleep (n = 10). Asterisks (*) above bars denote a significant change in coherence from wakefulness to sleep ($p < 0.05$). Error bars denote standard error of the mean (SEM).

18 of 28 brain site comparisons (each brain site on the right hemisphere compared to the other) for theta and 18 of 28 comparisons for beta showed differences in EEG power; similarly, during the first minute of stage 1 sleep, 21 of 28 comparisons for theta and 15 of 28 for beta exhibited differences in power]. The number of brain site differences for alpha power changed during the transition (i.e. intrahemispheric differences in alpha power practically disappear with the onset of stage 1 sleep—12 of 28 during wake and 1 of 28 during sleep).

Coherence analysis

To investigate further the question of topographical differences in EEG activity during the transition, interhemispheric and intrahemispheric patterning of EEG coherence was examined. Coherence measures of the EEG are used to compare brain activity at two or more brain sites and reflect the manner in which the two signals covary at a particular frequency or frequency range. Coherence is thought to be a measure of the functional and structural connectivity between two brain sites (17). To examine interhemispheric coherence patterning during the transition, two-way ANOVAs (brain sites by wake–sleep state) were computed for each EEG bandwidth for brain site comparisons Fp1 vs. Fp2, F3 vs. F4, F7 vs. F8, C3 vs. C4, T3 vs. T4, T5 vs.T6, P3 vs. P4, O1 vs. O2.

Figure 3 displays interhemispheric coherence data for the theta, alpha and beta ranges during the last minute of wakefulness and the first minute of stage 1 sleep. As seen, the largest decreases in alpha and beta coherence during the transition occur between brain sites furthest away from each other (e.g. T4 and T3, T6 and T5, F7 and F8). To determine whether topographical differences in interhemispheric coherence occurred during the transition, the interaction between brain sites and wake–sleep state was examined.

Table 1 shows a significant interaction between homologous brain sites and wake–sleep state for the alpha band and a marginal interaction for the beta band ($p = 0.095$). Post-hoc tests revealed significantly lower alpha coherence during sleep compared to wakefulness between brain sites T3 and T4 and between T5 and T6 and significantly less alpha and beta coherence during sleep between brain sites F7 and F8. For most other homologous brain sites, decreases in alpha and beta coherence were not significant. No significant interaction for theta coherence was observed.

Intrahemispheric brain activity was examined next to determine if the topographical patterning of EEG coherence changed with a change in wake–sleep state.

To examine intrahemispheric coherence patterning during the transition, a two-way ANOVA (eight brain sites by wake–sleep state) was computed for each EEG bandwidth (brain site comparisons—Fp1 vs. F3, Fp2 vs. F4, C3 vs. P3, C4 vs. P4, F3 vs. O1, F4 vs. O2, T3 vs. T5, T4 vs. T6).

Figure 4 displays these data during the last minute of wakefulness and the first minute of stage 1 sleep. Similar to the interhemispheric coherence analysis, brain sites furthest away from each other show the largest decreases in coherence (i.e. F3 vs. O1 and F4 vs. O2). Table 1 shows significant interactions between brain sites intrahemispherically and wake–sleep state for the theta, alpha and beta bands. Post-hoc tests show significantly higher theta coherence occurred during sleep compared to wakefulness between brain sites T4 vs. T6; lower alpha coherence during sleep compared to wakefulness was observed for brain site comparisons F3 vs. O1 and F4 vs. O2; and beta coherence was lower for brain site comparison F4 vs. O2 and higher for brain site comparison T4 vs. T6 during sleep compared to wakefulness.

