〈Review Paper〉

Effects of Ionizing Radiation on Plants and the Radiological Protection of the Environment

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Abstract - Differences between the principles for the radiological protection of man and the environment are compared. The derived levels of exposure for man and biota recommended by the international agencies with dose rates for chronic radiation producing effects at different levels of biological organization were given in terms of the biological effects. Cytogenetic effects on plants after an exposure to ionizing radiation at low doses alone and in combination with other factors are discussed. A wide range of experimental data were analysed and the general conclusions were extracted to cover the topics such as non-linearity of dose response, synergistic and antagonistic effects of the combined exposure of different factors, radiation-induced genomic instability, and the phenomena of radioadaptation.

Key words : ionizing radiation, plant, cytogenetic effect, protection, environment,

1. Difference between the principles for the radiological protection of man and the environment

Based on experience, a system of radiation consequence assessments and adverse effect prevention has been developed concerning population safety. The evolution of protection has often been from worker safety to public safety and only then to environmental safety. The recommendations of the International Committee on the Radiation Protection (ICRP) are good illustrations of this development (Holm *et al.* 2002). At the same time, a notion of the "protection of the environment from ionising radiation" remains uncertain up to now.

There is no uniform opinion, so far, even concerning the level of biological organization and alterations which should be admitted as essential and demanding an immediate response from man.

Nowadays accumulated experiences on radioecological investigations (Romanov and Spirin 1991; Shevchenko *et al.* 1992; Kryshev and Ryasantzev 2000; Alexakhin *et al.* 2001) testify that a large scale release of radionuclides into the environment can result in serious consequences for biota, including abnormalities at an ecosystem level. The South Urals (1957) and Chernobyl (1986) accidents are the most dramatic examples. For the last three decades, a scientific background for radiation protection of the environment has been based on the principles developed by the ICRP (1991). A sense of the most important among them can be formulated as 'if man is protected then the environment is also adequately protected'. Although standards derived from these principles guarantee the protection of humans, they are not always able to pledge equal protection for other living objects. A regulation with this approach implicitly assumes that doses absorbed by humans are close to the level of doses absorbed by other environmental objects

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Table 1. Differences between the anthropocentric and the ecological principles of a regulation

Criteria	Anthropocentric	Ecological
Doses to human and biota	Close	There are radioecological situations when some representatives of biota accumulate doses 10-300 times greater.
Object of application	Human	Systems of above-organismic level
End-points for regulation	Deterministic and stochastic effects	Survival in systems of above-organismic level

and, hence, if one provides low doses to the population then low doses to other living organisms will be automatically assured. But this is not necessarily true. Thus, dose values per unit of radioactive contamination density absorbed by plants and animals from radioactive fallouts can exceed the values for humans by a factor of 10-300 (Romanov and Spirin 1991; Kryshev and Ryasantzev 2000). Taking into account the similarity of radiosensitivity of humans and some edificator species determining the function and stability of ecosystems (coniferous trees and many mammalians), such a relationship between doses absorbed by humans and environmental objects makes clear that special attention should be paid to the protection of plants, animals and their communities. Therefore, notwithstanding the merits of the system that has been developed for the radiological protection of man, there is still a need to develop criteria and frameworks for the system to protect the environment from ionizing radiation.

The sophisticated framework for the radiological protection of humans is mainly based on the limitation of the calculated risks for long-term effects, e.g. induction of hereditary effects and of cancers in the exposed populations. In theory, ALARA (as low as reasonably achievable) could be applied to the protection of the environment by adding the environmental detriment. There are, however, uncertainties as to what damages are critical and which quantities should be used instead of the effective dose. The protection of other species requires a completely new set of criteria derived from the identification of relevant biological effects. A hierarchic structural-functional organization of the living matter determines a multi-level response to an external impact. An important problem in this connection is the choice of the level of biological organization, which is to be used with the purposes of radiological regulation of the effects on the environment. As a matter of fact this means a choice of parameters, which modification should be admitted as essential and demanding implementation of certain protective measures. Radiological protection practices most often use genetic tests as the most sensitive indices of radiation exposure, that are simultaneously reliable enough, or abnormalities on a population level as an indicator of serious alterations occurring in an ecosystem. A mode of plants and animals' existence in the environment is a population, therefore, when one switches from the anthropocentric to ecological principles of regulation, modifications not only should occur in the indicators applied because of the regulation strategy chosen (Table 1) but also in the object of the indicators application itself. A role of such an object is now occupied not with individuals, as it was in the case of the anthropocentric approach but with systems of the above-organismic levels, that are populations, ecosystems, and biogeocenosis.

