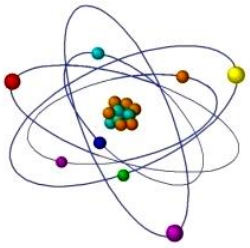
GENERAL PRINCIPLES OF THE ORGANISATION OF THE MECHANISMS OF BIOLOGICAL ADAPTATION



[1]Mikhyeyev O.M., [2]Lapan O.V.
[1]Institute of Cell Biology and Genetic Engineering, National Academy of Science of Ukraine
[2]National Aviation University, Ukraine

ABSTRACT**:** *The existence of a hierarchy of mechanisms of their functioning and a hierarchy of mechanisms of the response to stressors is substantiated. That is based on the fact of the existence of a hierarchical organization of biological systems. It was shown that the adaptive response had been based on the hormesis action of the factor, and the study of the mechanism of adaptive action can be reduced to the study of the mechanism of hormesis effects caused by hypercompensatory processes in objects exposed to a certain stress factor. There is constitutive and inducible/stimulated phenotypic hyperadaptation (PHA). It occurs at the certain stage of positive readjustment of the initial state of the biological object in response to the action of above-threshold levels of factors of any nature. PHA is a process and it is the result of the functioning of constitutive or inducible/stimulated mechanisms of recovery. The whole hierarchy of recovery mechanisms, of which there are as many as there are recovery mechanisms (levels), can provide PHA at a particular level of the organization. PHA has a transitive and transient nature. There is a possibility of consolidating the state of hyperadaptation, when post-factor (post-stress) conditions contribute to its manifestation. At the base of PHA there are the processes of modification (in particular, degradation), the result of which is the emergence of appropriate signals that determine the final implementation of the mechanisms of hyperadaptation.*

Key words: system approach, radiohormesis, adaptation.

INTRODUCTION

One of the areas of modern biology is the study of resistance of biological objects to extreme factors - low and high temperatures, drought, anoxic conditions, heavy metals, ionising radiation, etc. [Baraboy, 2006, Cordyum et al., 2003, Calabrese, 2000]. Along with the development and application of measures which aim is usual protecting or protecting biological objects, including humans, from the effects of stressors, the study of means to increase the initial (current, constitutive, "control") resistance to their action is not less important. At the same time, well-studied phenomenology and developed practice of hardening and training of biological objects to the action of inhibitory factors [Henkel, 1982, Kaplan, Tsyrenzhapova, 1990] created an empirical basis for basic research focused on revealing the actual mechanisms of stability and theoretical justification of methods of its modification and, in particular, increasing the initial level of stability, i.e. adaptability.

In its theoretical and experimental components, the problem of adaptation, from our point of view, with its significance (scale) is in the same range with such archival important medical and biological problems as the mechanism of aging, cancer transformation, morphogenesis, evolution, principles of the human brain and more. What are the difficulties along the way? Firstly, subjective, i.e. "human":

– lack of skills to develop and use meta-knowledge (philosophical, systemic, etc.) or general disregard for the need and possibility of their application;

– inability to form full-fledged cognitive information blocks that could be used to construct a general theory;

– inability to use heuristics or their complete ignorance;

– logical categoricalness and one-sidedness of statements;

– unclear understanding of the concept of "mechanism" and, as a result, the dominance of vulgar reductionism, when there is a reduction of multilevel mechanisms only to the molecular-biological;

– abuse of "native" terminology and unwillingness to unify it;

– subjective orientation to create "finished" theories and "adjust" the existing facts to them;

– vague awareness of the need to distinguish between the adaptation of systems organized on stochastic and structural principles.

The objective difficulties should include, first of all,:

– complex dynamic and spatial nature of biological processes and phenomena, their multilevel, multistage, large length of time, for instance, large time intervals in which adaptation processes can unfold;

– lack of adequate and unified language for formulating problems and describing the phenomena themselves;

– insufficient development of the theory of dosimetry of stressors (for example, dosimetry of antioxidants);

– incomplete phenomenology of adaptive processes;

– undeveloped metascientific (for instance, the same systemological) approaches, non-usage of methods and techniques of related sciences;

– the difficulty of determining the contribution of genetic and epigenetic components of the adaptation mechanism.

