Physics – Uspekhi **57** (1) 37 – 65 (2014)

REVIEWS OF TOPICAL PROBLEMS

PACS numbers: **07.57.–c**, **61.20.–p**, **65.20.–w**, 83.10.Mj, 89.70.Cf

Long-term dynamic structural memory in water: can it exist?

G R Ivanitskii, A A Deev, E P Khizhnyak

DOI: 10.3367/UFNe.0184.201401b.0043

Contents

Abstract. There is no experimental evidence to support the hypothesis that water retains a memory of mechanical, magnetic, and electromagnetic influences it has been exposed to and of substances it has dissolved. After its solutes have been fully removed by repeated dilutions, the water does not remember having contained them or the external physical influences exerted upon it. There is no arguable reason that water should have a molecular information matrix capable of serving as long-term memory.

G R Ivanitskii, A A Deev, E P Khizhnyak Institute of Theoretical and Experimental Biophysics, Russian Academy of Sciences,
ul. Institutskaya 3, 142290 Pushchino, Moscow region,
Russian Federation
Tel. + 7 (0967) 73 24 81. Fax + 7 (0967) 79 05 53
E-mail: ivanitsky@iteb.ru, deev@iteb.ru, eugene@iteb.ru

Received 25 April 2013, revised 30 July 2013
Uspekhi Fizicheskikh Nauk **184** (1) 43 – 74 (2014)
DOI: 10.3367/UFNr.0184.201401b.0043
Translated by Yu V Morozov; edited by A Radzig

> *A macroscopic observer behaves like a military commander: he is not interested in the biography of individual molecules; in fact, individuality of molecules makes no difference for him since he has no means to identify them; even with the best will in the world, he can but determine the number of identical molecules whose position and velocity are confined within certain limits.*
> Marian Smoluchowski (1872–1917), "Limits of the validity of the second law of thermodynamics" [1]

1. Introduction

1.1 Topicality of the problem

To begin with, physicists continue to retain keen interest in water as a particular form of condensed media, even though water has been studied throughout the centuries from different viewpoints. An analysis of the contents of *Physics–Uspekhi* since its foundation in 1918 reveals over 50 reviews and research articles dealing with a variety of condensed matter theories. However, these theories can explain in full measure only the behavior of single-atom liquids. A water molecule ($H \rightarrow O \leftarrow H$) consists of three atoms, and its behavior cannot be comprehensively described by any existing theory.

Second, all organisms (both living and extinct) on this planet owe their existence to water and harbor, in fact, 99% of water. Terrestrial organisms contain less water than aqueous ones; still, water makes up a substantial part of any one of them. Normally, the body of an adult human weighing 70 kg contains up to 75% water, including 27.2 l (40%) of intracellular liquid, 20.4 l (30%) of tissue liquid and lymph, and 3.4 l (5%) of blood plasma. Fats of various compositions are the second most abundant component of the human body, but their content is much lower than that of water. The human body usually contains some 10.2 kg of fatty substances (including cell membranes), i.e., roughly 15% of the total weight [2]. All other components (proteins, and amino acids) account for only 10% of the body weight, even though it is these compounds that are responsible for the 'specificity' that makes human beings unique. Protein structures contain from 25 to 70 vol.% of bound water. A living organism cannot exist unless it is saturated with bound and free water [3].

Third, since Robert Brown discovered in 1828 that particles suspended in water execute permanent motion, this latter (termed Brownian motion) has become a subject of study as a form of chaos. To recall, J Ingenhausz was the first to notice movements of particles in a liquid as early as 1785, i.e., 150 years after Anton van Leeuwenhoek laid the foundation of optical microscopy. Leeuwenhoek himself observed movements of bacteria, spermatozoa, and protozoa in water that proved very similar to those of nonliving subjects (tiny charcoal particles on the surface of alcohol) discovered later by Ingenhausz. Particles $10^{-6}-10^{-8}$ m in size (soot or dust) suspended in a liquid execute stochastic motion under the effect of collisions with one another or with liquid molecules ('billiard model'). Brownian mobility was described theoretically by A Einstein and M Smoluchowski in 1905. The theory was extended by P Langevin in 1908. In the 20th century, however, many authors [3–13] wondered if Brownian motion is actually 'random'. The answer to this question was of importance not only for condensed matter physics but also for understanding diffusion-controlled processes in living organisms.

According to Einstein [14], the diffusion coefficient is proportional to the mean square of a particle displacement, on the one hand, and depends on the number of molecules in 1 mol of matter (the Avogadro constant), on the other hand. In other words, Avogadro's constant can be retrieved from measurements of Brownian particle displacements as described by J Perrin [15], who obtained the most probable value close to 6.85×10^{23} mol^{-1}. However, the Avogadro constant found by the X-ray scattering technique is smaller: 6.022045×10^{23} mol^{-1}. The discrepancy between the two values amounts to 14%, although Perrin believed that the error in his measurements did not exceed 3%.

Hence, the question: Is the above discrepancy physically meaningful? For example, the motion of Brownian particles may reflect a 'deterministic' water component, i.e., the presence of certain spatial structures in water. This problem remained in the focus of attention till the end of the 20th century.

Fourth, the hypothesis of spatial structures in water looked justified, since it stemmed from observations of its unusual specific properties. Water consists of polar molecules. It might contain spatial structural networks with temporal changes in the bonds [16, 17]. Each water molecule can form bonds with its neighbors. The specific thermal capacity, melting and boiling heats of water are abnormally high compared with those of other group VI hydrides (H_2Te, H_2Se, H_2S) [18]. Water has at least two markedly pronounced temperature extrema. Its specific heat capacity C_p is minimal at $\approx 35\,^{\circ}\mathrm{C}$, while maximum density occurs at $\approx 4\,^{\circ}\mathrm{C}$. The viscosity of water decreases rather than increases (as might be expected on the analogy with other fluids) with growing pressure. Its compressibility is low and temperature-dependent. Minimal isothermal and adiabatic compressibilities are recorded at about 45 °C and 60 °C, respectively [18].

Fifth, the ability of a liquid water sample to retain information about various external influences exerted upon it has been widely discussed over the last decades in the scientific literature, and especially in the mass media. Many casted some doubt upon such ability. Suffice it to mention publications even in *Homeopathe* journal [19], e.g., the article by José Teixeira entitled "Can water possibly have a memory? A skeptical view." Some 30 reports on water properties in biological systems (almost 10% of the total) were recently presented again to the *Fourth Congress of Russian Biophysicists*, held at N I Lobachevsky State University, Nizhny Novgorod, on 20–26 August 2012. The authors of 5 reports advocated the hypothesis for a *long-lived network* in water that is supposed to serve as an *information matrix and an element of long-term memory*. Similar reports were delivered at the *International Conference 'Water Structure: Physical and Biological Aspects'* (St. Petersburg, 11–16 September, 2013). With this in mind, the present review was designed to answer the question in the title.

1.2 Lessons from the past

Let us recall a scandal that broke out in the scientific community 25 years ago (1988). J Benveniste, an immunologist, and co-workers published a paper in *Nature* [20] in which they analyzed the binding force of antigen–antibody reaction. Today, this method is considered to be the most sensitive tool for detecting antibodies in a solution. Chemical laws state that the rate of an antigen–antibody binding reaction in an aqueous medium must decrease with a decreasing concentration of either reactant, and the reaction must terminate as soon as one of the reactants is exhausted.

However, the above authors revealed that the reaction rate did not decrease as the concentration of one of the reactants in an aqueous solution fell as a consequence of dissolution; instead, the reaction passed into an oscillatory regime, and its rate was not zero at any dilution of the solution with antibodies. In other words, the reaction continued in the absence of antibodies as well. It seemed that water not only 'remembered' the previously dissolved matter but also continued to exert an influence on human basophils.

The publication was accompanied by an editor's note predicting the revision of certain physical and chemical laws if J Benveniste's results were confirmed in other laboratories. Moreover, it was suggested that the experiment be reproduced under the observation of a group of experts. J Benveniste and his co-authors (Institut National de la Santé et de la Recherche Médicale, Paris) repeated the experiment designed as a double-blinding study in the presence of experts. Nothing like the previously reported effects could be seen. The expert opinion, under the title "'High-dilution' experiments a delusion," was published in the very next issue of *Nature*. It read as follows: *We conclude that there is no substantial basis for the claim that anti-IgE at high dilution retains its biological effectiveness, and that the hypothesis that water can be imprinted with the memory of past solutes is as unnecessary as it is fanciful.* Nevertheless, the discussion continued. The paper by P Coles, also published in *Nature*, was entitled "Benveniste controversy rages on in the French press" [22].

The debates have not yet subsided [23]. Many new hypotheses are offered that can be neither proved nor completely discarded [24–29]. It cannot be suggested *a priori* that 'pure' aqueous solutions containing active compounds in the past might store the 'memory' of them after they are removed and the transient process is completed, the more so since other experiments confirm the falsity of the hypothesis for the existence of long-term dynamic structural memory in water. But the question remains as to why serious researchers who can hardly be suspected of committing fraud fostered the discussion and why it still continues.

As mentioned above, this issue was also discussed at the *Fourth Congress of Russian Biophysicists* in August 2012, and at a conference in St. Petersburg in September 2013 with the participation of advocates of the hypothesis in question. It appears that each new generation of researchers tends to address this hypothesis, even if most 'new' arguments in its favor are nothing more than long forgotten and rejected ones.

The main argument in support of the hypothesis for the occurrence of dynamic structural information matrices in water is that it is impossible to explain the observed bioeffects of high dilution of biologically active compounds in water, i.e., different aspects of homeopathy, without assuming the availability of memory in water. Other arguments are drawn from the realm of condensed matter physics, e.g., *water behavior at the macrolevel is fairly well described, but its peculiarities at the molecular level are not known in full measure; meanwhile, water may exhibit new specific properties at the molecular level in vivo. Statistically significant therapeutic effects of multiple dilutions have been documented in clinical practice*.

The present review is designed to consistently disprove all arguments of advocates of the *water memory* hypothesis and show that the molecular mechanisms of water behavior are presently known perfectly well. Known equally well is their influence on macroscopic processes, which implies a negative answer to the question put in the title of this review.

2. Definitions. Description of water parameters. Hydration

2.1 Information and memory

It may be inferred from what was said in the Introduction that advocates of the *water memory* hypothesis mean two different *notions* by this term. First, water memory is understood as the ability to retain *information* about past maximally diluted solutes. This definition was proposed in order to explain the anticipated therapeutic effects of homeopathic medicines prepared so that the solution does not contain even a single molecule of the active substance. The second definition implies that by the *water memory* we mean stable correlations in its structure that change in response to external physical influences (acoustic, mechanical, or electromagnetic) exerted upon it and *remain, while in altered form, long* after the influences are discontinued.

A few remarks regarding the terminology being used are in order before presenting experimental evidence invalidating both conjectures about the existence in liquid water of the long-lived information matrix as the basis for so-called water memory.

To begin with, when methods of statistical thermodynamics were accepted by the entire scientific community, the *probabilistic* description of the processes was gradually substituted by the *informational* one. Such a substitution made it possible to clarify the interpretation of the second law of thermodynamics in applications to the mechanism of Carnot cycle processes and to assess from the new standpoint the conversion of energy from one form into another as it is being depreciated [30]. E Schrödinger proposed supplementing the notion of thermodynamic entropy by negative entropy. For brevity, L Brillouin called the latter quantity negentropy or *information* [31]. The reason for the introduction of the new term for the description of closed system behavior was very simple: the term *information* allowed describing the slowdown of continuous entropy augmentation inside the system of interest, where energy depreciated as it converted into heat, while the system tended toward equilibrium.

This situation can be illustrated by a simple example. Given the mean temperature of water is $\bar{T}$ and the temperature of a portion of it is T_1, the difference $\bar{T} - T_1$ may perform work regardless of which is higher, $\bar{T}$ or T_1. In either case, a thermal machine can be designed in which only directions of the thermal flows doing work are different. If the flow energy is not used to do work, the temperature gradually equalizes up to temperature fluctuations due to the thermal diffusivity of water. Entropy augmentation in such a system reflects the reduction in negentropy, i.e., information. It should be emphasized that entropy consists of adiabatic and nonadiabatic contributions. External influences disturb detailed balance. A boundary of equilibrium disturbance may persist for some time. However, such a boundary appears due to internal fluctuations in water even in the absence of external impacts. In this case, it is unrelated to the externally introduced information.

Second, each researcher appears to treat the term *information* in their own way. D S Chernavskii [32] distinguishes 19 definitions of *information*. For example, *information represents the remembered choice of a single variant out of several possible and equitable ones*. However, water does not choose variants under external influences. The choice is made by the one exerting such influence and not necessarily obeying thermodynamic laws or postulates of the information theory. Water responds to the action of an external agent by changing its internal state.

Furthermore, it is possible to estimate the amount of information I through *a priori* probabilities p_i as proposed by K Shennon [33], according to whom the information gain is proportional to the uncertainty lost. This author also specified requirements for its measurement through informational binary entropy H that must satisfy certain conditions. Shennon showed that this entropy has the form

$$H = -K \sum_{i=1}^{n} p_i \log_2 p_i \,, \tag{1}$$

where K is a constant necessary only for the choice of measurement units (bits, bytes, or other units of information). Shennon argues that the measure of entropy expresses the degree of uncertainty associated with realization of a random variable. In this case, $\sum_{i=1}^{n} p_i = 1$. Thus, entropy is the difference between the total information contained in a message and a part of it either known *a priori* or readily predictable. Expression (1) holds true when *a priori* probabilities p_i of the choice of the ith variant are not equal to each other $(p_1 \neq p_2 \neq \ldots \neq p_i)$. If $p_1 = p_2 = \ldots = p_i = \ldots = p_n$, formula (1) transforms into an ordinary expression for new (previously unknown) information I contained in the message:

$$I = H = K \log_2 n \,. \qquad (2)$$

The cause of such a transformation is evident. At $i = n$, one has $p = 1/n$, i.e., $-\log_2(1/n) = \log_2 n$.

However, the use of formulas (1) and (2) to describe processes in water is problematic, as discussed below in Section 2.2.

Third, M D Bal'makov tried to adapt the notion of information capacity to the description of condensed media. His article "Information capacity of condensed media" in *Physics–Uspekhi* [34] showed that *information* can be defined from the first principles of quantum mechanics as the number of minima of the adiabatic electron term when copying a polyatomic system.

However, this description is unproductive for water that constitutes a *nonequilibrium system changing its state with time*. If water residing in detailed (local) equilibrium is affected from the outside by changing some equilibrium condition (e.g., temperature, pressure, concentration of doping molecules, or external electromagnetic forces), the appropriate processes leading to compensation of the external influence become enhanced (as in any other system). This well-known principle was formulated by Henry Le Chatelier in 1884 and later substantiated from the thermodynamic standpoint [35, 36].

Fourth, the application of the term *memory* in relation to water encounters as many difficulties as the use of the term *information* does. *Memory* is a polysemic notion but related in any event to temporal characteristics of a system, responsible for its ability *to store information* about previous events of its disturbing for a long time. Operation of any data storage device is based on the use of a physical effect that brings the system into two or more stable states under the influence of external factors. Therefore, memory can be referred to as the ability to sustain a response to an external action over a certain *time period*. Then, *entropy* and *temperature* can be defined using the term *information*. In this case, *entropy* is said to be a measure of information in bits stored in numerous but very small (and therefore difficult to identify) molecular structures of water, while temperature is spoken of as a measure of thermal energy gain in the system as a result of the splitting of one bit of entropy. Thus, it can be concluded, based on the laws of thermodynamics, that *the entropy of water enhances as the temperature rises, which leads to the reduction of the amount of information, if any, that can be 'extracted' from water*.

Fifth, the definition of terms and language for the description of one or the other of the events is a matter of agreement. The essence of the notion of *memory* is *the storage of introduced information over a long time*. The notion of *long-term storage* needs to be clarified. How long should it be: seconds, minutes, years? Let us assume conventionally, bearing in mind the temporal scales generally used in real life, that a system having *memory* must store *information* for at least *a few days*. For many short-lived organisms, such as insects or bacteria, the interval measured in seconds may be considered as rather long. In other words, the *length of the period* during which information is stored should be considered a matter of agreement, too. After the external influence is discontinued, the length of this period depends on the characteristic time needed to reach *thermodynamic detailed equilibrium* in a given physical system, e.g., ice, water, or vapor. However, establishment of equilibrium in each parameter of a multiparameter system proceeds in a different way, because a hierarchy of various time scales simultaneously coexists. For example:

— femto- or picosecond time scales for hydrogen bond breaking are determined by the quantum-to-thermal energy ratio $h/k_{\mathrm{B}}T \sim 1.6 \times 10^{-13}$ s, where k_{B} is the Boltzmann constant, h is the Planck constant, and T is temperature;

— minute scales for the establishment of equilibrium between gases dissolved in water are determined by diffusion transfers in water (diffusion coefficient $D \sim 10^{-10}$ m^2 s^{-1});

— hour scales for water cooling are determined by diffusive heat transfer, i.e., water thermal capacity and diffusivity $\chi_{\mathrm{w}} \sim 10^{-7}$ m^2 s^{-1};

— many-hour scales for convective mixing of water due to its volume expansion and evaporation in open containers (water volume expansion coefficient $\beta \sim 10^{-4}$ K^{-1}), etc.

Problems with nonzero initial conditions are characteristic of water, because none of its states is an equilibrium system in the full sense of the word. Water always stores the thermal energy maintaining movements of its molecules. The hierarchy of temporal scales creates the hierarchy of spatial scales s_i.

Evidently, quantum transitions should be used as measuring tools to register individual molecular events in water. The borderline between classical and quantum mechanics was first drawn in 1958 by Niels Bohr, who wrote in his book *Atomic Physics and Human Knowledge* (chapter Quantum Mechanics and Biology) [37]: "*It follows from determinism inherent in classical physics that any perturbation of a system consisting of a huge number of parts inevitably leads to chaotic disorder. In quantum physics, this description reflects the result of interaction between stable atomic systems; therefore, it is based on the outcome of competition between various individual processes. These processes determine in a simple way the state of new systems via atomic particles they contain similar to how they would determine the initial state of the system. Analogous descriptions with due corrections correspond to chemical kinetics.*"

A continuous emergence of molecular disorder in water would erase structural memory, if any. Moreover, the process of measuring itself enhances entropy and destroys information. Bohr consistently emphasized the presence of the *principle of complementarity* in research. This principle can be illustrated by a simple example of surveying a certain landscape in two electromagnetic wavelength ranges (Fig. 1a, b).

Bohr's principle of complementarity is rather simple. Each substance (process) has a hierarchy of forms (external appearances) determined by the nomenclature of constituent chemical elements, their spatial arrangement, bonding forces between them, rates of their temporal and spatial changes under ordinary and extreme conditions, which are responsible for structural distortion, and, finally, structure self-healing time. High-sensitivity infrared (IR) matrix imaging proved instrumental in studying the behavior of water by making possible visualization of time-related changes in *water macrostructure*. However, this method has many limitations as well; specifically, it does not allow one to observe molecular events creating such macrostructures. Other methods are needed for this purpose (see Section 4.1).

The totality of infinitely large numbers of collisions between water molecules transforms into macrostructures on a different (larger) spatial–temporal scale. For this

Figure 1. The *principle of complementarity* as exemplified by two images of one landscape. Photographs (a) and (b) were taken simultaneously: (a) in visible light, and (b) in IR light with a wavelength of 3–5 μm; (c) difference image between (a) and (b). Water fairly well absorbs IR waves; therefore, clouds and other water-saturated elements of the landscape are clearly visible.

reason, it is necessary to simultaneously take into consideration several (at least two) hierarchical levels to better understand processes proceeding in water. The starting point for the coupling between spacetime layers is the resolution of the force acting on a particle (ion, molecule, or molecular cluster) at any hierarchical level into systemic (friction $-\alpha v_t$ or viscosity; see Section 2.3) and random (F_t) components, the latter arising from the ceaseless thermal motion of water particles. Newton's classical mechanics makes it possible to write the equation of motion:

$$m\dot{v}_t = -\alpha v_t + F_t \,. \tag{3}$$

Because the force F_t originates from numerous collisions between light particles (ions, molecules) and various heavier molecular clusters (the mechanism of their formation is considered in Section 4.1), it may be suggested that F_t changes on a fast-time scale. After dividing both parts of Eqn (3) by mass m, it can be written out in the form

$$\dot{v}_t = -\gamma v_t + \xi_t \,, \tag{4}$$

where $\xi_t = F_t/m$. Assuming ξ_t to have short but nonzero memory, one can interpret expression (4) as a system of ordinary differential equations for trajectories; this means that the problem can be solved using the path-wise method. This simplified approach in terms of classical mechanics hardly poses a serious risk, assuming that water's linear behavior at the molecular level is valid. The solution to Eqn (4) has the form

$$v_t = v_0 \exp\left(-\gamma t\right) + \int_0^t \xi_s \exp\left(\gamma(s-t)\right) \mathrm{d}s \,. \tag{5}$$

Here, it is assumed that the time interval $[s, t]$ can be broken down by a sequence of points, i.e., $s = t_0 < t_1 < \ldots < t_n = t$. Then, the discrete time becomes continuous if the step tends to zero as $n \to \infty$.

If distribution of velocities v_t is Gaussian and starting velocity v_0 is a function of average water temperature prior to exposure to an external influence, this initial condition will depend only on the reservoir temperature. The process is then fully characterized by the mean value $\overline{X}\{v_t\}$ of one of the time-related water parameters X, and by the correlation function $X\{v_t, v_{t+\tau}\}$ that describe structural changes.

