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Article in *Proceedings of SPIE - The International Society for Optical Engineering* · September 1993

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# Holographic associative memory and information transmission by solitary waves in biological systems

P.P. Gariaev, A.A. Vasiliev, A.A. Berezin\*

P.N. Lebedev Physical Institute, Russian Academy of Sciences,  
53 Leninsky Prospect, Moscow, 117924 Russia

\*Visiting Fellow, Princeton Engineering Anomalies Research,  
Princeton University, Princeton NJ, 08544-5263, USA

## Abstract

We consider some specific problems and phenomena of morphogenetic information storage, reproduction and transfer including phantom leaf effect and field-induced morphogenetic translations between different taxonomic units. Several experimental results are presented and their explanation is given using a new approach to morphogenesis which combines some physical models of holographic associative memory and mathematical formalism of Fermi - Pasta - Ulam recurrence for solitary waves in deoxyribonucleic acid.

## 1. Introduction

Some fundamental properties of eucaryote genome can not be reasonably explained in the framework of conventional biology. These phenomena include the genome "redundancy", its mosaic structure, splicing of pro- mRNA, mobile dispersive genes [1], coherent radiation of the chromosome DNA in the spectral range of 300-800 nm<sup>2</sup>, and finally the collective symmetry of genetic code whose nature appears to be artificial [3]. Understanding and explanation of the Kirlian photographs containing restored images of the removed parts of plant leaves present even more difficulties [4,5]. This phenomenon is usually referred to as phantom leaf effect and can apparently be an indication of some unknown important features of genome [5,6].

It is quite obvious that the striking success of genetic engineering can only emphasize the fact that the well known linear genetic code represents the protein synthesis code rather than the program of constructing multidimensional eucaryotic organism. This disagreement between genetics and embryology was predicted by A.A. Liubischev [7] and A.G. Gurwich [8] long before the above mentioned phenomena were found out. The contradiction became more significant when the problem of genetic degeneration of some nations arose due to the enormous environmental pollution whereas biological restoration techniques for radiatively and chemically damaged chromosomes are absent. This represents a strong motivation to develop new approaches to morphogenesis that would give relatively consistent treatment of the new experimental data and, which is more important, would provide a clear mechanism of developing an embryo to an adult organism. This paper presents some experimental results on phantom leaf effect (Section 2) and field-induced morphogenetic translations (Section 3). The experimental data are treated using a new approach to morphogenesis which combines some physical models of holographic associative memory and mathematical formalism of Fermi - Pasta - Ulam (FPU) recurrence for solitary waves in deoxyribonucleic acid (DNA) [6].

## 2. Associative memory considerations of phantom leaf effect

Phantom leaf effect is usually observed in Kirlian photography which is a type of electrophotography implemented using high voltage high frequency pulses applied across the object to be photographed [4,5]. In these experiments a freshly plucked leaf is sandwiched between two metal electrodes together with transparent insulation and a photographic film (the detailed description of the experimental arrangement, regimes and results can be found elsewhere [5,9]). With a pulse voltage of specific waveform applied to the electrodes a bunch of discharge channels out through the leaf, and an aura produced thereby is photographed directly on the film. If the leaves were damaged before the exposure, in some cases (about 5% of the trials) the developed photographs contained restored images of the inner structure and the profile of the removed parts of the leaves (Fig. 1). The phantom images can be also obtained with no discharge present when only ultra weak endogenous radiation of the leaves is registered.

When analyzing the nature of phantom images we used the concept of chromosome field which controls the embryo morphogenesis and the adult organism structure [6]. In the framework of this approach the phantom generation can be considered as an attempt of the organism (leaf) to reconstruct and regenerate its lost parts, which demonstrates associative properties of the chromosome field [5,6]. To explain this associative behavior we use the well known holographic associative memory approach [10-12]. To this end, we assume the morphogenetic information to be stored in the form of holograms distributed in so called redundant or selfish DNA which is estimated to be 95-98% of genome in higher biosystems [13]. In fact, the information capacity of the chromosome DNA molecule is actually high enough to store not only 1-D genetic codes but the complete scenario of the organism development in space and time. We now discuss possible holographic mechanisms of morphogenetic information storage and retrieval with attention to specific issues of coherent radiation sources, nonlinear storage medium and and holographic memory configurations which can be implemented in biological systems to satisfy the requirements of stability and reliability of the restored fields.

