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NEW NEURODIAGNOSTICS TECHNOLOGY FOR BRAIN RESEARCH ON THE BASIS OF MULTIVARIATE AND NONLINEAR (DETERMINISTIC CHAOS) ANALYSIS OF AN EEG

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Abstract

The new approach and tools for investigating some fundamental properties of integrative brain activity and mental activity violations were worked out. Within the framework of the qEEG system for computer diagnostics of EEG NeuroResearcher®'2003 (Version 10.5) is created neurodiagnostics information technologies for investigation of multivariate neurodynamic systems of the brain on the base of multivariate spectral EEG analysis and deterministic chaos methods. This qEEG system includes modules for clinical, spectral, multivariate analysis (unit NeuroResearcher-Multivariate Analysis® '2003), heart rate variability (unit Cardio-Tension-Test®'2003 for HRV analysis) and modules for investigation of non-linear dynamics and chaos in neurodynamic systems (unit NeuroResearcher-Chaos®'2003). Applications for estimation of various parameters of Deterministic Chaos in EEG are circumscribed: the correlation dimension, the embedding dimensions, the correlation entropy, the maximum Lyapunov exponent, Kolmogorov-Sinai entropy and some others.

1. Introduction

Development of computer facilities in the last years has allowed realizing advanced achievements of mathematics for creation of qualitatively new technologies for quantitative research of bioelectrical activity (qEEG, EP, ERP, etc.) of the brain.

Traditionally for EEG research uses classical methods of correlation, spectral and pair coherent analyses [1]. However these methods are effective only for an estimating of functional state of the brain regions, for researching of pair interactions of two areas or structures of the brain. The direct use of auto-spectra and cross-spectra, even taken together to judge properties of the structures system seems to be of little promising. However, it is not enough at all for research of integrative activity of the brain and for revealing thin displays of mental activity violations.

1.1 Multivariate analysis for evaluation of system activity of the brain by EEG

Modern views on neurophysiological mechanisms of perception, thinking, emotions, motivations, memory and so on are based on the ideas about the system principle of brain functioning. So neuroscience's achievements allow considering system character as the main principle of the brain activity.

The functional unification of brain formation finds the reflection in an EEG. In all known qEEG systems, only two (but not more) brain structures are investigated simultaneously. In fact, only hypothetical assumptions about the system activity character are made on this ground. In other words, there were lacks of characteristics allowing to evaluate and to quantitatively measure a degree of functional organisation of investigated brain mechanisms in unified systems. We have created methods of application of mathematical theory and applied apparatus of multivariate spectral analysis of multidimensional linear neurodynamic systems on the basis of EEG, received from many brain formations simultaneously [2]. It allows investigating some fundamental properties of integrative brain activity. New secondary EEG indices and their physiological interpretation are proposed to use [1 - 7].

1.2 Nonlinear Dynamics and Chaos in EEG

The widely used spectral analysis is the method for the analysis of linear systems and also the EEG is considered as stochastic process [1]. So, that does not allow evaluating comprehensively all EEG properties. Alternative to traditional approach is the hypothesis, according to which an EEG signal is necessary to consider as an output of nonlinear system that is in a state of dynamic chaos [8-11].

For diagnostics of a condition of the brain or various mental diseases, outcomes of the nonlinear analysis are extremely important [8-11]. They are objective and give the additional information. The basic information consists in evaluation of some "norm of chaos" ("norm of chaotic state"), and also in evaluation of deviations from "norm" (in this or that leg) under influence of those or other actions. There may be various mental, endocrine, neurological diseases, emotional stresses, which are called deviations of a degree of a chaos (chaotic state) from "norm". Thus deviations in those and other legs may mean "illness" [11-12].

If we will manage to reveal for given neurodynamic system (or an aspect of cerebral activity, for example, perception, memory, emotions, motivations etc.) for this or that cerebral process "norm" of a chaos deviations in both legs can be surveyed as "illness" and, hence, as a degradation. Further it is possible to inspect a choice of a technique of "treatment". Here the criterions of relative degree of chaotic state again enter in game. If by this criterion "treatment" approximates a condition of an open system to "norm", it means that process of self-organizing takes place. Otherwise "treatment" calls the further degradation [12].