Frequency analysis

A frequency analysis of the EEG was undertaken to examine changes in the periodicity of the wave form

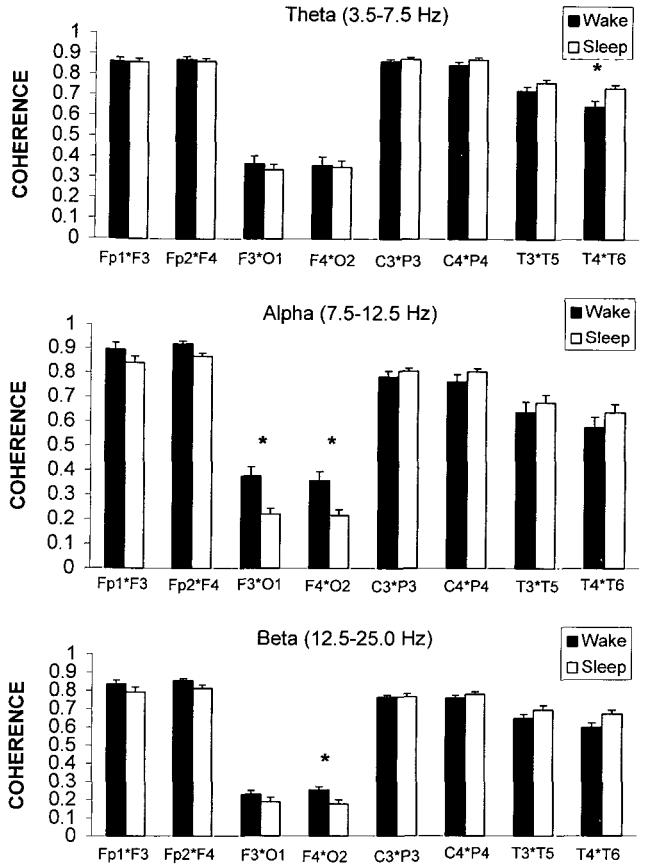


FIG. 4. Intrahemispheric coherence data during the last minute of wakefulness and the first minute of stage 1 sleep (n = 10). Asterisks (*) above bars denote a significant change in coherence from wakefulness to sleep ($p < 0.05$). Error bars denote SEM.

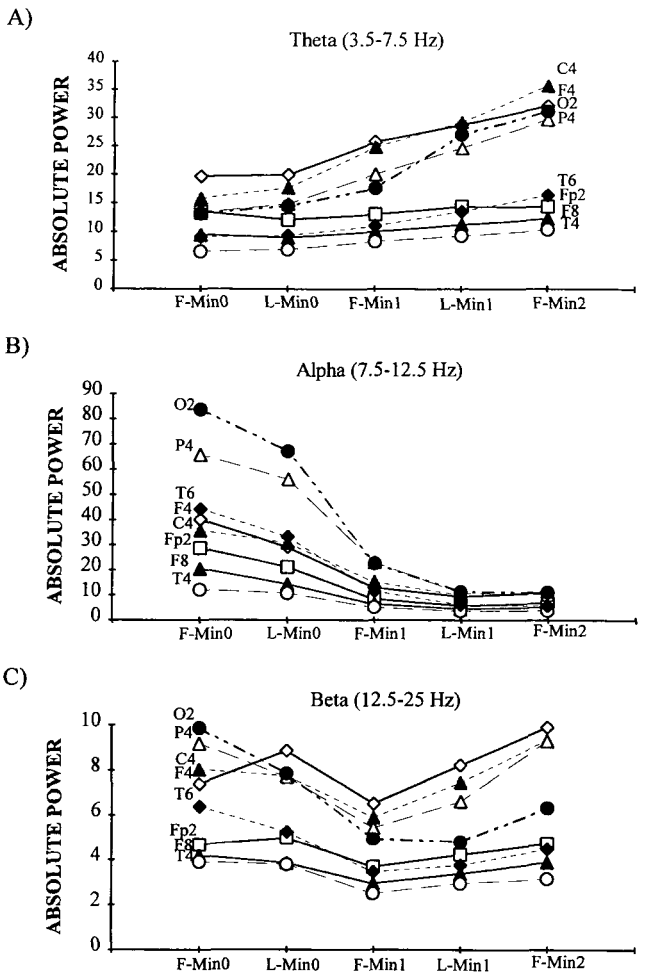


FIG. 5. EEG power data for the first minute of wakefulness (F-Min 0), the last minute of wakefulness (L-Min 0), the first minute of stage 1 sleep (F-Min 1), the last minute of stage 1 sleep (L-Min 1) and the first minute of stage 2 sleep (F-Min 2) for eight brain sites on the right hemisphere (n = 8).

with less emphasis on EEG amplitude. For these analyses, the same brain site comparisons used for the power analyses were used (see above). A Bonferoni Correction Factor was also used to correct for multiple comparisons for the interhemispheric analysis.