Natural and agrarian ecological systems have a diverse variability of responses to irradiation. A range of dose rates at which biota irradiation actually takes place covers five orders of magnitude (Shevchenko *et al.* 1992). The derived levels of exposure of man and biota recommended by the international agencies are compared with dose rate values of chronic radiation producing effects at different levels of the biological organization in Table 2. It can be seen in Table 2 that irradiation with dose rates of up to 10 Gy y^{-1} does not lead to any irreversible modifications in the environmental plant community. The corresponding doses exceed the maximum permissible dose to the population of 1 mSv $year^{-1}$ 10^4 times, that certainly exceeds possible differences in doses obtained by man and biota. Therefore, the principle of radiation protection of the environment developed by the ICRP- "if man is protected then the environment is also adequately protected"-is not broken in an overwhelming majority of ecological situations. But at the

Table 2. Comparison of the derived levels of exposure of man and biota recommended by the international agencies with dose rates of chronic radiation producing effects at different levels of biological organization

Biological effect	Dose rate, Gy y^{-1}
Dose limit for humans (ICRP, 1990)	**10^{-3}**
Casual detection of genetic effects	0.05
Steady registration of genetic effects in the most radiosensitive species	0.1
Dose limit for deterministic effects (ICRP, 1990)	**0.15**
Increase of mean population radioresistance (radioadaptation)	0.2
Doses to biota considered by the IAEA (1992) as not providing any hazard	**0.4**
Inhibition of growth and development in radiosensitive species	1-3
Disappearance of sensitive species from a biotic community	4
Radiation damage to ecosystems:	
Coniferous forests	10
Deciduous forests	30
Agricultural crops	50
Herbacious phytocenoses	70

same time, in radioactively contaminated territories there were real cases where clear signs of radiation damage were registered in plant and animal individuals, populations and even their communities (Romanov and Spirin 1991; Shevchenko *et al.* 1992; Kryshev and Ryasantzev 2000; Alexakhin *et al.* 2001).

On the other hand, being necessary to protect the biota at a population level, the principle suggested by the ICRP, is not sufficient to rule out possible significant changes within a population that cause a breaking of relations between individual elements of ecosystems and, at the end, a destruction or radical rearrangement of natural communities. Moreover, the most basic, testable piece of information from which a dose-effect probability factor could be derived (Penetreath and Woodhead 2001) is that which applies to an individual organism. In this context, a question arises: changes at what level of the biological organization are the first to indicate negative effects in the environment? It is shown in Table 2 that genetic effects and alterations of genetic structure in wild plant and animal populations are observed at dose rates that are below the level considered by the IAEA as safe to biota.

Nevertheless, it is changes at the molecular-cellular level of the living organisms that give (Geras'kin and Koz'min 1995) the earliest and most confident information about any negative changes in the environment. In addition, the genetic tests reveal the most substantial effects of environmental pollution related to an increasing mutagenic pressure on the biosphere. This appears in an increasing incidence of cancer and hereditary diseases, an increasing genetic load in humans, animals, and plants, and a changing genetic and species structure of biocenoses. Therefore, it is the genetic test-systems that should be used for an early diagnosis of the alterations resulting from human industrial activity.

What changes on the cytogenetic level can be induced by low doses of ionizing radiation under conditions of single and combined with the factors of different types of exposures? Important features of the biological effect of low-level radiation that don't follow from well-known effects of high and moderate doses are:

- non-linearity of dose response;
- synergetic and antagonistic effects of different nature factors' combined exposure;
- radiation-induced genomic instability;
- phenomenon of radioadaptation.

