METHODS & DESIGNS

Some stochastic properties of sleep spindles*

B. VO-NGOC†, D. POUSSART,
and J. M. LANGLOIS

*Département de Génie Electrique
et*

*Centre de Recherche en Bionique
Université Laval, Québec, P.Q., Canada*

The present work utilizes the data obtained from a spindle detection method to study some stochastic properties of this particular type of activity. The results obtained show that: (1) on any given EEG lead, there is no clear evidence of a statistical dependence either between the duration of a spindle (or the interspindle interval) and the duration of the next spindle (or the next interspindle interval) or between the duration of a spindle and the interspindle interval that precedes or follows; and (2) there is evidence of a difference in the spatial distribution of sleep spindles recorded from various brain regions during natural and barbiturate sleeps. This difference may be explained by the degree of inactivation of the ascending reticular activating system in these two types of sleep.

It is well known that there exists a certain form of simultaneity between spindle activity recorded from various cortical and subcortical regions of the brain. However, one also observes that this type of activity includes significant random aspects: the precise relative times of onset in different recording sites fluctuate, the duration of successive spindles from one or from different brain regions varies in a random fashion, and the presence of a spindle in one region is not always accompanied by a spindle in another region.

Although there exist several qualitative reports on this subject [for instance, Hess, Koella, & Akert (1953) and Andersen, Andersson, & Lomo (1967)], the statistical aspects of spindle activity do not appear to have been studied quantitatively. The present work deals with such aspects. In particular, it is concerned with the duration of spindles and interspindle intervals.

METHODS

Biological Techniques

Experiments were carried out on 30 adult cats of both sexes, including one chronic preparation. For acute preparations, surgical procedures were performed under ether anesthesia. Small holes were drilled in the skull, and deep electrodes were implanted bilaterally into the thalamus, particularly in the centrum medianum and into the caudate nucleus according to the stereotaxic atlas of Jasper & Ajmone-Marsan (1960). These electrodes consisted of pairs of stainless steel insect pins (Size 00), separated by 1 mm and insulated with Insl-Clear E-33 varnish, except for a 500-micron tip. Small screws were also fixed to the skull in order to record cortical activity. After the surgical phase, wound margins and pressure points of the

stereotaxic apparatus were infiltrated with Xylocaine 2%. The animal was then kept motionless by intravenous injection of d-Tubocurarine, and artificial ventilation was provided. Body temperature was monitored with a rectal thermometer and kept constant around 37°C by a warm-water coil.

Recording sessions began at least 2 h after cessation of ether anesthesia. Barbiturate sleep was induced by injection of Pentothal (10 mg/kg) or Nembutal (5-10 mg/kg), whereas somnolence or light natural sleep was obtained by keeping the surroundings completely quiet.

Potentials from the cortex and subcortical structures were amplified with a Beckman Dynograph unit, monitored with a long-persistence Statham Type 170 oscilloscope and fed to an Ampex SP-300 magnetic tape recorder.

At the end of each experiment, a small current of about 3 microA for 15 sec was applied to the deep electrodes. The cat was then perfused with 10% Formalin and 1% of potassium ferrocyanide to stain the iron deposit, which permitted precise localization of the electrodes.

For the chronic preparation, the procedures were the same as above, except that the surgical phase was performed under barbiturate anesthesia (Nembutal, 30 mg/kg) and that the electrical connections were through two 10-pin miniature connectors cemented to the skull.

Analysis

An approach to automatically recognize sleep spindles has been described previously (Vo-Ngoc, Poussart, & Langlois, 1971). This detection approach, which basically utilizes spectral analysis techniques, transforms the original electroencephalogram (EEG) into a rectangular wave signal with two possible distinct states: presence or absence of spindles. Tests have shown that this automatic scheme yields a performance that is comparable to that of trained Os.

It is fully recognized that electrocortical activity cannot be considered as a stationary random process in the strict sense. However, the segments of data used in the present study were sufficiently short (typically 15 min) and screened for gross changes of activity so that a statistical analysis of the parameters discussed here could be meaningful.

The statistical relationship between pairs of events of interest (durations of consecutive spindles, durations of consecutive interspindle intervals, duration of a spindle and its preceding or following interspindle interval) was studied through scatter diagrams such as described by Rodieck, Kiang, & Gerstein (1962). Scatter diagrams consist of cross-plots of two random variables, X and Y, on rectangular coordinates. The statistical correlation between the variables is easily visualized through particular symmetries or concentration of data points.

In addition, histograms of spindle duration and interspindle intervals were computed for each EEG lead. Histograms of these parameters obtained from different brain regions were then compared. The mean and the variance of the relevant probability distributions were estimated from these histograms.

A general interactive program has been developed for analysis and display of such data. The main hardware used consisted of PDP-8 computer, DECtapes, CRT display, and point plotter.

RESULTS

Relationship Between Spindle Durations and Interspindle Intervals

Figure 1 shows some typical examples of scatter diagrams. From over 700 scatter diagrams observed, we have not detected any evident indication of a clear

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†Present address: Institut National de la Recherche Scientifique (Santé), Hôpital St-Jean-de-Dieu, Montreal, P.Q., Canada.

Fig. 1. Typical scatter diagrams. One time unit = 0.16 sec.

relationship between spindle durations and interspindle intervals or between the duration of a spindle and the interspindle interval which precedes or follows.

Our results suggest an independence between (1) two consecutive spindle durations, (2) two consecutive interspindle intervals, and (3) the duration of a spindle and the interspindle interval which precedes or follows.

These data agree with the qualitative observation of Andersen, Andersson, & Lomo (1967). These investigators, in examining a great number of spindles appearing simultaneously in various brain regions, have concluded that the beginning and the duration of individual spindles vary apparently in a random manner.