### 2.1. Holographic model of morphogenetic information storage and retrieval

To solve the problem of coherent radiation sources and, to some extent, of possible holographic recording and restoration configurations, the concept of local references [14] can be involved [6]. This concept is based upon the peculiarities of scattering electromagnetic waves emitted by a single atom, e.g. a heavy metal embedded in a DNA molecule. Consider a metallo-organic molecule with a single heavy metal atom in a well defined orientation, which is typical for liquid-crystal DNA. Irradiate the molecule with X-rays slightly above the  $K$ -edge of the heavy metal and observe the angular distribution of the characteristic X-rays emitted by it. In the absence of surrounding atoms, this radiation represents a spheric wave, which is assumed to be monochromatic. This assumption does not restrict the validity of the consideration as can be seen below. In the presence of the surrounding atoms some of the emitted photons are scattered. Assuming the presence of discrete atoms at positions  $r_i$  and weak scattering (see Fig.2b), the total electric field at the point of observation, at a distance  $R$ , can be written as

$$E = A \frac{\exp(i k R)}{R} + \sum_i \frac{l_i f_i(\Theta_i)}{r_i} \exp[i k_i(1 - \cos\Theta_i)] , \quad (1)$$

where  $k = 2\pi/\lambda = \omega/c$  is the wave number and  $A$  is the complex amplitude,  $l_i$  is the scattering length (possibly complex),  $f_i(\Theta_i)$  is an angular distribution. We can make now an important observation: the angular distribution of the characteristic radiation contains a fringe pattern, which is a hologram of the surroundings of the emitting atom. The fringes are of macroscopic dimension being always in the far field. This configuration is usually referred to as Fourier-Fraunhofer hologram [15]. The fringe visibility decreases rapidly with the distance of the scatterer from the emitter. The fringe pattern has an angular width of about  $(\lambda/r_i)^{1/2}$  in the direction of  $r_i$ , and  $\sim \lambda/r_i$  in the perpendicular direction. In case many similarly oriented molecules are present, each metal atom emitting a photon produces a hologram of its environment. The waves emitted by different atoms are incoherent and therefore do not interfere. Thus, if the metallo-organic molecules (crystallites) are oriented within an angle  $\delta$  (typically  $\sim 1^\circ$ ) all the individual holograms are in register within  $\delta$ . Therefore their incoherent superposition produces a single hologram that resolves the environment within  $r_i \ll \lambda/\delta$ . Also, the crystal size,  $L$ , should be smaller than  $R/r_i$ . Neither of these conditions imposes any practical limitations on the method. Note that, compared to ordinary holography, the coherence requirement of the source is easy to satisfy. The periodicity of the crystal is immaterial, so the holographic experiment could be done equally well on a liquid crystal (e.g. DNA), a stretched fiber, or a well oriented membrane.

The approach of local references can be easily extended to randomly assorted metal atoms ejecting photoelectrons and Auger-electrons. Some of the ejected electrons get scattered by the atom's environment producing the electron angular distribution described by the equation similar to Eq. (1). If this electron distribution is recorded an electron hologram of the emitting atom's closed environment is obtained. This mechanism is of particular relevance to the phantom leaf effect.

Let us discuss now the holographic recording and reconstruction problem. Suppose the hologram is linearly recorded on a sphere of radius  $R$ . Using Eq.(1) and assuming a strong reference wave or a weak scatterer, we can easily get the hologram transmission which is equivalent to the famous Gabor's hologram [15]. Indeed, being irradiated with a spherical incoming wave, which is the complex conjugate of the reference, this hologram reconstructs the field inside the now empty sphere: the light intensity inside the sphere reproduces the reference beam and the scatterer. If the first term is filtered out, the intensity of the second term reproduces the object, within the limitation of the uncertainty principle. Note that if the hologram is recorded on the full sphere, there is no doubling of the image (only one real image is reconstructed) and the resolution of about  $\lambda$  is achieved in all three dimensions.