Decreases in mean, median and peak frequency occurred to a similar degree across the brain (both between and within hemispheres) during the transition (data not shown). The average decrease in mean frequency was around 0.45 Hz, 0.70 Hz for median frequency and 2.0 Hz for peak frequency. Repeated measure ANOVAs showed no significant interaction between brain sites and wake–sleep state for mean, median or peak frequencies interhemispherically or intrahemispherically.

Temporal differences

Figure 5 displays EEG power data for the first minute of wakefulness, the last minute of wakefulness, the first minute of stage 1 sleep, the last minute of stage 1 sleep, and the first minute of stage 2 sleep for eight brain sites on the right hemisphere (C4, F4, P4, T4, O2, FP2, F8, T6). Two subjects were dropped from the analysis because they did not have enough of either stage 1 or stage 2 sleep. Repeated measure ANOVAs were used to examine differences in EEG power among brain sites across stage samples (Table 2). The interaction between brain sites and stage was examined to test for differences in the magnitude of change from one EEG stage to another.

First minute of stage wake compared to the last minute of stage wake

The posterior regions of the brain showed the largest changes in EEG power from the first minute of wakefulness to the last minute of wakefulness (Fig. 5). A significant interaction between brain sites and EEG stage was observed for beta power (Table 2). Post-hoc tests revealed significantly lower beta power during the

TABLE 2. *Summary of effects (intrahemispheric EEG power) of stage sample comparisons during the transition to sleep*

Effect	df	F-Min 0 vs. L-Min 0	F-Min 1 vs. L-Min 1	L-Min 1 vs. F-Min 2
Site				
Theta	7,63	11.26	35.33	63.39
Alpha	7,63	16.24	13.36	28.01
Beta	7,63	16.14	13.52	15.83
State				
Theta	1,7	0.24	9.51	1.86
Alpha	1,7	8.09	3.69	0.45
Beta	1,7	0.42	2.30	1.87
Site × state				
Theta	7,63	1.03	4.16	1.25
Alpha	7,63	1.64	4.41	2.84
Beta	7,63	4.87	2.79	2.04

Underline denotes significance at $p < 0.05$.
F-Min 0 = first minute of wakefulness, L-Min 0 = last minute of wakefulness, F-Min 1 = first minute of stage 1 sleep, L-Min 1 = last minute of stage 1 sleep, F-Min 2 = first minute of stage 2 sleep.

last minute of stage wake compared to the first minute of stage wake for brain site O2 ($p < 0.05$).

First minute of stage 1 sleep compared to the last minute of stage 1 sleep

Once again, the posterior regions of the brain showed the largest changes in EEG power (Fig. 5). Table 2 shows a significant interaction between brain sites and sleep stage for the theta and alpha bands. Tukey LSD post-hoc tests revealed significantly higher theta power for brain site O2 ($p < 0.001$) and marginally higher theta power at brain site P4 ($p < 0.089$) during the last minute of stage 1 sleep compared to the first minute of stage 1 sleep. Significant decreases in alpha power were also found at the same brain sites (P4 vs. O2) from the first minute of stage 1 sleep to the last minute of stage 1 sleep (both $p < 0.001$). Nonsignificant increases in beta power across the majority of brain sites were observed from the first to the last minute of stage 1 sleep.

Last minute of stage 1 sleep compared to the first minute of stage 2 sleep

As seen in Fig. 5, little difference for the magnitude of change in EEG power from the last minute of stage 1 sleep to the first minute of stage 2 sleep was observed. A marginal interaction between brain sites and sleep stage was observed for alpha activity (Table 2). Tukey LSD post-hoc tests revealed higher alpha power during the last minute of stage 1 sleep compared to the first minute of stage 2 sleep for brain site F4 ($p = 0.057$). Increases in beta and theta power from the last minute of stage 1 to the first minute of stage 2 sleep were nonsignificant.