Without any doubt, this is not a full list of difficulties in studying adaptation, but it still gives the idea of the complexity of this problem, which is almost equivalent to the problem of determining the essence of life.

Phenomenology of adaptive answer (answer to the question "What?")

It should be noted that almost all the problems of resistance of biological objects to extreme influences of the factors of different nature are centered around the nature and the mechanism of stress in general, as well as its varieties - eustress and distress (Selye, 1972; 1982). The greatest difficulties in solving this problem arise in relation to plant objects, as indicated by the paradoxical situation in the sphere of plant physiology. Its essence is that with the widespread use of the term "stress", introduced into scientific usage by Hans Selye, in the literature on the biology of stress in plants (plant stress biology) almost does not pay attention to the impossibility of direct (practical) usage of traditional definitions of stress to describe this phenomenon in plants. This is due, on the one hand, to a very high degree of generalization of the proposed definition, and, on the other hand, the presence of specific signs of plant reactions to extreme actions. In addition, mutual understanding among scientists studying the reactions of plants to prolonged or chronic exposure to extreme factors is complicated by the ambiguity of their use of the term "stress". Thus, in some cases, stress is understood as an extreme factor of the external environment that acts on the body [Kostyuk, Ostaplyuk, Levenko, 1994]. Most often, the interpretation of this concept is based on the understanding of stress as an altered state of biological objects, which arose as the result of the action of environmental factors on it [Baraboy, 2006; Veselova, Veselovsky, Chernavsky, 1993; Urmantsev, Gudskov, 1986]. However, despite the difficulties above , this definition of stress by G. Selye due to the same high degree of its abstraction causes a high level of its heuristics, which allows to identify the universal elements in the response to

the mechanisms of biological objects of any level of integration to extreme factors. in different doses, including those that are actually adaptive, i.e. those that increase the initial level of stability. In particular, there is an opportunity and necessity to study the features of the multi-stage process of response of biological objects to the entire range of doses and capacities of possible extreme effects (distressors). There is also an obvious need to study multilevel mechanisms of adaptation as opposed to attempts to reduce them only to intracellular mechanisms. Indeed, it is difficult to assume that the change in resilience, for example, of any level of integration of the ecological system (population, group, etc.) is due solely to molecular, in particular, reparation mechanisms. There is no doubt that other recovery systems are involved in this process - cell-repopulation, regeneration, repopulation processes at the population level, and so on**.**

All the above determines the relevance and necessity of studying the peculiarities of the manifestation of the effects of adaptation of biological objects at different levels of their integration. Note that from the point of view of this relevance, the results of the study of actual hormesis (positively stimulating) effects are also of interest for this topic, as our results proved the connection of adaptation processes with hormesis and, in particular, radiohormesis processes (Mikheev, 2018).

Given the complex dynamics of the response of biological objects to the stressful effects of factors of different nature, from a purely phenomenological (observational, descriptive) standpoint, all reactions of biological objects at certain levels of their organization, depending on the direction of change (modification) of the initial level of stability can be divided into three types: 1) reactions without a final change (even a temporary excess during the observation) of the initial level of adaptability; 2) reactions with an increase (at least temporarily during the observation) of the initial level of adaptability - hyperadaptive (hyperbiotic); 3) reactions with a constant (irreversible) decrease in the level of initial adaptability - hypoadaptive (hypobiotic). Note that in the literature, the concept of "hyperadaptation" corresponds to the concept of "adaptive response" (Volkert, 1988). Of course, each type of reaction corresponds to a certain dose / concentration / power range of the active factor, i.e. any factor with certain quantitative characteristics of the effect can be neutral, hypoadapting or hyperadapting. For instance, based on these positions, we can assume that at certain concentrations, antioxidants will act as carcinogens (eg, aminophenols), and carcinogens will have antitumor effects.

The result of modification of the initial level of stability of a biological object under the influence of alternating (modifying) action of a factor of any nature to the action of a stressor (stress factor) of any nature, only potentially occurs to either adapt (hyperadapt) or maladapt (hypoadapt) object. The sign (direction) and the magnitude of the influence of the modifying factor can be detected only with the subsequent application of the so-called "test factor", also called "damaging factor", which, in our opinion, adequately reflects the interaction of factor and object. to establish the level of organization of the object, where there is rebuilding (in particular, destructive) changes under the influence of stress. If such a factor increases the initial level of stability of the object, it is called "hormesis" or "adaptive factor".

