Correlation of spindle activity recorded from different brain regions*

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 temporal relationship between spindle activity appearing in different brain regions is investigated by means of the cross-correlation function method. The results obtained indicate that there exists a particular tendency of simultaneity of this type of rhythmic activity recorded from homologous brain regions. In addition, spindles appearing in parieto-occipital regions of the cortex have a tendency to precede those in frontal regions, but they appear in synchronism with those in the thalamus. Moreover, spindle activity in the caudate nucleus has a tendency to precede that in the frontal cortex and to be in lag with respect to that in the thalamus. A functional relationship between different brain structures is proposed.

In our preceding paper (Vo-Ngoc, Poussart, & Langlois, 1973), spindle activity observed in each brain region was evaluated separately. Overall comparisons of this type of activity, recorded in different locations in terms of duration and number of spindles, were presented.

The present work concentrates on the precise temporal relationship between spindle activity appearing in different recording sites of the cerebral cortex and in the thalamus. In addition, an attempt has been made to study the temporal relationship between spindle activity appearing in the caudate nucleus and in the brain regions mentioned above. This has been motivated by the fact that spindles can be generated by electrical (Buchwald, Wyers, Okuma, & Heuser, 1961) or chemical (Langlois & Poussart, 1969) stimulation of the caudate nucleus.

It would be expected that such study might contribute to the understanding of the underlying generation mechanism and the origin of this particular type of activity.

METHODS

The temporal relationship between spindles recorded from different brain regions is evaluated by means of the cross-correlation function. This approach was selected because it readily yields an overall appraisal of relative delays and timing relationship between two random processes. Simple differences in time of onset of spindles can hardly be measured on a spindle-to-spindle basis. In fact, it is not possible, in general, to assign unequivocally a particular spindle in any given region to another particular spindle in a different region.

The cross-correlation function is calculated according to the following expression:

*This work was supported by Grants A-4939 and A-5274 from the National Research Council of Canada and a research grant from the Ministry of Education of the Government of Quebec.

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

$$C_{ij}(\tau) = \frac{1}{T} \int_0^T f_i(t) \cdot f_j(t + \tau) dt$$

where $f_i(t)$ and $f_j(t)$ are the rectangular wave outputs of a spindle detection program for two EEG channels, which has been described elsewhere (Vo-Ngoc, Poussart, & Langlois, 1971).

In general, we have chosen $\tau_{\max} = 5.12$ sec and $T = 15$ min, so that $(\tau_{\max}/T) \ll 1$. In the ideal case, where $T \rightarrow \infty$ and where $f_i(t)$ and $f_j(t)$ are stationary, this expression can be identified with the conventional definition of the cross-correlation function of two stochastic signals.

Here, $f_i(t)$ and $f_j(t)$ can only have the values 0 or 1, corresponding, respectively, to the absence or presence of spindle activity. The product $f_i(t) \cdot f_j(t)$ becomes a simple AND logic operation. Therefore, the computation time is considerably reduced.

$$f_i(t) \text{ or } f_j(t) = 0 \rightarrow f_i(t) \cdot f_j(t) = 0$$

$$f_i(t) \text{ and } f_j(t) = 1 \rightarrow f_i(t) \cdot f_j(t) = 1$$

The flow diagram of the program which computes the cross-correlation functions of spindle activities, as identified by the detection program and stored on DECTape, is shown in Fig. 1.

First, one specifies to the program all required parameters, such as the starting block and the number of blocks of data stored in the DECTape obtained from the spindle detection program, and the maximum delay $\tau_{\max}$. The program then clears all counter registers and tables of results.

For practical reasons related to the computer memory capacity, the computation of correlation functions is worked out as follows: (1) For each value of τ , the data on DECTape is divided into groups of two blocks each. (2) The program transfers two consecutive blocks of data to computer memory, for example, Blocks n and $n+1$, computes the partial correlation functions, $C_{ij}(\tau)$, and stores the results. (3) The data transfer is repeated, this time with Blocks $n+1$ and $n+2$. The new partial functions, $C_{ij}(\tau)$, are then added up to the previous $C_{ij}(\tau)$. (4) The process is repeated automatically. After all specified blocks have been analyzed, the program transfers to display mode.