The development of a new concept of radiation protection for humans and the environment should be based on the clear understanding of these effects and their contribution to the response of biological objects.

2. Non-linearity of dose response

The analysis of experimentally observed reactions of cells in low level irradiation showed (Geras'kin 1995a, b) that the regularities of cytogenetic disturbances yield in this range are characterized by a sound non-linearity and have a universal character. To check this state, an experiment has been carried out on barley seedlings (Geras'kin *et al.* 1999). It is apparent from the results presented in the recent publication, even without using precise quantitative criteria, that the piecewise linear model fits the data much better than the linear one (Kim *et al.* 2003). It is important, that the improvement of the quality of approximation does not reach as an account of model complications but because it is possible to achieve a mutual conformity (functional isomorphism) between a biological phenomenon and its mathematical model on a set of piecewise linear functions. Comparison of approximation quality that can be achieved with models of different complexity by the most common quantitative criteria testifies well to this.

3. Synergistic and antagonistic effects of different factors' combined exposure

In the studies (Geras'kin *et al.* 1996; Evseeva *et al.* 2001; Evseeva and Geras'kin 2001; Geras'kin *et al.* 2002) on the combined effect of such frequently occurring agents as acute and chronic γ-radiation, pesticides, heavy natural radionuclides, compounds of heavy and alkaline earth metals on spring barley, bulb onion and spiderwort, it is shown that synergetic and antagonistic effects are most often registered at combinations of low doses and concentrations; moreover, these nonlinear effects make a governing contribution to a biological system response in these conditions. A study of cytogenetic disturbance induction in intercalary meristem cells of spring barley grown in soil contaminated with low concentrations of ^{137}Cs and cadmium nitrate (Geras'kin *et al.* 2002) has shown that the effect of combined exposure exceeds the sum of the separate effects by as much as 70%. On the contrary, the observed effect on the soil polluted by radioactive caesium, lead and pesticides was, on an average, only 50% of the anticipated value from the additive model. Therefore, the application of finding from separate action to forecast the biological effects of combined exposure is unacceptable and causes an essential distortion from experimental data.

4. Radiation-induced genomic instability

In 1987-1989 an experimental study on the cytogenetic variability in three successive generations of winter rye and wheat, grown at four plots with different levels of radioactive contamination, was carried out within the ChNPP 10-km zone (Geras'kin *et al.* 2003a). A dose on a growing point varied within the range of 18-717 cGy between plots for the vegetative season 1987-1988, and of 11-417 cGy for 1988-1989. Fig. 1 shows that, in the autumn of 1989, aberrant cell frequencies in leaf meristem of winter rye and wheat of the second and third generations significantly exceeded the parameters for the first generations. The distinctions between cytogenetic indices obtained for the second and third generations were small and statistically insignificant, so, the observed effect is of a threshold character.

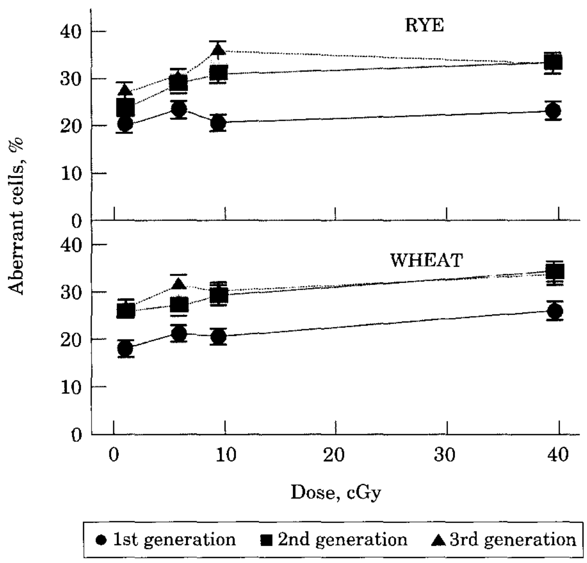

Fig. 1. Changes of aberrant cell frequencies in the leaf meristem of winter rye and wheat in three generations grown on radioactively contaminated plots.