Because ξ_t varies on a fast-time scale, the stationary process function over space, $Y\{\xi_s, \xi_{s'}\} = \varphi(s - s')$, must have a sharp peak near zero and tend to vanish with decreasing $|s - s'|$ over the time scale. For Gaussian distribution, it can be assumed that under quasiequilibrium conditions $v_0 = \bar{v}$, where $\bar{v}$ is the mean molecule displacement rate, and the mean characteristic time of a molecule displacement is $\bar{\tau} = 1/\bar{\gamma}$ [see expression (3)]. Mean times of particle displacement by $\bar{l}$ are different for each reservoir temperature: $\bar{l} = \bar{v}\bar{\tau}$.

The value of $\bar{\tau}$ is of the same order of magnitude as the time during which local equilibrium is reached in a distinguished microvolume $V \sim \bar{l}^3$ of the liquid, where $\bar{l}$ is the mean molecule linear displacement [38]. Given that the reservoir size L is much bigger than $\bar{l}$, i.e., $L \gg \bar{l}$, transition from local to overall equilibrium includes many random collisions at the molecular level. The reservoir needs to be temperature-controlled in order to prevent large variations in the number of collisions. For example, characteristic time τ_T of temperature equalization in a reservoir of size L is estimated as

$$\tau_T \sim \frac{L^2}{\chi} \,. \tag{6}$$

Because thermal diffusivity χ of water is proportional to $\bar{l}^2$, one obtains

$$\tau_T \sim \left(\frac{L}{\bar{l}}\right)^2 . \tag{7}$$

In other words, the *time period needed for thermodynamic equilibrium to be reached* increases by a factor of $(L/\bar{l})^2$. It is therefore clear that *time intervals depend on the size of the system*. What we survey in the ocean [39–45] cannot be observed in a Petri dish; on the contrary, what we reveal in thin layers in a small dish at small times [46–58] passes unnoticed in the ocean.

Sixth, *the time interval during which information is stored* after cessation of an external influence on water, including removal of dissolved substances (e.g., by distillation or multiple dilutions), is always *limited* (as in any physical system). In engineering, *memory* is usually realized by means of a *threshold triggering mechanism*, one state of which can be assigned value 1, and the other 0. However, memory in liquid water can be created in a different way — from long-term relaxation after cessation of excitation. Even if the recorded parameter of interest, e.g., local temperature, varies with time in a transient process, the introduction of the registration threshold for local temperature variations leads to the appearance of two states. The suprathreshold state can be regarded as 1, while the subthreshold one as 0. In physics, such a time interval is usually referred to as *characteristic relaxation time* [39].

Strictly speaking, the time interval needed to reach *complete thermodynamic equilibrium* is infinitely long; nonetheless, relaxation always leads to a situation in which parameters X_{ij} describing the state of the system (e.g., density ρ, temperature T) are virtually indistinguishable from their equilibrium mean values $\overline{X}_{ij}$. This difference cannot be detected, because the registration of minor changes requires that high energies be introduced into the system. As a result, it is the system's reaction to the process of measuring that is assessed rather than the time interval of interest. Notice that the rates of change with time correspond to the expressions [59]

$$\dot{X}_{ij} = \frac{\mathrm{d}X_{ij}}{\mathrm{d}t}\,, \qquad \dot{X}_{ij} = -\frac{1}{\tau_{ij}}\left(X_{ij} - \overline{X}_{ij}\right).$$

Whence, we arrive at

$$X_i(t) - \overline{X}_i = \left(X_i - \overline{X}_i\right)_{t=0} \exp\left(-\frac{t}{\tau_i}\right) \tag{8}$$

for each jth parameter, where time interval τ_i is the *relaxation time* or the *characteristic time* needed to reach equilibrium in the ith parameter. The quantity $1/\tau_i = \nu_i$ can be called the *relaxation frequency*. Evidently, a physical system in which the equilibrium of certain parameters is reached may also have other parameters departed from equilibrium for some time, i.e., it has not yet reached the full equilibrium state. From the standpoint of a statistical thermodynamic description, *entropy increases and the stored information is lost* as all initially nonequilibrium processes come to equilibrium [31]. Examples of information restoration mechanisms within a relaxation time interval are considered in Section 2.2.

Seventh, as shown in Section 4, liquid water cannot, in principle, serve as long-term information storage, since it is subject to unavoidable and uncontrolled continuous changes in the course of its movement. Even ice, where dislocations, internal stresses, and displacements take place, cannot be regarded as being in absolutely stable equilibrium (see Section 4.2), whereas liquid water undergoes surface evaporation. In a word, liquid water constitutes a nonequilibrium system in which only *detailed* (*local*) *balance* can exist due to the *quasi-equality of continuous* direct and reverse transitions between its discrete states. These processes are always accompanied by deviations from full equivalence of direct and reverse transitions. It will be shown below that a failure to satisfy the condition of full equivalence leads to the destruction of any molecular matrices (hence, long-term memory) in water.

It appears appropriate to clarify the notion of *detailed balance principle* employed in describing condensed systems in both classical physics and quantum mechanics. In general, this principle can be formulated as the equality between the probabilities of transition related to the final *quasistable state*. The following condition must be fulfilled for the final equilibrium state:

$$\frac{\mathrm{d}p_n}{\mathrm{d}t} = \sum_{n \neq m} \left(\varpi_{mn} p_m - \varpi_{nm} p_n\right) = 0\,, \tag{9}$$

where t is time, $p_m \sim \rho_{mm}$ and $p_n \sim \rho_{nn}$ are the probabilities that the system resides in states m and n corresponding to the diagonal elements of density matrix ρ_{ij}, ϖ_{nm} is the probability of direct transition of the system from state n into state m, and ϖ_{nm} is the probability of reverse transition. Detailed balance implies that only certain members of sum (9) equal zero, namely

$$\varpi_{mn} p_m = \varpi_{nm} p_n\,, \quad \text{or} \quad \frac{\varpi_{mn}}{p_n} = \frac{\varpi_{nm}}{p_m}\,. \tag{10}$$

For closed isolated systems, the principle of detailed balance is reduced to equality $\varpi_{mn} = \varpi_{nm}$, because $\rho_m = \rho_n$ (hence, $p_m = p_n$). It seems that these conditions are satisfied by a water-filled reservoir covered with a lid to prevent evaporation at constant temperature and pressure. For an open system interacting with another (bigger) system, one finds in accordance with the detailed balance principle:

$$\frac{\varpi_{mn}}{\varpi_{nm}} = \exp\frac{E_n - E_m}{k_{\mathrm{B}} T}\,, \tag{11}$$

where E_n and E_m are the energies of states n and m, respectively. For a vapor, as for a gas obeying the Boltzmann statistics, this principle takes the form of the Fokker–Planck equation relating the rate of probability change in time t to the energy maximum coordinates over space x. For the one-dimensional case, the Fokker–Planck equation assumes the simple form [38]

$$\frac{\partial \varpi}{\partial t} = \frac{\partial}{\partial x}\left(D\,\frac{\partial \varpi}{\partial x}\right), \tag{12}$$

where D is the diffusion coefficient.

If a near-equilibrium system is subjected to the action of an external agent, this equilibrium shifts in the direction in which the effect of this influence weakens. This Le Chatelier principle is applicable to transient processes in any system, including water, tending toward equilibrium (e.g., the Lenz effect, and Peltier phenomenon). In condensed media, elevated pressure shifts equilibrium toward reactions responsible for a volume decrease. A rise in the concentration of parent substances and the removal of reaction products lead to the shift of equilibrium toward the direct reaction, etc.

Introducing the term *information* would hardly add a new aspect to the flow of condensed media studies. Researchers of condensed media, including water, have managed without it for two centuries. But today the terms *memory* and *information* are interrelated. Therefore, in this review dealing with water *memory*, we cannot do without an information-based description of processes in this fluid.

2.2 Discussion topic in terms of the theory of information

Three types of models of systems remembering information can be arbitrarily distinguished, namely static determined, dynamic determined, and dynamic determined-stochastic models. The differences among them can be illustrated by simple examples.

Figure 2 displays variations in image quality with time, characteristic of any printed image. With time, it fades, the paper turns yellow, the picture disappears, and the paper disintegrates. If the amount of information is denoted by I_0, then, in accordance with formula (2), writing in binary code at $t = 0$ yields

$$I_0 = k \log_2 N\,, \tag{13}$$

where N is the number of points (pixels) in the image space, and k is the number of intensity gradations recorded at each

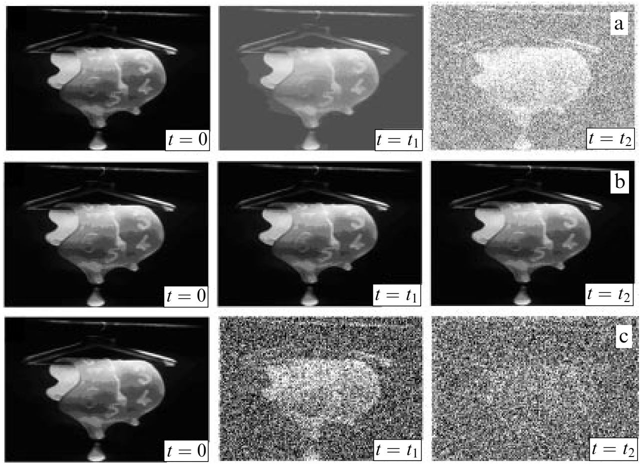

Figure 2. Image metamorphosis for (a) static determined memory, (b) dynamic determined memory, and (c) dynamic determined-stochastic memory.

point of the image. The amount of information I will decrease (Fig. 3a) according to the law

$$I = I_0 \exp\left(-\frac{t}{\tau}\right). \tag{14}$$

If the signal amplitude has k gradations and they are assessed using log base b instead of 2, then

$$I_0 = k \log_b N. \tag{15}$$

The value of k at the reference points can be determined with an accuracy admissible by the signal/noise ratio. It follows from the theory of information that in the case of equiprobable appearance of the image signal amplitude at any point, the entire range of amplitude changes can be broken down into k gradations:

$$k = \sqrt{1 + \alpha \frac{P_\mathrm{s}}{P_\mathrm{n}}}, \tag{16}$$

where P_s is the signal power, P_n is the noise power, and α is the assurance factor depending on signal and noise statistical properties. The presence of unity in the expression under the root sign is due to a certain level (e.g., black) for zero signal energy. The phase portrait of a system having such static determined memory has the form of a spiral shrinking to a point (Fig. 3b).

Figure 2b demonstrates how the quality of the image changes with time for static determined memory in the absence of noise. Such a change might correspond, for example, to a feedback system that periodically restores information at a low noise level. It is not difficult to create a technical model of such a dynamic determined memory setup. Figure 4a shows a variant of this device consisting of a digital camera tube and a digital monitor coupled with feedback loop.

It may be thought that the fulfillment of condition $P_\mathrm{s} \gg P_\mathrm{n}$ prevents the loss of information, $I_0 = \mathrm{const}$ (Fig. 4b), and ensures that the system has long-term dynamic memory, with the information retention period depending on the lifetime of the system's elements and the reliability of the energy supply to the elements maintaining feedback (in the present case, the digital monitor and the television picture tube).

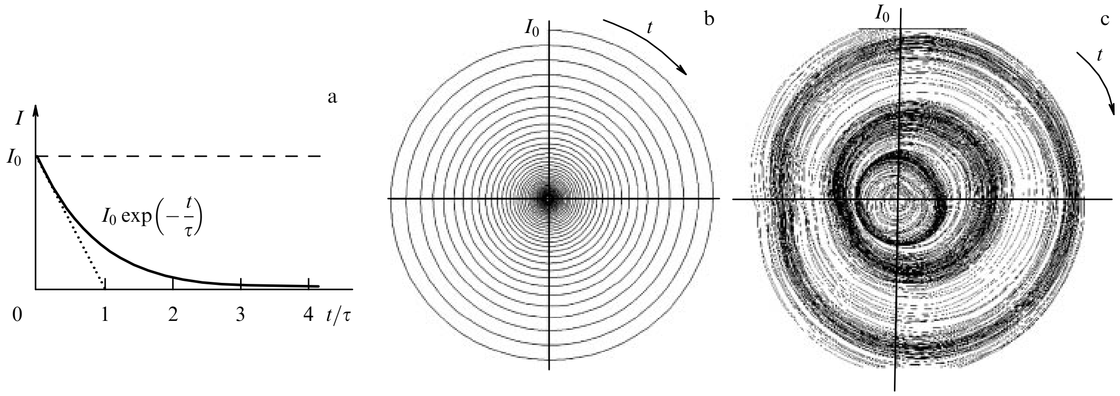

Figure 3. Variation of the amount of information in systems having static determined memory: (a) in Cartesian coordinates, (b) in polar coordinates disregarding noise, and (c) in polar coordinates taking account of noise (one of variants).

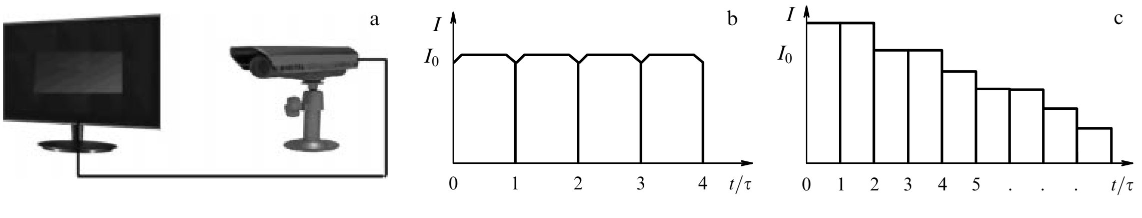

Figure 4. Feedback system: (a) television camera tube with the frame rate τ receives a picture from a monitor and again displays it on the monitor; (b) the time-varying amount of information in such a system in Cartesian coordinates disregarding noise is practically independent of time; (c) the time-varying amount of information in such a system in Cartesian coordinates taking account of noise depends on time.

Proponents of long-term dynamic structural memory of water argue that it contains something like such a feedback device because water constitutes a nonequilibrium open system with a dynamic permanently recoverable molecular structure based on hydrogen bonds and van der Waals forces. Such a structure could dynamically retain its appropriate information for a long time. Is it true?

In accordance with expressions (14)–(16), a system with $P_s \geqslant P_n$ must rapidly lose information: $\lim I \to 0$ as $\tau \to 1$ and $t \to \infty$. Let us assume that we are dealing with an ideal one-dimensional feedback system with a wide transmission band (similar to that in Fig. 4a) in which signals co-exist with 'white noise'[1] (i.e., thermal noise with a uniform spectrum and Gaussian amplitude distribution), and information at each point is simultaneously renewed at instants of time $n\tau$, i.e., at integer values of t/τ. The following may be expected:

(1) the signal is present if $A/2$ (where A is the signal amplitude) at a given point is higher than the noise amplitude;

(2) the signal is absent if $A/2$ at a given point is lower than the noise amplitude.

However, this inference is wrong, since it takes no account of noise dispersion. In the case of white noise, the probability of an error function of a one-dimensional random quantity x is expressed as

$$p_1 = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{\lambda^2}{2}\right) d\lambda\,, \tag{17}$$

where $\lambda = x - \mu$, with μ being the mathematical expectation of noise as a random quantity. With such a probability distribution, the statement that *the exceeding of* $A/2$ *over noise amplitude necessarily indicates the presence of a signal* may be wrong. The error probability in a Gaussian distribution is $p_2 = 1 - p_1$ or $A/2\sigma$; whence it follows that

$$\frac{A}{2\sigma} = \sqrt{\frac{P_s}{4P_n}}\,, \tag{18}$$

where σ is the mean-square noise value, with the signal power being $P_s \sim A^2$, and the noise power $P_n \sim \sigma^2$. The P_s/P_n ratio rapidly decreases with decreasing signal power P_s. Even a small reduction in the P_s/P_n ratio renders the problem of information storage at any point of the system unresolvable. Information will be lost even if the information loss histogram has flat portions, as shown in Fig. 4c.

Figure 2c illustrates the appearance of some image noise with the admixture of white noise to a feedback system. The phase portrait of a system undergoing noise-induced reduction of the information content (Fig. 4c), as well as that of the system with noise presented in Fig. 3c, becomes a strange attractor.

This brings up the question: Is it possible to improve an image by periodically removing its related noise through the agency of feedback? No, it is practically impossible, because for reconstructing the image one should know the contribution of noise and its distribution in time. Moreover, a decoder is needed that would free the image from noise during each feedback operating cycle. In other words, the decoder must 'remember' the previous image and compare it with the new one, i.e., it must have memory. If the state of memory at a given ith instant of time is denoted by β_i and the next image by X_i, function $y_i = f(\beta_i, X_i)$ will be a coded notation of the image X_{i+1}. In this case, memory must assume a new state also dependent on X_{i+1} and β_i at each consecutive step of freeing signal from noise:

$$\beta_{i+1} = g(\beta_i, X_{i+1})\,. \tag{19}$$

This leads to the recurrent operation that could conserve the initial information unaltered. However, the decoder must have an *infinitely large memory* in order to store information for a long time. This result of C Shannon (Shannon's seventh theorem)[2] is in line with the situation in thermodynamics where only a totally reversible process does not change entropy, whereas an irreversible one increases it [31, 33].

There is one more problem. Specifically, a certain interval between the neighboring levels of code combinations on the gradation scale is needed. This condition is indispensable to ensure separation of noise dispersion in the neighboring levels. This is intuitively understandable, because reading any text written without spaces between words is difficult, and the perception of information contained in text messages can be grossly distorted.

Let us denote this interval by $\theta\sigma$, where θ is constant, and σ is the mean-square noise value. The total range of amplitude assessment is given by $\pm\theta\sigma(k-1)$. A useful signal power extremum appears as a function of $\theta\sigma(k-1)$. Given the function is symmetric with respect to zero, the minimal value of the extremum falls within the interval [60]

$$\left(-\frac{\theta\sigma}{2}(k-1)\,,\; \frac{\theta\sigma}{2}(k-1)\right). \tag{20}$$

The mean signal power, on the assumption of equal probability for all levels, has the form

$$\overline{P}_s = \theta^2\sigma^2\,\frac{k^2-1}{12} = \theta^2 P_n\,\frac{k^2-1}{12}\,. \tag{21}$$

Expressions (18)–(20) can be interpreted in terms of water parameter extrema. On the one hand, *a rise in water density* at around 4 °C (Fig. 5a) corresponds to the minimal value of the necessary signal. On the other hand, decomposition of water molecules, say, into H^+, $(OH)^-$ or H_3O^+, $H_5O_2^+$ ions, etc., as well as the relatively long presence of these ions in water, may correspond to a change in log base b in expression (15) for heated water having *minimal thermal capacity and low isothermal compressibility at* 40 °C (Fig. 5b, c).

According to Boltzmann, entropy S_0 has the form $S_0 = k_B \log_b N$. This expression coincides with Eqn (13) for information (N is the number of microstates). The distinction between entropy and information is only that they have different signs and are antipodes. Entropy is an analogue of lost information (in the present case, a function of noise), while information is a function of the signal.

In cold water possessing maximum density, all rates of transient processes slow down and relaxation times increase; therefore, information introduced by some means or another is stored longer and entropy rises more slowly. Conversely, relaxation times in warm water decrease, the information lifetime shortens, and entropy grows faster. In any system, both noise and signal distortions tend to accumulate. The bigger the system, the stronger the noise.

---

[1] Such noise occurs in the presence of light-scattering particles between the camera tube and the monitor.

[2] Shannon's seventh theorem reads as follows: *any technical device* (*either coding or decoding*) *reduces and at best stores the available information.*

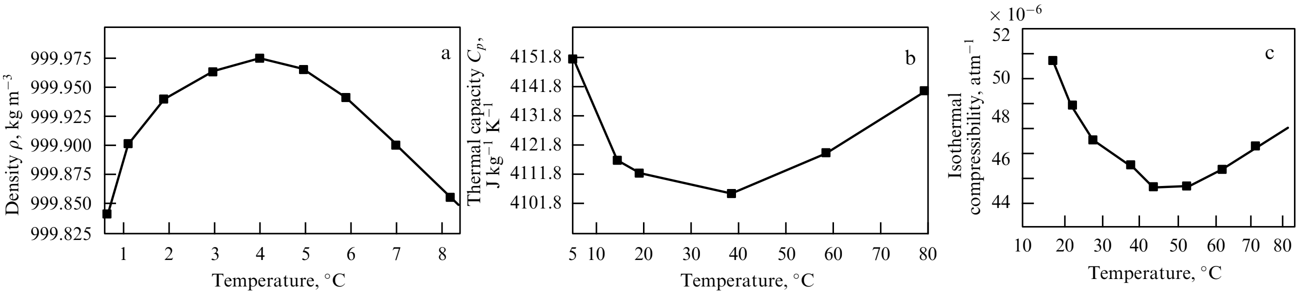

Figure 5. Temperature dependences of liquid water parameters showing extrema under constant atmospheric pressure.

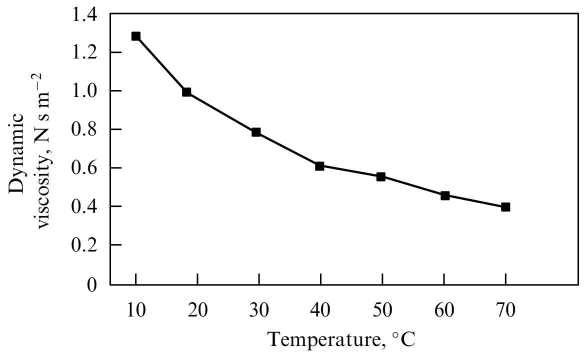

Figure 6. Temperature dependence of the water dynamic viscosity under constant atmospheric pressure.

Any reaction in water proceeds faster as temperature increases. Photodissociation of water induced by ultraviolet (UV) radiation results in decomposition of its molecules into H^+ and $(OH)^-$ ions. Another well-known reaction is radiolysis of water under the action of ionizing radiation with the formation of H_2, H_2O_2, and free H^+, $(OH)^-$, HO_2^{-5} ions. In this process, four water molecules are decomposed on the average for each 1.6×10^{-17} J of energy [61].

