FOURIER TRANSFORMS OF THE ELECTROENCEPHALOGRAM DURING SLEEP[1]

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Previous analyses of the EEG during sleep (1, 2, 4, 6, 7, 8) have relied upon categorical descriptions of the record in terms of predominant types of electrical activity. Categorical descriptions of any phenomena mask the dimensionality of the data to which they are applied and may thus be somewhat incomplete, if not misleading. In the case of the EEG, categorizing masks the fact that the record is composed of a continuous series of frequencies and amplitudes. The current nomenclature applied to the EEG during sleep suggests that energy is released at certain modes of the frequency continuum rather than at others, while a system of analyses based on the assumption of continuous dimensions demonstrates that this is not literally true, but that more energy is released at certain points than at others.

The present investigation has attempted to analyze the EEG during sleep in terms of a bidimensional system—energy *vs.* frequency. In this manner a more accurate and complete picture of cortical activity under the condition studied is made available.

Apparatus and Procedure

The apparatus consisted of high-gain, low-frequency amplifiers which drove an electrodynamic oscillograph element recording on moving film to give a variable area shadowgraph. This record was then analyzed by means of the Grass low-frequency wave-analyzer (3). The resultant record was a plot of energy *vs.* frequency.

Records were made under two plans of experimental attack. In the first series, six subjects were studied during all-night sleep, the EEG's being recorded continuously on a multi-element ink-writing oscillograph. At irregular intervals 30–45 sec. runs of the film camera were made to record for analyses particularly clear exhibitions of the traditional categories of electrical activity during sleep (low voltage, spindles, spindles plus random). Monopolar leads from the left motor area were used. (This series was obtained by J.R.K. and C.E.H.)

In the second series, one subject was recorded during alternate 30-sec. intervals from retiring to awakening, all records being made on the camera. A monopolar left occipital lead was used. The subsequently obtained energy-frequency transforms were then photographed on moving

[1] This research was a joint project conducted at Boston City Hospital and at the University of Iowa. All records in *Part A* were secured in the laboratory of physiological psychology at the University of Iowa; all records in *Part B* were secured at Boston City Hospital. All analyses were made at Boston City Hospital.

picture film in consecutive order, in a manner analogous to that followed in the making of animated sketches. When viewed by projection, this analysis provided a three-dimensional picture of electrocortical phenomena during sleep: energy *vs.* frequency *vs.* time. This last method is dynamic, the former, static. (This analysis was devised and conducted by F.A.G.)

Results

A. Static Analysis.—The data secured in this section of the investigation indicate that the traditional classification of sleep rhythms of the EEG does not take into account all of the phenomena exhibited. Figs. 1, 2, 3, 4, 5, and 6 show the relative (percent) energy *vs.* frequency during the categorical activities of 'low voltage,' 'spindles' and 'spindles plus random' in each of the six subjects. It will be observed that a classification into any given type for all of the subjects, which would imply an identity of electrocortical activity, is not associated with identical energy *vs.* frequency characteristics. Within a given subject, it was also found that the same categorical type of activity did not serve as an index of identity of these characteristics.

It appears that the major differentiation of states of sleep and waking is characterized, in terms of the EEG, by differences in the distribution of energy in various portions of the frequency continuum. While waking states are associated with release of relatively little energy in the bands below three cycles, sleep is associated with relatively great energy in this area. To a lesser extent, while waking states are associated with release of relatively little energy in the 13–15 cycle bands, sleep is associated with release of relatively greater energy in this area. To a still lesser extent, while waking states are associated with relatively great energy in the 8–12 cycle bands, sleep is associated with relatively less energy in this area.

Fig. 7 indicates the extent to which these statements were found to be true. In these data, the percent energy between one and three cycles, between eight and twelve cycles, and between thirteen and sixteen cycles have been computed from the energy-frequency spectra of four subjects upon whom satisfactory pre-sleep records were available. These values have been plotted against the categorical type of record as determined by evaluation of the concomitantly recorded ink-writer records.

It will be seen that in all of these cases there was at one time or another more energy in the 1–3 cycle band (in categorical terms, 'random') during sleep than during waking. In three of these four cases this was true throughout practically all of the samples obtained.

The increment in the 13–16 cycle band is clear in three out of these four cases, while the other exhibits a decrement in energy in this band, even though, categorically, there were clear exhibitions of 'spindles.'