2. Multivariate approach for evaluation of system activity of the brain by EEG

The systems analysis of EEG is realised in the framework of NeuroResearcher®'2003 by application program package NeuroResearcher-Multivariate Analysis®'2003. The method is the basis for creating a qualitatively new approach for investigation of neurodynamic structure of cerebral mechanisms. This application consists of following units: 1. Elucidating systems. 2. Blocking influences. 3. 'Pure' pair interactions. 4. Detection of "Contributions".

2.1 Elucidating systems of the brain

This method serves for investigation of neurodynamic systems of the brain (Fig.1, 2). It makes possible: 1) to detect complex of the structures that takes part in the investigated system activity; 2) to investigate simultaneously the interaction of several (more than 2) formations of the brain; 3) to study systems including up to 256 brain formations; 4) to study the mechanisms of brain system activity.

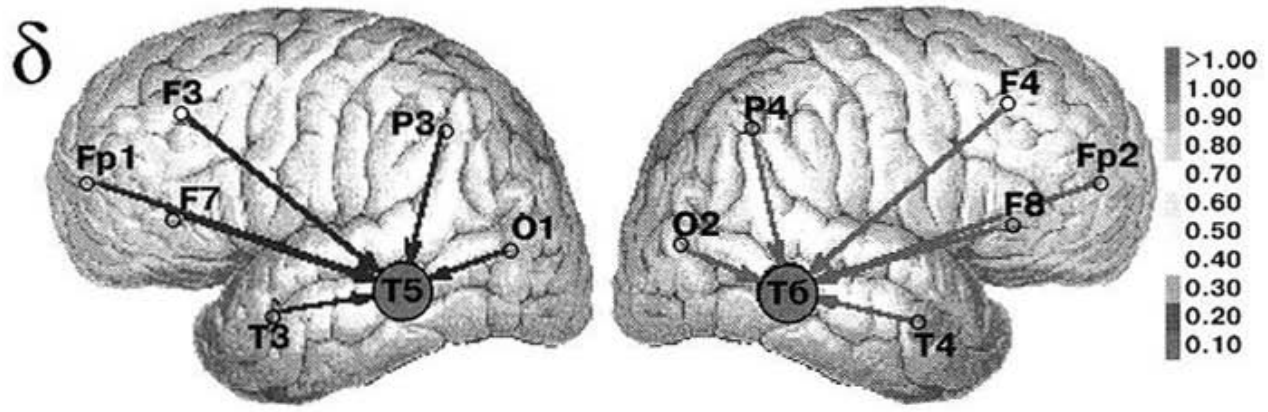

Fig.1 Elucidating systems of the brain (scheme).