The program is fully interactive. By a suitable command at the Teletype, one can choose the type of correlation function for display, change the scales, observe the results on the CRT display, or also obtain a duplicate of results on graph paper with the point plotter.

The main hardware used in this analysis consists of PDP-8 computer, DECTapes, CRT display, and point plotter. The program uses 2.5K of core memory.

The data used in this study was obtained from the same biological preparations as those used previously (Vo-Ngoc, Poussart, & Langlois, 1973); that paper also describes the experimental procedure.

RESULTS

An example of correlation functions obtained with the above program is illustrated in Fig. 2. Spindle activity recorded from Channel 0 appears to be in lag with respect to that recorded from Channel 1 by two time units (one time unit = 0.16 sec).

The global results obtained from one preparation are

Fig. 1. Schematic flow diagram of the program that computes the intercorrelation function $C_{ij}(\tau)$.

shown as a typical example in Fig. 3. The arrows are directed toward the regions where spindle activities are in lag with respect to those of the corresponding regions.

For natural sleep, typical results obtained from four acute and one chronic preparation indicate that spindles

have a tendency to appear synchronously in homologous cortical regions (9 cases out of 12) and in the two thalami (6 cases out of 6). In addition, spindle activities in parieto-occipital regions of the cortex have a tendency to precede those in frontal regions (9 cases out of 9), the

Fig. 2. Typical examples of intercorrelation functions (chronic preparation, natural sleep: 0—right frontal cortex, 1—right parieto-occipital cortex). One time unit = 0.16 sec.

delay being of the order of one to two time units, i.e., 0.16 to 0.32 sec. Besides, comparisons of spindle activities in parieto-occipital regions of the cortex and those in the thalami show that they appear in synchronism, although the results are less conclusive (6 cases out of 10).

For Nembutal- or Pentothal-induced sleep, the results obtained from acute and chronic preparations are the same as those obtained during natural sleep, that is, spindles have a tendency to appear synchronously in homologous cortical regions (6 cases out of 6) and in the two thalami (3 cases out of 3). Also, spindle activities in parieto-occipital regions of the cortex have a tendency to precede those in frontal regions (6 cases out of 6, the delay being of the order of 0.16 sec), but they appear in synchronism with those in the thalami (5 cases out of 6).

As far as the functional relationship between the caudate nucleus and other brain regions is concerned, the results obtained during natural and barbiturate sleeps indicate that spindle activity in the caudate nucleus precedes that in the homo-lateral frontal cortex (5 cases out of 6, the delay being of the order of 0.16 sec). However, comparison of spindle activity in the caudate nucleus and that in the homo-lateral thalamus yields less conclusive results: in 3 cases out of 7, spindle activity in the thalamus precedes that in the caudate nucleus (the delay being of the order of 0.16 sec), whereas in 4 cases out of 7 it appears in synchronism in these two regions.

DISCUSSION

According to Brazier and Casby (1952) and Bremer (1958), there exists a clear tendency for spindles to appear synchronously at different homo-lateral and contro-lateral recording sites. Hess, Koella, and Akert (1953) have noted that, during somnolence or light sleep, spindles appeared almost simultaneously in different brain regions, but a perfect synchronism was rather rare.

However, Adrian and Yamagiwa (1935) and Rubin (1938) have observed great variations in the onset and end times of spindles and the intraspindle frequency of spindles recorded from different cortical regions. Andersen, Andersson, and Lomo (1967) have made the same observations for spindles recorded with surface electrodes separated by 2 mm or more. These differences increase with the distance between electrodes, and they are more pronounced with spindles recorded from contro-lateral regions. In addition, these authors have observed a great correlation between spindle activities in the thalamus and those in a cortical region with the condition that this cortical region correspond to the projection of the corresponding group of neurons in the thalamus. These investigators have, therefore, introduced a new concept, according to which, in barbiturate sleep, small groups of neurons in the thalamus appear to be able to generate independently rhythmic activity and each group of neurons controls the activity of the corresponding cortical region to which it projects.

Our results show a particular tendency of simultaneity between spindle activity recorded in homologous brain regions. We observe also a tendency according to which spindle activity in parieto-occipital regions of the cortex precedes that in frontal regions, in natural as well as in barbiturate sleep. Furthermore, spindle activity in the two thalami has a tendency to appear in synchronism with that in the parieto-occipital regions of the cortex.