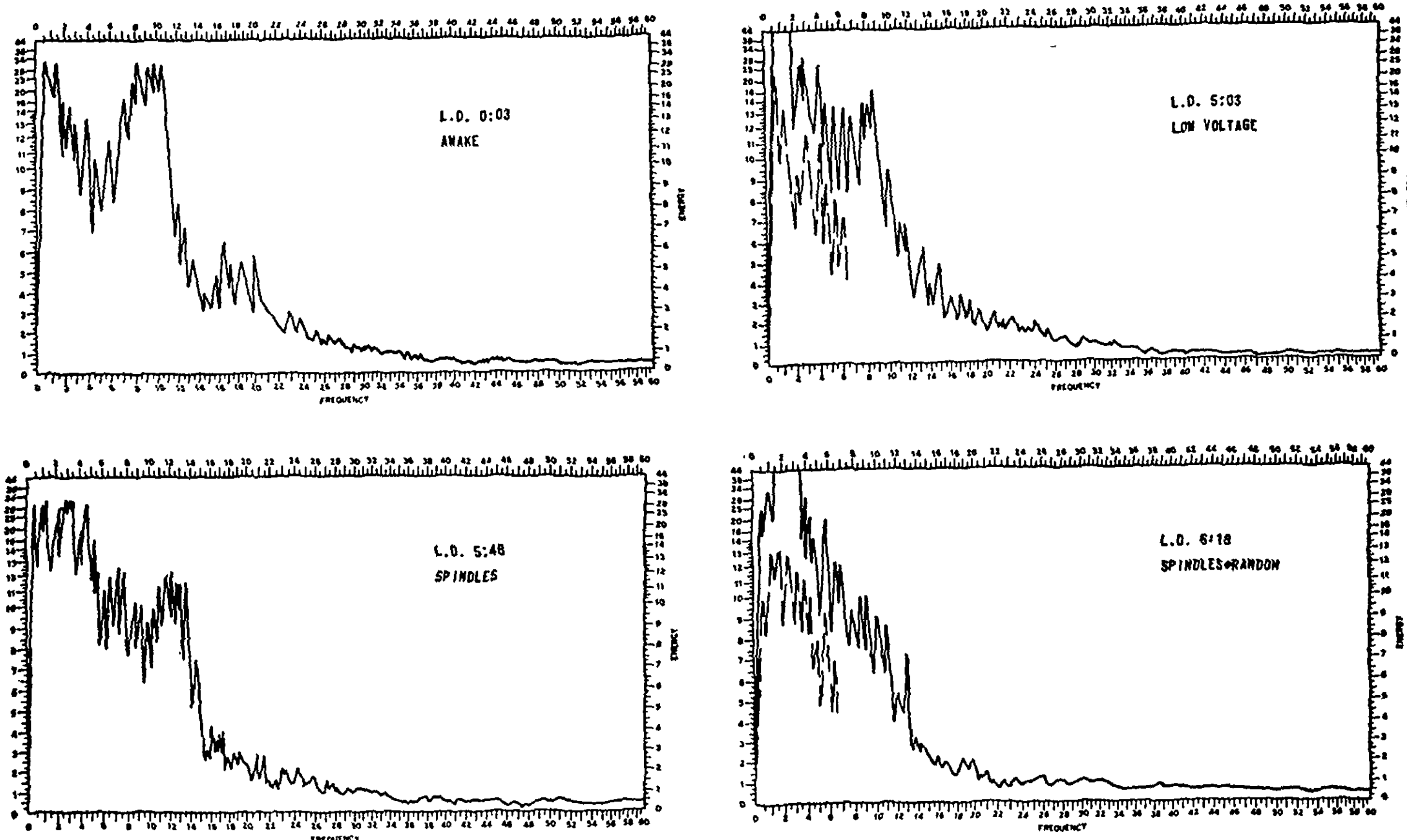

Fig. 1. Energy-frequency transforms of the electroencephalogram during waking and three 'stages' of sleep: 'Low voltage,' 'spindles,' 'spindles plus random.' The dashed line represents one-half the energy signified by the solid line.