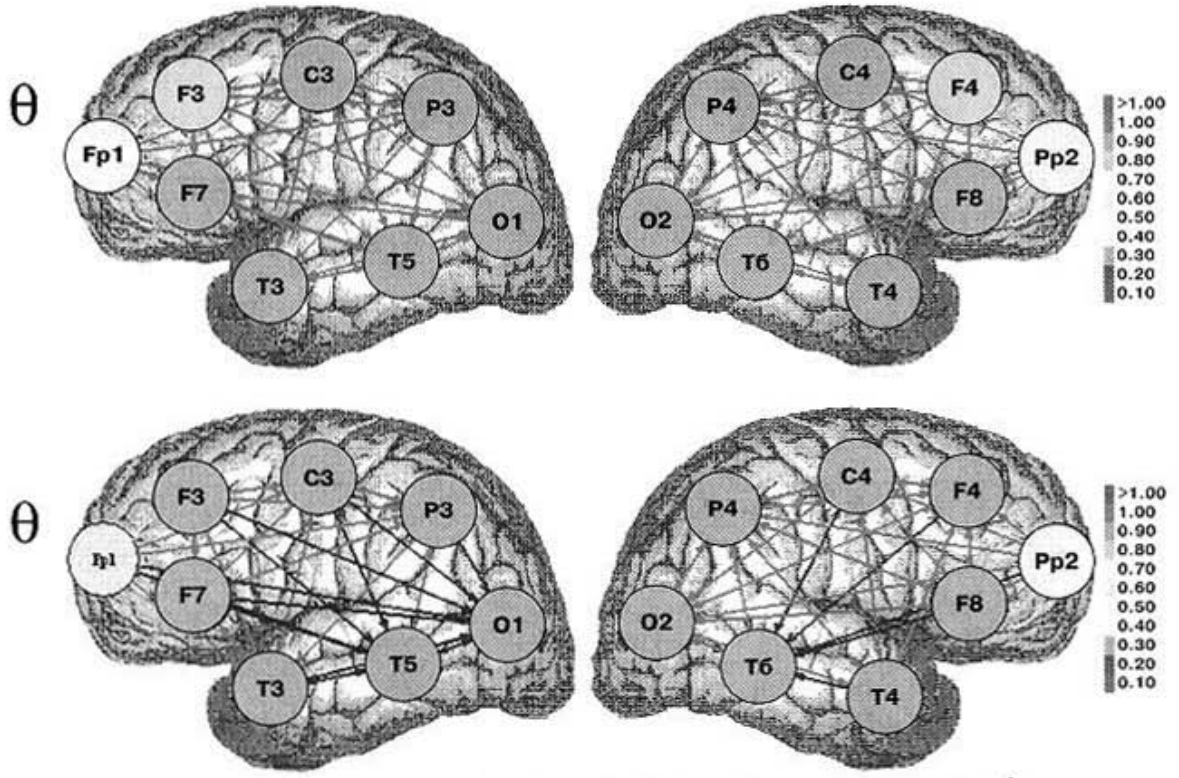

Fig. 2. Elucidating systems of the brain (A. Background EEG in θ range, B. Visual hallucinations after Δ9THC 1 hour later).

2.2 Blocking influences

This method serves for investigation of system interactions in 'pure' form, excluding (blocking) influences of separate structures or whole systems on INTRA/INTER-system interactions (Fig. 3). In other words: simulate mathematical "cutting" of INTRA- and INTER-system mutual influences. This method allows: 1) to estimate in 'pure' form the

intra-system interactions and inter-system influences; 2) determine 'input', 'output' and 'relay' elements of neurodynamic systems; 3) to solve problems of identification of signal propagation channels, location of one or more signal sources.