Since the scheme of studying modifying effects involves the use of two doses (alternating and testing), in the case of observational response (hyperadaptation), it is significant to emphasize that there is a paradoxical nature of such effects, when the negative impact of one stress factor is more pronounced than the combined effect adaptive (hormesis) factor and the same test factor.

This refers, in fact, to the possible preventive action of the factor-modifying the initial stability of the object, when its action precedes the action of the test factor. But the therapeutic (post-stress, "therapeutic") effect of the modifying factor is also possible. We have called this phenomenon "reverse adaptation", the mechanism of which is probably the ability to activate the recovery system in the post-stress period, i.e. to find (unfortunately, purely empirically) the balance between damage and recovery. In other words, there is a relative symmetry of the joint action of the two factors, i.e. the

order of their action may not be significant, which, in relation to hyperadaptive response, means the possibility of hyperadapting effect after testing as a therapeutic, not just prophylactic (Mikheev, Shilina, Ovsyannikva, 2008).

Note that we consider only the phenotypic manifestation of the hyperadaptive response - phenotypic hyperadaptation - PHA, which has a transitive (transient), i.e. transient in nature, relativity by parameters and a certain nonspecificity to subsequent effects. The duration of PHA is determined by the duration of the phases of positive re-regulation of the transition period (process), For example, the transient increase in the level of ROS under the action of stressors (Kolupaev, Karpets, 2019) can be considered as the primary mechanism of PHA.

Given the fact of the existence of endogenous rhythm of the values of structural and functional parameters of a biological object, we can assume the existence of constitutive (synonyms: spontaneous, initial, "control", endogenous, background) along with inducible / stimulated (synonyms: induced, induced) (epigenetic) hyperadaptation (PHA).

From a practical point of view, it is important to point out the possibility of consolidating the state of hyperadaptation, when post-factor (post-stress) conditions contribute to its manifestation. Thus, the hormesis effect (PHA condition) of plants obtained from seeds irradiated in a potentially hormesis dose depends on the conditions of their post-factor cultivation. Thus, in the field, when irradiated seeds are often sown in insufficiently moist soil, stimulated by irradiation seedlings with longer roots are found to be better supplied with water and nutrients. And the longer the period of arid conditions, the greater the growth stimulation and the greater will be (positive towards plants from irradiated seeds) differences in the phases of development and yield (Churyukin, Geraskin, 2013).

To create a consistent concept of adaptive response, it is necessary to study the structure of transients induced by extreme influences and establish their relationship with the types of adaptive response (actually adaptation or maladaptation), as well as show the role of multilevel mechanisms in adaptive response. PHA occurs at a certain stage of positive overregulation (overrecovery) of the initial state of the biological object in response to the action of the transboundary level of a factor of any nature (Mikheev, 2015).

Manifestation of PHA of biological objects is possible at any level of their structural and functional organization. The higher this level is, the higher is the dose of stressor to which it can be induced hyperadaptive response, and the higher the hyperadaptive dose. In other words, if the dose / power of the stress factor exceeds the threshold of the object's response for a specific level of its integration, it induces / stimulates the transition process, the presence of a hypercompensatory phase in terms of parameters that positively characterize its viability (for example, growth rate), is a necessary condition for obtaining a hyperadaptive response. In general, the higher the level of absorbed doses / capacities / concentrations of the active factor is, the higher the structural-functional level induces / stimulates the transition process.

Mechanisms of PHA (answer to the question "How?")

Given the multilevel structural and functional organization of biological systems, we can assume that there is a whole hierarchy of mechanisms of their functioning in general and a hierarchy of mechanisms of response (perception, transduction, recovery, etc.) to the action of stressors. What meaning do we put into the concept of "mechanism", the interpretation or definition of which most researchers do not consider necessary and use only an intuitive perception of its content? In our judgment, to reveal the mechanism of a phenomenon means to describe a phenomenon established for any system by describing the behavior and interaction of the elements of this system. For instance, if the phenomenon of radiation inhibition of root growth activity is described with the involvement of data on the reaction of its tissue components (rest center, meristem, differentiation zone, etc.), then this

is exactly the description of the direct mechanism of this phenomenon. It is obvious that the contribution of individual tissue elements in this situation will be well defined for a given inhibitory dose, and some tissues are likely to be critical in terms of their determinant contribution to the reaction mechanism. In a different dose range, the "weight" of the tissues may change and, consequently, there may be a different mechanism with other critical structures in the main "roles".