Spindle Duration and Interspindle Interval

Figure 2 illustrates two sets of histograms of spindle durations and interspindle intervals. The mean, variance,

and number of spindles or interspindle intervals are indicated in the upper right corner of each histogram.

We note that spindle durations are clearly much shorter than interspindle intervals (means of 1.6 and 1.92 sec vs 6.24 and 6.56 sec). However, the dispersion of spindle durations is about the same as that of interspindle intervals, with a coefficient of variation (standard deviation/mean) of the order of 0.6 in both cases.

As mentioned by Hess, Koella, & Akert (1953) and confirmed by our data (Tables 1 and 2), the envelope and rate of occurrence of spindles vary according to the state of the preparation during natural as well as barbiturate sleeps. It is therefore necessary to study the results obtained for each preparation separately.

Table 1 summarizes typical overall results obtained on four acute and one chronic preparation during somnolence or light natural sleep. We clearly note that

Fig. 2. Typical histograms of spindle durations and interspindle intervals. One time unit = 0.16 sec.

Table 1
Duration (Upper Number, One Time Unit = 0.16 Sec) and Number of Spindles (Lower Number): Natural Sleep

Preparation	Left Frontal Cortex	Right Frontal Cortex	Left Parieto-Occipital Cortex	Right Parieto-Occipital Cortex	Left Thalamus	Right Thalamus	Left Caudate Nucleus
Acute 3-3-1972	9 136	9 139	8 173	7 121	6 49	7 117	6 90
Acute 7-4-1972	12 132	12 121	11 106	10 113	7 70	6 60	12 102
Acute 26-5-1972	15 176	15 176	12 186	12 186	8 140	10 186	10 191
Acute 24-11-1971	18 139	15 147	8 138	10 153	12 170	11 158	— —
Chronic, recorded on 28-2-1972	10 142	10 147	7 131	7 122	8 130	— —	— —
Chronic, same as above, recorded on 21-6-1972	9 141	10 142	6 67	6 112	6 100	6 105	7 97

Table 2
Duration (Upper Number, One Time Unit = 0.16 Sec) and Number of Spindles (Lower Number): Barbiturate Sleep

Preparation	Left Frontal Cortex	Right Frontal Cortex	Left Parieto-Occipital Cortex	Right Parieto-Occipital Cortex	Left Thalamus	Right Thalamus	Left Caudate Nucleus
Chronic, Nembutal Sleep	9 150	10 151	7 140	7 153	9 184	9 175	9 151
Chronic, Pentothal Sleep	10 150	11 148	5 90	6 104	6 126	6 102	7 125
Acute, Pentothal Sleep 26-5-1972	11 91	10 95	12 91	9 97	11 103	10 103	10 101

spindles are generally longer in the frontal regions of the cortex than in the others (25 cases out of 27) and that spindles appear more frequently in these same regions than in the others (18 cases out of 27).

As shown in Table 2, these differences are not apparent during barbiturate sleep induced by Nembutal. In fact, the spindle duration and the number of spindles are about the same in different recording sites (5 cases out of 7 for the duration and 5 cases out of 7 for the number).

However, Pentothal-induced sleep yields different results, depending on the type of the preparation. For the acute preparation, the duration as well as the number of spindles are about the same in different brain regions (6 cases out of 7 for the duration, and 7 cases out of 7 for the number). On the contrary, for the chronic preparation, the results are identical with those obtained during natural sleep, that is, spindles are longer (5 cases out of 5) and more numerous (5 cases out of 5) in the frontal regions than in the others.

DISCUSSION

The above results agree in part with those obtained by other investigators. In the case of natural sleep, our results indicate that spindles recorded from the frontal regions are longer and more numerous than those recorded not only from the subcortical structures, but also from the parieto-occipital regions of the cortex. These results seem to support, at first, the cortical theory of Hess, Koella, & Akert (1953). However, for Nembutal-induced sleep, we have observed that the duration and the number of spindles are about the same in different regions. Furthermore, with Pentothal, the acute preparation yields the same results as those obtained during Nembutal-induced sleep, whereas the chronic preparation gives the same results as those obtained during natural sleep. We can explain this difference by the fact that, in the chronic preparation, the administration of Pentothal is done by intraperitoneal injection. This drug is an ultrashort-acting barbiturate (10-15 min). Moreover, when given intraperitoneally, its absorption is gradual and slow so that its action becomes much less effective. Therefore, what is obtained in this case is only an induction to sleep, in contrast to the state of hypnosis produced by intravenous injection of this barbiturate, where the effect is immediate and complete.

The above observations can be summarized by a difference in the spatial distribution of sleep spindles recorded from various brain regions during natural and barbiturate sleeps: during natural sleep, spindles recorded from frontal regions of the cortex are longer and more numerous than those recorded from other regions, whereas, during barbiturate sleep, the duration and the number of spindles are about the same in different locations.

A possible explanation of these results is as follows: In barbiturate sleep, the ascending reticular activating system (ARAS) (Moruzzi & Magoun, 1949), which has an important function on the control of the electrocortical activity, is profoundly depressed, since the barbiturate affects mainly this region of the central nervous system. This causes a generalized and uniform appearance of spindles at cortical as well as at subcortical levels. On the contrary, in somnolence or light natural sleep, the level of inactivation of the ARAS is lighter since the cortex can still respond to important stimuli. This partial inactivation would then be illustrated by an unequal or nonuniform distribution of spindles over different brain regions.

It would seem, therefore, that the abundance of spindle activity in the frontal regions of the cortex does not imply necessarily that spindles originate from these regions, as suggested by Hess, Koella, & Akert (1953).

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