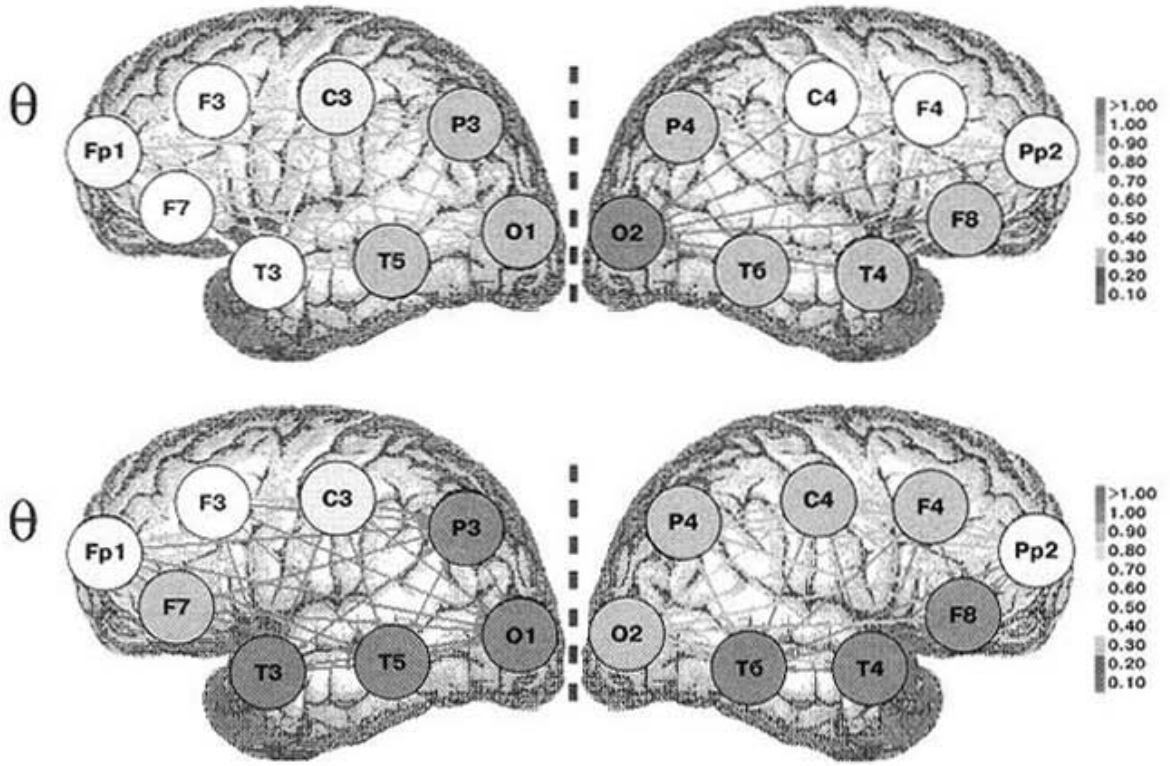

Fig.3. Blocking Influences of Hemispheres (A. Background EEG in θ range, B. Visual hallucinations after Δ9THC 1 hour later).

2.3 "Pure" pair interactions

This method intends for investigating INTRA-system interactions and INTER-system influences in 'pure' form, eliminating ('blocking') the influence of separate structures or whole systems on pair interactions. In other words, to simulate mathematical 'cutting' of INTRA- and INTER-system influences on the investigated pairs of the brain formations.

2.4 Detection of "Contributions

This method serves for investigating neurodynamic systems of the brain (Fig.4). It is recommended to use this mode after "Elucidating Systems" and "Blocking Influences" modes. "Contribution" determination unit allows: 1) to estimate quantitatively the 'contribution' of separate structure in system activity under investigation; 2) to detect a set of structures that actually take part in system activity under investigation; 3) to determine 'input', 'output' and 'relay' elements of neurodynamic systems, reveal fine neurodynamic structure of brain interactions; 4) to solve problems of identification of signal propagation channels, locating of one or more signal sources; 5) to evaluate 'contributions' to systems comprising up to 64 brain formations; 6) to investigate a neurodynamic structure of normal and pathological processes of sleep, emotions, motivations, thinking, memory and motions.