In water, as in any fluid, viscosity slows down relaxation processes, but viscosity itself depends on temperature as well (Fig. 6).

2.3 Possible inaccuracies in interpreting the term 'viscosity'

The probabilities of microstate processes for slow relaxations in liquids are, generally speaking, unequal. In *molecular liquids*, kinetic coefficients are expressed through probabilities of collisions, not only between individual molecules but also between their ensembles, i.e., aqueous clusters of same temperature in which molecules are bound by hydrogen forces and van der Waals attractive interactions.

The presence of *viscosity* in a liquid explains the aforementioned Le Chatelier principle. It looks trivial, but triviality hides a misunderstanding that may lead to erroneous conclusions. What is the physical sense of the notion of *dynamic viscosity*?

Motion of liquid is accompanied by momentum transfer, as heat conduction is accompanied by thermal energy transport, and diffusion by mass transfer. Viscosity-related phenomena dissipate energy and make the process irreversible. Isaac Newton introduced the notion of 'lack of slipperiness' in his *Philosophiae Naturalis Principia Mathematica* (late 17th century): "*The resistance which arises from the lack of slipperiness originating in a fluid* (*other things being equal*) *is proportional to the velocity with which the parts of the fluid are being separated from each other*" Book II, Section IX: 'The circular motion of fluids' (cited from Ref. [62]).

The 'lack of slipperiness' may seem like a synonym of the currently accepted notion of 'viscosity', but it is not so. Newton understood *viscosity* very differently than we do. He believed that *viscosity* is proportional to fluid *velocity*, whereas it is actually proportional to the *velocity squared*, i.e., energy. This error was noticed by G G Stokes in the late 19th century [63]. Were Newton right, the system would be time reversal; in other words, a change in the direction of molecule velocity in a liquid to the opposite are would make the system re-assemble into the initial structure, meaning that water would have *memory* and retain *information* that could be extracted by reversal of motion in time. However, it is in conflict with the second law of thermodynamics, because *any process proceeds with increasing entropy*, while *information is lost*.

It seems possible to design an artificial system that would ensure time reversal in water motion and retain information. Consider, by way of example, a device in the form of two coaxially rotating cylinders of different radii r and R $(R > r)$ embedded in a liquid. Let us first rotate the inner cylinder with the outer one remaining fixed during time $\Delta\tau$. Then, we stop the inner cylinder and rotate the outer one in the opposite direction for the same time $\Delta\tau$. Will the water molecular structure return to its original state after counter-rotation? No, it will not.

If rotation time intervals $\Delta\tau$ are much in excess of water characteristic times τ_1 and τ_2, the system will have time to reach a detailed stationary state. According to Newton, the time of one revolution of a fluid layer at a distance L from the axis of rotation of the cylinder with radius l is defined as

$$\tau_1 = \tau_0 \, \frac{l}{L} \, ,$$

But Stokes showed that it is actually given by

$$\tau_1 = \frac{\tau_0 l^2}{L^2} \, , \qquad (22)$$

where τ_0 is the time of one cylinder revolution.

It follows from Newton's line of reasoning that in the stationary case the moment M of tangential forces acting on unit length of the cylindrical surface of a fluid layer lying L apart from the axis of rotation is equal to

$$M = 2\pi L^2 \eta \, \frac{\mathrm{d}V}{\mathrm{d}L} \, , \qquad (23)$$

where η is the dynamic viscosity coefficient, and V is the velocity of motion.

However, the introduction of angular velocity

$$\omega = \frac{V}{L} \tag{24}$$

leads to a different expression for M:

$$M = 2\pi L^2 \eta \, \frac{d\omega}{dL} \, L\,. \tag{25}$$

In the case of steady-state motion, the liquid enclosed between two cylindrical surfaces has an angular momentum that must remain unaltered; however, it depends on L in expression (25). In order to eliminate this discrepancy, the fluid rotation frequency ω must be assumed to have the form

$$\omega = \frac{C_1}{L} + C_2\,, \tag{26}$$

where C_1 and C_2 are constants. Thus, Newton's equation holds true only for solids, but does not work for liquids.

These paradoxes were considered for the first time by Stokes and Saint-Venant (see I L Fabelinskii's article [64] in *Physics–Uspekhi* for an analysis of these studies).

If a liquid occupies a large volume and executes a steady-state rotation, while the inner cylinder revolves with angular velocity ω_0, then

$$\frac{\omega}{\omega_0} = \frac{l^2}{L^2}\,. \tag{27}$$

This means that the moment of friction force applied to unit length of the liquid surface layer is

$$M = 4\pi\eta l^2 \omega_0\,. \tag{28}$$

In a situation in which two co-axial cylinders have similar radii, $R - r \to \varepsilon$, calculations give the following result [64]:

$$\omega = \frac{r^2}{L^2}\,\frac{R^2 - L^2}{R^2 - r^2}\,\omega_0\,. \tag{29}$$

Then, one obtains

$$M = 4\pi\eta\,\frac{r^2 R^2}{R^2 - r^2}\,\omega_0 \tag{30}$$

instead of formula (25) for the moment of friction force. As $R - r \to \varepsilon$, expression (30) assumes the form

$$M = 2\pi\eta\,\frac{r^3}{\varepsilon}\,\omega_0 \xrightarrow{\varepsilon \to 0} \infty\,. \tag{31}$$

Water in a thin layer is not a good lubricant. *The laminar motion of a thin water layer turns into a turbulent one, which accounts for an increased moment of friction force.* Its value for water will depend on the cylinder surface properties, either hydrophobic or hydrophilic, i.e., on the adhesion of water to a surface that may undergo hydration.

2.4 Bound states of water

Bound water is of importance for all systems residing in an aqueous medium. Almost all biological molecular-level processes depend on hydration (penetration of ions into a cell, conformation and enzymatic activity of proteins and nucleic acids). The binding of water to organic and inorganic compounds is largely a result of breaking molecular bonds between a proton and molecular group $(OH)^-$, yielding ions. The inclusion of water molecules frequently leads to the formation of *crystallohydrates*, some of which have a beautiful color or tone, e.g., brilliant blue hydrate $CuSO_4 \times 5H_2O$ or copper sulfate.

Crystallohydrates and hydroxyls are frequently formed in reactions that release large amounts of heat. For example, the formation of concrete from combining cement with water is associated with the liberation of up to 120 cal per gram of cement. This reaction can be reversed by depositing high energy, e.g., by mechanical fragmentation of the concrete or by multiple strong heating and cooling. Copper sulfate crystallohydrate may be turned back into an anhydrous salt by heating to 531 K in a reaction that proceeds via the formation of consecutive transition states changing their color: $CuSO_4 \times 5H_2O$ (brilliant blue) → $CuSO_4 \times 3H_2O$ (blue) → $CuSO_4 \times H_2O$ (white) → $CuSO_4$ (white-greyish anhydrous salt).

Composite materials containing hydroxyl OH and bound water are also rather stable. To mention but one example, hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ goes to work as an important component of human bones, packed into plates around collagen fibers. Such a structure accounts for high bone resistance to compression. Bones have the following composition: water makes up 25% of their weight, organic matter 30%, and minerals 45%. The amount of water decline with aging. By virtue of such a composition and morphological structure, bones are long-lived mobile elements of a living body [65].

Binding of water molecules and ions to colloid particles is also called hydration. Active nonequilibrium colloid suspensions possess physical properties absent in 'pure' water: they decrease viscosity, increase self-diffusion, and exhibit other unusual properties. An interesting paper titled "Active colloids," by I S Aranson [66], has recently been published in *Physics–Uspekhi*.

If the initial substances have a heterogeneous surface with alternating hydrophilic and hydrophobic zones, water adheres to the former (and gradually dissolves them), while the latter tend to close on themselves or attach to the reservoir boundary if its walls are made of a hydrophobic material. This circumstance can give rise to appearing structures of various configurations [67]. Thin water layers lose fluidity; they may exist for a long time and serve as *memory* elements.

Water molecules and ions become mobile around a polymer stretched like a string with alternating hydrophilic and hydrophobic fragments. Water molecules are attracted to the former and repulsed by the latter. Viscosity and continuity give rise to oscillating movements of water layers. Such motion may last till all hydrophilic fragments of polymer string are occupied by water molecules or ions. Various interesting mobile structures can be seen at the phase boundaries of water-insoluble liquids [55, 60, 68]. However, it has nothing to do with dynamic structural memory in water; rather, it is the memory of a system comprising 'water molecules or ions + hydrophilic and hydrophobic surfaces of inclusions'.

Figuratively speaking, on the molecular level, water is nothing more than 'thermal molecular roulette' with an almost equiprobable presentation of situations for hydration, where the choice itself is made by the introduced agent, i.e., hydrating substance. The speed with which a 'field' is chosen in this quasiroulette depends on the rate at which the molecular states of water are sorted out, which, in turn, depend on temperature, pressure, and composition of material surfaces.

2.5 Local changes in entropy associated with water binding to other substances

At first sight, it may seem that the formation of stable complexes with water and its ions is in conflict with thermodynamic laws, because it increases the characteristic relaxation time of a system comprising 'water molecules or ions + hydrophilic and hydrophobic surfaces of inclusion'. However, it is not so [31].

A microparticle of a certain substance, capable of binding water molecules or ions, accumulates therewith information about its interaction with the aqueous environment by means of changing its own physical parameters, e.g., volume. At the first stage of such binding, the structural energy of the substance decreases (or increases) due to the increase (decrease) in entropy of the aqueous environment alone, but not of the entire system. Additional mechanical or thermal energy should be deposited to the system if the starting volume of the substance is to be recovered. Only part of this energy accumulated in the stressed structure of the substance during its hydration is given back off again; the other part transforms into heat and dissipates in the water, raising its temperature.

A particle is an ordered element of a 'water + particles' system. Seemingly, a rise in the particle's mass must increase order in the system as a whole, i.e., decrease its entropy. However, both water molecules and embedded particles were in the same system before; hence, a paradox brought up: Where did the energy for the reduction in entropy come from in the absence of its external input? The answer is rather simple. In this case, the energy contained in the system from the very beginning and consumed to change the particle during hydration ('the structural energy') undergoes redistribution. Taking the structural energy into consideration in the energy balance of the 'water + particles' system shows that its entropy always increases and information decreases.

This inference is illustrated by the example of concrete formation in the process of cement hydration. Let each water molecule attach to a cement particle and as the former breaks down its fragments change the particle's mass by Δm. As a result, energy Δq is liberated into the aqueous medium, thus enhancing its entropy by

$$\Delta S_{\mathrm{w}} = \frac{\Delta q_{\mathrm{w}}}{T_{\mathrm{w}}}\,, \tag{32}$$

where Δq_{w} is the amount of heat imparted into water, and T_{w} is the water temperature. Cement hydroxyl (concrete) heated to T_{c} transfers heat to water having temperature T_{w}. Then, one obtains $T_{\mathrm{c}} > T_{\mathrm{w}}$, since the hydroxyl loses heat and water temperature rises: $|-\Delta q_{\mathrm{c}}| = |\Delta q_{\mathrm{w}}|$. Because $|\Delta q_{\mathrm{w}}| > 0$, the following relationship is valid:

$$\Delta S_{\mathrm{w}} + \Delta S_{\mathrm{c}} = |\Delta q_{\mathrm{c}}| \left(\frac{1}{T_{\mathrm{w}}} - \frac{1}{T_{\mathrm{c}}} \right) > 1\,. \tag{33}$$

It follows from this expression that the overall entropy of the 'water + hydrated particle' system increased, while information decreased. The rate of evaporation also increases as the water is heated, which leads to the enhancement of the entropy of the entire 'water + particle-hydrates + vapor' system:

$$S = S_{\mathrm{c}} + S_{\mathrm{w}} + S_{\mathrm{v}}\,, \tag{34}$$

where S_{v} is vapor entropy. Elementary calculations showed that all hydration processes obey thermodynamic laws.

It should be noted that substances binding water molecules and ions can be attached and detached to the walls of water-containing containers only under the effect of strong thermal fluctuations in water. These events are possible but rare. The decomposition of such substances, i.e., the reversibility of the process, is equally rare in the absence of an additional energy deposition.

Still, the reversibility is probable even if it is determined by fluctuations (mechanical, thermal, or induced by electromagnetic fields) on the container walls rather than by changes in the water volume upon dilution. On the whole, contamination of water by substances that form complexes with it is a major source of errors in the interpretation and argumentation of dynamic structural memory in 'pure' water. Here is an example from our experience.

2.6 Effect of spring water

Water used to dilute medicinal preparations *always contains impurities*, if only for no other reason that it dissolves gases. Any dilution is fraught with water contamination by particles of other substances having a practically unpredictable composition. Evidently, contamination particles have to exert a much greater influence on the water structure than the initial substance, of which only one or two molecules remain in the entire water volume.

Our interest in water properties was provoked by an observation made during preparation of an artificial perfluorocarbon-based blood substitute with a gas transport function (*perftoran* emulsion) in the early 1980s [61]. For this purpose, water taken from one and the same well near Pushchino was cleaned of mechanical admixtures and purified by double distillation. We noticed that perftoran prepared each spring during the snowmelt period using the proven technology showed pyrogenic activity when tested in rabbits — that is, caused a rise in their body temperature (Fig. 7).

Even at that time, some researchers argued that snowmelt water possesses a *particular* structure of biological significance, responsible for its *specific* properties. We had to verify this hypothesis starting from the assumption that the pyrogenic reaction developed as a result of seasonal variations of our test objects (rabbits).

Seasonal changes in the activity of living organisms and their basal metabolism, growth and reproduction rates have long been known. They occur throughout the year due to seasonal variations in the environmental conditions. In spring, all living organisms are more active than in other seasons. The results of relevant extensive studies starting in the 19th century have been published in many review articles and monographs (see the list of references in

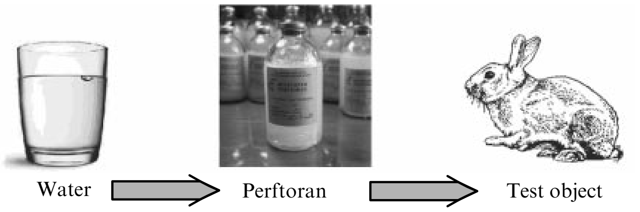

Figure 7. Spring water utilized to prepare *perftoran* raised body temperature in rabbits.

collected work [69]). Although rabbits are higher active *in spring*, the hypothesis that the pyrogenic effect of perftoran was related to accelerated metabolism was not confirmed. The administration of perftoran samples prepared in other seasons and stored deep-frozen did not raise the temperature in the experimental animals.

In the second hypothesis to be tested, it was assumed that spring water is distinct from water in other seasons. The quality of water purification was checked from changes in specific electrical conduction or pH level. However, these methods were later found to lack the sensitivity needed to control water quality for biological purposes.

In the first place, water had to be checked for the presence of isotopes, the content of which could increase in the snowmelt period. It is known that microorganisms are able to adapt themselves to existence in heavy water, while multicellular organisms poorly tolerate the addition of heavy water to ordinary water [70]. We failed to detect deuterium in the ground water in excess of normal values, and its isotope composition did not vary significantly in different seasons. The bulk of natural water (above 99.9%) was of the ${}^1H_2{}^{16}O$ type. The amount of additional oxygen isotopes remained normal, viz. $\approx 0.01\%$ ${}^1H_2{}^{18}O$, and $\approx 0.001\%$ ${}^1H_2{}^{17}O$. The mixture of ${}^1H_2{}^{16}O$, ${}^1H_2{}^{17}O$ and ${}^1H_2{}^{18}O$ contained isotopes in the same proportion as in the air. Other isotopes were normally presented, too.

Finally, we had to study the content of volatile substances accumulated in snow as liquids and solids at low winter temperatures and thereafter transferred into thawed water. It turned out that distillation is a simple but not most effective method to prepare apyrogenic water for intravenous injection. Distillation kills and eliminates bacteria, viruses, and cysts, and it also removes heavy metals, radionuclides, particulate material, and organic and inorganic compounds. Moreover, it cleans water of minerals regarded to be inorganic pollutants capable of forming hydroxyls and crystallohydrates. Under the current environmental conditions, however, snowmelt water comprises increased content of volatile admixtures that mix with water vapor and are not removed by distillation.

Volatile contaminants are represented by organic and inorganic substances with a boiling point below that of water (chlorine, ammonia, benzene, trichloroethylene, methanes, etc.). If present in water, they evaporate in boiling tank together with water vapor. Modern distillation units have a special ventilation valve to exhaust volatile gases, i.e., a narrow canal at the top of the condenser coil that is opened for a short time at the onset of water boiling. In the past, there were no such vents.

The use of the valve and ion-exchange filters helped to eliminate pyrogenic activity in snowmelt water. It was revealed that water, like living organisms, obeys seasonal cycles arising from seasonal variations in the concentration of pollutants accumulated in winter time and entering artesian well during snowmelt. In other words, we failed to document any *specific properties of thawed water*, besides an enhanced impurity level.

3. Memory of mechanical cutting in water

3.1 Inscription lifetime on water

A steamy glass can be inscribed. The inscription becomes invisible after the glass dries. If, however, the inscription was made by a finger, it comes back as soon as the glass becomes wet again. The finger leaves hydrophobic (water repulsing) fat on the glass surface. After all, it is possible to write on water, despite the proverbially ephemeral nature of such inscriptions. But how long does such an inscription exist? It depends on the thickness of the water layer and the chemical composition of the wetted surface.

Very thin water layers are adsorbed on the substrate surface, e.g., glass, where water is distributed over the entire solid–liquid interface and held by electrostatic adhesive forces and van der Waals forces [71]. Physical adsorption on hydrophobic surfaces is weak and, therefore, reversible, while the desorption heat is low (a few kJ mol^{-1}). Physical adsorption on hydrophilic surfaces is much stronger and virtually irreversible, the desorption heat amounting to tens of kJ mol^{-1}.

The characteristic 'lifetime' of an inscription on a thin water layer may be a *few dozen seconds*. Vortices may form as the layer thickness increases. These processes result from the hydrodynamic transport of water masses. Filling a water cut through a thick layer owing to directed mass transfer under the effect of pressure takes little time: in fact, a *few fractions of a second*. Since we are concerned with 'molecular dynamic structural memory in water', let us consider the total relaxation time including both slow and rapid processes. Figure 8a illustrates movie frames to time variations of the brightness of a thermal inscription on water in a glass Petri dish, and Fig. 8b is a plot of the diagram showing the time dependence of these variations. Curve *1* in Fig. 8b is not an exponent in the full sense of the word, but its initial part can be approximated by an exponent. A change in temperature T with time can be described as

$$\Delta T = T_0 \exp\left(-\frac{t}{\tau}\right), \tag{35}$$

where T_0 is the water temperature (in our case, $\approx 25\,^\circ\mathrm{C}$) up to the moment of cutting, t is the current time, and τ is the characteristic time of inscription fadeaway. It follows from

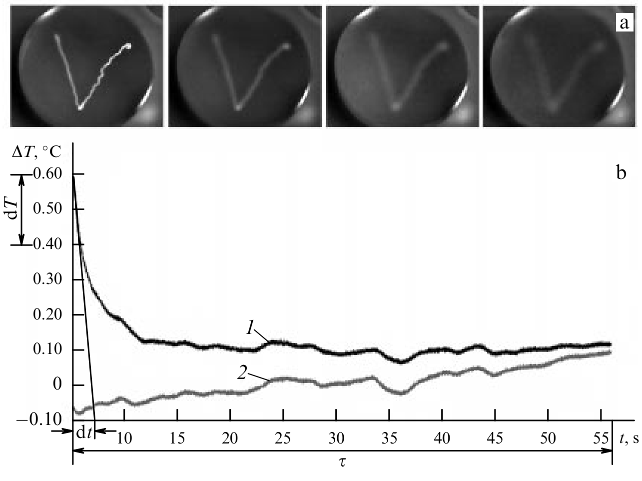

Figure 8. (a) Consecutive movie frames of a closing water cut in a round Petri dish 10 cm in diameter with the water layer depth $h_1 = 0.5$ mm at room temperature $T_0 = 25\,^\circ\mathrm{C}$ and atmospheric pressure. The movie was taken with a matrix IR camera in a wavelength range of 3–5 μm. Inscription lifetime ≈ 56 s. (b) Changes in the cut and background temperatures with time: temperature increment $\Delta T = T - T_0$ inside the cut (curve *1*), and near it (curve *2*).

plot *1* (Fig. 8b) that

$$\frac{\mathrm{d}t}{\mathrm{d}T} = \frac{7}{0.2} = 35\,. \tag{36}$$

Prior to cutting, $T_0 = 25.6\,^\circ\mathrm{C}$. The lifetime of the inscription on water is $\tau = 56$ s.

However, the results of such calculations do not give an answer to the question as to how the inscription lifetime is related to the parameters of the cut. The answer can be obtained by using the water thermal diffusivity coefficient χ [$\mathrm{m}^2\ \mathrm{s}^{-1}$] to arrive at the following simple dependence for the characteristic lifetime τ_0:

$$\tau_0 = \frac{lL}{\chi}\,, \tag{37}$$

where l is the cut width (equaling the 'knife' width), and L is the cut length. The thermal diffusivity of water at $T = 25\,^\circ\mathrm{C}$ is $\chi = 143 \times 10^{-9}\ \mathrm{m}^2\ \mathrm{s}^{-1}$. The 'knife' width and length in the experiment were $l = 2.7 \times 10^{-5}$ m and $L = 10$ cm $= 10^{-1}$ m, respectively. Substituting these values into formula (37) yields $\tau_0 = 18.6$ s. The lifetime of the inscription on water $\tau = 3\tau_0$, i.e. 55.8 s, in agreement with experiment.

All these results hold for a *thin layer*, i.e., a water depth of ≈ 0.5 mm in a Petri dish.

3.2 Vortex behavior dynamics in a cut through a thickening water layer

Figure 9a illustrates the experimentally examined dynamics of the behavior of an inscription on a thicker water layer ($h \approx 2$ mm) in a Petri dish.