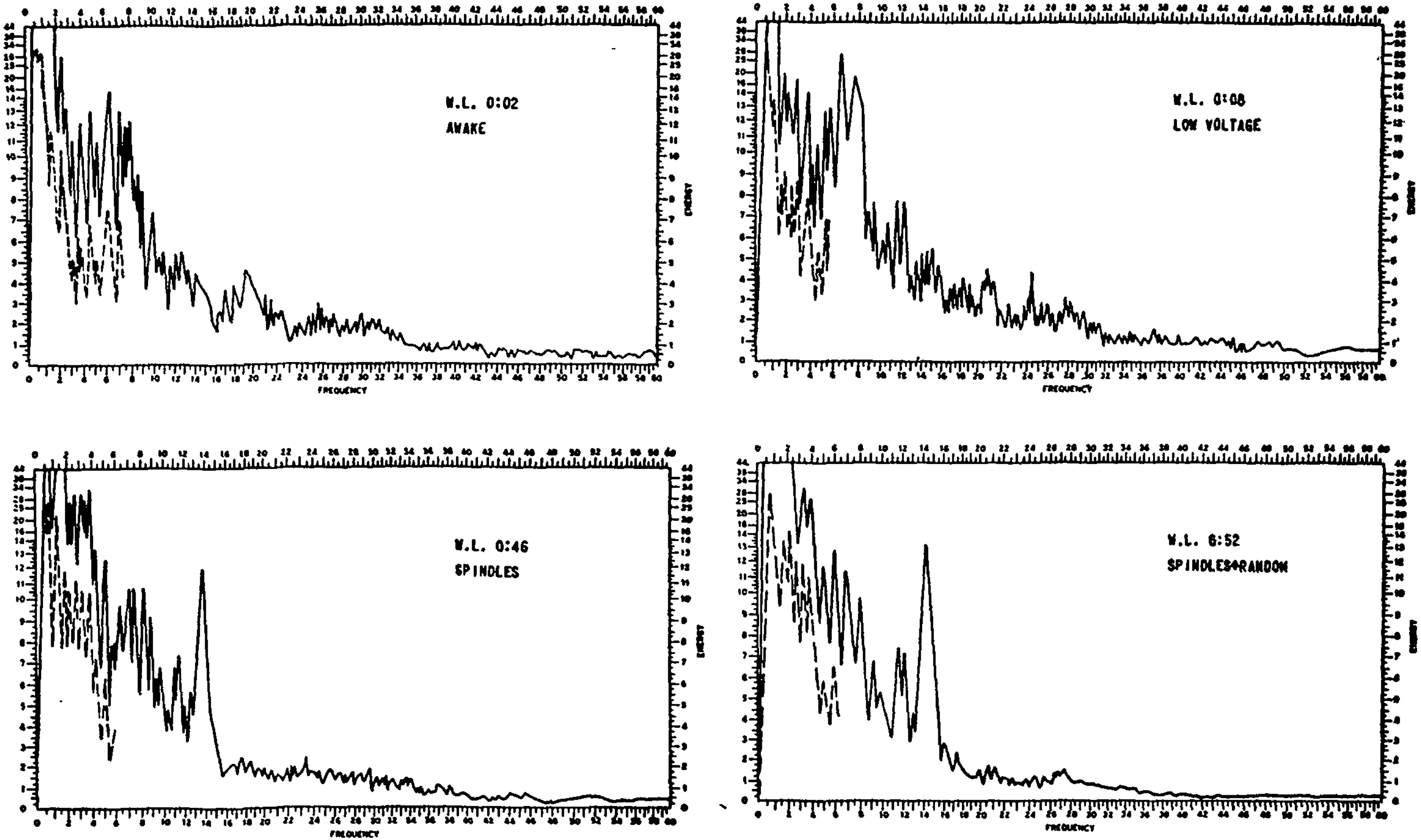

FIG. 2. For description see Fig. 1.