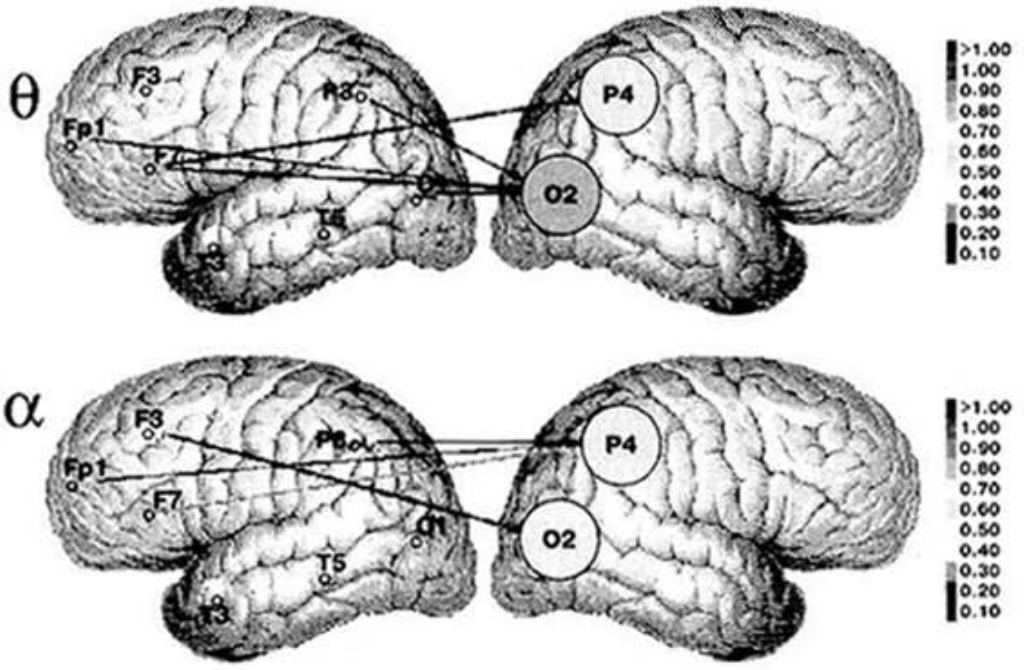

Fig.4. Investigation 'Contributions' during Inter Hemispheric Interactions (Calculation in Memory EEG in θ and α ranges).

3. Applications for valuation of Nonlinear Dynamics and Chaos in EEG

Quantity indicators of various properties of chaos are Correlation dimension, Embedding dimension, Maximal Lyapunov Exponent, Kolmogorov Entropy.

Within the framework of the qEEG system for computer diagnostics of EEG NeuroResearcher-Chaos®'2003 (Version 10.5) are created modules for investigation of nonlinear dynamics and chaos in neurodynamic systems of the brain on the base of deterministic chaos methods. These applications are in program package NeuroResearcher-Chaos®'2003. The package consists of following units: 1. Delay (on the base of Correlation Method). 2. Correlation Dimensions. 3. Embedding Dimensions. 4. Correlation Entropy. 5. Maximal Lyapunov Exponent (three different methods). 6. Lyapunov Spectrum and Kolmogorov-Sinai Entropy. 7. Estimation of Nonlinearity. 8. Outcomes result mapping. 9. Archive and Reference Database. 10. The Import R-R intervals. This software package allows applying set forth above methods of deterministic chaos to the analysis of ECG and R-R intervals.

3.1 The Delay estimating (on the base of Correlation method).

This method computes the autocorrelation of time series (EEG signal, row of R-R intervals). Having the correlation function, it is possible to estimate a value of a log at which the correlation function is peer zero (0) [12], and to use this value of a log for choice of a value of delay time at reconstruction of a phase space and in other evaluations where it is used (d_2, h_2, λ_1).

3.2 The Correlation dimensions, the Embedding dimensions and the Correlation entropy

This method is for evaluation of *the embedding dimensions* of an attractor of dynamic system of the brain, *the correlation dimensions* and *the correlation entropy.* That is for

estimation of those parameters of dynamic system of the brain which may be calculated on the basis of the correlation sum. It may calculate these parameters to the multivariate data.

3.2.1 The Correlation dimensions

The correlation dimension is designated in the literature as D_2 [11, 12]. It is performance of the dimension of an attractor of a dynamic system of the brain. *The correlation dimension* (d2) allows estimating complexity (dimension) of strange attractor, which reflects properties of neurodynamic systems on one researched lead. Fractional part of d2 allows to estimate a level of chaos on its size.

3.2.2 The embedding dimension

The embedding dimension (n) allows to make the supposition about how many components form a given neurodynamic system. It may calculate these parameters to the multivariate data.