A phenomenological estimation of the inscription lifetime in this case is made exactly as is done in the preceding one, i.e., by using the plot in Fig. 9b and the following parameters: $\mathrm{d}t/\mathrm{d}T = 2.5/0.13 = 19.23$, $T = 25\,^\circ\mathrm{C}$, and $T_0 = 25.6\,^\circ\mathrm{C}$. Then, the lifetime sought is $3\tau \approx 31$ s.

The question is brought up: Why does the cut in water have a swirling character in this case? The cause concerns the peculiarities of the interaction between water and the 'knife' with which it is cut to write the letter V. This process is illustrated in Fig. 10. Water adheres to the knife's hydrophilic blade and drains down into the dish as the knife moves. The knife blade can enter the water in two different ways, as shown in Fig. 10.

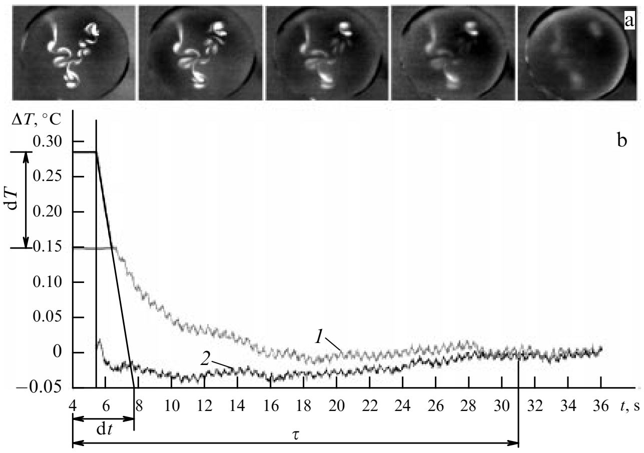

Figure 9. (a) Sequence of images (see movie 1) showing dynamics of water cut behavior in a round Petri dish 10 cm in diameter with the water layer depth $h_1 \approx 2$ mm at room temperature $T_0 = 25\,^\circ\mathrm{C}$ and atmospheric pressure. The movie was taken with a matrix IR camera in a wavelength range of 3–5 μm. Inscription lifetime equals ≈ 31 s. (b) Changes in temperature in the cut and around it with time: temperature increment $\Delta T = T - T_0$ inside the cut (curve *1*), and near it (curve *2*).

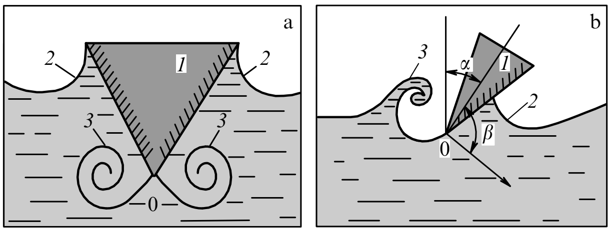

Figure 10. Water cutting with a wedge knife blade: (a) perpendicular insertion, and (b) oblique insertion [72].

This situation was first considered by M W Kutta and then by Nikol'skii [73–75] (when bypassing an infinite wedge) and Betyaev [72]. When the knife (*1*) is inserted perpendicularly to the water layers adjacent to its sides (*2*), the water draining down from it produces two symmetric spiral vortex structures (*3*) (Fig. 10a). Then, the vortices dissipate. When the knife blade is inserted at an angle, the vortices are asymmetric. The asymmetry parameters (angle α between the vertical line and the bisectrix of the wedge, and angle β between the bisectrix and entry velocity direction) can be fairly large. The scheme of the water draining from the knife blade therewith changes. In the present case, a free water layer draining down from point 0 at the tip of the knife (Fig. 10b) winds itself into a spiral (*3*) as a result of impact interaction with the wedge tip at the moment it touches the water. This causes the wave to swirl and forms a vortex whose dissipation continues in the course of relaxation (Fig. 9a).

The rate of temperature dissipation over the water volume increases by virtue of additional intermixing promoted by the newly formed vortex; as a result, the characteristic relaxation time decreases.

3.3 Influence of convection on the characteristic time of equilibrium restoration in a thickening water layer

Convection in liquids has attracted much attention since the publications of Bénard [76], Rayleigh [77, 78], and Marangoni [79]. The water convection is a lively illustration of unstable nonlinear processes in this liquid; it exemplifies the transition from chaotic movements of molecules to their organized cooperative motion [53, 60].

Curiously, it is possible at times to observe a process (called sometimes anticonvection) that seems to be paradoxical at first sight and creates an illusion of the violation of the Archimedes principle. This paradox and its explanation were described in a study by Welander [80]. The essence of this phenomenon reduces to the possibility, under certain conditions, of emerging a vertical pressure gradient due to liquid evaporation into the air at the liquid–air interface, such that a pressure force constituent is directed from the vapor produced in the air toward the liquid. The pressure creates an additional inwardly directed hydrodynamic flow that prevents the expanded fluid from migration into the top layers. In this case, convection disappears [81–83]. Surface heating of the reservoir has a similar effect, which is easy to demonstrate by spreading a thin alcohol vapor layer over the water surface. Alcohol dissolves in water with the release of heat. The hot vapor formed from mixed alcohol and water molecules immediately stops a water convection.

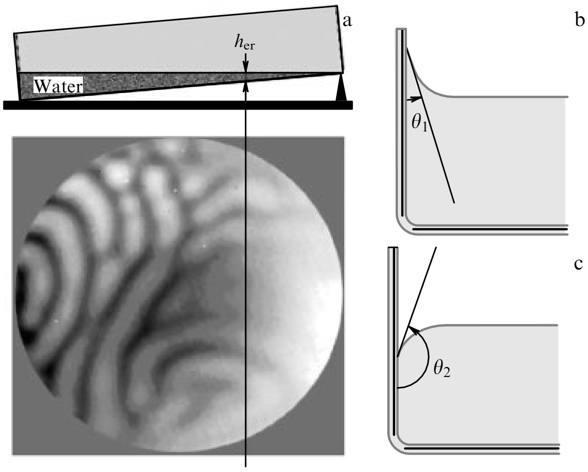

Figure 11. Structures formed in an inclined container 17 cm in diameter. (a) Changing water layer thickness h; $h_{\rm cr}$ is the critical thickness above which convective structures can no longer form. Left top corner: water layer depth 10 mm, 0.2 mm $\leqslant h_{\rm cr} \leqslant$ 2 mm (depending on hydrophobicity or hydrophilicity of the bottom substrate). Water wetting of hydrophilic (b) and hydrophobic (c) surfaces of the container, $\theta_2 > \theta_1$. Water fairly well wets clean glass surfaces but poorly wets most plastic surfaces. Glass surfaces are hydrophilic, whereas plastic surfaces are hydrophobic.

The convection of water is easy to observe [53, 60]. Its necessary but not sufficient emergence condition is an adequate thickness of the water layer, as is confirmed in a simple experiment (Fig. 11a) [60]. The critical thickness of the layer depends on the wettability of water reservoir surfaces (Fig. 11b, c).

A cut on the surface of a water layer thicker than 2 mm closes for approximately 15 s (Fig. 12), The mechanism of such short-term dynamic structural memory is water mixing by convection.

Thus, 'dynamic structural memory in water' experiencing mechanical influences does exist except in thin layers and for a few dozen seconds, *with relaxation time intervals being dependent on the size of the system* [see relation (7)]. The wake left by a motor boat skipping across calm water persists somewhat longer, a few minutes (Fig. 13a). Trails of water bugs (water striders, *Gerris remigis* or *Gerris paludum*) running over the water surface disappear within several seconds (Fig. 13b).

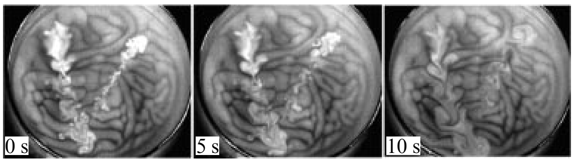

Figure 12. Sequence of images (see movie 2) showing water cut behavior in a round Petri dish 10 cm in diameter with the water layer depth $h > 2$ mm at room temperature (25 °C) and atmospheric pressure. The movie was taken with a matrix IR camera in a wavelength range of 3–5 μm.

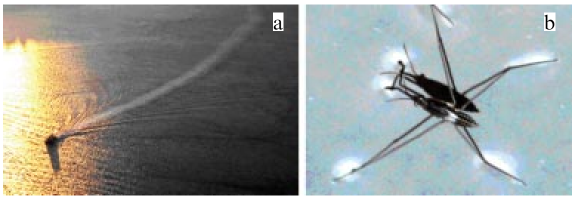

Figure 13. Wake left by a motor boat on the sea surface (a), and trails of a water bug on the water surface (b).

Aquatic animals living on the water surface seem to benefit from such rapid decay of water perturbation. For example, water striders can transmit information by deforming the water surface with their legs. Metaphorically speaking, they 'talk' with the legs and 'hear' with the entire body [84].

The propagation velocity of perturbations (sound) depends on medium elasticity and density. Sound in gases propagates more slowly than in water, and in water more slowly than in solids. Water is 800 times denser than air. The speed of sound in clean water is roughly 1500 m $\rm s^{-1}$. The speed of sound in salty ocean water has applied implications; it increases with salinity and in colder water [85].

4. Molecular structures of water and their relationship with its macrostructures

4.1 Water as a mixture of different types of molecular structures

In the late 1960s, B V Deryagin and co-workers claimed to have discovered two different forms of water: ordinary and dense. According to them, any water is a mixture of at least two molecular structures. The latter form was called polywater or water II. The authors reported their findings [86] at the sessions of the Division of General Physics and Astronomy, Russian Academy of Sciences, in 1968 and 1969. The properties of polywater and ordinary water seemed different. Water II had a higher viscosity (density 1.4 g $\rm cm^{-3}$) and refraction index (1.48), lacked volatility at room temperature, and underwent linear expansion in a temperature range from −40 to −60 °C. Polywater solidified in a glassy state at −40 °C [87]. The authors conjectured that this 'anomalous' water consisted of hexameric molecules $(\rm H_2O)_n$.

However, Deryagin's assertions were met with skepticism. Suffice it to say that *Physics–Uspekhi* published an article by V L Ginzburg under the title "What problems of physics and astrophysics are of special importance and interest at present?" [88]. An excerpt from Section 3 of that publication reads as follows: "*...polymer* $(\rm H_2O)_n$ *molecules are involved here. These results were, it would appear, fully confirmed* [89–92]*; anomalous water was also obtained in capillaries containing no silicon* [93]. *On the other hand, recent communications* [94–98] *state on the basis of a number of experimental data that 'anomalous water' is a mixture of ordinary water and a number of impurities* (*hydrosols*, $\rm HNO_3$, Na, Cl, *etc*.).

Thus, the question should be regarded as open, although, in my opinion, the communications [94–98] *leave little hope for the existence of pure polymer* (*superdense*) *water. Regardless of the final answer, however, the investigations already performed indicate how difficult it is to answer such a question as the possible appearance of a new form of one of the most abundant substances; theoretical calculations* [99, 100] *are likewise not reliable in this case. This example is instructive in many respects, particularly as a reminder of the need to regard any discovery as finally established only after repeated and exhaustive verification.*"

B V Deryagin sent a letter to the editorial board of *Physics–Uspekhi*, where it was published [101]. He insisted on his discovery and the existence of superdense polywater. This provoked a dispute [102]. By that time, several reports had appeared in foreign journals that also put into question the existence of superdense polymer water [103, 104]. Notably, Ref. [104] ended in the following words: "*Considering our own results in the light of research of other authors, we feel strongly that anomalous water is not polymer water*."

B V Deryagin argued that ordinary water stably co-exists with water II, having molecular weight $M = 150 \pm 30$. It was pointed out that water II undergoes depolarization at high temperatures and transforms into ordinary water. Later on, a molecular description of water, suggesting alteration of hydrogen bonds where they link hydrogen and oxygen together (H-bonds near the oxygen K-edge), made possible theoretical estimation of the putative mechanisms underlying the formation of anomalous water. A detailed presentation of the evolution of the views about water's molecular structure can be found in review [105].

The main sources of information about the molecular structure of water were neutron and X-ray diffraction data, together with the results of Raman spectroscopy. The advent of powerful synchrotron X-ray sources opened up new possibilities for the detailed analysis of reflexes in the diffraction spectra. The near-field region was found to exhibit peaks that characterized the behavior of hydrogen bonds close to oxygen atoms (extended X-ray absorption fine structure (EXAFS) spectroscopy) [106]. However, *long-range order was absent in water*. In other words, it had no coupling matrix spread over the entire volume.

In the end, the researchers managed to better understand the mechanisms of dense water formation and had to recognize that water contains a mixture of different types of equally sized (1–2 nm) molecular heterogeneities of higher or lower density. Low-density heterogeneities proved more stable and, therefore, had low energy and entropy, in contrast to high-density ones with higher energy and entropy.

A recent paper on this issue [107] reports the application of X-ray diffraction spectroscopy with a resolution of about 12 Å to detect a peak of the correlation function in water vapors. This peak suggests the presence of a minor admixture of tetrahedral structures formed from water molecules. These experiments were reproduced at different water temperatures (7, 25, and 66 °C) under normal pressure. The results of observation and computer simulation of the molecular dynamics confirmed that the structure of liquid water can be described, even at high temperatures, in terms of a set of water states and a phase transition from one structural form to another. However, these studies have been preceded by hundreds of studies on water's molecular structure since the 1930s (see the list of references in paper [107]).

The ratio of high- to low-density clusters at ≈ 25 °C was roughly 2.5:1.0 [108–110]. From the thermodynamic standpoint, the higher the entropy, the smaller the information component of the system (see above).

The refraction index of dense water structures differs from that of the normal water molecular structure composed of individual free molecules ($n_{\mathrm{i}} = 1.309$ for ice, and $n_{\mathrm{w}} = 1.33$ for water). Therefore, structural rearrangements in a 'dense water + ordinary molecular water' system must be accompanied by local fluctuations of the refractive index and its related parameters. B V Deryagin argued that the properties of water II differ from those of ice and normal water. Polywater with a refractive index of 1.48 had a higher viscosity. In other words, the values of the refractive index varied within a range of 1.309 to 1.48. Irradiation of water vapors by a Nd:YAG laser emitting low-intensity light pulses (< 30 mW cm^{-2}) at its second harmonic frequency revealed oscillations with a spatial frequency up to 50 cm^{-1} in the spontaneous Raman spectrum [111].

Let us briefly consider the molecular mechanism of dense water formation. The intermolecular hydrogen bonds are weak. The average energy of hydrogen H$-$O bonds between H_2O molecules is only 0.1067 ± 0.0011 eV (≈ 5 kcal mol^{-1}) or slightly higher than the characteristic thermal motion energy of water molecules at 300 K. X-ray and neutron diffraction investigations yielded information about the molecular structure of water. However, additional energy imparted to the water broke the hydrogen bonds. This means that the water was actually studied in a different state. Moreover, hydrogen bonds are readily broken down by thermal fluctuations. In other words, a hydrogen bond lives only 3.2×10^{-12} s on the average.

The break of a chemical bond must lead to disintegration of the water polymeric structure. In this process, a proton become almost naked and electrostatic attractive forces bring O$-$O or O$-$H atomic pairs closer together, even if this interaction is notably compensated by mutual repulsion of electrons and nuclei. Taken together, the electrostatic forces and donor–acceptor interactions account for a binding energy in water on the order of 5–10 kcal mol^{-1}, while the proton continuously changes partners.

For all that, relaxation processes in water do not take more than a few seconds. Weakly damping oscillations with a period of 30 s, if any, reflected the temperature-dependent initial composition of a mixture of single-molecule and clustered water rather than the memory of influences to which it was exposed.

To sum up, water constitutes a dynamical system composed of individual molecules and their clusters, i.e., $(H_2O)_n$, residing in dynamic equilibrium. Based on the results of above-mentioned studies, it might be concluded that *water contains at room temperature structures of at least two types unable to integrate into a unified polymeric network occupying the entire water volume*. Were the whole water volume held together by dynamically stable bonds, its viscosity would be too high and the water could not flow. However, water is an easy-flowing liquid and its viscosity is low compared with other well-known fluids, as can be seen from Table 1.

Hydrogen bond lifetimes calculated by various molecular dynamics methods differ at room temperature and normal pressure by no more than 6.8 ps. As regards the entire set of hydrogen bonds in a water volume, it can be concluded based on molecular water dynamics [112] that *long-lived hydrogen*

Table 1. Viscosity of water and some other liquids at 25 °C.

Liquid	Viscosity, mPa s
Water	0.894
Benzene	0.604
Methanol	0.544
Acetone	0.306
Liquid nitrogen (at 77 K)	0.158
Ethanol	1.074
Nitrobenzene	1.863
Sulfuric acid	24.2
Ethylene glycol	16.1
Olive oil	81
Castor oil	985
Glycerol (at 20 °C)	1490

bonds are randomly distributed in water bulk. They are renewed so quickly that all attempts to elucidate their influence on long-term memory in water based on the knowledge of their mutual spatial arrangement are destined to fail. Short-lived hydrogen bonds have practically no effect on the dynamics of liquid water behavior and relaxation time extension when there is exposure to external influences.

Thermodynamic investigations into the water macrostructure have led to the same conclusions (see Section 4.3). There are three approaches to studying water kinetics in the context of structural, thermodynamic, and dynamic transitions of water from chaos to order and then back into chaos. Let us consider each of them successively.

4.2 Structural approach — from ice to liquid water

The fashion in which molecules are packed in freezing water *under atmospheric pressure* has been well-known since J Bernal and R Fowler published their classical study, "A theory of water and ionic solution, with particular reference to hydrogen and hydroxyl ions" in the 1930s [113]. They used an X-ray technique to observe the three-dimensional crystalline structure of ice characterized by hexagonal symmetry (hexagonal syngony with an angle of 120°). Ice density proved lower compared with liquid water, which explained why ice floats on water. At zero Celsius temperature, ordinary ice density is 916.7 kg m^{-3} and water density 999.8 kg m^{-3}. Only water and certain alloys, e.g., type metal, condense when passing into the liquid state.

Ice formed at a temperature below zero centigrade under atmospheric pressure has some reserve of heat, and its atoms oscillate without (*or almost without*) changing their positions in the lattice. To recall, a hydrogen bond relates to the category of bonds with an energy of 5–10 kcal mol^{-1}, the energy of a covalent $\mathrm{O} \leftrightarrow \mathrm{H}$ bond being an order of magnitude higher (109 kcal mol^{-1}). Atomic oscillations occur even near absolute zero. Each atom is coupled with its neighbors, and its movements depend on their motion. The thermal motion of atoms can be regarded, following P Debye [114–116], as a result of interference of a large number of acoustic waves with different frequencies generated by atomic oscillations in the lattice.

The oscillations propagate in an ice crystal in various directions. Where monatomic liquids were involved, helium conserves heat at absolute zero better than ice. It does no freeze under atmospheric pressure and can be obtained in the solid state only under high pressures. Ice also responds to pressure changes. In order that a crystal should be melt it is necessary that the oscillation amplitude be commensurate with the interatomic distance. Neighboring molecules will interact only at a high enough Debye temperature [115, 116].

To recall, the Debye temperature introduced into the heat capacity theory, i.e., the temperature at which all oscillation modes are excited in ice molecules, is defined by the formula

$$\theta_{\mathrm{D}} = \frac{h}{k_{\mathrm{B}}}\, \nu_{\mathrm{D}} \,, \tag{38}$$

where h is the Planck constant, ν_{D} is the maximum oscillation frequency of atoms in the ice crystal lattice, and $h/k_{\mathrm{B}} = 6.626 \times 10^{-34}/1.38 \times 10^{-23} = 4.8 \times 10^{-11}$ s K.

A further rise in temperature does not induce new modes but increases the amplitude of already existing oscillations, which means that an average oscillation energy grows with increasing temperature. The Debye temperature characterizes the crystal properties of a given substance and represents a physical constant for it. This temperature describes such properties of crystals as thermal capacity, electrical and thermal conductivities, broadening of X-ray spectral lines, and elasticity.

At temperatures below the Debye temperature, the thermal capacity of a crystal lattice depends in the first place on acoustic oscillations and is proportional to the temperature cubed. If a temperature is much higher than the Debye temperature, the thermal capacity is constant and equals $3Nrk_{\mathrm{B}}$ (the Dulong–Petit law), where N is the number of unit cells in the crystal, and r is the interatomic distance in crystal cells. The physical sense of the Debye temperature consists in defining a provisional temperature boundary below which quantum effects begin to prevail. For ice formed under atmospheric pressure, Debye temperature $\theta_{\mathrm{D}} \approx 192$ K (or $-81\,^{\circ}\mathrm{C}$). Such a low temperature is rare on this planet.[3] Practically in most cases, the Debye temperature will be higher.

The crystalline structure of ice depends not only on temperature but also on pressure applied during its formation. The molecular lattice of a glacier ice crystal is different from that of river water ice [117]. Amorphous ice forms and overcooled water are comprehensively reviewed in Ref. [118]. A new crystalline form of ice XV was discovered in 2009 [119]. Specific growth conditions and external influences account for distortions and dislocations in the molecular lattice of ice crystals. However, their main property, i.e., the position of atoms in the lattice, is conserved only in the average.

Natural ice is usually cleaner than the water from which it formed, because water molecules embed themselves into the lattice during crystallization earlier than impurities; hence, the possibility of purifying water not only by distillation but also by freezing. However, the latter technique is less cost-effective.

Melting 1 kg of ice consumes as much energy as heating 1 l of water from 0 to 80 °C. Water freezing does not completely remove particulate matter, gas bubbles, salt molecules, or bacteria. The specific heat of ice melting is 330 kJ kg^{-1}, in comparison with 270 kJ kg^{-1} for iron. It is difficult to completely demineralize salt water in multiple freeze–thaw cycles.