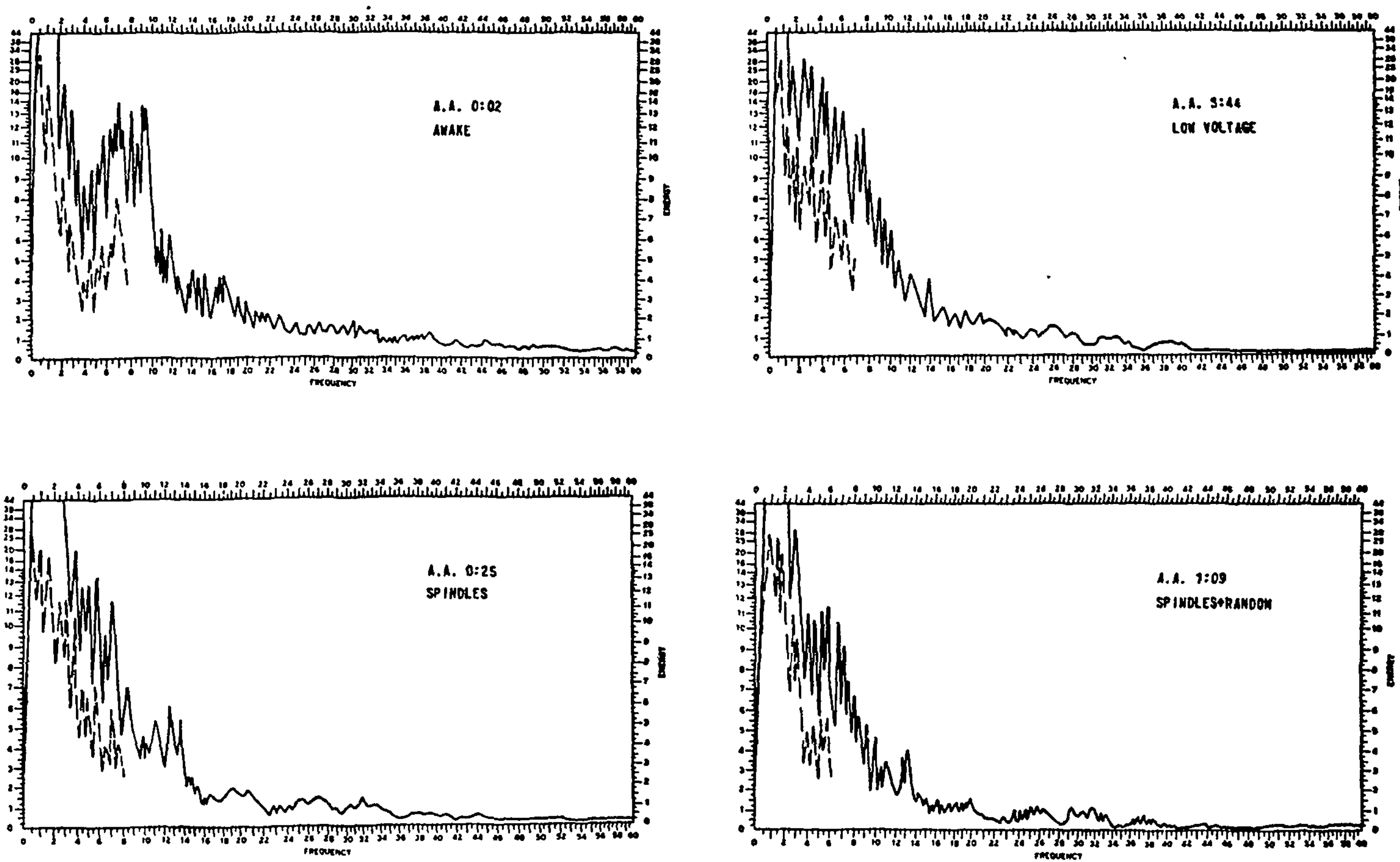

FIG. 3. For description see Fig. 1.

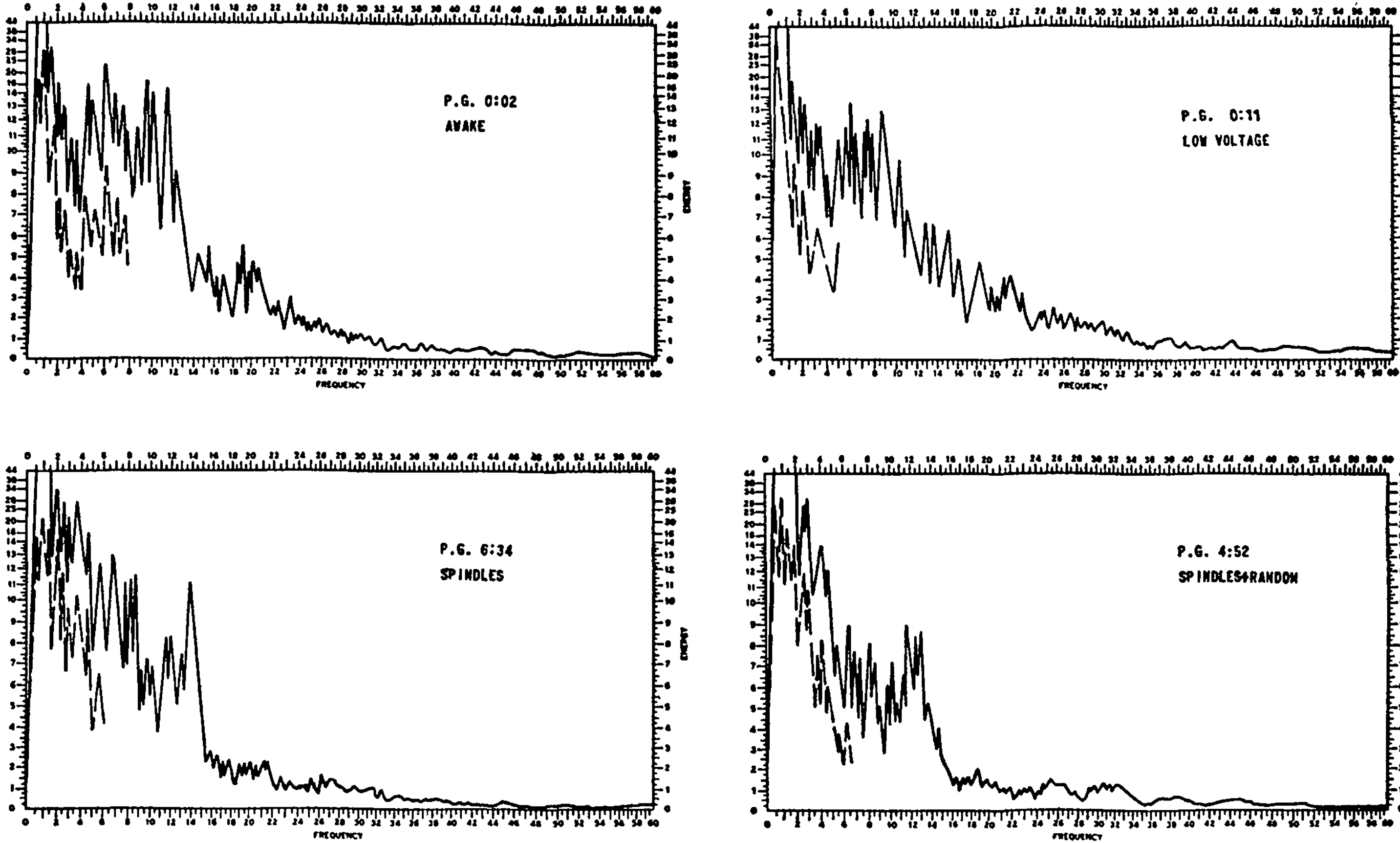

FIG. 4. For description see Fig. 1.