Unfortunately the ideal recording and reconstruction conditions are not fulfilled even for linear medium response and stable recording/retrieval configuration. Since the reference and reconstructing waves acquire an additional modulation due to the scattering on the object, a more general holographic reconstruction problem is the following. Assume that a complicated, but known

(reference) wavefront interferes with an unknown (object) wave, and the intensity of the interference pattern is recorded on a sphere. Find an algorithm to reconstruct the source distribution of the unknown wave, whose intensity can be written symbolically as

$$I = r(R + O)(R^* + O^*) = r(RR^* + OO^* + RO^* + R^*O), \quad (2)$$

where  $r$ ,  $R$  and  $O$  are the reconstructing, reference and object waves respectively, symbol  $*$  denotes complex conjugate. The two principal terms,  $rRO^*$  and  $rR^*O$  can be recognized as real and virtual images of the object only if  $r = R^*$  or  $r = R$ , respectively. Moreover, for both cases, the reconstructed wavefront in the far field represents the Fourier transform  $F\{I\}$  of the field observed just behind the hologram containing the component  $F\{rRO^* + rR^*O\}$ , which is the convolution of the reconstructed object with the autocorrelation of the reference. Hence, undistorted image restoration is possible only for  $F\{RR^*\} = \delta(r)$  (delta-correlated reference [15]). And even in this case the other terms of Eq.(2) will introduce noise, affecting the accuracy of restoration. Thus Eq.(2) constitutes an ill posed problem due to imperfect knowledge of the hologram impulse response, i.e. the auto correlation  $F\{RR^*\}$ . It can be solved using optical data restoration technique, e.g holographic associative memory systems with feedback and iterative data recall [10-12]. An outstanding merit of such systems is their explicit and close analogy to Human brains, artificial neural networks [10,11] and the phantom leaf effect [5,6].

## 2.2. Holographic associative memory approach

An optical system with associative properties analogous to those of phantom leaf effect is illustrated in Fig.2a. The memory contents is stored in superimposed Fourier holograms, each of them being equivalent to the holographic matched filter of a stored image  $a_m$  recorded with angularly multiplexed plane reference waves  $B_m$ . The memory also includes optical feedback and nonlinearities in the correlation domain to improve system performance. To this end, the phase conjugate mirrors (PCMs) 7 and 8 are positioned in the object and reference legs of the holographic filter optical system.

Suppose the system input is an image  $\hat{a}_{mo}$  representing partial or distorted copy of one of the stored objects  $a_{mo}$ . Then, a set of partially reconstructed reference beams  $\hat{B}_{mo}$  is generated in the Fourier plane which corresponds to  $\hat{b}_{mo} = \hat{a}_{mo}^* a_m$  in the correlation domain [10]. Thus, each reconstructed reference beam is weighted by the correlation of the input object with the stored object related to that particular reference beam. The reference beams are phase conjugated by PCM 7 and reflected back toward the hologram, which reconstructs all the stored objects. In the resonator configuration of Fig.1a, the reconstructed object waves are phase conjugated by PCM 8 and incident back to the hologram, i.e. the feedback loop is closed. The process is iterated until a self-consistent solution of the system is found. The complete set of the solutions or eigenfunctions of the system is merely the stored object set. Nonlinearities in one or both of the PCMs tend to form the basin of attraction in state space around the stored objects. The output of the associative memory after PCM 8 (first iteration) is given by

$$\tilde{a}_{mo} = N\hat{L}_2 \left\{ \sum_{m'} \left( N\hat{L}_1 \left[ \sum_m (\hat{a}_{mo} * a_m) \otimes b_m \right] * b_{m'} \otimes a_{m'} \right) \right\}, \quad (3)$$

