BRAIN POTENTIALS DURING SLEEP

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Electrical potentials of the human brain, led from the intact scalp, afford an objective measure of the activity of this organ which may be correlated with other physiological or psychological states. The striking change in neural function between wakefulness and sleep has already been examined with the electrical technique by several workers. Adrian and Yamagiwa (1935) as well as Loomis, Harvey and Hobart (1936) have found the 10/sec. rhythm of the resting wakeful state gone or rare in sleep; when it is replaced by random potentials, or more regular ones at 3–5/sec. (Gibbs, Davis and Lennox, 1935), or brief trains at 14/sec. (Loomis et al.) which wax and wane during a period of a second. The present experiments were likewise directed to a study of the depth of sleep, and to a lesser extent of hypnosis, with the aid of cerebral potentials.

METHODS.

1. Electrodes. Copper or silver disc electrodes 1 or 2 cm. in diameter were placed on occiput and forehead. Electrode jelly insured good contact, with the total input resistance regularly under 5000 ohms. Stray potentials from heart, respiratory and eye muscles, etc., were largely eliminated or were controlled.

2. Recording system. A four-stage, resistance capacity-coupled amplifier fed a loud speaker, a cathode ray oscillograph, and a crystograph (Offner and Gerard, 1936) or some pair of these. The amplifier reproduced $\frac{1}{2}$ microvolt well above the base line and sine waves at 1/sec. showed a reduction in amplitude of only 10 per cent. At times a variable low-pass filter was inserted in the output to attenuate the higher frequencies, chiefly above 100/sec. Records were taken continuously through the night or at desired intervals.

3. Measurement of sleep depth. Since the primary objective of this work was to establish a correlation between depth (or intensity) of sleep and electrical patterns, it was necessary to test the former independently. Sleep intensity is usually measured by the minimal intensity or duration of a stimulus necessary to elicit some predetermined response. Obviously sleep intensity might be modified by each test, so that valid depth curves could be obtained only when 1 or 2 tests were made a night and many data considered statistically. We have ordinarily used 3 or 4 stimuli in one night, which probably have not seriously altered the curve; but even con-
considerable disturbance would not be important since the significant relation is between actual sleep level and potential pattern at the time the test is made. Actually the curve of sleep intensity through the night is in good general agreement with that which Monninghof (1883) and Czerny (1891) obtained under more rigorous conditions and with more extensive material. Further, such other indications of sleep depth as the presence and amount of spontaneous movement, type of breathing, and impressions of the observer agreed with the test stimuli. Finally, since a definite correlation between potential patterns and sleep level did emerge, there is still further assurance that sleep level values were correctly assigned.

The actual procedure, with the subject comfortably in bed, was to ask just audibly, "Are you awake?" The question was repeated at intervals when respiration, movement, response to noise, etc., indicated some change in sleep level. That the question of itself had little influence on the course of sleep is shown by its failure to awaken subjects even in a light stage or to modify the other criteria; and the voice was not above background noise level (a sound-proof room was not used).

As a quantitative test, when some one type of potential wave was clearly present, a note of constant intensity at 1000 cycles a second (on the flat sensitive portion of the auditory acuity curve), obtained from a tuning-fork oscillator amplified into a loud speaker, was sounded. "Are you awake" was repeated at intervals until the subject responded, or until one minute, when the oscillator was stopped. (Auditory adaptation interferes too greatly for longer durations.) Response to a query, rather than some spontaneous signal, was used to indicate awakening since less complete wakefulness is required to obtain it; and often the subject reported in the morning an unbroken night's sleep. It regularly appeared that a second or two before movement no answer to the query was forthcoming while a second or two later the subject replied. As a routine, therefore, the question was asked at 10 second intervals and immediately following the first movement.

The two indices of awakening, visible spontaneous movement and reply to a question, showed consistent agreement with one another. Exceptions occurred in cases of very light sleep, when the response was obtained within 3 or 4 seconds of starting the stimulus without visible movement, and in a very few cases of deep sleep when movement occurred without response. Muscle tone, as measured by potentials led from the gastrocnemius, parallels sleep. During quiet rest volleys appear at brief intervals, which become longer with advancing sleep, until a silent period is reached in deepest slumber. Simultaneous recording of muscle and brain potentials suggests that the fast waves (30/sec.) are closely related to movement and tone—recalling the finding of Jasper and Andrews (1936) that they are centered on the Rolandic region.
Eight men and eleven women in the 20–30 age group served as normal subjects. Twenty-two all-night records were obtained from seven individuals; eight were studied during shorter periods of day-time sleep, and five after voluntary insomnia lasting 36 to 60 hours.