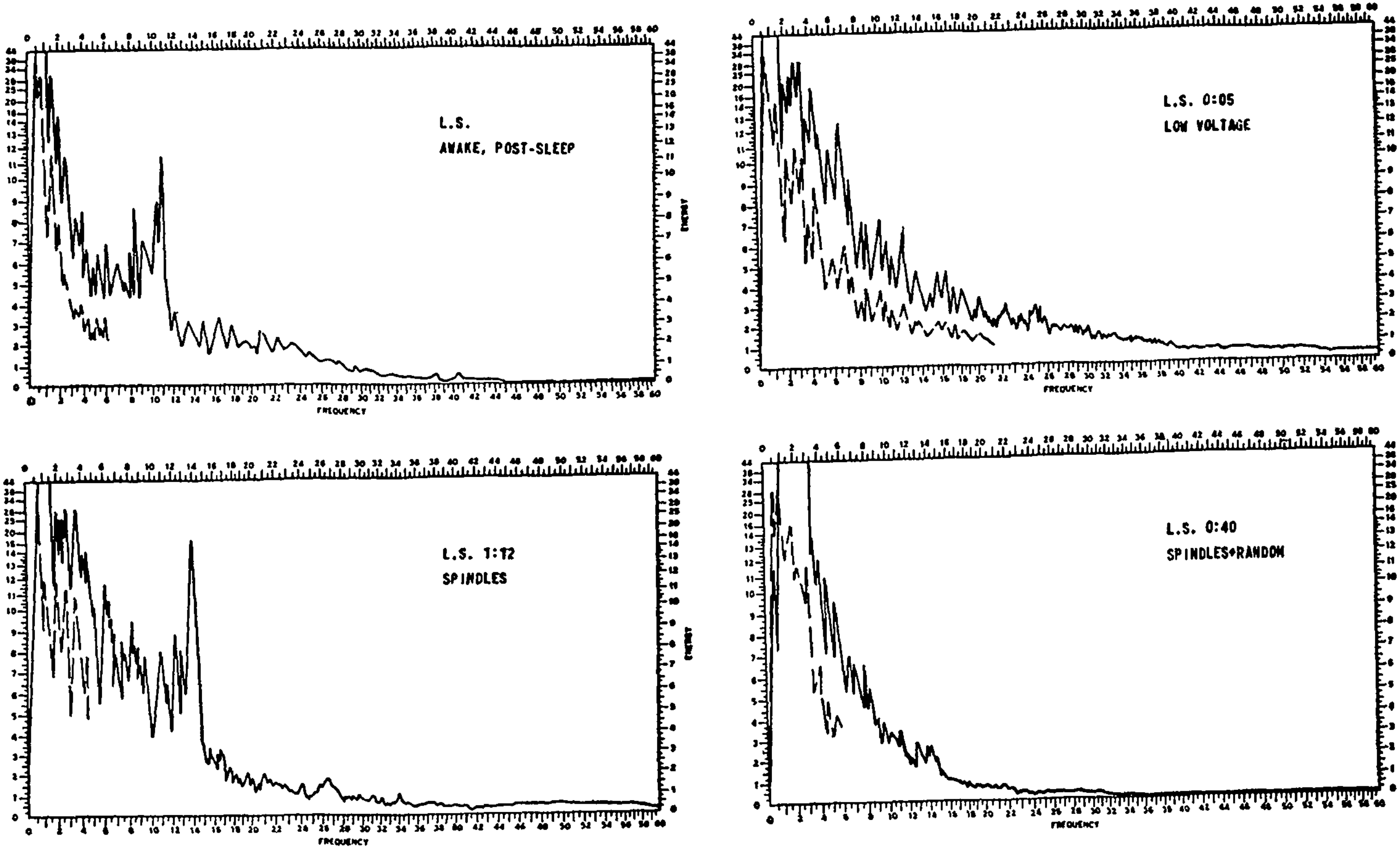

FIG. 5. For description see Fig. 1.