Topographical brain site differences in EEG power during different wake and sleep stages

Power data for the first minute of wakefulness, the last minute of stage 1 sleep and the first minute of stage 2 sleep were examined. Many site differences in EEG power were observed for the different wake–sleep stages. The data are summarized as follows: during the first minute of wakefulness 18 of 28 brain site comparisons for theta, 21 of 28 for alpha and 19 of 28 for beta showed site differences. During the last minute of stage 1 sleep 20 of 28 for theta, 2 of 28 for alpha and 18 of 28 for beta showed differences (the data for the last minute of stage 1 sleep are very similar to those reported for the first minute of stage 1 sleep in the section entitled "Topographical differences"). Finally, during the first minute of stage 2 sleep 16 of 28 for theta, 19 of 28 for alpha and 18 of 28 comparisons for beta showed site differences.

DISCUSSION

A summary of the major findings follows. The time of significant change in EEG power varies among brain regions. Decreases in alpha power continue to occur later into the transition period for the posterior regions of the brain (O2 and P4—i.e. the posterior regions of the brain "go to sleep last"). Other topographical differences were also observed during the transition (i.e. some brain sites show decreases in alpha and beta power and increases in theta power, and some do not). In this regard, brain sites closest to the midline (e.g. F4, C4, P4, O2) showed significant changes in EEG power during the transition to sleep. However, brain sites most lateral to the midline (e.g. Fp2, F8, T4) showed little change in EEG power during the transition. Intrahemispheric and interhemispheric differences in EEG coherence were also found. Brain sites farthest from each other (F3 and O1, F4 and O2, T3 and T4, T5 and T6, F7 and F8) showed the largest changes in alpha and beta coherence during the transition to stage 1 sleep. Interhemispheric differences in EEG power were not observed. Similar decreases in mean, median and peak frequencies were observed for all brain sites during the transition.

Temporal differences

Differences among brain sites were apparent in both the magnitude and timing of significant change in EEG power. Specifically, the posterior regions of the brain continued to show changes in EEG power further on

into the transition period (i.e. increases in theta and decreases in alpha power from the first minute of stage 1 sleep to the last minute of stage 1 sleep). Most brain sites showed significant increases in theta and decreases in alpha only from the last minute of wakefulness to the first minute of stage 1 sleep. Thus, the parietal and occipital regions of the brain are still changing ("making the transition to sleep") when the more anterior portions of the brain have already "gone to sleep". This finding is consistent with previous evidence showing that different brain areas exhibit EEG changes earlier than others (3,8–10). A common finding among all studies is that the posterior regions of the brain are the last to show EEG changes from wake to sleep.

Topographical differences

Decreases in alpha and increases in theta activity were expected to occur for all brain regions during the transition to sleep. However, some brain sites showed decreases in alpha and beta power and increases in theta power, and some did not. Brain sites closest to the midline (e.g. F4, C4, P4, O2) showed significant increases in theta and decreases in alpha power during the transition, but brain sites most lateral to the midline (e.g. Fp2, F8, T4) showed little change in power for these EEG bands. Several factors may account for these findings: 1) variations in skull thickness and resistivity (18), 2) choice of reference (e.g. monopolar linked mastoid references vs. either a Cz reference or other bipolar references) and 3) source-generator of the signal (e.g. it is accepted that the source of the alpha rhythm resides in the occipital lobe of the brain).

Although there exist topographical differences for increases in theta power during the transition, the focus of theta power remained relatively similar during the transition to sleep (i.e. high at central brain sites during both wakefulness and sleep). In addition, the number of brain sites showing magnitude differences in theta power changes very little with a change in wake–sleep state.