Due to the hierarchical organization of biological systems, the description of the mechanism of the phenomenon of higher structural and functional level will be both a phenomenon for a lower level of organization. In the example above, if the determining role of the meristem in the mechanism of inhibition of root growth is clarified, the reaction of the meristem itself to radiation will already act as a phenomenon that requires its procedure to determine the contribution of its (meristem) components.

Thus, PHA is a process and result of the functioning of constitutive or inducible / stimulated mechanisms for the restoration of such changes. PHA at a specific structural and functional level can be provided by the whole hierarchy of its recovery mechanisms, starting with reparation and ending, for example, repopulation. There are as many mechanisms (levels) of hyperadaptation as there are mechanisms (levels) of recovery, which, among other things, work in the normal conditions of existence of a biological object. In other words, there is a need for recovery mechanisms to function regardless of the presence or absence of a stressor. It is these mechanisms that ensure the dynamic stability (homeostasis) of biological systems and they also determine a certain rhythm of the level of stress resistance (endogenous rhythm of stability). The latter means that organisms are able to go spontaneously into a state of increased or decreased level of stability.

Another paradox of PHA is that it is based on the processes of degradation (destruction, change, modification in the broadest sense), the result of which is the emergence of appropriate signals that ultimately lead to the implementation of hyperadaptation mechanisms. It should be noted that just as there are endogenous recovery processes, there are endogenous degradation processes (for instance, apoptosis), which are only enhanced (stimulated) by stressors in high doses.

The above-mentioned concept of "destructive changes" or the concept of "degradation processes" allows for a fairly broad interpretation, covering all possible ways of transforming the system-object (CO). The basis for this statement is the results obtained in the framework of the general theory of systems (ZTS), developed by Yu.A.Urmantsev (1974). According to the basic law of this theory, a particular system-object is able to pass (a) either into itself - by identical transformations, (b) or into other CO - by means of one of seven, and only seven different transformations of elements, and namely changes: (1) quantity, (2) quality, (3) relations, (4) quantity and quality, (5) quantity and relations, (6) quality and relations, (7) quantity, quality, and relations of all or part elements of CO. Obviously, with any type of transformation of CO changes the rest of all the characteristics of its elements, i.e. in its pure form, each of the rearrangements does not exist, but dominant in a certain period of time or place may be one or another type. In addition, it is important to emphasize that these types of transformations can act as a signal that can trigger a cascade of recovery mechanisms.

The classification of types of transformation of systems is considered, we took as a basis and with its help the classification of primary types of adaptive transformations (mechanisms) of biological CO in case of action on it of system-factor (SF): 1) proliferative (caused by modification) numbers of pre-existing CO elements; 2) functional (associated with changes in the quality of functioning of CO elements); structural (due to changes in the relationship between the primary elements of CO).

One of the theoretical bases of our proposed approach to the description of PHA mechanisms is to substantiate the position that adaptive (adaptive) reactions are primarily due to inertia (imperfection, inaccuracy) of recovery systems and, in particular, the phenomenon of overregulation of certain structural and functional parameters. The reason for this idea is the fact that the course of reactions of

objects in response to extreme factors is characterized by phase, which, in turn, causes a change in the resistance of the biological object to repeated influences. It is with the phase of overrecovery (one of the types of overregulation) and associated adaptive response, i.e. this type of reaction, when the initial level of adaptability increases. From these positions all responses of an organism or any other biological system to action of above-threshold doses of stressors are considered from the point of view of modification of their adaptive ability (potential) which is shown at the subsequent influences of the same or other by the nature factor.