Liquid water can be obtained in two ways: either by ice melting or by vapor condensation. The question naturally arises as to whether thawed water and rain water have different molecular structures. Intuitively, the answer is yes: they might differ, for instance, in the concentration of dissolved gases and the amount of 'cold' (dense) and 'hot' (loose) molecular structures.

The air is essentially a mixture of four gases (nitrogen, oxygen, argon, carbon dioxide) and water vapor. The solubility of each of these gases in the air over a water surface obeys Dalton's and Henry's laws, i.e., it is proportional to the partial pressure of a given gas in the mixture. The air contains 21% oxygen and 78% nitrogen; therefore, equilibrium solubilities of oxygen (O_2) and nitrogen (N_2) in distilled water at 20 °C under atmospheric pressure are $44.3 \times 0.21 = 9.3$ and $19.5 \times 0.78 = 15.21$ mg l^{-1}, respectively.

Thus, water in *equilibrium* with the environment at room temperature and atmospheric pressure contains some three

---

[3] A temperature of $-(88.3-89.2)\,^{\circ}\mathrm{C}$ was recorded at the Vostok Research Station in East Antarctic. The estimated temperature within the 'inaccessibility belt' (78°S, 96°E) at the same period might be below $-90\,^{\circ}\mathrm{C}$.

volume percent of the main air gases. However, more gaseous molecules are taken up from the air than from their number contained in melting ice at the onset of vapor condensation into water. When a thin stream of water is poured into a container, its saturation with gases increases due to the high surface-to-volume ratio for the stream [60]. Characteristic equilibration time τ in the course of gas dissolution in water is rather long. Gas dilution being a diffusion process, its characteristic time $\tau \sim (V/S)^2$ (in accordance with the Einstein–Smoluchowski formula [14, 120] for such processes) is inversely proportional to the square of the surface area S through which the gas dissolves and directly proportional to the square of the volume V to be filled with the gas. If a container with water is shaped like a cylinder of height H with the base area A, its volume $V = AH$ and the open surface is equal to A; therefore, one obtains

$$\tau \approx \frac{(AH/A)^2}{\alpha D} \approx \frac{H^2}{\alpha D}\,, \tag{39}$$

where D is the gas diffusion coefficient in a liquid, and α is the assurance factor (given the Gaussian distribution of water-soluble gas molecules, then $\alpha = 3-4$). If the liquid water temperature (hence, viscosity) is assumed to be virtually unaltered, the rate of gas mass transfer by diffusion increases with increasing the velocity of a kinetic motion of the molecules:

$$D = \frac{k_{\mathrm{B}} T}{6\pi\eta r}\,, \tag{40}$$

where η is the water dynamic viscosity, and r is the molecule radius. Temperature (T) or pressure (p) gradients serve as the driving forces. The mean radius of an oxygen molecule on the assumption of its approximation by an equivalent sphere is $\bar{r}_{\mathrm{O}_2} = 1.5 \times 10^{-10}$ m, $k_{\mathrm{B}} = 1.38 \times 10^{-23}$ J K^{-1}; at a temperature of 20 °C ($T = 293$ K) and atmospheric pressure, viscosity $\eta = 10^{-3}$ Pa s. Substituting these values into formula (40) yields $D_2 = 1.46 \times 10^{-10}$ m^2 s^{-1}. The characteristic time of 1.7×10^5 s, i.e., about 2 days, can then be found from expression (39) for a Petri dish of height $H = 0.01$ m. If a system (water + dissolved gas) departed from equilibrium by at least 10% as a result of temperature or pressure changes, it takes around 5 hours to come back to equilibrium. This inference holds for motionless unstirred water. However, these times are almost an order of magnitude smaller for thick water layers (see Section 3.3) where *convective mixing* always takes place; their values depend on convection intensity.

After the temperature is elevated above zero, atomic oscillations in an ice crystal build up and the molecules escape from their sites. This gives rise to the *melting* phase. X-ray diffraction studies have shown (see Section 4.1) that water lacks long-range order of the molecular positions [121]. The diffraction curve for water decays much faster than for most other liquids. For example, the distribution of oxygen interatomic distances at around 20 °C exhibit three maxima of different intensities (at 2.8, 4.5, and 6.7 Å distances). The first one is roughly equal to the length of a hydrogen bond. The second maximum with a lower amplitude nearly corresponds to the edge length in a hexagonal packing of 'frozen' ice molecules. The third, very weak, maximum corresponds to the distance to farther neighboring molecules. There are no other maxima. However, the third maximum is so weak that it is impossible to draw a reliable conclusion about the presence of long-range order in water. Thus, we came to the same point as above when considering the intermolecular interactions in water: *water does not have a polymeric molecular matrix spreading through its entire volume; at least such a matrix has not yet been discovered.*

4.3 Thermodynamic approach to the description of water at the molecular level

Experiments on quasielastic scattering of neutrons and ultrafast IR spectroscopy, as well as water diffusion studies with the use of NMR spectroscopy and labelled atoms, have made it possible to measure the self-diffusion coefficient in water at different temperatures and pressures. Determining the self-diffusion coefficient from the quasielastic scattering of neutrons implies the necessity of an assumption about the character of molecule movements.

As far back as the first half of the 20th century, the scientific community divided into two camps [122]. One tried to apply gaseous state laws to the theory of liquids, while the other addressed the same problem in terms of solid-state physics. Historically, the former group proceeded from accounting for long-range attractive forces discovered by van der Waals [123–128], while the latter used the theory of melting of solids, and, in particular, crystals, as it was interpreted in the works of Ya I Frenkel' [129–132].

The van der Waals theory explained certain properties of water based on the concept of long-range forces and the continuity of liquid–vapor phase transition. However, Frenkel' noted in review [130] that it resulted in the unjustified preference for hypotheses laying emphasis on vapor transition into a liquid state in the description of the nature of this state. It is clear *a priori* that a microscopic approach using a solid with a density differing from the liquid density by only 10–20% as the zero-order approximation would be more productive than the approach using a vapor having 1000 times lower density than a liquid as such an approximation. The same issue was raised by G E Uhlenbeck in the section "The problem of phase transitions" of his review [128, p. 288]): "*One of the most remarkable properties of matter is that all substances can exist in three so-called phases: solid, liquid, and gaseous.... Furthermore, a known universal property is a critical point for the gas–liquid transition, i.e., it is impossible to liquefy a gas above a certain temperature. There is no such critical point in the solid–liquid transition; accordingly, there is no critical melting temperature. Thus, isotherms of all substances are roughly similar in shape as shown schematically in Fig. 9.*" (Figure 14c in the present review corresponds to Fig. 9 in Ref. [128]).

Let us consider isotherm T_1 in Fig. 14c. Temperature T_1 is lower than critical temperature T_{c}. Point C (Fig. 14b) lies on the critical temperature isotherm (Fig. 14c). A change in the volume, as a rule, leads to a change in pressure. Sometimes, however, the pressure remains unaltered in a liquid + vapor mixture. On a graph, this situation is depicted as a horizontal segment of the isotherm (plateau) in the $V_{\mathrm{b}} < V < V_{\mathrm{a}}$ region corresponding to the mixture of water and saturated quasi-vapor. The liquid phase occurs for $V_{\mathrm{b}} > V$. A rise in pressure results in a shorter horizontal section of the curve ($V_{\mathrm{e}} < V < V_{\mathrm{d}}$) corresponding to the mixture of quasi-ice particles and water molecules. Finally, a solid, i.e., ice, forms as $V < V_{\mathrm{e}}$. The plateau for $V_{\mathrm{b}} < V < V_{\mathrm{a}}$ corresponding to condensation may disappear at a certain temperature; then, the curves connecting the terminal points of the

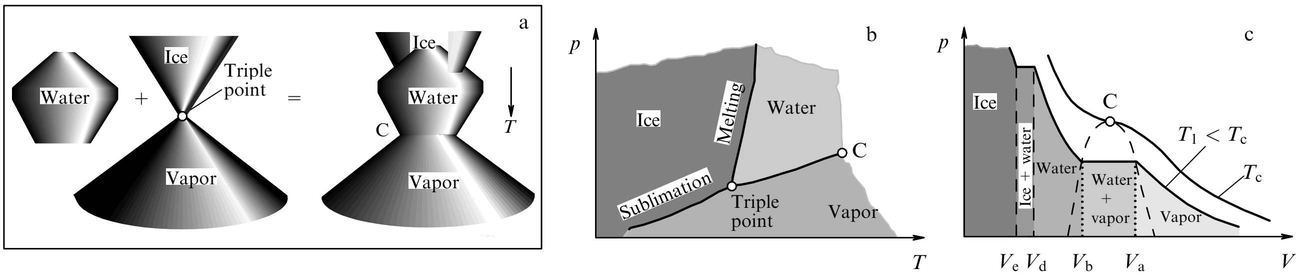

Figure 14. (a) Schematic representation of water phase states: ice, liquid, and vapor. Liquid water consists of ice quasiparticles, vapor quasiparticles, and water molecules. (b) Diagram of water phase states with the triple point in temperature–pressure ($T-p$) coordinates. The three states originate at the *triple point* shown in figures (a) and (b), with vapor and liquid equilibrium spreading toward infinity in the direction of point C. (c) Diagram of water phase states with critical temperature (T_c) isotherm in volume–pressure ($V-p$) coordinates.

horizontal segments converge to the critical point (dashed curve in Fig. 14c). Isotherm T_1 becomes a smooth curve resembling an exponent. Thus, the problem is how to explain interaction between water molecules based only on the peculiarities of intermolecular forces, including van der Waals forces. Thermodynamics is of no practical help here. What it offers are only *phase equilibrium conditions*. The thermodynamic equilibrium condition implies equality of chemical potentials and has the following form in the case of two phases:

$$\mu_1(p, T) = \mu_2(p, T), \qquad (41)$$

where $\mu_{1,2}$ are the chemical potentials. Expression (41) describes the relationship between temperature and pressure for a system in equilibrium. However, it is unproductive to use the mathematical apparatus of thermodynamics in describing a system with continuously proceeding transient processes where matter resides in a nonequilibrium state. Departure from equilibrium *is a kinetic but not a thermodynamic property*. Thus, it may be argued that the existence of a triple point of water (Fig. 14a, b) cannot be described in thermodynamic terms.

Broadly speaking, the theory of water has been developing more slowly than the theory of gases and solids, because it proved difficult to find a small parameter and a fairly universal distribution function of the interaction potential. The intermolecular interaction energy in the gaseous phase is *low, and individual molecules are subject to marked displacement*. In ice, the interaction energy is *high and molecular displacements are small*. Liquid water is characterized by *a strong interaction energy and molecular displacement*, with intermolecular interactions being chaotic and eluding experimental observation.

Ya I Frenkel' advocated the second option, i.e., solid-to-liquid phase transition [131]. He believed that many important general characteristics of water can be described in terms of the properties of a crystal with dislocations and changes in its behavior at an elevated temperature. Frenkel' proposed a theory of vacancy (hole) formation taking into account mechanisms behind deviations from an ideal bulk and surface crystal structure. Metaphorically speaking, he postulated '*void dissolution during crystal melting*', manifested as a rise in the number of holes at the sites abandoned by atoms. Frenkel' showed that the kinetics of crystal behavior varies as temperature increases, giving rise to new dislocations (vacancies) and thereby affects the plastic and elastic properties of the crystal and hole diffusion. This theory was called a 'jump–wait' model. The period of 'settled life' of a molecule (between jumps) was estimated at 3.2 ps.

Liquids and solids share many common properties at near-crystallization temperatures. Specifically, they have almost identical thermal capacities and volumes and, therefore, similar interparticle adhesion forces. Solids are known to show some, even if very low, fluidity, whereas liquids exhibit low shear elasticity and high fluidity. These characteristics of liquids appear essential in light of the fine structure of the Rayleigh line wing discovered in low-viscosity liquids back in 1933; this structure arises from modulation of elastic shear waves of light scattered due to liquid anisotropy fluctuations [133]. Thus, the hypothesis suggested by Ya I Frenkel' as long ago as 1933 [132] has become an experimental fact. Numerical computer experiments based on imitational modeling of molecular dynamics have confirmed Frenkel's hypothesis, which is now preferred over other hypotheses of the liquid state [134–136].

Further studies have demonstrated that relaxation time is the key factor responsible for the fine structure of the Rayleigh line in the light scattered by water where Mandelstam–Brillouin components are displaced with the speed of sound at a frequency of about 1010 Hz. Unfortunately, it is impossible to generate high frequencies in water by direct ultrasonic methods. Nevertheless, the advent of lasers with Kerr cell shutters made it possible to observe this phenomenon even in water. The thin lines appear as a result of light wave modulation by thermal fluctuations in the milieu.

4.4 Behavior of water molecular structure in terms of order–chaos transitions

Describing water in terms of the ice–liquid transition further promotes understanding the molecular mechanisms underlying structural rearrangement in water but does not completely disprove the existence of its *long-lived molecular backbone*.

In order to refute this hypothesis, we shall turn back to ideas of molecular dynamics and thermodynamics to consider them in the context of the *synergetic* theory with *chaos–order* transitions (in application to water: *from turbulent to laminar motion*) that rapidly developed in the late 20th century [137–140].

The theory of turbulence can be constructed using different description languages [138]. Three aspects of this theory (statistical, structural, dynamic) developed parallel to one another and practically independently. The results pertained to practical issues and helped to answer questions arising in qualitatively different experimental situations.

These various approaches were in use till the late 20th century, i.e., up to the time when researchers felt the need for a unified kinetic theory of water behavior based on the chaos–order transition concept.

As early as the 18th century, A de Chézy tried to derive a formula describing uniform water motion in a narrow channel on the assumption that frictional resistance is proportional to the square of the average flow velocity over the cross section (Chézy law). In the 19th century, J L M Poiseuille showed that resistance to water motion corresponded to first but not second degree of water velocity as the channel cross section increased (and water flow velocity decreased). Further experiments confirmed that both authors were right. The Chézy law holds true for turbulent motion (with high velocities), and the Poiseuille law for laminar motion (with low velocities).

O Reynolds experimented with streams of water colored jets and introduced the dimensionless number $\mathrm{Re} = VL/\nu$, where L is the characteristic flow size, V is the velocity, and ν is the kinematic viscosity. He was the first to relate the Poiseuille law to a stratified, laminar liquid flow, and the Chézy law to an irregular random, turbulent motion. A transition of the laminar liquid flow to time-dependent turbulent motion occurs when a certain dimensionless combination of liquid velocity and viscosity with the tube size reach a certain value. It was shown that laminar flow is stable only for $\mathrm{Re} < 2000$ but turns into turbulent motion at a higher Re. For example, the laminar motion of water in a tube 1 cm in diameter at room temperature discontinues, as a rule, already at an average flow rate of $\leqslant 30$ cm s^{-1}.

The first stage of unification of different theories became possible due to successful experiments that showed turbulence to be a space-time chaos of interacting molecular structures. This fact was qualitatively confirmed by visualization of hydrodynamic flows and received quantitative substantiation by the results of measurements. Experimental data were found to agree with the results of numerical computer simulation of two-dimensional turbulence described by the Navier–Stokes equations with *periodic boundary conditions* [141].

This suggested two types of water instability transitions. One is molecular structural instability due to ice–liquid transitions with elevating temperature. The other is kinetic instability related to enhancing layer-specific pressure exerted on the moving fluid along a chain of transitions from laminar motion to quasilaminar motion and to turbulence. Evidently, in this case, the quasilaminar liquid flow is a transient regime, i.e., a combination of two types of transitions, structural and kinetic.

Such a composition can be regarded as a set of nonisochronic pendula oscillating either randomly or (under definite conditions) synchronously. In other words, water is inherent in a set of oscillation modes. As the flow rate changes, the system disintegrates into numerous modes giving rise to vortices. Minor structural fluctuations in the fluid are unable to destroy the strange attractor formed by fluid shear kinetics, and exponential layering of the trajectories inside the attractor prevails over a random external force at small fluctuations [141]. An ensemble of a larger number of modes with varying characters of interaction between them may exhibit both coherent dynamic and stochastic dynamic behaviors, meaning that a transient fluid comprises a *deterministic–stochastic system*. In media with dispersion, such as water, such waves result from frequency synchronization of an infinite number of spatial harmonics.

Two instability mechanisms are inherent in the system being considered. The first mechanism is associated with the development of instability in the course of molecular structure disintegration upon increasing the criticality, while the second, in line with Frenkel's idea, is correlated with a dislocation appearance in the ordered network of structures [142, 143]. The former is probably related to the nontrivial time-dependent behavior in different flows either due to variations in proper dynamics of individual structures or the appearance of collective excitations in the ensemble of structures. Intricate behavior and even chaotic dynamics can emerge in spatially ordered flows without changes in their molecular structure.

Transitions from simple to complex dynamics in an intact spatial structure are no different from known bifurcations in systems with lumped parameters; therefore, results of the theory of finite-dimensional systems must hold for them [38]. It is especially true of the dynamics of azimuthal modes on Taylor vortices during fluid motion between rotating cylinders [133] or the origin of Obukhov vortices [144]. Given a thin layer and a small reservoir, the character of instability may be due to irremovable friction on the reservoir walls. This friction plays the key role in the formation of overcritical eddy flows, the appearance of coherent structures, or turbulence [140].

It follows from the above that the strange attractor for water represents a visual mapping of turbulence that allows for the finite-dimensional representation of instability in the solution of Navier–Stokes equations in partial derivatives. For two-dimensional flows or movements of a fluid in a confined reservoir, its borders serve as a mode-selecting resonator. This process is illustrated by an experiment with a Hele–Shaw cell in which water is injected from above or below into a thin gap between two transparent hydrophobic or hydrophilic plates (a time-varying image can be seen). The boundary conditions for such water flows are determined by water pressure and surface tension. These experiments, as well as our experiment with thermal convection in water [60], confirm the validity of the attractor model of turbulence and demonstrate the dependence of the emerging cells on the shape of reservoir boundaries. According to the theory of hydrodynamic turbulence, the strange attractor in a nonequilibrium dissipative milieu is characterized by a continuous spectrum in time, and a discrete one in space. The attractor relates temporal kinetic instability to spatial structural instability of fluid [144, 145].

To sum up, the order–chaos transition when applied to water is not an abstract hypothesis but a quantitative characteristic of real disordered processes. The order–chaos transition with respect to turbulence means the appearance of localized metastable states in molecular structures [137, 138].

However, these facts failed to convince proponents of the hypothesis for an existence of the long-lived molecular information matrix in water. Their objections reduced to the following: *a laminar-to-turbulent flow transition is equivalent to shaking a container with water. This may destroy the structure of the information matrix that would otherwise remain intact for a long time.*

In what follows, we shall demonstrate that molecular structures in pure (admixture-free) water involved in laminar flow cannot live too long as well.

4.5 Comparison of water structures in the form of cells

Let us consider structures in the form of cells commonly encountered in nature.

Figure 15 demonstrates four types of such cells in liquids observed in our different experiments. All of them emerge from convection, even though by different mechanisms, depending on the milieu. In sperm whale blubber and water, they form through thermal convection. In a thin fat layer heated from below, this process is described by hydrodynamic and thermal conduction equations in the Boussinesq approximation [148]. In thermal convection, a vertical force plays a leading role. In water, thermal convection develops as a result of both heating from below and cooling from above (due to evaporation). In this case, the liquid layer in a small reservoir loses stability because the less dense stratum inside the liquid begins to ascend, while the more dense top stratum descends through the liquid, giving rise to cells [60]. In an analogous manner, the centrifugal force acting on individual microvolumes of a rotating fluid induces horizontal convection. In this way, structures are formed in the Taylor–Couette flow, which may be laminar if it appears in a viscous fluid between two parallel walls (not necessarily flat) moving relative each other. The laminar flow stabilizes under the effect of dynamic viscosity forces and shear stress parallel to the walls. It becomes unstable (turbulent) due to the weakening of circulation of the outer fluid layers with increasing distance from the axis of rotation [133]. A similar phenomenon is the formation of rectangular grids of Faraday ripples in a fluid layer on a vibrating substrate [149].

The physical mechanism of instability emergence in a shear flow of a thin fluid layer (i.e., a flow with a transverse velocity gradient) is related to the increasing periodic interface deflection caused by pressure fluctuations. It is easily shown (it is now set as an exercise to students) that, in an ideal case, perturbations in a thin layer increase exponentially at any wave number. This phenomenon was qualitatively explained in due time by Einstein (see also Section 5.1).

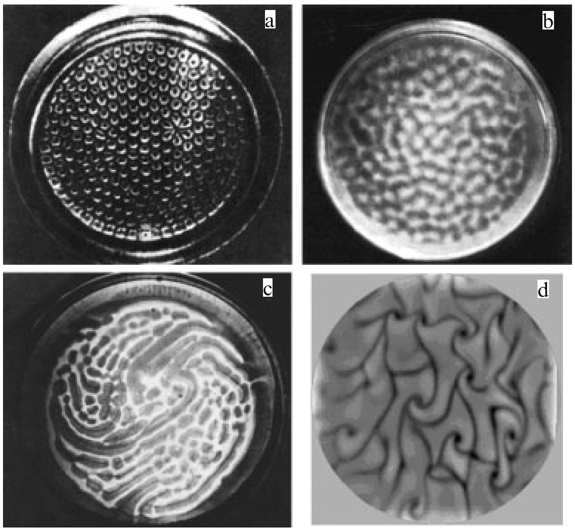

Figure 15. Different types of cellular patterns: (a) cells in an experiment with sperm whale blubber heated from below [76]; (b) cellular pattern created by bioconvection of infusoria (Tetrachymena) showing oxygen and gravity taxis [146]; (c) cellular pattern in the Belousov-Zhabotinsky oscillating chemical reaction [147]; (d) cellular pattern created due to convection during evaporation from the warm water surface in a Petri dish observed by matrix IR imaging in a 3–5-μm wavelength region [60].