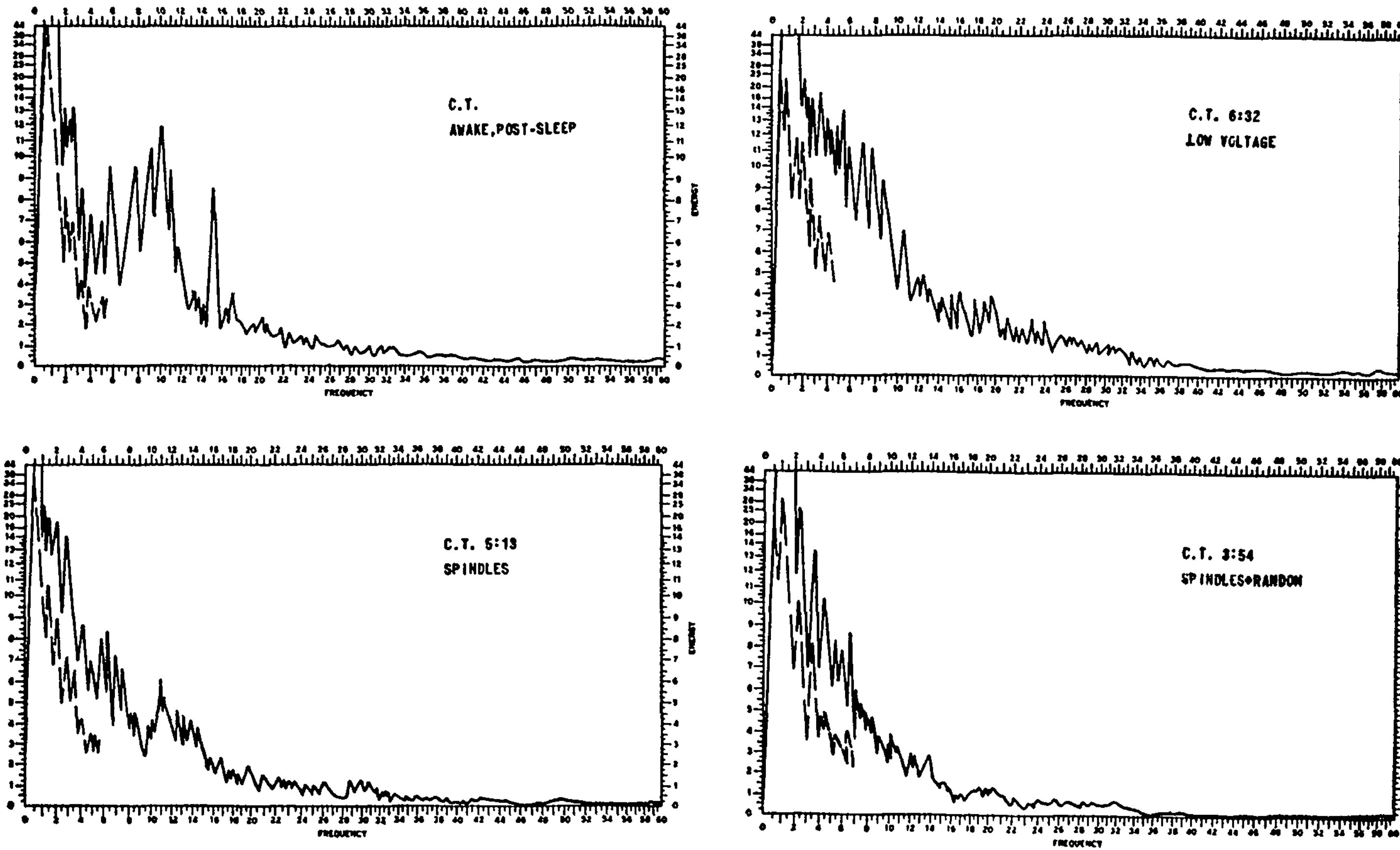

Fig. 6. For description see Fig. 1.