It should be noted that the analysis of cytogenetic disturbances was done on the intercalary meristem of the plants. It means that most of the radiation-induced alterations accumulated during the previous vegetative season were realized into real mutations long before the samples were fixed for cytogenetic analysis. In the autumn of 1989, plants of all three generations were developed in identical conditions and were exposed to identical doses so that the most probable explanation of the registered phenomenon was related to a genome destabilization in plants grown from seeds affected by radiation. From these viewpoints, the results observed in this

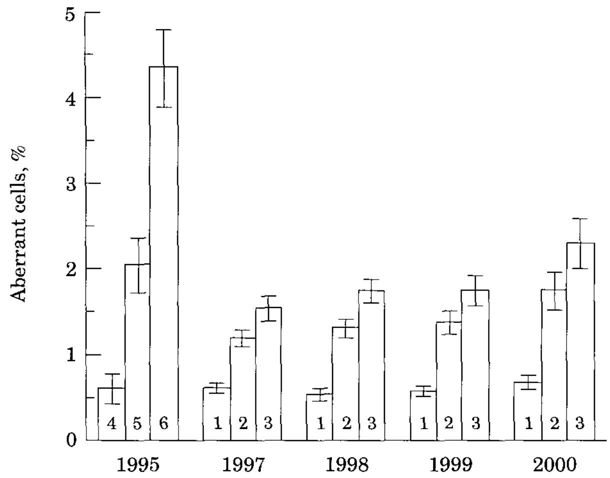

Fig. 2. Aberrant cell frequencies within root meristem of *Pinus sylvestris* L. seedlings in 1995-2000. Experimental sites 1, 2 and 3 in the Sosnovy Bor region, and 4, 5 and 6 in the 30-km zone of the Chernobyl NPP.

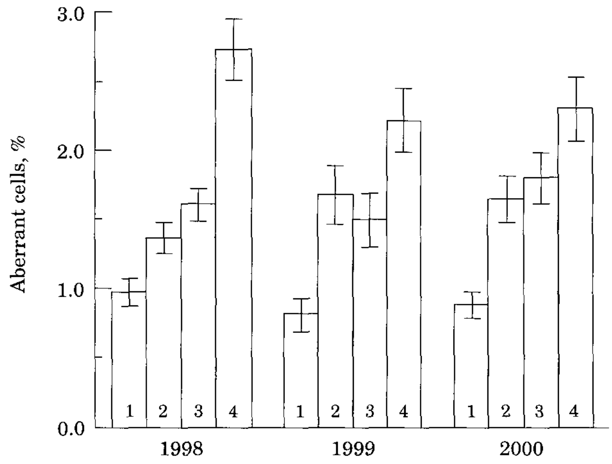

Fig. 3. Aberrant cell frequencies in intercalary meristem of needles of *Pinus sylvestris* L. in 1998-2000. 1, 2, 3 and 4-Experimental sites in the Sosnovy Bor region.

study, indicating a threshold character of genetic instability induction, may be a sign of the beginning of cytogenetic adaptation, that is, the chronic low-dose irradiation appears to be an ecological factor creating preconditions for possible changes in the genetic structure of a population.

5. Phenomenon of radioadaptation

A study (Geras'kin *et al.* 2003b) of cytogenetic damage in the vegetative and reproductive organs (needles and seeds) of *Pinus sylvestris* L. populations growing at sites contaminated by radioactive materials in the 30-km ChNPP zone and also in a region of the arrangement of the 'Radon' enterprise for the processing and storage of radioactive waste (the town of Sosnovy Bor, Leningrad region) was concerned with the question about the role of such alterations in population structure. From the results of this study presented in Fig. 2 and 3, a conclusion is that there is an expressed genotoxic influence in the investigated regions. And, while the incidence of cytogenetic damage in the samples collected from the Chernobyl NPP region correlates with dose rate, there is no correlation in the samples taken from the Sosnovy Bor region.