Results. 1. Normal sleep. Despite marked individual differences in depth of sleep through the night, the gross picture is reasonably constant. In the first hour or two, sleep is very deep: a full minute of test stimulus elicits no response, the subject is relaxed, breathing is deep and regular, and visible movements occur about once an hour. Following this, sleep becomes lighter and progressively shorter stimuli, down to 5 seconds, cause awakening. By the fourth hour the stimulus is effective in about two seconds, and even without it the subject is restless and moves approximately once in 10 minutes. In the fifth hour sleep sometimes becomes deeper again, the test sound may fail to awaken in 60 seconds, and then recedes until spontaneous awakening in the morning.

This description of sleep depth is only grossly correct since there are swings of considerable magnitude within each period. Our observations are consistent with, but not complete enough to be a confirmation of, the finding (Mullin and Kleitman, unpublished) that a periodic oscillation continues throughout the night, with successive periods showing first higher and then progressively lower maxima but with a final increase in the early morning hours. Further, characteristic sleep patterns, both as to depth and associated potentials, tend to recur in individual persons.

Corresponding to the different sleep levels, not only in time of night but, more convincingly, from moment to moment in the individual case, are distinctive brain potentials. These can be briefly described in terms of the magnitude and regularity of waves at about 30/sec., at 10/sec., and $\frac{1}{2}$ to 3 a sec. and the extent to which one or another dominates the picture.

During wakefulness, the 10/sec. rhythm is present to the extent characteristic of the individual, accompanied by smaller potentials at 20–30/sec. With the onset of sleep both frequencies decrease in amplitude and regularity. As slumber deepens the 10/sec. waves gradually pile up, sometimes with an intermediate stage of improved regularity, and merge to give still slower oscillations; until in deep sleep there remain only regular smooth waves lasting from $\frac{1}{2}$ to 3 seconds. During the genesis, and again later with the decomposition, of these smooth slow waves all transitional stages between them and the 10/sec. rhythm can be observed (fig. 1). When sleep again becomes lighter, during the middle portion of the night, the slow waves melt away and the 10 and 30 a second rhythms reappear fitfully, usually as accompaniments of movements or following a slight sound or other stimulus. In the last third of the night the sequence is sometimes repeated, the slow waves first increasing and dominating the picture and then fading out towards morning, leaving very feeble and irregular potentials like those present in the middle portion.
During deep sleep the test stimulus, which fails to arouse the subject, still modifies the potentials. The slow waves are commonly accentuated and regularized during the first few seconds of stimulation, partially decompose into the 10/sec. rhythm after fifteen, and usually after a minute revert to the original profile (fig. 2). If the stimulus does cause awakening, the 10/sec. waves appear and persist for from 1 or 2 minutes to half an hour. Awakening in response to a stimulus is ordinarily abrupt and accompanied by a similarly sharp appearance of the 10/sec. waves. Spon-

![Fig. 1. Crystograph record, medium speed. 1. Awake, 10/sec. waves marked. Modulation strong. 2. Moderate sleep, 10/sec. waves as notches on 1/sec. ones. 3. Deep sleep, 1/sec. waves strong (4+).](image1)

![Fig. 2. Crystograph, slow speed. Effect of extraneous noise. Early night, subject falling more deeply asleep. Between stars an aeroplane rapidly approached and receded. Continuous record. Note temporary return of good 10/sec. waves.](image2)

taneous waking is more gradual and the sequence is: appearance of slow potentials, first moderately and then quite regular; movement; response to the test question; and, finally, disruption of the slow waves with the appearance of faster ones. In a significant number of cases, however, clear consciousness reappeared before the fast rhythms; and with a subject remaining quiet after waking the rhythm may be absent for five or more minutes—until a voluntary movement or some outside stimulus initiates it.