The above observations suggest that spindles appearing in

Fig. 3. Correlation of spindle activity recorded from different brain regions (chronic preparation, Nembutal-induced sleep; L FC and R FC—left and right frontal cortex, L POC and R POC—left and right parieto-occipital cortex, L CN and R CN—left and right caudate nucleus, L Th and R Th—left and right thalamus). One time unit = 0.16 sec.

different brain regions are not completely independent, but that there exists a certain statistical relation between them. Our results do not support, therefore, the theory of independent generators of sleep spindles. Moreover, the functional relationship between the thalamus and the parieto-occipital region of the cortex is more direct than that between the thalamus and the cortical frontal region. This assumption agrees with the results presented in the preceding paper (Vo-Ngoc, Poussart, & Langlois, 1973). In fact, spindle activity recorded in the thalami during natural sleep, expressed in terms of duration and number of spindles, is closer to that recorded in the parieto-occipital regions than in the frontal regions of the cortex.

In addition, our results show that spindle activity in the caudate nucleus precedes that in the frontal cortex. It is, therefore, assumed that spindles would follow a loop which includes the thalamus instead of going directly from the caudate nucleus to the frontal cortex. This assumption is supported by the fact that anatomical studies have never revealed any direct connection in the direction from the caudate nucleus to the cortex.

It is generally recognized that the thalamus is one of the main generators of electrocortical activity. However, it has been shown that spindles can be generated by stimulation of the caudate nucleus (Buchwald, Wyers, Okuma, & Heuser, 1961; Langlois & Poussart, 1969). Although our results do not allow us to state clearly the dominant part of either of the above structures with respect to the other, they nevertheless suggest a temporal relationship in the thalamus-caudate nucleus direction.

REFERENCES

- Adrian, E. D., & Yamagiwa, K. The origin of the Berger rhythm. *Brain*, 1935, 58, 323-351.
- Andersen, P., Andersson, S. A., & Lomo, T. Nature of thalamo-cortical relations during spontaneous barbiturate spindle activity. *Journal of Physiology*, 1967, 192, 283-307.

- Brazier, M. A. B., & Casby, J. U. Crosscorrelation and autocorrelation studies of electroencephalographic potentials. *Electroencephalography & Clinical Neurophysiology*, 1952, 4, 201-211.
- Bremer, F. Cerebral and cerebellar potentials. *Physiological Reviews*, 1958, 38, 357-388.
- Buchwald, N. A., Wyers, W. J., Okuma, T., & Heuser, G. The "caudate spindle." I: Electrophysiological properties. *Electroencephalography & Clinical Neurophysiology*, 1961, 13, 509-518.
- Hess, R., Jr., Koella, W. P., & Akert, K. Cortical and subcortical recordings in natural and artificially induced sleep in cats. *Electroencephalography & Clinical Neurophysiology*, 1953, 5, 75-90.
- Langlois, J. M., & Poussart, Y. Electro cortical activity following cholinergic stimulation of the caudate nucleus in the cat. *Brain Research*, 1969, 15, 581-583.
- Rubin, M. A. The distribution of the alpha rhythm over the cerebral cortex of normal man. *Journal of Neurophysiology*, 1938, 1, 313-323.
- Vo-Ngoc, B., Poussart, D., & Langlois, J. M. Automatic recognition of sleep spindles using short-term spectral analysis. *Behavior Research Methods & Instrumentation*, 1971, 3, 217-219.
- Vo-Ngoc, B., Poussart, D., & Langlois, J. M. Some stochastic properties of sleep spindles. *Behavior Research Methods & Instrumentation*, 1973, 5, 449-452.

(Received for publication July 20, 1973;
accepted September 17, 1973.)

ERRATUM

RUMBAUGH, D. M., ET AL. A computer-controlled language training system for investigating the language skills of young apes. *Behavior Research Methods and Instrumentation*, 1973, 5, 385-392—The correct order of authorship is Duane M. Rumbaugh, E. C. von Glasersfeld, Harold Warner, Pier Pisani, Timothy V. Gill, Josephine V. Brown, and C. L. Bell.