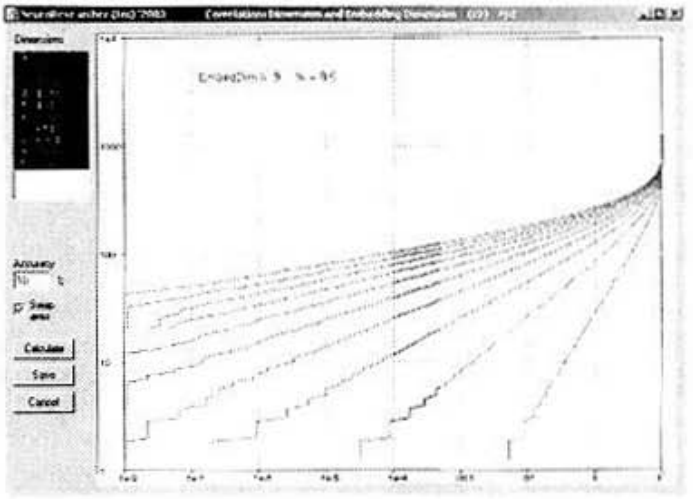

Fig. 5. The tool for manual visual estimation of the Correlation dimensions and the Embedding dimensions.

3.2.3 The Estimation of Nonlinearity

This mode allows estimating a degree of nonlinearity of bioelectric signals of the brain (or series of R-R intervals at analysis of Heart Rate Variability). The nonlinearity can be measured by method of the Surrogate data [12, 15].

3.2.4 The Correlation entropy

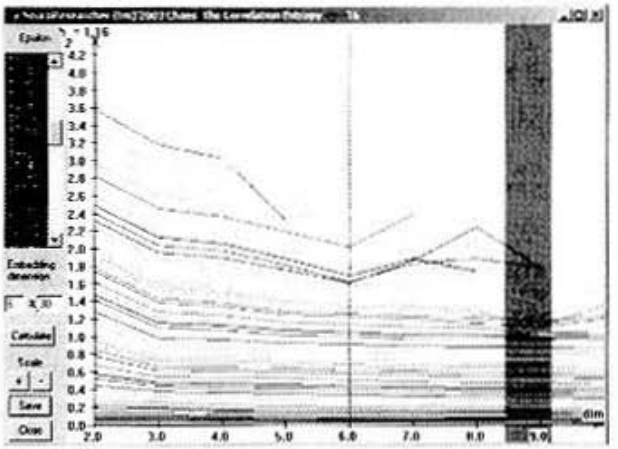

Fig. 6. The tool for manual visual estimation of the Correlation entropy.

This method is for evaluation of the correlation entropy. The entropy characterizes a degree of divergence close phase trajectories. It allows estimating an amount of the information, which is necessary for the prognosis of behaviour of dynamic system of the brain in the future. Differently, it allows estimating a time interval on which it is possible to make the prognosis (than less value of entropies on the greater interval of time is possible to make the prognosis) [11,12].

3.2.5 The Reconstruction of the phase space

This method allows reconstructing a phase space of the brain dynamic system on one measured coordinate of this system if no coordinates of a real phase space are accessible. The reconstructed phase space visually allows studying the data at dimension of this space peer 2 or 10. It allows making correct choice of delay for higher dimensional embeddings.