where  $a_m$  are the stored objects,  $b_m$  are the amplitude of their associated references in the input plane,  $N\hat{L}_1$  and  $N\hat{L}_2$  represent point nonlinearities of PCM 7 and 8,  $*$  and  $\otimes$  denote correlation and convolution, respectively. The double sum over the object subscripts  $m$  and  $m'$  is due to the light beam passing twice through the hologram. If the references  $B_m$  are assumed to be angularly multiplexed plane waves, the corresponding distributions  $b_m$  in the input and correlation planes are spatially displaced delta functions, i.e. point light sources. The separation  $\Delta x, \Delta y$  between reference functions  $b_m$  must be large enough to separate spatially different correlation/convolution terms in the reference leg. If the nonlinearities  $N\hat{L}_1$  and  $N\hat{L}_2$  are properly chosen (e.g., thresholding), then the self-consistent solution  $a_{mo}$  will ultimately be reached after several iterations, which is the nearest to  $\hat{a}_{mo}$  in terms of correlation distance measure.

In a simplified single-pass single-PCM configuration of the associative memory [10,12], a diffuser is placed in contact with every stored object  $a_m$  in order to sharpen the autocorrelation peak of the object relative to the sidelobes and to spread the image information over the entire recording area of the hologram. The diffuser encoding also results in suppressing the cross-correlation noise and in improving the SNR. Taking into account that most biological objects possess the optical properties of diffuse scatterer, and that they can reproduce in fine details their structure during growth and development, we hypothesize that the diffuse character of the light scattering may play an important role in the morphogenesis. The intrinsic and individual diffuser encoding of the biological structures can provide not only high information capacity and reliability of the morphogenetic data storage but may represent some kind of key code which enables the system to recognize and adopt objects (i.e. proteins) of its own structure and reject the objects of other structure. This can be treated as a holographic concept of immunity.

Since in the optical system of Fig.2 the hologram is imaged onto the PCM 7 in the correlation leg and object plane is imaged onto the PCM 8, the PCMs can be placed directly in the hologram and object planes respectively. In this configuration, the DNA molecule represents also an appropriate medium for four-wave mixing, which is the main basis for PCM in the considered model. In fact, the DNA possesses excimer and exciplex states, which provide the population density inversion and laser effect in DNA pumped *in vivo* by metabolism of a cell [9]. The pumped DNA constitute a nonlinear medium and two conjugated pump plane waves are formed in the far field by any two neighboring local references between them (see Fig. 2b). This configuration is similar to double optical phase conjugation scheme in which two mutually incoherent counter-propagating pumps exist [16].

Self-sustained waves (autowaves) give another way of information transmission through the active media with the population density inversion [17]. Two pump waves propagating through the active medium become self-oscillating, their waveforms being determined by the boundary conditions, i.e. both by the hologram stored in DNA ("micro-structure") and, on the other hand, by the object macro-structure. Such a system is highly redundant, because the stored information is

distributed and multiply replicated. Thus, any perturbation of the system parameters immediately produces an additional modulation of the field, which is intended to compensate for the distortions introduced in the system structure. We assume the phantom of the removed part of a leaf to be an image of that very probe and correction field, which is also expected to occur in the form of holographic regulator field during the embryo development.

In conclusion let us address some issues to be resolved in connection with the justification of the holographic model of genome. First we should point out some difficulties in describing and building the model of a holographic associative memory in which both the recording medium and the input object are uniformly distributed in some volume. The waveguide hologram appears to be most adequate to this configuration [18]. This analogy, however, calls for a more detailed study and justification. Another problem arises in considering mapping properties of holograms. A 2-D or 3-D hologram usually interconnects two planes (input/output isomorphism) of the holographic memory optical system. Even in the case of a 2-D object this hologram (i.e. interconnection matrix) is described by a 4-tensor [10,11]. Since a volume hologram allows clean interconnection with only three dimensions, the dimensionalities of the input and output objects cannot sum to greater than three, e.g. both input and output can be 3/2-D fractal objects [11]. Note that the transmittance of an ideal diffuser is also a  $(3-\alpha)$ -dimensional fractal ( $0 < \alpha < 1$ ) [19]. It has been recently pointed out that the DNA molecular structure displays fractal dimensionality as well.