An analysis of one experiment is presented in table 1, and figure 3 reproduces electrical records corresponding to the categories of the table.
Sample records from another subject are presented in figure 4, and in figure 5 the data for 10 nights are averaged and diagrammed. The correlation between deep sleep and slow regular waves is striking, even through the minor oscillations early in the night, for both appear and disappear together (fig. 6). Hardly less regular is the appearance of the 10/sec. or faster rhythms immediately following a movement or a disturbing stimulus and their practical absence at all other times. Occasional exceptions occur, however, especially in that feeble irregular potentials may be present and yet the test sound evoke no response in 60 seconds. The later subjec-

### TABLE 1

<table>
<thead>
<tr>
<th>HOUR A.M.</th>
<th>BEFORE STIMULUS</th>
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- denotes complete absence of phenomenon.
+ denotes occasional waves. For other phenomena it denotes presence.
++ denotes poorly repeated wave trains which are not marked, regular or maintained.
++++ denotes good regular continued wave trains.
"Notches" denotes 10/sec. waves appearing as notches superimposed on 1/sec. waves.
"Spont. change" denotes spontaneous change in potentials observed.
Fig. 3. 1. Awake, 10/sec. waves good. 2. Light sleep, 1/sec. waves at intervals (2+). 3. Deep sleep, 1/sec. waves strong (4+). 4. Moderate sleep, 10/sec. waves as notches on 1/sec. ones.

Fig. 4. 1. 12:00 m. Awake 10/sec. and 30/sec. waves. 2. 12:30 a.m. Drowsing; No. 30/sec., feeble 10/sec., suggestion of 1/sec. 3. 1:10. Deeply asleep 1/sec. waves marked; at 1:11 awakening by hummer. 4. 1:13. Falling asleep; 10/sec. waves dominant. 5. 1:25. Fairly deeply asleep; 1/sec. waves good. 6. 1:26. From sleep to wake—sound stimulus on during length of record. No response to questions at star. Awake and moves at end. 7. 1:26$. Drowsy 30/sec. waves marked, actual small movement at star. 8. 1:30. Fair sleep; 10/sec. waves present; good spindle occurs. 9. 1:40. Deep sleep; 1/sec. waves present, good spindle occurs. 10. 2:00. Fair sleep. No response to question at star but wave follows. Irregular 10/sec. 11. 2:30. Fairly deep sleep 10/sec. waves passing into good 1/sec. ones.
five reports then indicate greater wakefulness than had been shown by the objective tests.

**Fig. 5.** Depth of sleep x-x-x, and prominence of slow waves o-o-o for first 6 hours of sleep. Average curves for 10 nights on five subjects. Sleep depth ordinates, duration of sound to awaken. Slow wave ordinates obtained by assigning 0 to 4+ (see table 1) for each five minute period and averaging for the hour. Arbitrarily plotted to same maximum as sleep depth curve. Abscissa, time in hours.

**Fig. 6.** Records of three single nights. Time in hours. Upper graph: Sleep depth, the height of the line indicates duration of stimulus required to elicit a response. Dotted lines estimated from movement, etc. Middle graph: Blocks represent 1/sec. waves. Cross-hatching indicates poor waves (1 or 2+). Lower graph: Blocks represent 10/sec. waves; cross-hatching indicates poor waves. Movements as vertical dashes between 1/sec. and 10/sec. blocks.

2. *Modified sleep.* In unconditioned subjects, daytime napping is ordinarily much lighter than the conditioned night sleep. Increase and decrease in intensity are more gradual and in very few cases was sleep deep enough for the slow potentials to appear. One seeming difference from
night sleep is in the 10/sec. rhythm which is often present and even exaggerated at sleep levels which, during the night, are associated with the absence of all regular rhythms.