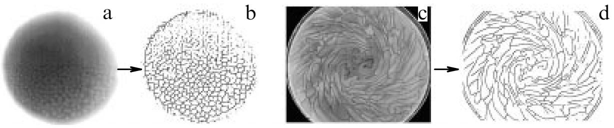

Figure 16. Contour recognition. (a, c) Initial cell images. (b, d) Transformed contour images.

Here is one more of our experiments on cell-pattern dynamics in water using matrix IR imagers with a thermal sensitivity of at least 0.02 °C and a recording rate of 150 frames per second in the wavelength range of 3–5 μm or sensitivity of 0.04 °C and a photodetector matrix size of 320 × 240 elements per frame in the wavelength range of 8–12 μm. These instruments being supplied with desired optical devices allowed detection of events with a spatial resolution of up to 30 μm. Changes in cell characteristics were monitored with a specially developed software package. Its digital image processing algorithms included sequential filtration of the images using Fourier transformation, differentiation, binarization, and skeletonization with subsequent vectorization of the resultant point sets to obtain coupled contours. Results obtained with this program are shown in Fig. 16.

Summation of contour lengths in each frame makes it possible to calculate time-related changes of the dimensionless integral parameter $\Phi(t)$ that characterizes the shape of the totality of cells in the reservoir:

$$\Phi(t) = \frac{\sum_i^N p_i(t)}{L}\,, \tag{42}$$

where $p_i(t)$ is the length of the ith contour, t is time, L is the characteristic size (Petri dish diameter), and N is the number of closed contours.

Having calculated the tangential vector direction for each point of the contour permits the construction of an integral histogram of contour direction distribution at each instant of time (Fig. 17), and thereby the estimation of their average predominant direction and obtaining the orientation parameter of water rotation as a whole. Water undergoes such a rotation under the effects of the curvature and limited size of the reservoir.

A sequential analysis of frames permits the determination of changes in the rotation rate of the entire water volume in the Petri dish. Figure 17 illustrates the motion of the entire volume of warm water in the Petri dish. This motion occurs spontaneously under the action of two temperature gradients, vertical and horizontal. The former results from water evaporation in the dish, and the latter from the curvature of the reservoir walls and fluctuations of heat transfer to them. Moreover, a vortex funnel can be observed at the center of the dish. Its length has to increase with decreasing diameter. In accordance with Helmholtz's second theorem [150], the product of angular velocity vectors by cylinder area must remain constant, namely

$$\mathbf{\Omega}_1 A_1 = \mathbf{\Omega}_2 A_2\,, \tag{43}$$

where $\mathbf{\Omega}_{1,2}$ are angular velocities, and $A_{1,2}$ is the surface area of the cylindrical funnel. Importantly, under low viscosity, all the forces on the surface of the cylindrical funnel volume are perpendicular to this surface. Pressure forces can change the cylindrical shape of the funnel, but the momentum of the fluid

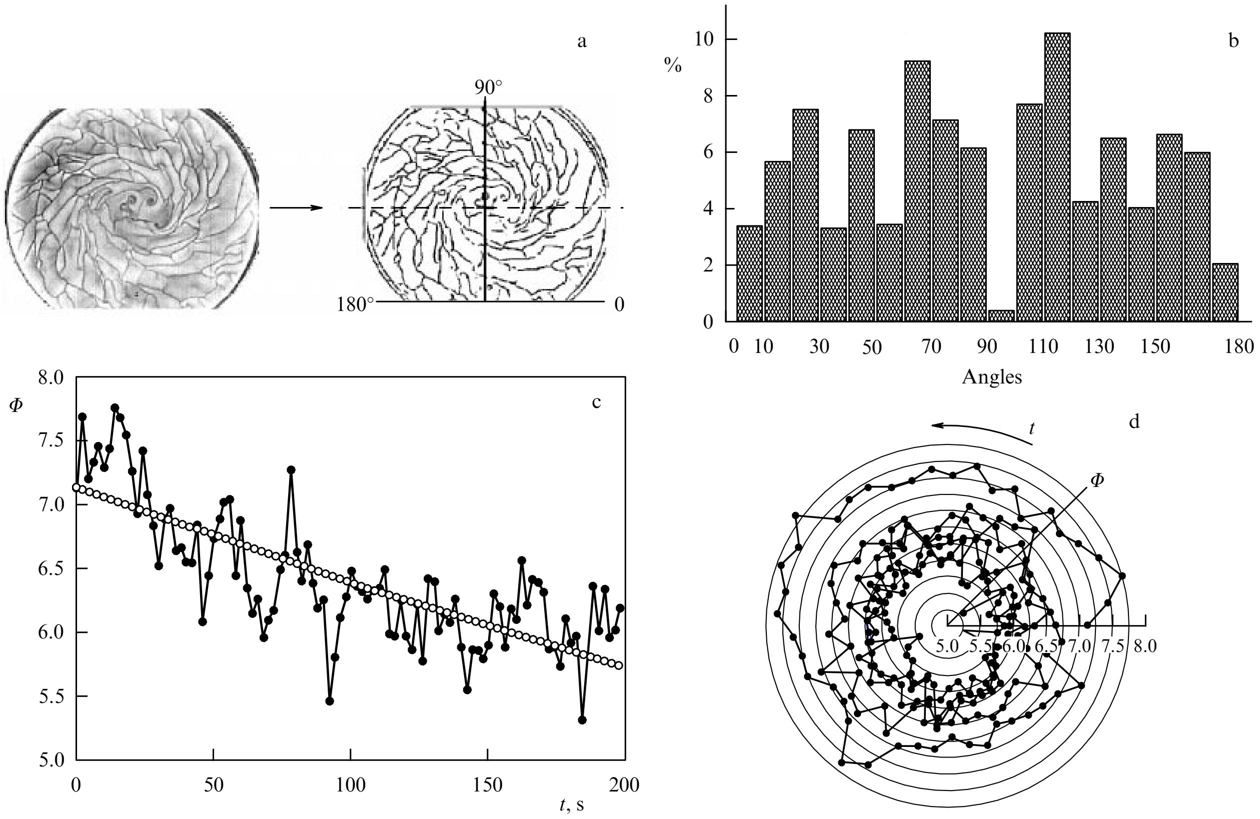

Figure 17. Various presentations of image processing data. (a) Contour recognition. (b) Histogram showing distribution of contour angular positions. (c) Variation of cell shape index $\Phi(t)$ over time in cooling water. (d) Diagram of variation in the cell shape index $\Phi(t)$ over time in polar coordinates.

inside the cylinder cannot change without contribution from tangential forces. The energy of motion E is proportional to the square of the rotational angular velocity ω, which is, in turn, proportional to vorticity $\mathbf{\Omega}$:

$$E = \frac{1}{4}\, mR^2\omega^2 \,, \tag{44}$$

where m is the water mass in the vortex, and R is the vortex radius. At a constant vortex mass, one obtains

$$(mR_1^2)\mathbf{\Omega}_1 = (mR_2^2)\mathbf{\Omega}_2 \,. \tag{45}$$

Expressions (44), (45) ensue from one and the same fact: namely, the angular momentum of each elementary cylinder inside the entire vortex cylinder in the funnel cannot change (a corollary of the third Helmholtz equation). The density of vortices will vary as the vortex radius changes, and the volume of the cylindrical vortex remains unaltered; therefore, the following relation holds:

$$\frac{R_1^2 H_1}{R_2^2 H_2} = 1 \,, \tag{46}$$

where H is the vortex height. This suggests that vortices cannot occur when the reservoir depth H tends to zero, since the vortex radius tends toward infinity. The reservoir area being limited, the vortex leaves it and disappears. The direction of vortex swirling in the case of full symmetry of the initial conditions appears to be equiprobable. Vortices can swirl to the right or left with an equal probability of 1/2. However, fulfillment of the full symmetry condition is hardly possible, as it is dependent on many factors, even such as the location of the observer and the registration camera, because both are sources of heat (Fig. 18). We would like to draw special attention to the last fact, since it accounts for the 14% discrepancy between the results of the Perrin experiments and the Einstein–Smoluchowski theory (see Section 1.1).

The intensity of convective *self-mixing* in water depends on temperature, pressure, and boundary conditions, i.e., the reservoir walls. It increases in hydrodynamic flows with increasing degree of criticality (Reynolds number, Rayleigh number, etc.). Supercriticality forms as a result of building up the hierarchy of instabilities, which is accompanied by both a

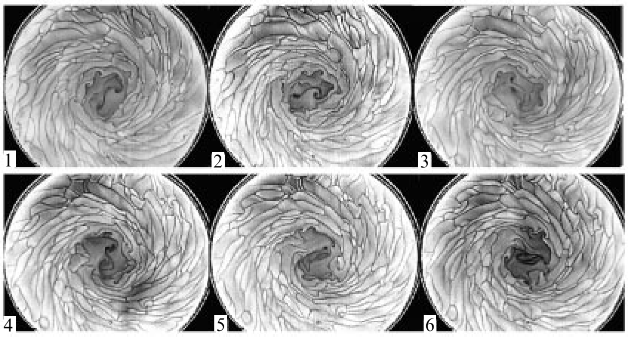

Figure 18. Typical movie frames (see movie 3) showing convective cells in consecutive frames (1–6) observed in the IR range of 3–5 μm in the transient process of water cooling in a round Petri dish 17 cm in diameter. Temperature decreased from 40 °C (frame 1) to 32 °C (frame 6). Room temperature of 21 °C under atmospheric pressure and humidity of 44%. The frames are 2 s apart. The entire water volume in the dish rotates at a frequency of ~ 0.1 Hz.

change in the structure scale and the spatial and temporal symmetry of structures. Despite the great variety of macrostructures and ways of transition from simple to more complex ones, the currently available experimental and theoretical (largely numerical calculations based on molecular dynamics methods) data make it possible to depict a general picture.

It follows from this experiment and the general theory that *water is almost always in a state of self-mixing. This leaves little hope for the existence of any information structural framework*. Such a framework would be destroyed by self-mixing as a result of convection caused by temperature fluctuations. Once an external influence exerted on water is terminated, it reverts to the original dynamic state of constant self-mixing that depends on ambient temperature, atmospheric pressure, and gravity.

The penultimate argument of those supporting the existence of a long-lived molecular information matrix in water is that *its structure can be maintained by electrostatic interactions that are stronger than gravitational ones*.

What follows illustrates the invalidity of this argument, too.

5. Unstable water behavior under the effect of extraneous forces

5.1 Rayleigh–Taylor instability effect

Let us consider two modes of water perturbation. One is the Rayleigh–Taylor instability that develops between two contacting fluids of different densities [151, 152].

When a more dense liquid is poured on top of a less dense one, the former sinks into the latter under the action of gravity. Such instability is exemplified by a drop of liquid perfluorodecaline or glycerol placed on the water surface. Any hydrophobic liquid heavier than water penetrates into it and creates a jelly-like flow with a set of 'hooked fingers' undergoing transformation (Fig. 19).

It is not difficult to explain this phenomenon. Rayleigh–Taylor instability develops due to the instability of the interface between two liquids with different densities when one of them moves faster relative to the other. The main parameter determining the rate of development of this instability is the similarity parameter characterized by the dimensionless Atwood number $\mathcal{A}$:

$$\mathcal{A} = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}\,, \tag{47}$$

where ρ_1 is density of the heavier liquid, and ρ_2 is the density of the lighter one.

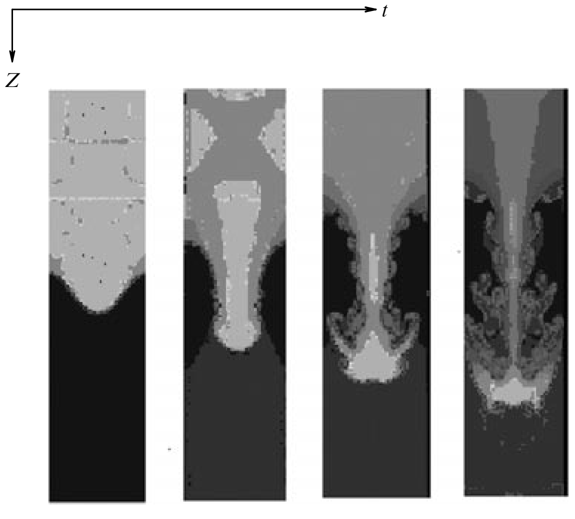

Figure 19. Frame-by-frame sequence showing development of Rayleigh–Taylor instability over time in a tube containing a hydrophobic liquid immiscible with water. Light top areas: moving hydrophobic liquid with density higher than water density. Shaded bottom areas: water.

The contact between plane-parallel layers of immiscible liquids (a more dense one in the upper part of a layer, and a less dense one in its lower part) transfers under the effect of gravity. Equilibrium at contact points on the phase boundary is unstable by virtue of a positive Lyapunov exponent. Therefore, random perturbations will increase, and thereby cause transformation of the contact boundary.

However, marked instability does not necessarily develop at any contact between the surfaces of different liquids. Layer shifting does not disturb the plane contact boundary if the Lyapunov exponent is negative. For example, clouds with sharply defined edges can be observed in Earth's atmosphere. However, if such clouds are scrutinized under large magnification, small vortices can be seen at the interface between the air and water vapor [153].

At the onset of motion from the plane $z = 0$, the sliding velocities u_1 and u_2 of the more dense liquid with respect to the less dense one equal zero, $u_1(x, z) = u_2(x, z) = 0$. The driving force for the layers is the gravitational field providing free fall acceleration with constant $\mathbf{g}$. This field directed along the z-axis gradually increases the velocity of a relative transfer of the contact boundaries, $\bar{u}_1 = gt$ and $\bar{u}_2 = -gt$. Equilibrium exists until a perturbation ε arises at the contact boundary described by the mean velocity field. In this case, $\mathbf{g} = -\varepsilon\hat{\mathbf{z}}$, and the Lyapunov exponent takes the form $\exp(\omega t)$ with $\omega = \sqrt{\mathcal{A}\varepsilon\alpha} > 0$, where α is the spatial wave number. Since the exponent is positive, instability will develop along the x-axis and lead to a bending of the contact boundary in the form of protuberances that curve along the direction of motion of the heavier liquid.

An approximate solution to the Rayleigh–Taylor instability problem is possible in the framework of the Boussinesq linear stability theory [154, 155]. There are many instabilities leading to various structures, such as Richtmyer–Meshkov [156] and Kelvin–Helmholtz [157] instabilities, mushroom clouds [158], Plateau-Rayleigh instability [159], and the Karman vortex street [160].

However, instability appears in these processes in the presence of contact between two liquids or gases of different densities. The question is whether similar instability is possible in water alone, in the absence of another liquid. The answer is yes, it is. Let us consider a variant of pure water perturbation under the effect of local irradiation by electromagnetic waves, as exemplified by one of our earlier experiments [161].

5.2 Are resonances possible in water?

As mentioned in a preceding section, a system on which an external action is exerted tends to remain in equilibrium. In water, such a tendency is due to viscosity, even if it is low.

A force f_i may cause system X_i to depart from equilibrium: $\Delta X_i = \tau_i f_i$. Let us consider how water will behave if the force acting on it changes with time, e.g., periodically with a frequency ω, i.e., $f_i(t) = f_i \cos(\omega t)$. Then, the deviation equals

$$\Delta X_i = \frac{\tau_i f_i}{\sqrt{1+\omega^2\tau_i^2}} \cos(\omega t + \varphi)\,, \tag{48}$$

where φ is the phase shift, and $\tan\varphi = \omega\tau_i$. In this case, function $\Delta X_i(\omega, \varphi)$ must be nonmonotonic and have an extremum. Energy $Q(\omega)$ absorbed by the system as a response to the action of the external force is given by

$$Q(\omega) \sim \frac{\omega\tau_i}{1+(\omega\tau_i)^2}\,. \tag{49}$$

Function $Q(\omega)$ at $\omega\tau_i = 1$ has a maximum, i.e., kinematic or *relaxation resonance*. Is an appreciable resonance possible on water molecular structures? No, it is practically impossible.

The reason is that water is a distributed, poorly compressible system containing a mixture of individual molecules, ions, and water-based molecular structures. Their combinations fluctuate with characteristic times on the order of $10^{-11} - 10^{-12}$ s, i.e., within a frequency range of several THz. Given that water particles have the mean energy $E = k_B\overline{T}$, their frequency, in accordance with the de Broglie theory, is defined as

$$\nu = \frac{E}{h} = \frac{k_B\overline{T}}{h}\,, \tag{50}$$

where $\overline{T}$ is the mean water temperature, and h is the Planck constant. At $\overline{T} = 300$ K, frequency $\nu \sim 6.6 \times 10^{10}$ Hz.

If electrons with energies in the range $10^0 - 10^4$ eV are used as water-exciting particles, the length of their de Broglie waves varies from 1 nm to 10^{-2} nm; in other words, the frequency will fall in the range of X-ray radiation wavelengths: $10^9 - 10^{11}$ Hz. However, such energies break hydrogen bonds, and local resonances, if any, become indiscernible in the noise produced by water ion movements. In other words, water has a low Q-factor. Although dynamic changes in water structures can be observed, these changes are related not to time-dependent molecular resonances but to the flow shear instability of aqueous surfaces in space. Here is an example of such an instability.

5.3 Specific instability effect under the action of an electromagnetic field

Continuous but local pumping of energy into a water layer, e.g., in the GHz region, by an unmodulated electromagnetic field causes at certain parameters of the system a variety of metamorphoses of the ascending heat flux. The shape of the flux transforms to resemble an overturned Rayleigh–Taylor instability structure (see Fig. 19), although this process is governed by a different mechanism, namely, the formation of a single thermoconvection cell. Furthermore, the Archimedes force emerging due to water volume expansion raises the cell to the surface. This process corresponds to the description of Rayleigh–Benard convection associated with the active heating of a water layer near the bottom of a reservoir. Emergence of convection excited by electromagnetic waves is related to heat and water mass transfer underlain by the relay mechanism of energy transfer by microvibrations of water molecules and ions. This process releases heat in the form of expanding cells on the water surface, depending on the layer thickness and the energy fed from the generator. The cells reaching the water surface may appear as double, triple, etc. structures, including periodic fluctuations of heat release (Fig. 20).

Briefly, water is locally heated in this experiment from below at the center of a Petri dish by 52.25 GHz electromagnetic waves from a low-power generator (42 mW). The waveguide cross section is $2.6 \times 5.2 = 13.52$ mm^2, and the distance from the water surface ≈ 1 mm. The layout of the experiment is presented in Fig. 21.

Figure 22 displays movie frames showing the dynamics of water heating by electromagnetic radiation during the first 12 s.

Water irradiation generates two fluxes. The locally heated water flux with density ρ_1 goes up, forcing out cold water and creating the cold flux of density ρ_2 that bypasses the ascending hot one as it moves downward. The following equation holds true for the equilibrium state of the system at the initial instant:

$$\frac{\partial u_1}{\partial z} - \frac{\partial u_2}{\partial z} = 0\,, \tag{51}$$

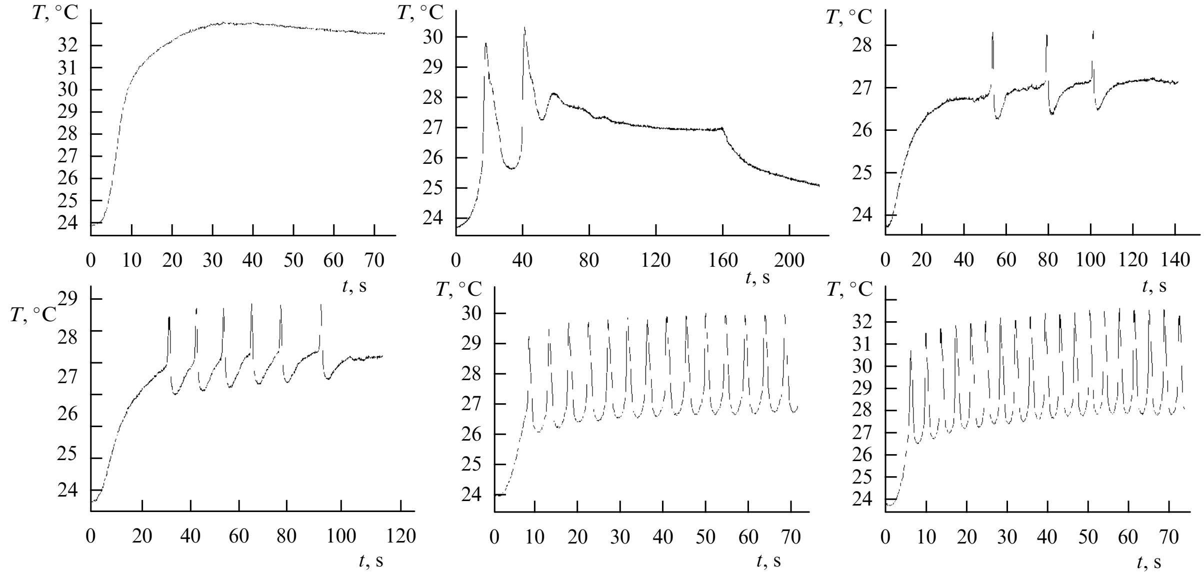

Figure 20. Heat discharges on the water surface at different water layer thicknesses and powers fed from the generator.