Alpha power is largest at posterior brain sites during both wakefulness and sleep. However, there is a marked attenuation of differences in alpha power across the brain with the transition to stage 1 sleep. This patterning changes once again with the transition to stage 2 sleep (i.e. the number of brain site comparisons showing a difference in alpha power increases with the onset of stage 2 sleep). In fact, the number of brain site comparisons showing a significant difference in alpha for the first minute of stage 2 sleep is similar to the number of significant comparisons seen during the first minute of wakefulness. Examination of the means and standard deviations suggests that this latter finding is most likely due to a decrease in the variance between brain sites during stage 2 sleep, making a smaller difference in power between brain sites significant. Two recent studies have also highlighted topographical differences in alpha power during the transition to sleep (19,20). They describe an anterior slow alpha activity of drowsiness that is "distinctly different from the alpha rhythm". The slow alpha activity in the more anterior portion of the cortex is thought to reflect a different source dipole generator—the thalamus—than the pareito-occipital alpha rhythm.

Unlike the theta and alpha bands, beta shows a change in the topographical focus of EEG power from wakefulness to stage 1 sleep [i.e. beta power is high across the midline of the brain during wakefulness (F4, C4, P4, O2) and high at the vertex (C4) during sleep]. The latter finding may, in part, be indicative of thalamocortical oscillations that occur during the onset of sleep (21). These oscillations are thought to be related to or reflect sleep spindle activity. The frequency of sleep spindles at the cortex ranges from 12 to 14 Hz. These frequencies overlap with the range for beta (12.5–25 Hz) used in the current study. Spindles are reported to occur subcortically (depth electrodes) a few minutes prior to being observed on the scalp (22), and the sigma band (12–14 Hz) is reported to increase 1.3 minutes prior to the onset of manually scored spindles (11). In addition, Hasan and Broughton (20) reported the topography of sleep spindles ("especially the first ones after sleep onset") to be largest at the vertex (i.e. Cz). Thus, it is possible that spindles, even though not present in the visible EEG record, were able to affect the EEG power spectrum in the present study, especially at the vertex, the focal point of spindle activity.

Results of the single Hz analysis showed that during the transition to sleep, changes in the theta and alpha bands are largest at 3 and 4 Hz (largest at the vertex) and 9 and 10 Hz (largest at the occiput), respectively. These results are consistent with previous findings (9,23,24) showing that changes in the theta and alpha bands during the transition are predominantly due to changes at a few select frequencies within the broad band range. These frequencies are also reported to best track rapid fluctuations between wake and sleep states (9,23,24).

Decreases in alpha and beta coherence between frontal and occipital brain sites were also observed during the transition to sleep. These results are consistent with prior research showing decreases in overall mean coherence from presleep waking to stage 4 sleep (25). The decreases in alpha and beta coherence between frontal and occipital brain sites may reflect a change in the functional connectivity between these brain areas during the transition to sleep.

Topographic differences in EEG frequency were not observed during the transition. All brain areas showed

similar decreases in mean, median and peak frequency. The slowing in EEG frequency complements the decreases in alpha and beta power and is consistent with the notion of decreased brain activation during the transition to sleep.

Hemispheric differences

There is some suggestion from behavioral data that hemispheric differences occur during the transition from wakefulness to sleep [i.e. a longer sleep onset latency for the left hand compared to the right in a finger tapping task (26)]. The use of brain mapping in the current study allowed for a detailed examination of this question. Significant differences between the hemispheres in terms of EEG coherence were observed for brain regions most lateral to the midline (T3 and T4, T5 and T6, F7 and F8). It should be noted that the decreases observed in alpha and beta interhemispheric coherence occur in the absence of interhemispheric differences in spectral power for the alpha and beta bands. Others have reported that changes in EEG coherence occur in the absence of changes in EEG power during waking (27).

What do these changes mean?

One researcher has suggested that the transition from wakefulness to sleep be thought of as a "sleep onset period" (28) and that the examination of changes in many measures (e.g. EEG, EOG, respiratory, behavioral responsivity, memory) will lead to a better understanding of the sequences and events occurring during the onset of sleep. The present results suggest that the examination of multiple brain regions is also important.