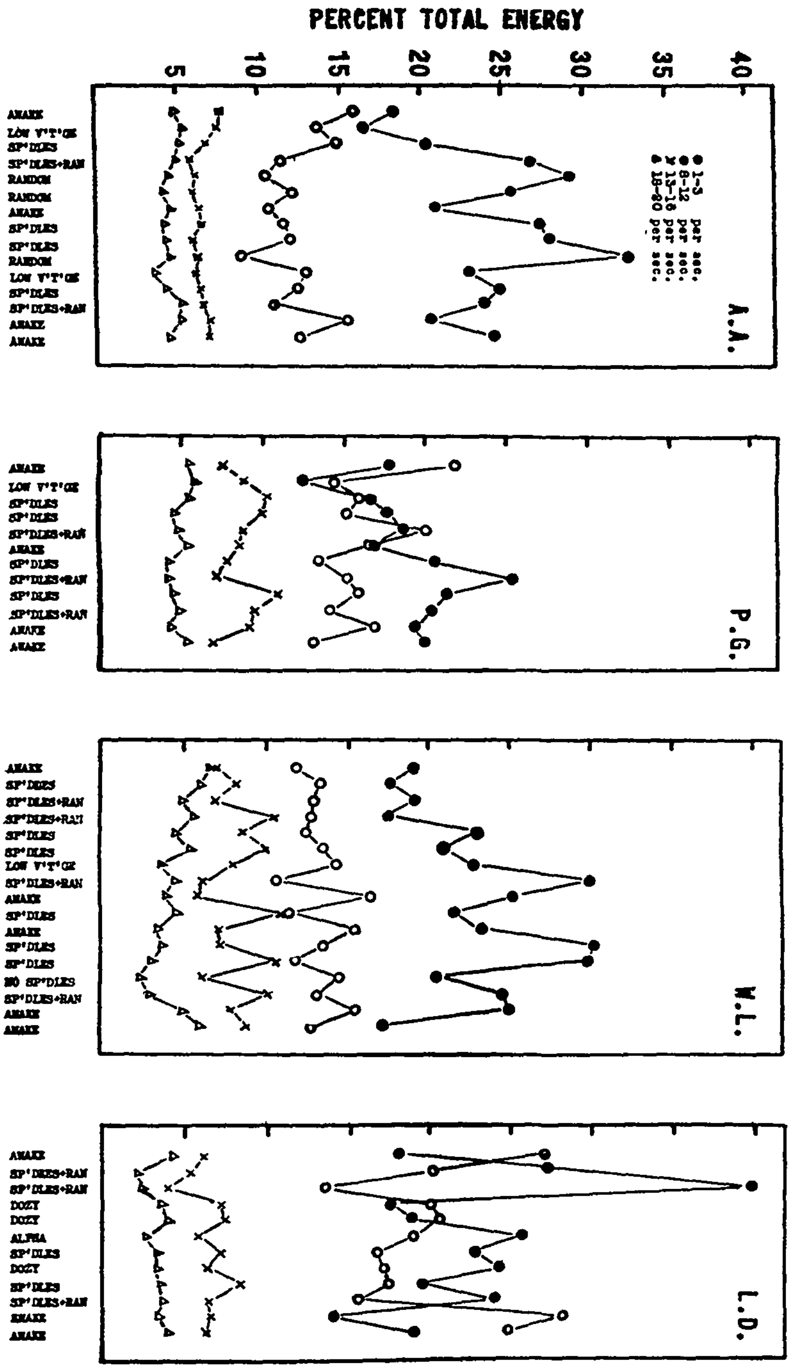

FIG. 7. Percent total energy in each of four bands (1–3; 8–12; 13–16; 18–20) during each recorded sample of EEG for the four subjects of Figs. 1, 2, 3, and 4. Each sample was categorically defined in terms of the ink-writer record. Inter-relationships among the bands are discussed in the text.

The 8–12 cycle bands exhibited less energy in sleep than during waking in three out of the four cases. This decrement was, in the cases in which it was exhibited, exceptionally clear.

The relationships between the percent energy released in these various bands can be determined from these data. It will be seen that, *in general*, as the energy increases in the 1–3 cycle bands, it decreases in the 8–12 cycle bands. *In general*, as the energy increases in the 13–16 cycle bands, it decreases in the 8–12 cycle bands. These generalizations do not hold for all cases, and there seems to be some variation within single cases.

In cases A.A., W.L. and L.D., the 8–12 : 1–3 relationship is essentially linear; in case P.G., it tends to be so; the other cases show little systematic variation. The 8–12 : 13–16 relationship is much less linear than the 8–12 : 1–3, although case W.L. tends to exhibit such a trend. The other cases are much more variable. It would appear fruitful to discover the factors responsible for this variability, since during some parts of the night the linearity and the trends are more apparent than at others.

B. Dynamic Analysis.—Certain general features of the EEG during sleep, as discovered by three-dimensional analysis, may be stated. Since this method includes the dimension of time, it contributes much to the study of variability of the relationships between the various bands. While there is a mutual verification by the static and dynamic analyses, the latter makes possible additional conclusions regarding the course of electrocortical events in sleep.

The high energy usually appearing in the 10 cycle band during waking initially oscillates along the frequency continuum during the early stages of drowsiness. The limits of this oscillation were observed to be between 11 and slightly less than 10 cycles. While the energy at 11 became less, the energy at the 9.5 point greatly increased in magnitude, the 11 cycle peak finally disappearing. In the meanwhile, the energy at one cycle greatly increased, while a mode of energy at 19 cycles became less. Soon after the disappearance of the 19 cycle peak, a new peak appeared at 17 cycles, with subsequent shift along the continuum between 17 and 18, then 18 and 16, and a final apparent stabilization at 15 cycles, at which point the energy increased greatly. The energy peak formerly falling at 9–9.5 now had become reduced in energy, apparently joining the 1–3 cycle bands.

This process was neither strictly progressive nor irreversible. Several times, before the 9–10 cycle peak disappeared, and before the disappearance of the 15–19 cycle peak, the process reversed as the subject roused slightly, as with a cough. Since the bodily disturbance usually preceded the shift in the energy *vs.* frequency distribution toward faster bands, it is reasonable to suppose that in these instances stimulation from the viscera and lower centers caused the shift in electrocortical pattern.