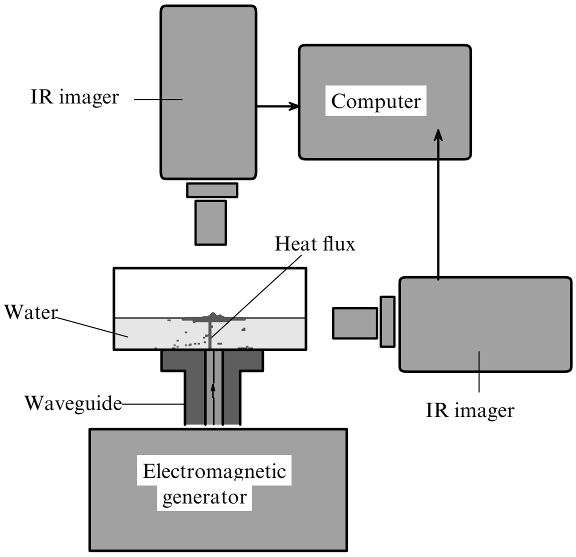

Figure 21. Experimental layout. An electromagnetic field is applied from below through a waveguide to a Petri dish 35 mm in diameter filled with a 2–3-mm thick water layer. Water heating kinetics are recorded by matrix IR imagers in a wavelength range of 3–5 μm.

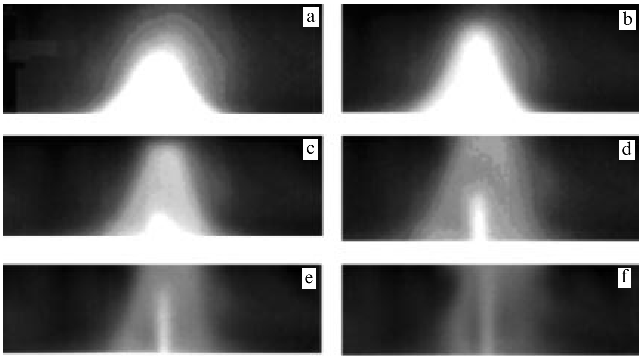

Figure 22. Dynamics of thermal relief behavior (side view) during the first 12 s recorded by an IR imager in a wavelength range of 3–5 μm with temperature sensitivity of at least 0.007 °C and recording rate of 150 frames per second. The frames are 3 s apart. Water layer is ≈ 2.5 mm thick.

where u_1 and u_2 are the upflow and downflow velocities, respectively, and z is the vertical axis coordinate. Instability at the interface between two fluxes moving in opposite directions results in decreasing pressure inside the ascending flux, which causes its compression with the formation of scarcely visible 'hooked fingers' on the plane boundary (Fig. 23). Moreover, surface tension at the interface may change due to different temperatures of two contacting counter flows. This effect, known as thermocapillary (Marangoni) convection, involves three different situations arising from the relationship between projections of pressure $\mathbf{p}_1$ onto the x- and z-axes inside the warm upflow and pressure $\mathbf{p}_2$ inside the cold downflow. Projections of pressure vectors onto the x- and z-axes can be related as follows:

$$\begin{aligned} &\text{a)}\;\; p_{1x} > p_{2x}\,, \quad p_{1z} > p_{2z}\,; \\ &\text{b)}\;\; p_{1x} < p_{2x}\,, \quad p_{1z} > p_{2z}\,; \\ &\text{c)}\;\; p_{1x} > p_{2x}\,, \quad p_{1z} < p_{2z}\,. \end{aligned} \tag{52}$$

Figures 23a, b, and c correspond to pressure relations (52). The total pressure $p_{\text{atm}} + p_\sigma$ on the water surface can be overcome to cause hot water discharge only in the case shown in Fig. 23b. Here, p_{atm} and p_σ are atmospheric pressure and surface tension pressure, respectively. In this situation, mechanical (Fig. 24a) and thermal (Fig. 24b) waves rapidly propagate over the water surface.

Also, heat discharges of paired, triple, and periodic long-lasting oscillations can occur as shown in Fig. 20. The mechanism of generation of oscillations in water is of special interest in view of the effect of electromagnetic waves on living systems and deserves a more detailed description. But in the context of the present review, of greater importance than the process of local thermal oscillations of water molecules and ions in and of itself [162] is water *memory*, i.e., water relaxation time after shutting off the generator.

The relaxation time of water coming to thermodynamic equilibrium depends on many factors, the key one being the restoration time of broken chemical bonds in water molecules. These breaks are responsible for the appearance of numerous water ions. Other important factors are the size of the reservoir L and thermal diffusivity of water χ. As noted above in Section 2.1, the characteristic time τ_2 of temperature equalization is directly proportional to L^2, and inversely proportional to χ: $\tau^2 \sim L^2/\chi$. The relaxation time of a long-lasting application of an electromagnetic field to water is around 24 hours. After this time elapses, water retains no memory of any electromagnetic influences exerted on it. This inference is an experimental fact, since neither the convective structures mentioned in Section 4.5 nor their dynamics in unaffected water differ from those in irradiated water.

The final argument of proponents of the water memory hypothesis *is the statistically proven facts of successful treatment of patients with highly diluted solutions, which are believed to confirm that water retains biological activity and 'remembers' having contained them.*

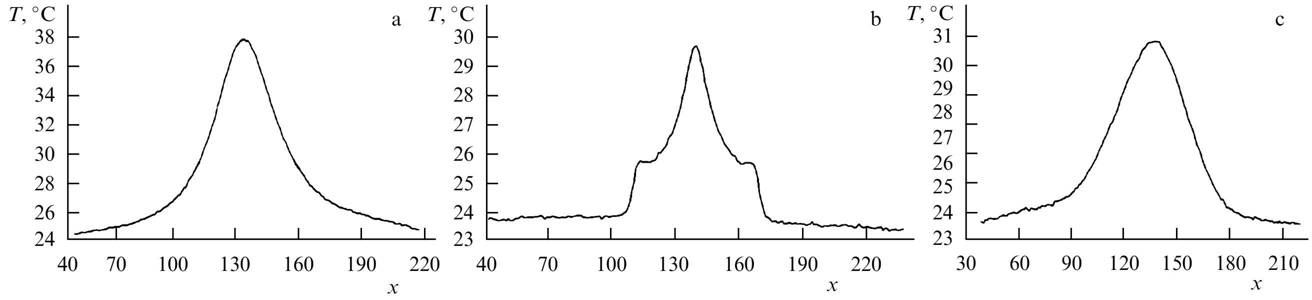

Figure 23. Three examples of upflow heating regimes. Abscissa: flow thickness in pixels (1 pixel = 0.15 mm); ordinate: its temperature.

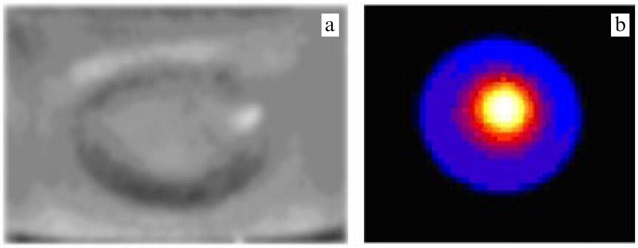

Figure 24. (a) An image of mechanical waves spreading over a water surface, obtained with a camera in visible light under oblique illumination. (b) An image of thermal waves spreading over the water surface (see movie 4) obtained with an IR imager in a wavelength range of 3–5 μm with thermal sensitivity of $\approx 0.007\,^\circ\mathrm{C}$ and recording rate of 150 frames per second. The expanding spot is 2 cm in diameter.

The explanation for this phenomenon (placebo effect) is beyond the scope of water physics; therefore, it is offered in the Appendix.

6. Conclusion

The importance of free and bound water in all molecular structures of living things can hardly be overestimated. Deoxyribonucleic and ribonucleic acids (DNA and RNA, respectively), all proteins, cell membranes, all organs and transport systems of an organism (blood, lymph, intracellular fluid, etc.) could not perform their biological functions without water. Water ranks next to oxygen in importance for life support.

Water is an important *partner* in the formation of relatively long-lived structures, both in technological processes and in living creatures. All structural elements of the living organism, viz. crystallohydrates, hydroxyls, colloids, gels, phlegms, phospholipid membranes, bones, etc., are formed in an aqueous milieu with the utilization of water molecules and ions. For all that, the hypothesis of memory in *extremely pure water* itself is refuted by the experimental data in the present review.

First, water is always in the state of thermal self-mixing, which leaves little hope for the existence of an information framework in its bulk.

Second, the hypothesis of long-lived water structures serving as information matrices and elements of memory is disproved by water mixing experiments described in Sections 3 and 4.5.

Third, water behavior at the molecular level gives no grounds to suggest a long-term memory in this liquid as well. Hydrogen bonds linking water molecules are weak, and their lifetime is only a few picoseconds, as shown in Section 4.

Finally, the hypothesis that pure water exposed to electromagnetic or other influences changes its properties to remember them is refuted by the experiment described in Section 5.3. Water exhibits normal behavior similar to that of the unaffected liquid within one day after termination of the impact.

Thus, it can be concluded that *water has no long-term memory of past mechanical, magnetic, or electromagnetic actions or substances dissolved in it. Its relaxation time after any influence does not exceed 24 hours. After complete removal of impurities by repeated dilutions, water retains no memory of them, nor does it remember past physical actions exerted on it. There is no arguable reason that water should have a molecular information matrix capable of serving as a long-term memory in its entire volume. The hypothesis that water has memory is "as unnecessary as it is fanciful; it is in conflict with results of physicochemical experiments."*[4]

7. Appendix

The placebo (Latin for 'I shall please') *effect* widely used in physiology and medicine, is controversial and may be deceptive. By placebo effect is meant a temporary improvement in human health when a patient given an *inert pill believes* it will change their condition. The level of trust depends on the suggestibility of a given object and external circumstances of the treatment, viz. the route of administration, drug advertisements designed to convince the patient to use the medicine in question, etc. Psychotherapists are well aware that the placebo effect can be achieved by telling the patient "you will be better in a few days," "the treatment will help you recover," "the pain will disappear," etc. [163]. The placebo effect demonstrates that humans and their brains are easy to deceive. The employment of a placebo as a treatment in evidence-based medicine is actually unethical, since it implies deception and runs contrary to the Hippocratic oath [164]. In the West, prescribing a placebo is regarded as bad medicine. At the same time, many religions have adopted a highly indulgent and even positive attitude toward faith healing.

In biophysics, hypnosis and mental healing remain research areas where full knowledge is thus far lacking. Nevertheless, it is well known that any interference in the behavior of a complex system leads to its reorganization. In the process of relaxation, the organism starts searching ways to a new equilibrium state to meet the changing environmental and internal conditions [165]. This issue was dealt with in a few reviews published in *Physics–Uspekhi* [165–168].

Why is it so difficult to differentiate between the placebo effect and the effectiveness of an active ingredient? Testing on animals would seem to rule out placebo effect, since they are not amenable to suggestion. Laboratory mice, rats, or dogs do not know that the drug of interest can heal them. The natural instinct of self-preservation enables them to avoid extraneous interference and protect themselves. However, even certain veterinary surgeons practice nontraditional medicine and homeopathy. Animal tamers, zoo personnel, and stock breeders know that the way we treat animals has a marked effect on them [169–171]. For example, a gentle stroke slows down the heart rate in dogs [172] and horses [173] and increases milk production in cows and litters of pigs [174]. This means that the way humans treat an animal influences the latter's responsiveness. A dog brought for the first time to a veterinary clinic shakes with fear. Children and many adults behave in a similar fashion when checking in to a hospital. However, if released from pain and caressed by the vet's hand, the animal acquires a positive conditioned reflex [175]. In contrast, rough treatment by an experimentalist or a veterinarian may provoke a negative response and aggression, bringing to naught the effect of medication.

---

[4] Today, some pharmaceuticals are steered clear of comprehensive clinical trials and are marketed as biologically active additives (BAAs). Part of them are dietary supplements, many others are medically ineffectual products capable of producing a placebo effect. Water subjected to an external influence makes up one of them.

Nocebo (Latin for 'I shall harm') *effect* is the total inverse of placebo and makes both humans and animals feel worse. For example, poorly suggestible patients of a control group given an inert substance reported feeling unwell [176]; a similar effect has been objectively documented in animals from alterations of the heart rate.

Self-healing. Evolving regulatory systems of all life forms, starting from bacteria, cells of separate organs and ranging to whole organisms, were evolutionarily designed to ensure survival in the changing external and internal environment [177–179]. For instance, warm-blooded animals respond to physiological interference (infection, injury, or stress) by fever, pain, increasing pulse rate, or elevated blood pressure. It is common knowledge that an increase of blood pressure and fever are manifestations of a medical self-treatment. These responses are known to be manifestations of self-healing processes by which the organism tries to arrest own reproduction of bacteria or viruses with which it is infected or to relieve stress, even if a rise in body temperature to above 42 °C may be harmful. In the course of evolution, subcortical brain structures developed into instruments for cost-effectiveness analysis from the perspective of a survival benefit. *Misinformation* may be a cause of the *placebo effect*, whereas false reports on the effectiveness of pseudomedical products are likely to sink people into temporary delusion and make them come to a wrong decision, despite short-term improvement of well-being.

Temporary health improvement after verbal suggestion is a result of excitation of the striated body in basal ganglia, amygdala, and some other brain structures. This excitation stimulates production of stress proteins, reducing the sensitivity of certain cellular receptors [179, 180]. These compounds include, in particular, endorphins, i.e., peptides synthesized in brain neurons that relieve *pain* like opiates. Sometimes, the placebo effect can be harmful, despite a temporary improvement in the patient's condition [181, 182].

The *placebo effect may last* even a few months. For example, it persisted as long as 8 weeks in a patient exhibiting neurotic panic disorder [183], up to 6 months in angina pectoris [184], and even for 2.5 years in rheumatoid arthritis [185].

Testing the clinical effectiveness of medicinal compositions requires large-scale studies designed to identify target organs and observe changes in the behavior of the entire organism in response to a given physico-chemical agent. By way of example, Fig. 25 presents schematically two phases of preclinical testing of a perfluorocarbon-based blood substitute with an oxygen transport function (perftoran) developed in our laboratory [186]. This preparation is a finely dispersed emulsion comprising two liquid perfluorocarbons stabilized by a surface-active compound (SAC). Particles of the emulsion are suspended in an aqueous physiological solution. Clinical application of perftoran had to be preceded by an estimation of its effectiveness and possible side effects, as well as those of all its components at the molecular and cellular levels (Fig. 25a), at the level of individual organs and the whole body of experimental animals (Fig. 25b). Transitions to higher hierarchical levels of the organism and clinical studies involving volunteers could be initiated only after identification of perftoran targets at the aforementioned levels. Up to now, assessment of the *placebo effect* has proven a serious challenge, even in evidence-based pharmacology.

To this end, three groups of examinees have been formed: one study group, and two control ones. Those included in the first group are treated with the preparation of interest. Patients of one control group are given an inert preparation, e.g., glucose, designed for the same method of administration in an identical package. The patients are told that it will produce a marked therapeutic effect. The members of group 3 receive no treatment.

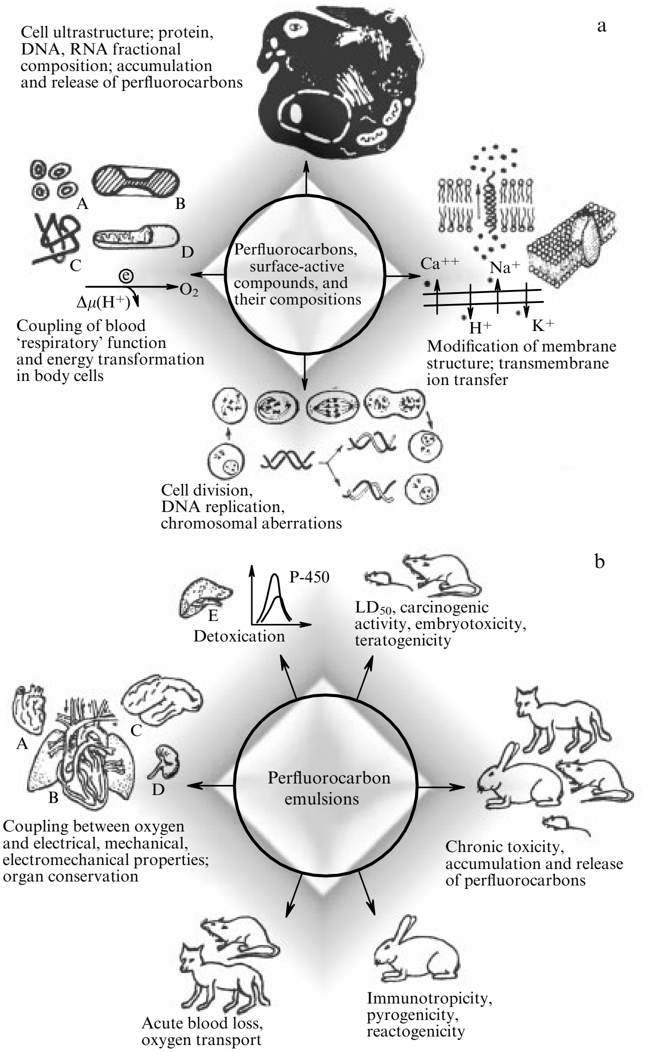

Figure 25. General scheme of two phases of preclinical testing of perfluorocarbons, surface-active compounds, their compositions (a) and finished emulsions (b) acting on biological targets at different levels of the structural organization of a living organism. (a) Molecular-cellular level (*in vitro* testing): A — whole blood and its components, B — erythrocytes, C — hemoglobin, D — mitochondria. (b) Organ-organism level (*in vitro* experiments with functioning organs): A — heart, B — heart–lung system, C — brain (*in vivo*), and nerve cell culture (*in vitro*), D — kidney, E — liver; LD_{50} (lethal dose 50) — average dose required to kill half the members of a tested population [186].

In controlled clinical studies, the placebo effect shows its worth for 20–25% of the patients on the average. The placebo effect varies considerably depending on the condition or disorder and can be as high as 70%, e.g., in neurasthenic states [87].

How far is homeopathy acceptable? Homeopathic remedies are currently used in medical practice, despite doubts about their benefit. On this ground, advocates of homeopathy maintain that water can remember solutes that it contained before dilution. The present review shows that this idea is incompatible with the current state of our knowledge of physical properties and the behavior of pure water.

If such an effect, *besides the placebo effect*, were proved (which is unlikely), researchers would have to concentrate attention on other aspects of the behavior of the solutes formerly diluted in water, such as the presence of their residues at phase interfaces, e.g., at the surface of gas microbubbles or dissolved molecules expelled into the surface tension zone or attached to the walls of the container.

The application of magnetized water or water treated by electromagnetic fields leaves equally little hope for a medical miracle. The therapeutic effectiveness of such water is pure fiction unsupported by experimental evidence. The myth of the efficacy of such a ‘drug’ has been created to deceive ill-informed people.