The revealed fact obliged us to make a more careful examination of these experimental data. The analysis of structural mutations spectrum (Geras'kin *et al.* 2003b) has exhibited a presence in the Sosnovy Bor data and an absence in all the controls and Chernobyl variants of tripolar mitoses, a rather rare type of cytogenetic alteration, whose appearance is possibly linked to spindle damage (Alieva and Vorobiev 1989). Bessonova (1992) reported that an increase in the yield of tripolar mitoses in *Syringa vulgaris* L. and *Armeniaca vulgaris* Lam. was associated with the contamination of the local soils with a heavy metal mixture. From this, together with the dosimetric data (Gera'skin *et al.* 2003b), it may be supposed that a considerable amount of genotoxic chemicals made contribution to the environmental contamination in the Sosnovy Bor region.

When an anthropogenic impact to biota has become one of the most significant ecological factors, it is pertinent to consider the adaptive potentials of natural populations. One consequence of chronic irradiation of natural populations is an apparent increase in the mean radioresistance-the so-called "radioadaptation phenomenon"; this has been observed by studies in the East Urals trail region (Cherezhanova and Alexakhin 1975; Kryshev and Ryasantzev 2000) and can be revealed by an exposure of seeds to an additional, acute γ-radiation. It was shown later (Sergeeva *et al.* 1985; Kryshev and Ryasantzev 2000) that the population divergence by radioresistance is connected to the selection for changes

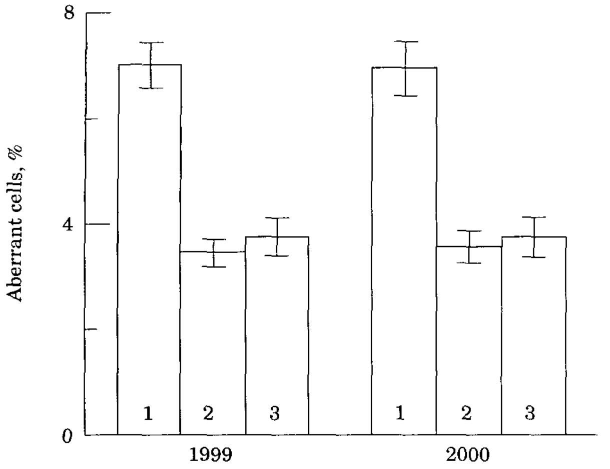

Fig. 4. Aberrant cell frequency in seedling root meristem of *Pinus sylvestris* L. exposed to acute γ-irradiation of 15 Gy in 1999 and 2000. 1, 2, 3-experimental sites in the Sosnovy Bor region

in the effectiveness of the repair system and is not accompanied by visible morphologic alterations.

A part of the seeds collected in the Sosnovy Bor region in 1999-2000 have been subjected to an acute γ-ray exposure. The seeds from the Scotch pine populations growing in the town of Sosnovy Bor and at the 'Radon' LWPE site appear to be significantly more resistant to the acute γ-radiation than the controls (Fig. 4). Notice, a number of pine generations replaced during the existence of the 'Radon' LWPE and the Leningrad NPP, unlike the East-Ural radioactive trial, are obviously insufficient for the natural selection of repair system efficiency in its classical meaning. There are different explanations for the phenomenon, regarded as a selection against radiosensitive cells (Kal'chenko and Fedotov 2001) as well as an inheritable change of spectrum of functionally active genes (Geras'kin 1995b, Geras'kin *et al.* 2003b). But, in any case, the findings show that there are processes of cytogenetic adaptation in the examined populations that can be revealed by an additive acute γ-radiation of the seeds.

6. Conclusion

Further investigation in this field should issue the development of theoretical bases and practical procedures for the protection of the environment from ionizing radiation, taking into account the new experimentally confirmed facts about the presence of such essentially important singularities of the biological effect of low ionizing radiation doses as the nonlinearity of a dose-effect relationship, radiation-induced genomic instability, phenomenon of radioadaptation, increased probability of synergetic and antagonistic effects of the combined action of different nature factors. The development of a new concept of radiation protection for humans and biota should be based on the clear understanding of these effects and their contribution to the response of the biological objects to single low-level radiation exposure and to radiation exposure combined with other anthropogenic factors.

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