Another fundamental aspect of the problem of stress state of biological objects is related to the need to take into account the multilevel structure of their structural and functional organization, which suggests the existence of a multilevel inducible / stimulated system that provides both multilevel reactions of biological objects and multilevel mechanisms adaptive reactions. The need for such an approach is due to numerous and not always successful attempts to reduce all the variety of mechanisms of adaptive responses only to mechanisms that function at the intracellular level, for example, this trend is observed in attempts to reduce various mechanisms of responses to radiation only to the mechanism of induction / stimulation repairing DNA enzymes or heat shock proteins in the case of elevated temperatures (Fippovich, 1991; Schwartz, 1998). This often does not take into account the presence and possibilities of hierarchical organization of the biological object, each structural and functional level of which (cell, tissue, organ, organ system, etc.) is capable under appropriate conditions, dose and power of the influencing factor, type of reaction, registered, the state of the biological object, etc.) to provide conditions for the adaptive response of the whole system. For example, the well-known processes of modifying the values of the parameters of cell proliferation, growth activity and reproduction of individuals at the population-organism level, etc., under certain conditions, the stage of recovery (hypercompensation), indicate the fundamental possibility of occurring with the participation of almost all levels of structural and functional organization of the biological object (Nefedov et al., 1991, Lekevicius, 1997).

If with respect to the induced / stimulated repair process (in particular, due to the higher power of the enzymatic repair system) it is clear how increased resistance to repeated stress is provided, then due to which mechanisms can increase resistance when increasing (at the stage of hypercompensation), for example, speed cell proliferation? It is clear that the increased rate of cell proliferation may be a factor in reducing the tolerance of cells to the re-action of the stressor, which is clearly indicated by the law of Bergonier-Tribondo. However, if our assumption is correct, then due to the higher rate of proliferation of modified adaptive cells can form a sufficiently large critical cell mass, which will provide a more complete and effective recovery of critical plant tissues. This assumption was confirmed in our studies of the role of proliferative activity of meristematic cells in ensuring the radioadaptive response of plants (Mikheev et al., 1998). Obviously, the enzymatic reparation system should be considered as the most fundamental (actually biological) system, the stimulation of the activity of which can directly increase the initial level of resistance (in particular, radioresistance). The stressor (stress factor) that induces the transition process in CO, in addition to stimulating the repair system, can provide at some point (phase, stage) of the transition process increased proliferative activity, for example, by irreversible damage (apoptotic or necrotic type) of cells, the degradation products of which are probably a "repopulation signal", the nature of which has not yet been fully elucidated. However, it is important to emphasize that the stressor can not only directly affect the reparation system, but also indirectly modify it through higher levels of structural and functional integration. Enhanced activity of genes encoding enzymes of the repair system can be provided not only by enhancing protein synthesis in a single cell, but also by increasing the proportion of cells synthesizing the desired complex of proteins. In addition, the total genetic activity is able to increase by increasing the number of relevant individuals, i.e. to be provided at the population level. In

favor of this assumption, in particular, the results of research VN Afanasyeva and NP Motilevich (1989), who found that a significant contribution to the process of restoring the rate of DNA synthesis in a population of irradiated cells on the background of recovery in each cell is a change in the structure of the cell population under the influence of ionizing radiation. Thus, the population of HeLa cells in the logarithmic growth phase consists of 60% of cells in the G1 (G0) phase, 23% in the DNA synthesis stage (S-phase) and 17% in the G2 + M stage. In the first hour after irradiation at a dose of 10 Gy, the distribution of cells by phase of the cycle differed little from the control, due to the delay in the progress of cells in the cycle. Further, because the cells irradiated in the S- and G2-phases stop for a longer time, there is a decrease in the number of cells in the G1 phase (G0) and an increase in the number of cells in the S-phase against the background of virtually unchanged number of cells in the G2 + M phases. Subsequently, the accumulation of cells in the G2 + M phases was noted. As it can be seen, some time, after irradiation in the cell population there is an increase in the proportion of DNA-synthesizing cells, which inevitably affects the process of restoring DNA synthesis and, as a result, the hyperadaptive response. The above authors speak of "true recovery in each cell", probably referring to the "falseness" of recovery at the population level. To our mind, the position of the authors is a consequence of explicit or implicit application of the principle of endocytocentrism, according to which an attempt is made to explain everything only on the basis of intracellular mechanisms. It is clear that cellular mechanisms provide the most fundamental mechanism of biological objects' responses to extreme factors, but the hierarchy of biosystems may not be limited to the cellular level and the "gene dose" can be increased by structures of higher integration than the cell.