### 3. Solitary-wave model of morphogenetic translations

As has been already mentioned, the coding of the biosystem structure may proceed in the form of autowaves and solitary waves, e.g., breathers, whose internal oscillatory structure is associated with a hologram in space and time domains, which stores and reconstructs specific spatial and temporal status of a developing or regenerating organism [6]. The formalism of this version is based upon the Fermi-Pasta-Ulam (FPU) recurrence phenomenon, which represents time periodic return of the energy spectrum of the initial perturbation in a distributed non-linear oscillatory system into its primary state without thermalisation [21]. It has been shown that the DNA molecule can be treated as a FPU resonator [6]. In this model the dynamics of electron density wave, distributed along the sugar-phosphate chains of the DNA is described by the non-linear Schrödinger equation. Hence, the electron density oscillations in the nucleotide structures can be considered as excitation point sources, uniformly distributed along the sugar-phosphate chain, representing a kind of a long electric line.

#### 3.1. Experimental morphogenetic translations

The proposed model of organizing genetic material can be useful for understanding the nature of biosystems distant interaction. Experimental investigation of distant interaction of biosystems was carried out using the primary embryo induction technique. Any induction includes two components: inductor tissue (donor) and induced part, i.e., target tissue (recipient). The donor tissue should be able to affect in some specific way the recipient tissue and stimulate its development. In turn, the recipient should possess sufficient competence to respond to this action and develop through corresponding embryo stages.

It was previously assumed that informative interactions between embryo tissues are possible only in mechanical way, e.g. due to the tension of cell membranes. A number of simple experiments show, however that embryo induction can occur also without mechanical contact of the tissues. Extracts from certain biological tissues acting on the recipient results in morphogenesis of corresponding embryo structures. Thus, morphogenesis (cell differentiation and structurogenesis) can be caused by the chemical action of specific morphogenetic substances whose influence on embryo is not clear either. Our model of morphogenesis allows us to assume donor and recipient tissues to interact by means of specific field generated by donor and modulated by genetic information in symbolic form. These fields can be also produced by morphogenetic substances.

In the experiments, the broad-band electromagnetic field was generated by specially designed electronic FPU-oscillator with a spatially distributed nonlinear resonator. It simulates hypothetical function of eucaryote chromosomes namely readout and translation of morphogenetic information from a certain biosystem to the genome of another biosystem being taxonomically identical to the first system. To verify this model we used the donor biosystem representing a tadpole of *Xenopus laevis* (a frog) at the stage NF 44-46 and the recipient biosystem being an ectoderm of early gastrula (outer layer of an embryo at an early stage of development) of the same frog at the stage NF 10 (the stages of embryogenesis have been classified according to [29]). Microsurgery operations, tissue cultivation and morphological analysis have been performed using conventional technique. Morphogenetic information translation was realized with 4 donors present inside the FPU-oscillator cavity and 24 accepters placed in Petri dishes with culture medium which were situated at distances 25 cm to 2 meters from the oscillator. The translations occurred when the FPU-oscillator was switched on during 5 minutes. The control experiments were made by switching on the oscillator for 5 minutes with no donors present.

The experiments demonstrated the possibility of morphogenetic information transfer by the broad-band electromagnetic field modulated by the living tissues of tadpoles of *Xenopus laevis* (donor) on the cell differentiation of an embryo tissue of the same species. In some cases (about 1%) the embryo tissues developed into the structures containing the complete set of mesoderm and neural derivatives of the primary embryo tissue (Fig.3). The differentiation was not observed in 100% of control experiments in which the donors were subjected to the action of "pure" broad-band electromagnetic field of the FPU-generator with no inductor tissue present. The results obtained confirm the soliton-holographic hypothesis of eucaryote genetic mechanism and cannot be explained in the framework of traditional concepts of biological morphogenesis.