Recently, Ogilvie et al. suggested that the electrical activity of the brain rapidly synchronizes as sleep begins (29). The decrease in topographical differences for alpha power during the transition provides further support for this idea. However, other observations question the notion of "mass synchronization" across the brain. Specifically, 1) the number of topographical differences for theta does not change substantially from wakefulness to sleep, and 2) theta coherence within and between hemispheres does not significantly increase during the transition. If the brain were becoming more synchronized, one would expect to see a global decrease in the number of topographical differences for theta power and an increase in inter- and intrahemispheric coherence. It should be noted that the data showing synchronization across EEG frequencies come from a behavioral criterion of sleep (failure to respond) and not EEG criteria exclusively.

Limitations of the current study

It should be noted that we did not examine EEG frequencies ≤ 2 Hz due to concern of artifact from slow eye movements (15). Hasan and Broughton (20) described the presence of high-amplitude, mainly negative waves occurring in isolation with a frontopolar–frontal maximum during stage 1 B sleep. Increases in slow oscillations (<1 Hz) have also been reported to occur intermittently during delta sleep and sometimes with the occurrence of spindle activity (30). Results from these studies suggest that examination of frequencies <2 Hz may prove helpful in describing changes during the transition to sleep.

As noted, our beta band (12.5–35 Hz) overlaps with the frequency of sleep spindles (12–14 Hz). Future studies should avoid this overlap and examine spindle and beta frequencies separately. Another and possibly more fruitful alternative is to examine changes at individual EEG frequencies (9,23,24) and determine the frequency components responsible for changes observed in the broad EEG bands during the transition to sleep, as well as to, from and during different sleep states and during the transition from sleep to wakefulness.

Pinpointing sleep onset

The present results suggest that the disparity in pinpointing a precise moment of sleep onset in previous EEG studies is primarily due to 1) topographical and temporal differences among brain sites during the transition from wakefulness to sleep and 2) different findings depending upon the QEEG analysis used. Thus, depending upon the specific brain site examined, the moment of sleep onset may vary. In addition, the type of QEEG analysis used (e.g. spectral power or coherence) may determine whether the activity of a particular brain region changes from wakefulness to sleep.

Further research is needed to examine the relationship between topographical and temporal differences in the brain during the transition and during sleep with behavioral measures of sleep. Examination of these relationships will further our knowledge of brain functioning during waking and sleep states; such research will allow a better understanding of the links between brain and behavior.

REFERENCES

1. Davis H, Davis PA, Loomis AL, Harvey EN, Hobart G. Changes in human brain potentials during the onset of sleep. *Science* 1937;86:448–50.
2. Davis H, Davis PA, Loomis AL, Harvey EN, Hobart G. Human brain potentials during the onset of sleep. *J Neurophysiol* 1938; 1:24–38.

