PARTICIPATION OF NONLINEAR DYNAMIC PROCESSES IN THE FORMATION OF THE HIGH-FREQUENCY EEG OF THE RABBIT

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The informativeness of the high-frequency EEG for the assessment of the functional state of the brain has been proven by means of a new method of analysis of the EEG which is suitable, by contrast with the traditional spectral correlation analysis, for the description of nonlinear processes. Evidence has been obtained in favor of the hypothesis that a deterministic chaotic component, the parameters of which depend on the region of recording of the EEG and which changes conjointly with change in the functional state of the brain, is present in the EEG of the neocortex and hippocampus of the rabbit.

Results which we have obtained in recent years of the spectral analysis of the EEG in the high-frequency portion of the spectrum (14.7–100 Hz) have made it possible to advance the hypothesis that there is present in the EEG, along with rhythmic and noise components, a deterministic chaotic component which is visually indistinguishable from a random component due to the nonlinearity and great complexity of the processes generating it (possibly associated with the synchronization of excitation in small neuronal assemblages, segments of the neuronal network) [1]. Papers have appeared abroad in the last decade on the investigation of chaotic processes in the EEG of man and animals [3–9]. A new approach to the analysis of the EEG was used in them. The interpretation of temporal signals as multidimensional geometrical objects is its principal feature. Such a perspective on the examination of dynamic processes is based on the hypothesis that the signals are generated by some finite-dimensional dynamic system which is not obligatorily the superimposition of periodic oscillators. In that case the signal being observed may be interpreted as the projection of a multidimensional trajectory in phase space, in which the axes of the coordinates are the degrees of freedom of the system. A point in the phase space characterizes the state of the process at a given moment in time. The universe of points which the points of the trajectory of the system approach, given a long time interval, is the attractor. The dimension of the attractor determines the minimal number of nonlinear equations necessary for the description of the process, yielding a quantitative measure of the complexity of the organization of the EEG.

In the studies indicated above human EEGs recorded in the frequency range from 1 to 20 Hz in the state of resting wakefulness, in sleep, during intellectual activity and in epilepsy were mainly investigated. Attractors with a dimension value from 2.05 to 9.7 were identified. The general lawfulness of these results consisted in the fact that the values of the dimensions of the EEG attractors changed with change in the functional state of the object investigated; in the process the least values were found in the course of an epileptic attack and in the state of deep sleep, while the greatest values were found in the process of intellectual activity.

We do not know of studies on the investigation of the chaotic constituent of the EEG in animals or man in the high-frequency portion of the spectrum in the range up to 100 Hz. Nevertheless, there are grounds for hypothesizing its presence in the structure of the EEG [1]. The investigation of this question makes it possible to construct a more complete notion of the functional organization and functional significance of the EEG, by supplementing the information which has been obtained along these lines through the use of spectral correlation analysis. In a recently published study [9], the functional role of chaotic processes has, not without reason, been linked to the processes of information processing in the central nervous system.

It should be noted that a majority of the mathematical methods of analysis used at the present time, including the spectral correlation method, have been developed to fit linear processes. The EEG, on the other hand, as is well known, manifests marked nonlinear properties. Recently developed methods of analysis of nonlinear dynamic systems [6] are more appropriate for the analysis of the EEG.
The purpose of the present study was to search for and describe the chaotic constituent of the high-frequency portion of the spectrum (14.7–100 Hz) of the EEG of various regions of the rabbit cerebral cortex in the state of resting wakefulness and during change in the functional state of the brain due to the administration of pharmacological substances which reduce (nembutal) and increase (caffeine) the level of brain activation.

The following questions were posed in the present investigation. 1. Are there phenomena in the structure of the high-frequency EEG of the rabbit which are explainable by the presence in it of the chaotic deterministic component? If so, what are its parameters? 2. Are there spatial differences in these parameters in the cerebral cortex of the rabbit? 3. How stable in time are the parameters in question of the chaotic deterministic component of the EEG? 4. Are there lawful changes in the values of these parameters during change in the functional state of the brain?

METHODS

The study was carried out in four rabbits with Nichrome electrodes, 90 μm in diameter, implanted in four regions of the cerebral cortex of the left hemisphere: the sensorimotor (SM), the visual (Vi), the auditory (Au), and the CA3 region of the dorsal hippocampus (DH) following the coordinates of the atlas of F. Fikova and G. Marshal. SM: AP = +2.0, SD = 1.0, V = 2.5; Vi: AP = +6.0 to +9.5, SD = 8.0–9.0, V = 2.5; Au: AP = +5.0 to +13.5, SD = 6.5, V = 2.5; DH: AP = +5.0, SD = 5.0, V = 5.0.

The operation of scalping and implantation of the electrodes was carried out under local novocaine anesthesia. The animals were brought into the experiment three weeks after the operation. Then they were accustomed to the experimental situation over the course of three weeks prior to the beginning of the recording of the EEG.

During the experiment the rabbit, flexibly attached by the paws to the mount, was kept in a dark soundproof chamber. The biopotentials were recorded monopolarly; the indifferent electrode was placed on the rabbit’s ear; the lower and upper boundaries of the filters were set respectively at 14.7 and 128 Hz. Active recursive digital Bessel filters were used. The slope of the amplitude-frequency characteristic was 32 dB per octave; the nonuniformity of the amplitude-frequency characteristic did not exceed 0.5 dB.

The EMG, which was picked up from the flexor of the right paw by means of needle electrodes, was used for the recording of movements; the amplifier with filters, the lower and upper boundaries of which were set respectively at 10.0 and 700.0 Hz, was used.

The EEG was recorded over the course of 2 min; the recording of the baseline EEG was repeated over the course of three to five days with an interval of one to three days.

At the next stage the rabbits were administered intramuscularly a solution of nembutal in a dose of 60 mg/kg three times at an interval of one to three days. Following this, a solution of caffeine was injected subcutaneously in a dose of 80 mg/kg following the same procedure.

Four-second segments of the EEG of four regions of the brain were analyzed using a PC AT computer: the SM, the Vi, the Au, and the DH. The method of the determination of the correlational dimension using a modified Grassberger-Procaccia algorithm was used to identify and evaluate the chaotic constituent [6].

A 1536 point segment of EEG (4.1 sec) was selected at a sampling frequency of 375 Hz. Then in a space of assigned dimension d (d = 2.21), a set of d-dimensional vectors was formed with components \{x(i), x(i + t), ..., x(i + td)\}, in which x(i) is the amplitude of the normed EEG at point i (0 ≤ x(i) ≤ 1), t is the value of the interval between the points which ensures informativeness of the state’s vector and which is equal to the number of points of the autocorrelation function of the EEG before the first intersection of zero [6]. Then a d-dimensional ball of radius r was described around the end of each such vector, representing a point on the trajectory of the EEG in the state’s space, and the frequency with which points of the trajectory fall within their sphere C (r, d) was calculated.

The estimate of the correlational dimension V(d) was found as the value of the coefficient of regression of the equation

\[
\log C(r, d) = a + V(d) \log r,
\]

calculated for n adjacent values of \log r (n ≥ 7 at an interval of change in \log r = 0.05), where n is chosen such that the coefficient of linear correlation between C (d, r) and \log r was maximal.

The dimension of the attractor, equal to the limiting value \( V = \lim_{d \to \infty} V(d) \) as \( d \to \infty \) was estimated by means of the calculation of the asymptote A of the equation

\[
V(d) = A \left(1 - \exp(-bd) \right).
\]