### 3.2. Dynamic Light Scattering in DNA

Nonlinear dynamics of chromosomes including self-oscillations and solitary waves in DNA are relevant to the proposed model of morphogenesis. Thus, the search for actual nonlinear phenomena in DNA was an aim of this work. In studying nonlinear properties of informative biopolymers we used the photon correlation spectroscopy technique. For this purpose the Malvern spectrometers were applied along with correlators 4300 and K7032. The experimental conditions were similar to those described elsewhere. The samples of native highly polymerized DNA from calf's thymus were used. The control experiments to check possible background vibrations of the cuvette were made with a sample of silica gel possessing a strong light scattering.



In the experiments, a variety of quasi-periodically repeated self-oscillating correlation functions were obtained, which demonstrated the similarity to FPU recurrence (Fig.4). Most exciting are phantom autocorrelations observed in some cases after removal of the DNA samples from the cuvette space (see Fig.4c). Unfortunately, we cannot reasonably account for this phenomenon, which, however, appears to mimic the phantom leaf effect.

#### 4. Conclusion

In this paper, we have described several experiments, which can be explained in the framework of the proposed soliton/holographic approach to morphogenesis. The underlying principles of holographic storage and solitary wave transfer of morphogenetic information reveal some new aspects of genetic functions in biological systems which have never been known before. This new insight into the nature of morphogenesis makes it possible to treat genome as a biological-holographic computer which generates endogenous solitary electromagnetic and acoustic waves to carry 4-D epigenetic information used by biosystems for their spatial and temporal self-organizing.

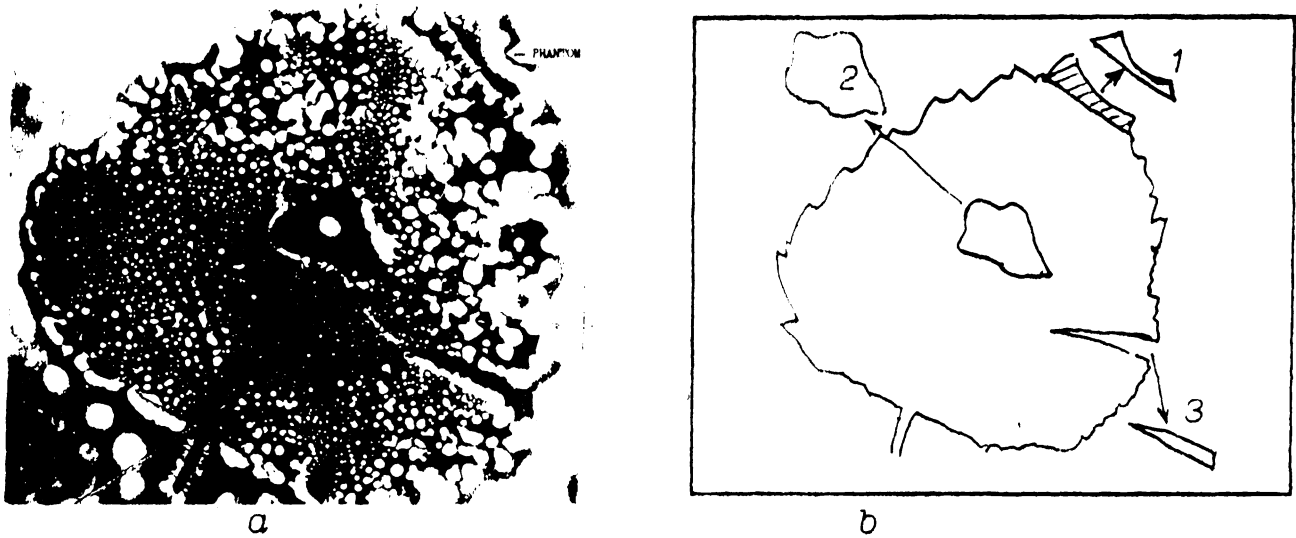
#### 5. Acknowledgments

The authors gratefully acknowledge a very helpful assistance of A.G. Kobzunenko, O.A. Khoperskaya, M.E. Bogdanov and O.V. Stolbovskaya in the experiments.