In sharp contrast to napping are the results following prolonged voluntary insomnia, in 3 cases lasting 60 hours. A subject in this condition, sitting quietly awake at any time of the day or night, shows the characteristic waking potentials. Simply relaxing precipitates him into a sleep of maximal intensity. The brain potentials similarly show a prompt change to very large, regular and slow waves; and forcible awakening restores the

Fig. 7. Cathode ray record. Subject after 60 hours' insomnia. 1. Awake. 2. Forty seconds later, deeply asleep.

original potential pattern. It is, in fact, possible to pass from 10/sec. to 1/sec. and back to 10/sec. waves within a minute by allowing the subject to sink into sleep and reawakening him (fig. 7). Further, when the subject is allowed to sleep undisturbed, after an insomnia period, the regular slow waves last 3–4 hours instead of their usual 2.1

3. Hypnosis. One subject was repeatedly brought into a deep cataleptic stage of hypnosis although never fully into the somnambulistic one. In this young man a good 10/sec. rhythm was normally present and persisted,

1 Kleitman has recently found benzdrene administration to counteract the effects of prolonged insomnia. We find, similarly, that it diminishes the potential pattern of deep sleep which appears after an insomnia period.
sometimes with diminished amplitude, throughout the hypnotic period. A 14/sec. rhythm was observed but the very slow waves of sleep were never definitely indicated. It proved possible, as reported also by Loomis, Harvey and Hobart (1935), to abolish the 10/sec. rhythm by suggesting a light shining in the eyes although actually none was present. The reverse experiment was not successful at this level of hypnosis, for actually shining the light while suggesting darkness in all cases abolished the rhythm. The same results were obtained whether the eyes were open or shut. Other suggested stimuli were without influence on the brain potentials, except that often with each assertion, "You are falling deeper asleep" the 10/sec. rhythm became more distinct.

Discussion. The primary conclusion permitted by these findings is that a definite parallelism exists between the type of brain potentials present and the stage of sleep or wakefulness. This is usually (but not always) so exact that from the appearance of the potential record it is possible to predict the amount of stimulus which will be required to awaken the sleeper.

Qualitatively, these potential patterns are closer to the findings reported by Gibbs, Davis and Lennox (1935) than those of Berger (1935), Adrian and Yamagiwa (1935) or Loomis, Harvey and Hobart (1936). The three latter groups of observers have emphasized the diminution of the 10/sec. rhythm without remarking the large, slow rhythm which replaces it. Even in the work of Gibbs et al. frequencies of 3-5/sec. have been emphasized rather than the $\frac{1}{2}$-3/sec. rhythm which we have found in deep sleep. Such waves are seen, however, in some of their records. Possibly in following subjects through the entire night we have dealt with deeper sleep than did earlier experimenters; or the slow waves may have been outside the amplifier range of some and so lost.

Although the slowest rhythm seems to be determined mainly by sleep depth, it is our impression that the 10/sec. and faster rates depend on at least two other factors in addition to actual sleep intensity. For one thing, when the subject reaches a certain level in the course of increasing sleep depth, these waves are often prominent, whereas when this same level is attained in passing from deep sleep towards wakefulness they may be nearly or entirely absent. The immediate past is therefore significant, presumably by virtue of the pre-existing excitation level. The second factor is related to muscle tone and movement, for the faster rhythms commonly appear in association with muscle contractions.

We can consider the 10/sec. rhythm as an index of the activity of brain cells relatively undisturbed by current transient stimulation yet, as the result of previous excitation, continuing their rhythmic activity. As their thresholds rise with continued absence of impinging impulses, that is,
as the facilitation produced by previous ones wears off and excitatory state decreases, the regular 10/sec. beat of the cerebral neurones gradually disappears. Inflow of new impulses, if not too intense, reéstablishes this rhythm; still stronger stimulation again disrupts it. On this view, the absence of the 10/sec. rhythm in or following deep sleep is due to failure of the electrical beat of the individual cells while its absence in ordinary wakefulness, with open eyes, body movements and directed attention, is due to asynchrony of the many beating cells. This interpretation and the evidence from many directions that favors it have been discussed at length elsewhere and need not be repeated (Gerard, 1936; Adrian, 1936; Bremer, 1936).

It remains to account for the striking slow rhythm of deep sleep. The change from a regular rhythm at 10/sec. to one at 1/sec. can hardly be due to an improved synchrony, for the regularity in rate and amplitude of the faster rhythm is evidence that excellent unison is already present at this frequency. Either some cells with a faster natural frequency of beat become inactive in sleep while slower ones become active, or the same cells markedly slow their beat. There is no basis for the more complex assumption involved in the first alternative while the second is quite in harmony with the interpretation already advanced for the 10/sec. rhythm. In this case, too, weak stimulation facilitates the rhythm whereas strong stimuli abolish it.