References

1. Smoluchowski M, in *Vorträge über kinetische Theorie der Materie und der Elektrizität* (Mathematische Vorlesungen an der Universität Göttingen, Bd. 6) (Leipzig: B.G. Teubner, 1914) p. 87 [Translated into Russian: *Usp. Fiz. Nauk* **93** 724 (1967)]
2. Lightfoot E N *Transport Phenomena and Living Systems*: *Biomedical Aspects of Momentum and Mass Transport* (New York: Wiley, 1974) [Translated into Russian (Moscow: Mir, 1977)]
3. Ivanitskii G R *Phys. Usp.* **53** 327 (2010) [*Usp. Fiz. Nauk* **180** 337 (2010)]
4. Shlesinger M F, Zaslavsky G M, Klafter J *Nature* **363** 31 (1993)
5. Shinbrot T et al. *Nature* **363** 411 (1993)
6. Smoluchowski M *Phys. Z.* **17** 557 (1916)
7. Debye D *Trans. Electrochem. Soc.* **82** 265 (1942)
8. Koch A L *Biochim. Biophys. Acta* **39** 311 (1960)
9. Noyes R M *Prog. React. Kinet.* **1** 129 (1961)
10. Adam G, Delbruk M, in *Structural Chemistry and Molecular Biology* (Eds A Rich, N Davidson) (San Francisco, Calif.: W.H. Freeman, 1968) p. 198
11. Berg H C, Purcell E M *Biophys. J.* **20** 193 (1977)
12. Guorhi Z *Sci. Sinica.* **22** 846 (1979)
13. Richter P H, Eigen M *Biophys. Chem.* **2** 255 (1974)
14. Einstein A *Ann. Physik* **322** 549 (1905) [Translated into Russian: in Einstein A, Smoluchowski M *Brounovskoe Dvizhenie* (Ed. B I Davydov) (Moscow – Leningrad: ONTI, 1936)]
15. Perrin J *Atoms* (New York: D. Van Nostrand Co., 1916) [Translated into Russian (Moscow: Gos. Izd., 1924)]
16. Matthews B W *J. Mol. Biol.* **33** 491 (1968)
17. Geiger A, Stillinger F H, Rahman A *J. Chem. Phys.* **70** 4185 (1979)
18. Eisenberg D, Kauzmann W *The Structure and Properties of Water* (New York: Oxford Univ. Press, 1969)
19. Teixeira J *Homeopathy* **96** 158 (2007)
20. Davenas E et al. *Nature* **333** 816 (1988)
21. Maddox J, Randi J, Stewart W W *Nature* **334** 287 (1988)
22. Coles P *Nature* **334** 372 (1988)
23. Pollack G H *The Fourth Phase of Water*: *Beyond Solid, Liquid, and Vapor* (Seattle, WA: Ebner and Sons, 2013)
24. Hirst S J et al. *Nature* **366** 525 (1993)
25. Josephson B D “Molecule memories” *New Scientist* (2106) 66 (1997)
26. Benveniste J et al. *FASEB J.* **13** (1) 33 (2000)
27. Jonas Wayne B et al. *FASEB J.* **20** (1) 23 (2006)
28. Ovelgönne J H et al. *Experientia* **48** 504 (1992)
29. Belon P et al. *Inflammation Res.* **48** (Suppl. 1) 17 – 18 (1999)
30. Gliozzi M *Storia della fisica* (Torino, 1965) [Translated into Russian (Moscow: Mir, 1970)]
31. Brillouin L *Scientific Uncertainty and Information* (New York: Academic Press, 1964); *Science and Information Theory* (New York: Academic Press, 1956) [Translated into Russian (Moscow: Fizmatgiz, 1960)]
32. Chernavskii D S *Phys. Usp.* **43** 151 (2000) [*Usp. Fiz. Nauk* **170** 157 (2000)]
33. Shennon K *Raboty po Teorii Informatsii i Kibernetike* (Works on the Theory of Information and Cybernetics) (Moscow: IL, 1963)
34. Bal'makov M D *Phys. Usp.* **42** 1167 (1999) [*Usp. Fiz. Nauk* **169** 1273 (1999)]
35. Le Chatelier H *Leçons sur le carbone, la combustion, les lois chimiques* (Paris: J. Hermann, 1926) p. 357
36. Atkins P W *The Elements of Physical Chemistry* (New York: W.H. Freeman, 1993)
37. Bohr N *Atomic Physics and Human Knowledge* (New York: John Wiley, 1958) [Translated into Russian: (Moscow: IL, 1961); in *Modelirovanie v Biologii* (Ed. N A Bernshtein) (Moscow: IL, 1963) p. 27, translation section “Quantum mechanics and biology” abridged]
38. Horsthemke W, Lefever R *Noise-Induced Transitions* (Berlin: Springer-Verlag, 1984) [Translated into Russian (Moscow: Mir, 1987)]
39. Sobolev S L *Sov. Phys. Usp.* **34** 217 (1991) [*Usp. Fiz. Nauk* **161** (3) 5 (1991)]
40. Monin A S *Sov. Phys. Usp.* **16** 121 (1973) [*Usp. Fiz. Nauk* **109** 333 (1973)]
41. Monin A S *Sov. Phys. Usp.* **21** 429 (1978) [*Usp. Fiz. Nauk* **125** 97 (1978)]
42. Monin A S, Zhikharev G M *Sov. Phys. Usp.* **33** 313 (1990) [*Usp. Fiz. Nauk* **160** (5) 1 (1990)]
43. Bershadskii A G *Sov. Phys. Usp.* **33** 1073 (1990) [*Usp. Fiz. Nauk* **160** (12) 189 (1990)]
44. Koshel K V, Prants S V *Phys. Usp.* **49** 1151 (2006) [*Usp. Fiz. Nauk* **176** 1177 (2006)]
45. Petnikov V G, Stromkov A A *Phys. Usp.* **54** 1176 (2011) [*Usp. Fiz. Nauk* **181** 1217 (2011)]
46. Luchinin A G, Khil'ko A I *Phys. Usp.* **54** 1181 (2011) [*Usp. Fiz. Nauk* **181** 1222 (2011)]
47. Ingel L Kh, Kalashnik M V *Phys. Usp.* **55** 356 (2012) [*Usp. Fiz. Nauk* **182** 379 (2012)]
48. Frumkin A N *Usp. Fiz. Nauk* **4** 172 (1924)
49. Langmuir I *Chem. Rev.* **13** 147 (1933) [*Usp. Fiz. Nauk* **14** 208 (1934)]
50. Freundlich H, in *Ergebnisse der exakten Naturwissenschaften* Vol. 12 (Berlin: Verlag von J. Springer, 1933) p. 82 [*Usp. Fiz. Nauk* **14** 742 (1934)]
51. Schaefer V J *Am. Scientist* **59** 534 (1971) [*Usp. Fiz. Nauk* **108** 577 (1972)]
52. Bogomolov V N *Sov. Phys. Usp.* **21** 77 (1978) [*Usp. Fiz. Nauk* **124** 171 (1978)]
53. Getling A V *Sov. Phys. Usp.* **34** 737 (1991) [*Usp. Fiz. Nauk* **161** (9) 1 (1991)]
54. Volobuev A N *Phys. Usp.* **38** 169 (1995) [*Usp. Fiz. Nauk* **165** 177 (1995)]
55. Stoilov Yu Yu *Phys. Usp.* **43** 39 (2000) [*Usp. Fiz. Nauk* **170** 41 (2000)]
56. Kuni F M, Shchekin A K, Grinin A P *Phys. Usp.* **44** 331 (2001) [*Usp. Fiz. Nauk* **171** 345 (2001)]
57. Vanag V K *Phys. Usp.* **47** 923 (2004) [*Usp. Fiz. Nauk* **174** 991 (2004)]
58. Tarasevich Yu Yu *Phys. Usp.* **47** 717 (2004) [*Usp. Fiz. Nauk* **174** 779 (2004)]
59. Prokhorov A M (Ed.-in-Chief) *Fizicheskii Entsiklopedicheskii Slovar'* (Physical Encyclopedic Dictionary) (Moscow: Sov. Entsiklopediya, 1983) p. 633
60. Ivanitskii G R, Deev A A, Khizhnyak E P *Phys. Usp.* **48** 1151 (2005) [*Usp. Fiz. Nauk* **175** 1207 (2005)]
61. Ivanitskii G R, Vorob'ev S I *Herald Russ. Acad. Sci.* **67** 452 (1997) [*Vestn. Ross. Akad. Nauk* **67** 998 (1997)]
62. Newton I *Philosophiae Naturalis Principia Mathematica* (Londini: Jussu Societatis Regiae, 1687) [Translated into English: *The Principia*: *Mathematical Principles of Natural Philosophy* (Berkeley, Calif.: Univ. of California Press, 1999); translated into Russian (Moscow: Nauka, 1989)]
63. Stokes G G *Mathematical and Physical Papers* (Cambridge: Univ. Press, 1880 – 1905)
64. Fabelinskii I L *Phys. Usp.* **40** 689 (1997) [*Usp. Fiz. Nauk* **167** 721 (1997)]
65. Pollard A M, Heron C *Archaeological Chemistry* 2nd ed. (Cambridge: Royal Society of Chemistry, 2008) Ch. 10, p. 346
66. Aranson I S *Phys. Usp.* **56** 79 (2013) [*Usp. Fiz. Nauk* **183** 87 (2013)]
67. Tarahovsky Y S, Ivanitsky G R *Biochemistry* **63** 607 (1998) [*Biokhim.* **63** 723 (1998)]
68. Betyaev S K *Phys. Usp.* **38** 287 (1995) [*Usp. Fiz. Nauk* **165** 299 (1995)]
69. Aschoff J (Ed.) *Biological Rhythms* (New York: Plenum Press, 1981) [Translated into Russian: Vol. 2 (Moscow: Mir, 1984)]

70. Molchanov M V, Kutyshenko V P, Budantsev A Yu, Ivanitsky G R *Dokl. Biochem. Biophys.* **442** 52 (2012) [*Dokl. Ross. Akad. Nauk* **442** 828 (2012)]
71. Winterton R H S *Contemp. Phys.* **11** 559 (1970) [*Usp. Fiz. Nauk* **105** 307 (1971)]
72. Betyaev S K *Sov. Phys. Dokl.* **26** 359 (1981) [*Dokl. Akad. Nauk SSSR* **257** 1310 (1981)]
73. Nikol'skii A A *Dokl. Akad. Nauk SSSR* **116** 193 (1957)
74. Nikol'skii A A *Dokl. Akad. Nauk SSSR* **116** 365 (1957)
75. Nikol'skii A A, Betyaev S K, Malyshev I P, in *Problemy Prikladnoi Matematiki i Mekhaniki* (Problems of Applied Mathematics and Mechanics) (Moscow: Nauka, 1971) p. 262
76. Bénard H *Rev. Générale Sci. Pures Appl.* **11** 1261, 1309 (1900)
77. Rayleigh, Lord *Philos. Mag.* **32** 529 (1916)
78. Rayleigh, Lord *Proc. R. Soc. London A* **93** 148 (1916)
79. Marangoni C *Sull'espansione delle gocce di un liquido gallegianti sulla superficie di altro liquido* (Pavia: Tipografia dei fratelli Fusi, 1865)
80. Welander P *Tellus* **16** 349 (1964)
81. Ingel' L Kh *Phys. Usp.* **40** 741 (1997) [*Usp. Fiz. Nauk* **167** 779 (1997)]
82. Ingel' L Kh *Phys. Usp.* **41** 95 (1998) [*Usp. Fiz. Nauk* **168** 104 (1998)]
83. Ingel' L Kh *Phys. Usp.* **45** 637 (2002) [*Usp. Fiz. Nauk* **172** 691 (2002)]
84. Han C S, Jablonski P G *J. Ecol. Field Biol.* **31** 1 (2008)
85. Harnwell G P *Am. J. Phys.* **16** 127 (1948) [*Usp. Fiz. Nauk* **36** 528 (1948)]
86. Deryagin B V *Sov. Phys. Usp.* **13** 305 (1970) [*Usp. Fiz. Nauk* **100** 726 (1970)]
87. Deryagin B V et al. *Izv. Akad. Nauk SSSR Ser. Khim.* (10) 2178 (1967)
88. Ginzburg V L *Sov. Phys. Usp.* **14** 21 (1971) [*Usp. Fiz. Nauk* **103** 87 (1971)]
89. Deryagin B V, Fedyakin N N *Dokl. Akad. Nauk SSSR* **147** 403 (1962)
90. Deryagin B V, Fedyakin N N *Dokl. Akad. Nauk SSSR* **182** 1300 (1968)
91. Deryagin B V et al. *Dokl. Akad. Nauk SSSR* **187** 605 (1969)
92. Lippincott E R et al. *Science* **164** 1482 (1969)
93. Middlehurst J, Fisher L R *Nature* **227** 57 (1970)
94. Leiga A G, Vance D W, Ward A T *Science* **168** 114 (1970)
95. Kurtin S L et al. *Science* **167** 1720 (1970)
96. Rousseau D L, Porto S P S *Science* **167** 1715 (1970)
97. Morariu V V, Mills R, Woolf L A *Nature* **227** 373 (1970)
98. Rabideau S W, Florin A E *Science* **169** 48 (1970)
99. Allen L C, Kollman P A *Science* **167** 1443 (1970)
100. O'Konski C T *Science* **168** 1089 (1970)
101. Deryagin B V, Churaev N V *Usp. Fiz. Nauk* **105** 179 (1971)
102. Ginzburg V L *Usp. Fiz. Nauk* **105** 180 (1971)
103. Bascom W D, Brooks E J, Worthington B N *Nature* **228** 1290 (1970)
104. Pethica B A, Thompson W K, Pike W T *Nature Phys. Sci.* **229** 21 (1971)
105. Zakharov S D, Mosyagina I V, in *Materialy Nauchnogo Simpoziuma "Mekhanizmy Uchastiya Vody v Bioelektromagnitnykh Effektakh", Makhachkala, 1–7 Iyulya 2010 g.* (Proc. of the Scientific Symp. "Mechanisms for Water Participation in Bioelectromagnetic Effects", Makhachkala, 1–7 July 2010) (Moscow, 2013) p. 8
106. Wernet Ph et al. *Science* **304** 995 (2004)
107. Huang C et al. *Phys. Chem. Chem. Phys.* **13** 19997 (2011)
108. Smolsky I L et al. *J. Appl. Cryst.* **40** (Suppl.) s453 (2007)
109. Mishima O, Calvert L D, Whalley E *Nature* **314** 76 (1985)
110. Kanno H, Miyata K *Chem. Phys. Lett.* **422** 507 (2006)
111. Pershin S M, in *Materialy Nauchnogo Simpoziuma "Mekhanizmy Uchastiya Vody v Bioelektromagnitnykh Effektakh", Makhachkala, 1–7 Iyulya 2010 g.* (Proc. of the Scientific Symp. "Mechanisms for Water Participation in Bioelectromagnetic Effects", Makhachkala, 1–7 July 2010) (Moscow, 2013) p. 22
112. Voloshin V P, Naberukhin Yu I, Malenkov G G *Strukt. Dinam. Mol. Syst.* (10A) 12 (2011) Electron. J.; http://old.kpfu.ru/sdms/files10/EJ_S&DMS _10A_p12_25.pdf
113. Bernal J D, Fowler R H *J. Chem. Phys.* **1** 515 (1933) [*Usp. Fiz. Nauk* **14** 586 (1934)]
114. Debye P "Die quasikristalline Struktur von Flüssigkeiten", in *Der feste Körper*; *Vorträge an der Tagung der Physikalischen Gesellschaft Zürich anlässlich der Feier ihres 50jährigen bestehens* (Leipzig: S. Hirzel, 1938) [*Usp. Fiz. Nauk* **21** 120 (1939)]
115. Debye P J W *Struktur der Materie* (Leipzig: S. Hirzel, 1933) [Translated into English: *The Structure of Matter* (Albuquerque: The Univ. of New Mexico, 1934); translated into Russian: *Usp. Fiz. Nauk* **14** 846 (1934)]
116. Debye P *Chem. Rev.* **19** 171 (1936) [*Usp. Fiz. Nauk* **17** 459 (1937)]
117. Maeno N *Nauka o L'de* (Science of Ice) (Moscow: Mir, 1988)
118. Loerting T, Giovambattista N *J. Phys. Condens. Matter* **18** R919 (2006)
119. Salzmann C G et al. *Phys. Rev. Lett.* **103** 105701 (2009)
120. Smoluchowski M *Naturwissenschaften* **6** (17) 253 (1918) [*Usp. Fiz. Nauk* **7** 329 (1927)]
121. Malenkov G G, Yakovlev S V, Gladkov V A "Voda" ("Water"), in *Khimicheskaya Entsiklopediya* (Chemical Encyclopaedia) (Ed.-in-Chief I L Knunyants) Vol. 1 (Moscow: Sovetskaya Entsiklopediya, 1988) p. 766
122. Weisskopf V F *CERN Courier* **9** (10) 295 (1969) [*Usp. Fiz. Nauk* **101** 729 (1970)]
123. Langmuir I *Chem. Rev.* **6** 451 (1930) [*Usp. Fiz. Nauk* **10** 463 (1930)]
124. de Boer J *Proc. R. Soc. London A* **215** 4 (1952) [*Usp. Fiz. Nauk* **51** 41 (1953)]
125. Bak B V *Usp. Fiz. Nauk* **15** 1002 (1935)
126. Skripov V P, Sinitsyn E N *Sov. Phys. Usp.* **7** 887 (1965) [*Usp. Fiz. Nauk* **84** 727 (1964)]
127. Nesis E I *Sov. Phys. Usp.* **8** 883 (1966) [*Usp. Fiz. Nauk* **87** 615 (1965)]
128. Uhlenbeck G E "Fundamental problems in statistical mechanics" (1968) [*Usp. Fiz. Nauk* **103** 275 (1971)]
129. Frenkel Ya I *Usp. Fiz. Nauk* **16** 955 (1936)
130. Frenkel Ya I *Usp. Fiz. Nauk* **25** 1 (1941)
131. Frenkel Ya I *Usp. Fiz. Nauk* **36** 328 (1948)
132. Frenkel J *Kinetic Theory of Liquids* (Oxford: The Clarendon Press, 1946) [Translated from Russian (Leningrad: Nauka, 1975)]
133. Taylor G I *Phil. Trans. R. Soc. London A* **223** 289 (1923)
134. Sarkisov G N *Phys. Usp.* **49** 809 (2006) [*Usp. Fiz. Nauk* **176** 833 (2006)]
135. Fabelinskii I L *Usp. Fiz. Nauk* **117** 711 (1975)
136. Fabelinskii I L *Phys. Usp.* **43** 89 (2000) [*Usp. Fiz. Nauk* **170** 93 (2000)]
137. Gaponov-Grekhov A V, Rabinovich M I *Sov. Phys. Usp.* **30** 433 (1987) [*Usp. Fiz. Nauk* **152** 159 (1987)]
138. Rabinovich M I *Sov. Phys. Usp.* **21** 443 (1978) [*Usp. Fiz. Nauk* **125** 123 (1978)]
139. Ezerskii A B, Rabinovich M I, Sushchik M M *Usp. Fiz. Nauk* **131** 306 (1980)
140. Rabinovich M I, Sushchik M M *Sov. Phys. Usp.* **33** 1 (1990) [*Usp. Fiz. Nauk* **160** (1) 3 (1990)]
141. Grappin R, Léorat J *Phys. Rev. Lett.* **59** 1100 (1987)
142. Kifer Ju I *Math. USSR Izv.* **8** 1083 (1974) [*Izv. Akad. Nauk SSSR Ser. Mat.* **38** 1091 (1974)]
143. Chandrasekhar S, Ranganath G S *Adv. Phys.* **35** 507 (1986)
144. Obukhov A M *Turbulentnost' i Dinamika Atmosfery* (Turbulence and Dynamics of Atmosphere) (Moscow: Gidrometeoizdat, 1988)
145. Pogorelov V E et al. *Sov. Phys. Usp.* **22** 270 (1979) [*Usp. Fiz. Nauk* **127** 683 (1979)]
146. Shvirst E M, Krinskii V I, Ivanitskii G R *Biofiz.* **34** 649 (1984)
147. Ivanitsky G R et al. *Biology Sov. Rev. D* **2** 279 (1981)
148. Busse F H, in *Hydrodynamic Instabilities and the Transition to Turbulence* (Topics in Applied Physics, Vol. 45, Eds H L Swinney, J P Gollub) (Berlin: Springer-Verlag, 1981) [Translated into Russian (Moscow: Mir, 1984)]
149. Betchov R, Criminale W O (Jr.) *Stability of Parallel Flows* (New York: Academic Press, 1967) [Translated into Russian (Moscow: Mir, 1971)]
150. Helmholtz H *Zwei hydrodynamische Abhandlungen* (Leipzig: W. Engelmann, 1896) [Translated into Russian (Moscow: IKI, 2002)]
151. Taylor G *Proc. R. Soc. London A* **201** 192 (1950)
152. Rayleigh (Lord) *Proc. London Math. Soc.* **14** 170 (1882)
153. Sharp D H *Physica D* **12** 3 (1984)
154. Labuntsov D A, Yagov V V *Mekhanika Dvukhfaznykh Sistem* (Mechanics of Two-Phase Systems) (Moscow: Izd. MEI, 2000) p. 143

155. Vekshtein G E *Fizika Sploshnykh Sred v Zadachakh* (Physics of Continuous Media in Problems) (Moscow: Inst. Komp. Issled., 2002) p. 109
156. Glimm J et al. *J. Stat. Phys.* **107** 241 (2002)
157. von Helmholtz H "Über discontinuierliche Flüssigkeits-Bewegungen" *Monatsber. Königl. Preuß. Akad. Wiss. Berlin* **23** 215 (1868)
158. Batchelor G K *An Introduction to Fluid Dynamics* (Cambridge: Cambridge Univ. Press, 2000) p. 470
159. Eggers J *Rev. Mod. Phys.* **69** 865 (1997)
160. von Kármán T, Rubach H *Phys. Z.* **13** 49 (1912)
161. Khizhnyak E P, Ziskin M C *Bioelectromagnetics* **17** 223 (1996)
162. Valiev K A, Ivanov E N *Sov. Phys. Usp.* **16** 1 (1973) [*Usp. Fiz. Nauk* **109** 31 (1973)]
163. Forrest D *Int. J. Clin. Exp. Hypnosis* **50** (4) 295 (2002)
164. Newman D H *Hippocrates' Shadow: Secrets from the House of Medicine* (New York: Scribner, 2008) p. 134
165. Rabinovich M I, Muezzinoglu M K *Phys. Usp.* **53** 357 (2010) [*Usp. Fiz. Nauk* **180** 371 (2010)]
166. Abarbanel H D et al. *Phys. Usp.* **39** 337 (1996) [*Usp. Fiz. Nauk* **166** 363 (1996)]
167. Ivanitskii G R, Medvinskii A B, Tsyganov M A *Phys. Usp.* **37** 961 (1994) [*Usp. Fiz. Nauk* **164** 1041 (1994)]
168. Borisyuk G N et al. *Phys. Usp.* **45** 1073 (2002) [*Usp. Fiz. Nauk* **172** 1189 (2002)]
169. *A. Durov v Zhizni i na Arene* (A Durov in Life and Ring) (Moscow: Iskusstvo, 1984)
170. Gantt W H et al. *Conditional Reflex* **1** 18 (1966)
171. Gross W B *Int. J. Stud. Anim. Prob.* **1** 147 (1980)
172. Newton J F, Ehrlich W W *Conditional Reflex* **1** 81 (1966)
173. Lynch J J et al. *Psychophysiology* **11** 472 (1974)
174. Hemsworth P H, Brand A, Willems P *Livestock Prod. Sci.* **8** 67 (1981)
175. Pavlov I P *Conditioned Reflexes: An Investigation of the Physiological Activity of the Cerebral Cortex* (New York: Dover Publ., 1960) [Translated from Russian: *Dvadtsatiletnii Opyt Ob'ektivnogo Izucheniya Vysshei Nervnoi Deyatel'nosti* (*Povedeniya*) *Zhivotnykh* (Moscow: Nauka, 1973)]
176. Rajagopal S "The nocebo effect", http://priory.com/medicine/Nocebo.htm
177. Reutov V P, Schechter A N *Phys. Usp.* **53** 377 (2010) [*Usp. Fiz. Nauk* **180** 393 (2010)]
178. Ivanitskii G R *Phys. Usp.* **55** 1155 (2012) [*Usp. Fiz. Nauk* **182** 1238 (2012)]
179. Kokkotou E et al. *Neurogastroent. Motility* **22** 285 (2010)
180. Benedetti F et al. *J. Neurosci.* **25** 10390 (2005)
181. Shapiro A K et al. *J. Operational Psychiatry* **6** 43 (1974)
182. Benedetti F et al. *Pain* **75** 313 (1998)
183. Coryell W, Noyes R *Am. J. Psychiatry* **145** 1138 (1988)
184. Boissel J P et al. *Eur. Heart J.* **7** 1030 (1986)
185. Traut E F, Passarelli E W *Ann. Rheum. Dis.* **16** (1) 18 (1957)
186. Ivanitsky G R *Biophysics* **46** 1 (2001) [*Biofiz.* **46** (1) 5 (2001)]
187. Hróbjartsson A, Gøtzsche P C *New Engl. J. Med.* **344** 1594 (2001)