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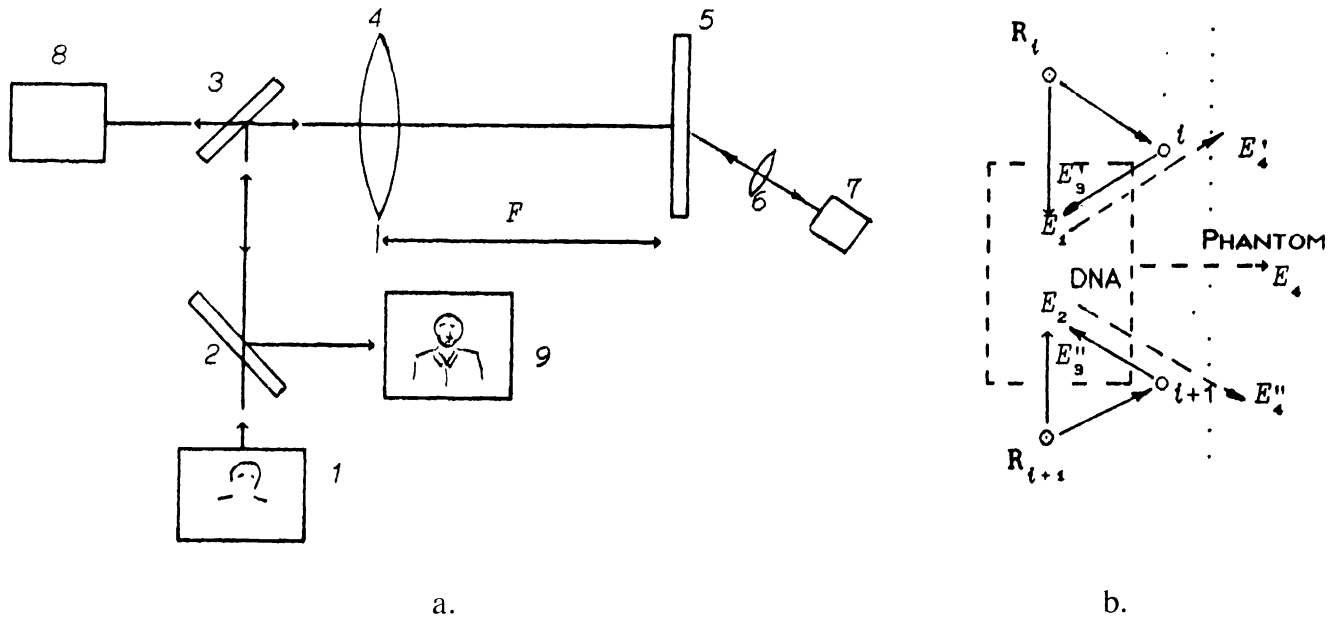
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a.

b.

Fig.1. Phantom effect on a birch leaf: a - Kirlian photograph containing phantom image of the removed part of the leaf edge (fragment 1); b - schematic of the sample preparation. No phantom is observed in the removed fragments 2 and 3.



a.

b.

Fig.2. Similarity between optical and biological holographic associative memory: a - optical associative memory with multiple-iteration recall; 1 - incomplete input image; 2,3 - beam splitters; 4,6 - lenses; 7,8 - phase conjugate mirrors; 9 - system output; 10 - reference beams; b - phantom image formation;  $R_i, R_{i+1}$  are local references;  $E_1, E_2$  are OPC pumps;  $E'_3, E''_3$  are signal (scattered) waves;  $E'_4, E''_4$  are the conjugate waves (phantom).