Let us assume that individual neurones beat at a rate of 10/sec. when their level of excitation is above some critical value but fall to a slower rhythm when the excitation level is lower. This seems highly probable since stronger excitation does give higher frequencies for natural stimulation of receptors (Adrian, 1932) or motor cells (Adrian and Bronk, 1929), or for electrical stimulation of muscle or nerve (Fessard, 1936; Katz, 1936; Erlanger and Blair, 1936; Gasser and Grundfest, 1936). The limits are complete inactivity, on the one hand, and, on the other, a frequency set by some recovery process in the cell (related to, but not necessarily the same as, the refractory period for repeated discharge of impulses). What is less clear is whether the change of frequency is continuous or by steps. The latter case is exemplified, for example, in the fall of nerve responses from one to each stimulus, to one to two or three or more, as the frequency of stimulation steadily increases (Derbyshire and Davis, 1935) or as the nerve progressively equilibrates to fixed stimuli (Gerard and Forbes, 1928). The present results are suggestive of a similar situation. The 10/sec. rhythm does not become progressively slower but rather continues as smaller and smaller ripples on an increasing slow wave, until indistinguishable; as would occur if one cell after another dropped abruptly from the fast to the slow rate. We cannot, however, insist on this interpretation
since, in long complex records, almost any potential profile can be found. In fact even the slow waves show frequencies ranging from 3 to \( \frac{1}{2} \) a second or less and it is not established that the shifts occur by steps.

It remains to consider the period of feeble irregular potentials that intervenes between the disappearance of the regular slow waves of deep sleep and the reappearance of the regular faster ones on waking or movement. Again, by analogy with the better studied 10/sec. rhythm, this may be regarded as a stage in which the cells are still beating at the slow rate but have become asynchronous under a mild excitation not sufficient to start a faster beat. The alternate view is not excluded, however,—that even the slow beat has petered out: which implies that following deep sleep the brain cells may be relatively free from stimulation yet highly irritable. This could occur if afferent connections become inactive during sleep, permitting the activity of cortical neurones to run down—as is indicated by the absence of discharges, while the rest period permits greater irritability to build up; then even feeble stimuli could reinitiate activity of the cells and also wake up the sleeper. In any event, afferent stimulation at this time commonly does first improve the slow rhythm and then disrupts it in favor of the 10/sec. one.

The findings during hypnosis throw additional light on the problem of the control of neurones by impinging nerve impulses. Since the suggestion of light, via auditory channels, can disrupt the regular beat of cells in the visual cortex it is not essential that the nerve impulses reach these cells along direct optic paths. Presumably indirect connections from the frontal lobes, under conditions of "visual attention," can exert the same control over the occipital neurones as can the fibers of cells in the geniculate body.

**SUMMARY**

Brain potentials of young adults were studied during normal night sleep, afternoon napping, post-insomnia sleep and, in one case, hypnosis.

Depth of sleep was independently determined by the duration of a fixed sound required to awaken the subject (response to a question), by movement, respiration, etc.; and an orthodox sleep-depth curve for the night so obtained.

Potential patterns correlate with sleep depth not only over long time changes but, in most cases, rather accurately over short time swings.

Deep sleep is regularly associated with a large regular potential wave at a frequency of \( \frac{1}{2} \) to 3 a second; lighter sleep with feeble irregular potentials or with the 10 a second rhythm. Further details on transition potentials from light to deeper sleep and especially during spontaneous or stimulated awakening are described.

The results are interpreted in terms of excitation levels of cerebral
neurones and of the play of nerve impulses upon them. With low excitation a slow rhythm is manifest, with stronger excitation a faster one, and in transition between these states asynchrony prevents the manifestation of any regular beat.

We are indebted to Dr. N. Kleitman for constructive criticism of this work.

REFERENCES

J. Physiol. 57: 83, 1936.
Erlanger, J. AND E. A. Blair. This Journal 114: 328, 1936.
ERLANGER, J. AND E. A. BLAIR. This Journal 114: 328, 1936.
GASSER, H. S. AND H. GRUNDFEST. This Journal 117: 115, 1936.
KATZ, B. J. Physiol. 88: 230, 1936.