Thus, the biological system has a kind of structural and functional memory of previous actions of exogenous and / or endogenous factors and this memory largely determines the nature of subsequent reactions to the action of "new" stressors. It is this memory that allows the biological system, which is, in particular, in a state of hypercompensation (in this example - in a state of increased rate of cell proliferation), to provide increased resistance to further influences of stress factors, which is not so much due to reparation mechanisms, how much due to the mechanisms of restoration of higher levels of integration, which also participate in the "memorization" of traces of stress factors.

An important challenge for stress biology is to elucidate the nature of the stress signal, which exerts an epigenetic effect and thus triggers an adaptive response. Thus, it is believed that the most universal system of this kind is a system of redox regulation (Kolupaev, Karpets, 2019), which triggers the mechanism of signal transduction. We believe that such a mechanism would be more accurate to call the most common, because biological objects are most often exposed to such factors that directly cause an increase in the content of reactive oxygen species (ROS) in tissues. The importance of ROS is also indicated by the possibility of amplification of the primary ROS signal due to the increased activity of ROS-generating enzymes (Mitter et al., 2011).

From our point of view, any biological structure can perceive the action of a stressor (i.e. act as a primary target). Depending on the characteristics of the stress factor (power, dose, concentration, quality), such target structures may be unique or multiple structures. For example, in the case of ionizing radiation, depending on the dose, the target may be a unique structure such as a nucleus, or a multiple structure in the form of membrane structures. The target of the temperature factor, in fact, is the whole organism, because its (i.e. temperature factor) level depends on the functioning of all body systems. In other words, there are non-specific and specific targets. In addition, specific targets may respond nonspecifically when the factor parameters go beyond the "working" area of the target (sensor).

What is the meaning of biological adaptation (hyperadaptation, PHA), if its price is destructive processes, the recovery of which requires the consumption of certain energy and substrate resources?

Actually, in this question there is an answer to it. Biological systems would not need to use stress mechanisms if stressors did not change. However, the biological system, as an open system, is constantly exposed to exogenous and / or endogenous factors that throw it out of balance and, thus, translates it into a state that needs to be restored to its original state.

CONCLUSIONS

We consider that it necessary to make some generalized conclusions and assumptions that may become the basis for the future theory of biological adaptation, namely: all reactions of biological objects to extreme influences can be divided into three types: a) reactions without changing the initial level of adaptability; b) reactions with increasing the initial level of adaptability - hyperadaptive; c) reactions with a decrease in the level of initial adaptability - hypoadaptive.

Manifestation of PHA of biological objects is possible at any level of their structural and functional organization. The higher this level is, the higher the dose of stressor to which it can be induced hyperadaptive response is, and the higher the hyperadaptive dose too.

Constitutive and inducible / stimulated phenotypic (epigenetic) hyperadaptation (PHA) is possible. PHA is a process and the result of the functioning of constitutive or inducible / stimulated mechanisms for the restoration of such changes. PHA at a specific structural and functional level can be provided by the whole hierarchy of its recovery mechanisms (starting with reparation and ending, for example, repopulation). There are as many mechanisms (levels) of hyperadaptation as there are mechanisms (levels) of recovery. The mechanism of PHA is based on the processes of modification (in particular, degradation) of the initial state of the system, the result of which is the emergence of appropriate signals, which ultimately determine the implementation of hyperadaptation mechanisms.

PHA happens at a certain stage of positive or negative overregulation (overrecovery) of the initial state of the biological object in response to the action of above-threshold levels of factors of any nature. PHA has a transitive, transient nature and relativity in parameters, i.e. a certain nonspecificity to the following effects; the duration of PHA is determined by the duration of the phases of re-regulation of the transition period.

There is a possibility of consolidating the state of hyperadaptation, when post-factor (post-stress) conditions contribute to its manifestation.

Exogenous and endogenous factors reach the hyperadapting level only when their quantitative characteristics (dose and power) approach the characteristics of a complex endogenous factor, which determines the constitutive (spontaneous) level of changes (in some cases, damage) in the system.

There is a relative symmetry of the joint action of the two factors, i.e. the order of their action may not be important, which in relation to the hyperadaptive response means the possibility of applying the hyperadaptive effect after testing as a therapeutic, not only prophylactic.