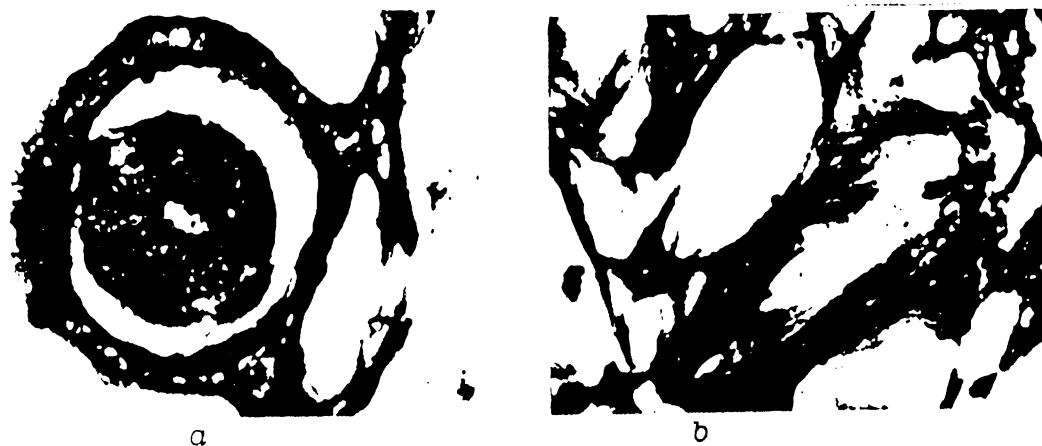


Fig.3. Photographs of a nerve fiber (a) and muscle tissue (b) which were developed from ectoderm of an early gastrula of *Xenopus laevis*. Magnification is 10×40.

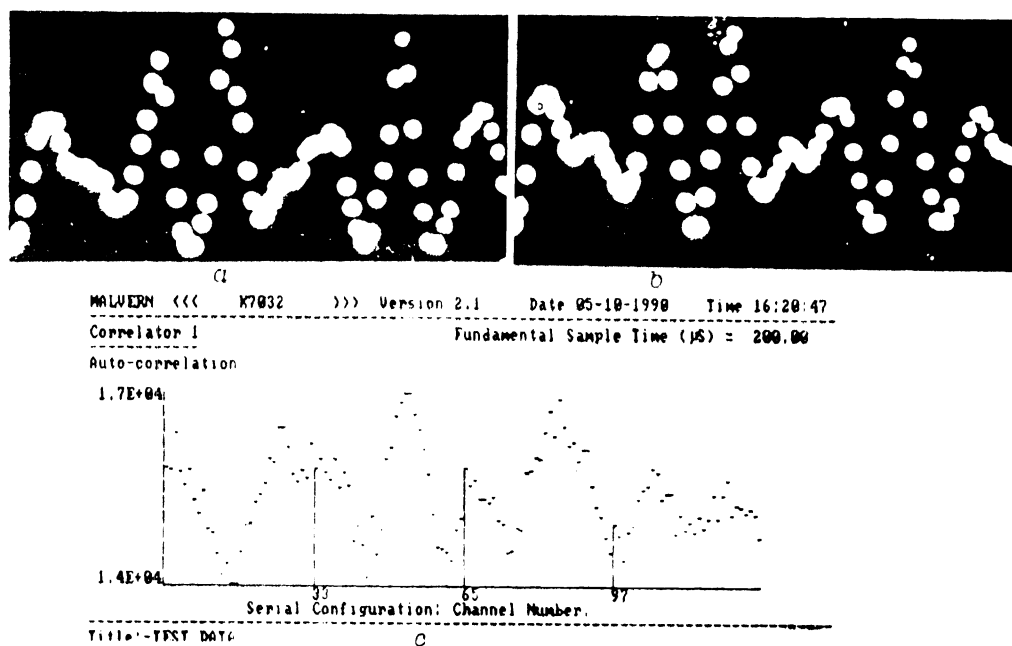


Fig.4. Autocorrelation functions of the light scattered on a DNA sample (hard gel) in the cylindrical cuvette of 1 cm diameter and 5 cm height. The angle of scattering is  $60^\circ$ ,  $\Delta\tau = 2000 \mu\text{s}$  per channel (correlator 4300). The repeated functions of plots a and b are obtained at 6 and 22 minutes after the beginning of the experiment. Intermediate functions dramatically differ from the functions of plots a and b. Plot of Fig.4c contains the phantom correlation obtained in spectrometer "Malvern-K7032" after the cuvette with DNA sample was removed from the cuvette space.