3. Loomis AL, Harvey EN, Hobart G. Cerebral states during sleep, as studied by human brain potentials. *J Exp Psychol* 1937;21: 127–44.
4. Dement W, Keitman N. Cyclic variations in EEG during sleep and their relation to eye movements, body motility, and dreaming. *Electroencephalogr Clin Neurophysiol* 1957;9:673–90.
5. Rechtschaffen A, Kales A. *A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects.* Los Angeles, CA: Brain Information Service, UCLA, 1968.
6. Santamaria J, Chiappa KH. The EEG of drowsiness in normal adults. *J Clin Neurophysiol* 1987;4:327–82.
7. Azekawa T, Sei H, Morita Y. Continuous alteration of EEG activity in human sleep onset. *Sleep Res* 1990;19:7.
8. Badia P, Wright KP Jr, Boecker MR. Changes in broad band and single hertz EEG activity during the transition from wakefulness to sleep. *Sleep Res* 1993;22:422.
9. Badia P, Wright KP Jr, Wauquier A. Fluctuations in single hertz EEG activity during the transition to sleep. In: Ogilvie RR, Harsh J, eds. *Sleep onset: normal and abnormal processes.* Washington DC: American Psychological Association, 1994: 201–18.
10. Hori T. Spatiotemporal changes of EEG activity during waking–sleeping transition period. *Int J Neurosci* 1985;27:101–14.
11. Hori, T, Hayashi M, Morikawa T. Topography and coherence analysis of the hypnagogic EEG. In: Horne J. ed. *Sleep '90: proceedings of the 10th European congress on sleep research.* Bochum, FRG: Pontenagel Press, 1990:10–2.
12. Merica H, Fortune RD, Gaillard JM. Hemispheric temporal organization during the onset of sleep in normal subjects. In: Terzano MG, Halasz PL, Declerck AC, eds. *Phasic events and dynamic organization of sleep.* New York: Raven Press, 1991: 73–83.
13. Osfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 1971;9:97–113.
14. Coburn KL, Moreno MA. Facts and artifacts in brain electrical activity mapping. *Brain Topogr* 1988;1:37–45.
15. John ER, Prichep LS, Easton P. Normative data banks and neurometrics: basic concepts, methods and results of norm constructions. In: Gevins AS, Remond A, eds. *Methods of analysis of brain electrical and magnetic signals: EEG handbook,* (revised series, vol. 1). New York: Elsevier Science Publishers, 1987: 449–95.
16. Keppel G. *Design and analysis: a researchers handbook, 2nd edition.* Englewood Cliffs, NJ: Prentice-Hall, 1982.
17. Ford MR, Goethe JW, Dekker DK. EEG coherence and power in the discrimination of psychiatric disorders and medication effects. *Biol Psychiatry* 1986;21:1175–88.
18. Law SK. Thickness and resistivity variations over the upper surface of the human skull. *Brain Topogr* 1993;6:99–109.
19. Broughton R, Hasan J, Dunham W. "Anterior slow alpha of drowsiness": topography, source dipole analysis. *Sleep Res* 1994; 23:5.
20. Hasan J, Broughton R. Quantitative topographic EEG mapping during drowsiness and sleep onset. In: Ogilvie RR, Harsh J, eds. *Sleep onset: normal and abnormal processes.* Washington, DC: American Psychological Association, 1994:219–35.
21. Steriade M. Basic mechanisms of sleep generation. *Neurology* 1992;42(Suppl 6):9–18.
22. O'Leary PM, Hauri P. Comparison of EEG sleep patterns between surface and depth electrodes in a human subject. *Sleep Res* 1984;13:22.
23. Wright KP Jr, Boecker MB, Badia P. Fluctuations in single hertz EEG activity during the transition from wakefulness to sleep. *Sleep Res* 1993;22:105.
24. Wright KP Jr, Badia P, Boecker M, Wauquier A, Harsh J. Changes in single Hz EEG activity during the transition from wakefulness to sleep. *Sleep Res* 1994;3:279.
25. Banquet JP. Inter- and intrahemispheric relationships of the EEG activity during sleep in man. *Electroencephalogr Clin Neurophysiol* 1983;55:51–9.
26. Casagrande M, Violani C, Braibanti P, De Gennro L, Bertini M. Performances in behavioral tasks reveal shifts in hemispheric asymmetries during the transition from wakefulness to sleep. *Sleep Res* 1992;1(Suppl 1):37.
27. Beaumont JG, Mayes AR, Rugg MD. Asymmetry in EEG alpha coherence and power: effects of task and sex. *Electroencephalogr Clin Neurophysiol* 1978;45:393–401.
28. Ogilvie RD. Behavioral and physiological investigations of sleep onset. Ph.D. dissertation. University of Cambridge, Cambridge, UK, 1985.
29. Ogilvie RD, Simons IA, Kuderian RH, MacDonald T, Rustenburg J. Behavioral, event-related potential, and EEG/FFT changes at sleep onset. *Psychophysiology* 1991;28:54–64.
30. Steriade M, Nunez A, Amzica F. Intracellular analysis of relations between the slow (<1 Hz) neocortical oscillation and other sleep rhythms of the electroencephalogram. *J Neurosci* 1993; 13:3266–83.