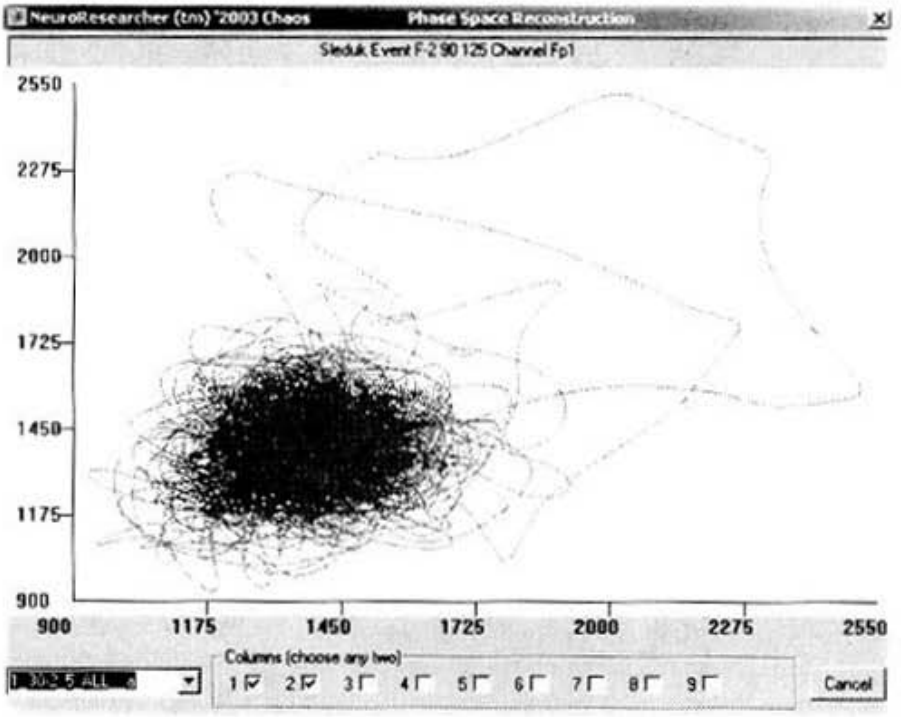

Fig. 7 The tool for reconstructed Phase space survey.

3.2.6 The Maximal Lyapunov exponent and the Maximal Lyapunov exponent viewer

The unit calculates maximum values of the Lyapunov exponents. This value is numerical performance of a degree of divergence of originally close trajectories and is performance of a randomness of behaviour of a dynamic system of the brain (dynamic systems of regulation and cardiovascular system on the basis of Heart Rate Variability analysis). If the value of maximum Lyapunov exponent is > 0 in a system there is a chaos [12, 13]. For check of reliability of evaluations we have created three various methods. The Maximal Lyapunov exponent viewer is created for manual visual inspection and manual evaluation of The Maximal Lyapunov exponent.

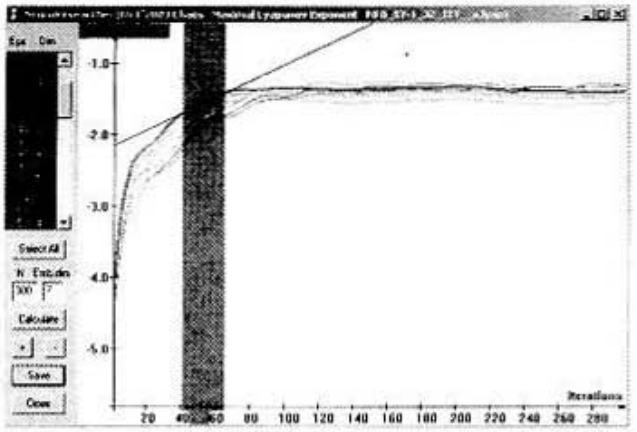

Fig. 8 The Maximal Lyapunov exponent viewer is created for manual visual inspection and manual evaluation of The Maximal Lyapunov exponent.

3.2.7 The Lyapunov spectrum

The spectrum of the Lyapunov exponents characterizes behaviour of a dynamic system of the brain (dynamic systems of regulation on the basis of Heart Rate Variability Analysis) is more thin, than only one Lyapunov exponent. On the basis of spectra of Lyapunov exponents it is possible to evaluate the Kolmogorov entropy [14]. The estimation of the Lyapunov spectrum of exponents is a difficult problem and number of exponential curves depends on the chosen dimension of the reconstructed space.

3.2.8 The Kolmogorov - Sinai entropy

This method allows estimating entropy of a dynamic system of the brain (or a cardiovascular system). The entropy characterizes a degree divergence close phase trajectories. It allows estimating an amount of the information, which is necessary for the prognosis of behaviour of a dynamic system of the brain in the future [12, 14]. Differently, it allows estimating a time interval on which it is possible to make the prognosis (than less value entropies on the greater interval of time is possible to make the prognosis).

3.2.9 The Deterministic chaos outcomes mapping

This unit shows results in all leads: 1.The Delay, 2.The Correlation dimension, 3.The Embedding dimension; 4.The Correlation entropy, 5.The Maximal Lyapunov exponent, 6.The Kolmogorov entropy. 6. The Surrogate data. Submode of measuring and displaying asymmetric leads only; possibility of 'freezing' interesting maps and storing them for various events and comparative viewing of stored maps for various events of one session (fig.9).