REFERENCES

1. Afanasyev V.N., Matylevich N.P. 1989.1 All-Union. radiobiol. Congress: Abstracts. report T. 1. Pushchino: 130-131.
2. Baraboy V.A. Stress: nature, biological role, mechanisms, outcomes. K .: Fitosotsiocenter, 2006: 424 p.
3. Veselova T.V., Veselovsky V.A., Chernavsky D.S. Stress in Plants (Biophysical Approach). M.: Publishing house Mosk. University, 1993: 144 p.
4. Genkel P.A. Physiology of heat and drought resistance of plants. Moscow: Nauka, 1982: 280 p.
5. Kaplan E.Ya., Tsyrenzhapova O.D., Shantalova L.N. Optimization of the adaptive processes of the body. Moscow: Nauka, 1990: 94 p.

6. Kolupaev Yu.E., Karpets Yu.V. Reactive oxygen species, antioxidants and plant resistance to stressors. K.: Logos, 2019: 277 p.
7. Kordyum V.L., Sytnik K.M., Baranenko V.V. et al. Cellular mechanisms of plant adaptation to adverse effects of environmental factors in natural conditions. K.: Naukova Dumka, 2003: 282 p.
8. Mikheev A.N. Hyperadaptation: Stimulated ontogenetic adaptation of plants. K.: Fitosotsiocenter, 2018: 423 p.
9. Mikheev A.N. Modification of ontogenetic adaptation. K:Phytosociocenter, 2018:396 p.
10. Mikheev A.N., Gushcha N.I., Malinovsky Yu.Yu., Grodzinsky D.M. The role of the proliferative activity of meristematic cells in ensuring the radioadaptive response of plants // Dopovidi NASU, 1998, No. 10, p. 174-177.
11. Mikheev A.N., Shilina Yu.V., Ovsyannikova L.G.Could chronic radiation be radiotherapeutic for plant objects exposed to the inhibitory effect of acute gamma radiation? (On the issue of low-dose radiotherapy) // Science Practices: Science-methodical journal. V. 102. V. 89. Ecology. Mikolaiv: View of MDGU im. Petra Mogili, 2008. P. 18-22.
12. Nefedov V.P., Yasaytis A.A., Novoseltsev V.N. et al. 1991. Homeostasis at various levels of the organization of biosystems. Novosibirsk: Science. Sib. department, 1991: 232 p.
13. Selye G. At the level of the whole organism. Moscow: Nauka, 1972: 123 p.
14. Selye G. Stress without distress. Moscow: Progress, 1982: 128 p.
15. Urmantsev Yu.A. Symmetry of nature and nature of symmetry. M.: Misl, 1974: 229 p.
16. Urmantsev Yu.A., Gudskov N.M. The problem of specificity and non-specificity of the response of plants to damaging effects // Journal of General Biology. 1986. V. 47, No. 3. S. 337-349.
17. Filippovich I.V. The phenomenon of adaptive response of cells in radiobiology // Radiobiology. 1991. V. 31, No. 6.S. 803-813.
18. Churyukin R.S., Geraskin S.A. Influence of irradiation (60Co) of barley seeds on plant development in the early stages of ontogenesis // Radiation and risk. 2013. V. 22. No. 3, p. 81-92.
19. Calabrese E.J., Baldwin L.A. Radiation hormesis: its historical foundations as a biological hypothesis // Hum. Exp. Toxicol. – 2000. – Vol. 19, № 1. – P. 41–75.
20. Lekevicius E. 1997. A model of adaptative rearrangements on community, population and organism levels: Thesis for Habilitation Natural Sciences, Vilnius, 81 p.
21. Mitter A.H., Whelan J., Soole K.L., Day D.A. Organization and regulation of mitochondrial respiration in plants // Annu. Rev. Plant Biol. – 2011. – V. 62. – P. 79-104.
22. Schwartz J.L. Alteration in chromosome structure and variations in the inherent radiation sensitivity of human cells // Rad. Res. 1998.V. 149, № 4. – P. 319-324.
23. Volkert MR. (1988). Adaptive response of Escherichia coli to alkylation damage // Environ. Mol. Mutagen. 1988. № 1(2). P. 241-55.