After a period of from two to three hours of sleep, the total (absolute) energy in the spectrum decreased, with no pronounced energy peaks in any of the bands above three cycles. Small energy peaks were observed to be transient in the 12–14 cycle band. It will be recalled that the energy originally exhibited as a peak at 19 cycles moved to slower frequencies, having been last observed at 14 cycles. Energy now being released at 12 cycles may presumably be the resultant action of elements formerly producing faster frequencies.

One of us (C.E.H.), in a serial analysis of continuous ink-writer records of 20 subjects during sleep, has observed that what goes under the categorical definition of 'spindles' (a phenomenon appearing at approximately 14 cycles) first appears at frequencies of 14–15 per sec., with a subsequent decrement in frequency to as low as 11–12 per sec. These slowest 'spindle' frequencies presumably appear during the deepest stages of sleep. Since these limits have impinged upon the defined limits of 'alpha' (8–12 cycles), there is a very real possibility that certain inconsistencies in the relationships between bands which were found in the static analysis are due to this overlap. This serves as an excellent illustration of the dangers of categorizing in a rigid manner, rather than measuring in terms of a continuum. Without the dynamic method of analysis, this factor would probably have not been so easily discovered.

Discussion

The observations based on both the static and the dynamic analyses lead to two explanations of the phenomena. According to the first of these, there is a shift in the rate of beat of certain cortical elements, the general rule being that there is a slowing of their rate of discharge. Thus the 12–14 cycle 'spindles' may be thought of as being produced by elements which produce 18–20 cycle activity in the waking record (as suggested by Jasper and Andrews, 5). Likewise, the 1–3 cycle 'random' waves of sleep may be thought of as being generated by elements producing the 8–12 cycle 'alpha' rhythm in the waking record.

The most adequately demonstrated relationship is that between the 8–12 and the 1–3 cycle activity; although the dynamic analysis indicated such a relationship between the 18–20 and the 12–14 cycle rhythms, the static analysis did not reveal such a trend, due, it is believed, to inadequacies inherent in that method of analysis.

The relationship between the 1–3 and the 8–12 cycle band which is so apparent in certain cases might lead to the supposition that the relative amount of alpha (8–12) activity limits the amount of random (1–3) activity which can be made manifest. This is not the case. It has been elsewhere demonstrated (4) that there is no relationship between the amount of random activity in sleep and the amount of alpha activity in the waking state, and it has been shown (6) that there is a great deal of similarity between dominant and rare alpha individuals during sleep. Thus, it would appear that there are mechanisms capable of producing alpha during waking (and which do produce random during sleep) which are prevented from doing so. The question of the differences between dominant and rare alpha subjects is thus not a question of the presence or absence of a particular mechanism, but of the degree to which it functions and the factors conditioning this degree.

A second interpretation of the data would suggest that sleep is a condition causally represented by the activity of certain bioelectric generators. These might be predominantly slow. As sleep progresses they would be expected to drive other generators, to a greater and greater degree, at their own rate. Alpha generators would thus be slowed, not by processes inherent within themselves, but by a spread of 1–3 cycle activity. It would be necessary, in order to make this interpretation consistent, to postulate a second generator which is causally characteristic of sleep, a 14 cycle generator. Since activity in this band seems to be present practically continuously throughout sleep, as one of us has observed (C.E.H., unpublished), appearing in high-gain, tuned filters from the earliest stages of sleep until awakening, this might be a very real possibility. A great deal more investigative work on this problem is needed before any durable conclusions can be reached. Rather than choose one horn of an either-or proposition, it would be best to admit both possible interpretations and attempt to discover the relative importance of each in the determination of the EEG in sleep.

Summary

1. Fourier transforms of the EEG during sleep have been obtained and subjected to two methods of analysis, one static, the other dynamic.

2. The static method of analysis indicates that the traditional categories of sleep do not take into account all of the phenomena appearing on the record. During sleep, as during the waking state, there is a continuous distribution of frequencies. Electrocortically, sleep differs from the waking state solely in the distribution of energy throughout the continuum of frequencies, not in the introduction of

new frequencies: during sleep there is an increase in energy in the 1–3 cycle and the 13–16 cycle bands, and a decrease in the 8–12 cycle bands. There appears to be a negative relationship between the activity of the 1–3 and the 8–12 cycle bands—as the former increases in energy during sleep, the latter decreases.

3. The dynamic method of analysis indicates that there is a progressive shift downward in the energy peaks along the frequency continuum, the slowest frequencies apparently being contributed to by the medium frequencies, and the 13–16 cycle band being contributed to by the faster 18–20 cycle bands.

4. It is assumed that two interpretations may be made of these data, one that there is a shift in the rate of discharge of generators composing the EEG, the other that the condition of sleep is a condition characterized by dominant activity of generators acting in the 1–3 cycle band and in the 13–16 cycle band. The first interpretation seems to be more adequately demonstrated by the data obtained in the present study, but the possibility remains that a complete account of the phenomena will include both interpretations.

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