3.2.10 The Import of R-R intervals in the Deterministic Chaos application

Effectiveness of deterministic chaos methods is shown at the analysis of heart rate variability [16]. For this purpose there is unit, in which after detecting of R-peaks in the mode of *Heart Rate Variability*, gauging of R-R intervals these intervals imports as time series in the *Deterministic Chaos* unit.

3.2.11 The Archive and the Reference (normative) database

This unit is for automatic choosing of key metrics of spectral, multivariate and deterministic chaos analysis and their saving in the database. It allows choosing of homoge-

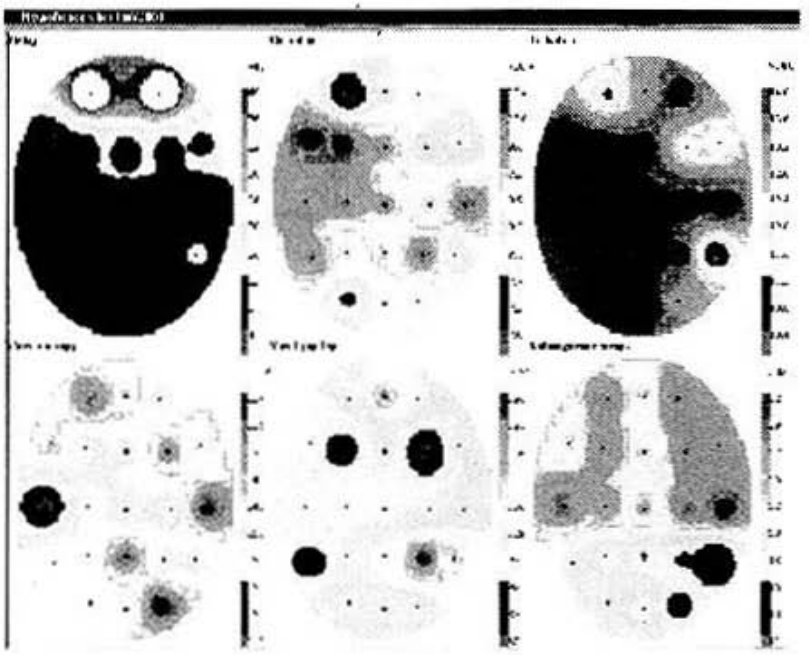

Fig. 9. The Deterministic Chaos outcomes mapping.

neous groups of patients and creating a statistical analysis of reference (normative) database on the basis of their outcomes.

4. Conclusions

The brain represents hierarchy of enough independent (autonomous) subsystems, in which one outgoing command signals from top level have no nature of rigid commands obeying to activity of all personal members more of low levels. Methods of multivariate system analysis and deterministic chaos allow to estimate properties of the separate elements, component of this or that system of the brain, and laws of interaction between them. These methods allow describing system and chaotic dynamics and to predict occurrence of chaos in those or other systems of the brain, enabling to predict the behaviour of chaotic systems, to operate their dynamics, enable to suppress chaos.
The criterion of occurrence of chaotic condition is the stability of formations originating in the brain system in relation to small perturbations (actions). If such stability is absent, the determined exposition of activity of the brain loses sense, and it is necessary to use statistical methods.
Quantitative EEG (qEEG) allows to apply circumscribed 'Multivariate analysis' and 'Deterministic Chaos' approaches for investigation of linear and nonlinear systems of the brain and inserting these methods in clinical practice and researches of the brain.

5. Summary

The Multivariate system analysis and Chaos theory are the basis for creating a qualitatively new approach for investigation of neurodynamic structure of cerebral mechanisms. These methods can be used to gain a better understanding and interpretation of observed complex dynamical behaviour of the brain systems. These methods can give an advantage in predicting or controlling brain state and behaviour.
Thus, this method is a perspective direction for brain system neurodynamic investigations by new medical computer technologies.

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