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Biological Detection of Physical Factors Related to the High-Current Electric Explosion of Conductors in a Vacuum

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Abstract—The effect physical factors associated with the high-current electric explosion of conductors in a vacuum (pulsed magnetic field, light exposure, radiation leaving specific tracks on nuclear emulsions and other materials) have on biological systems is studied. The effect is assessed from the level of nuclear DNA damage in human peripheral blood leukocytes, the frequency of chromosomal aberrations in the dividing cells of an onion root, the growth rate of green unicellular algae, and the germination and growth rate of plant seeds.

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INTRODUCTION

The electric explosion of metal microconductors have been studied intensively since the early 1960s. [1]. Interest in this phenomenon continues today, due to its wide use in both engineering and fundamental scientific research [2–5]. A number of studies have shown there is a connection between factors associated with the electric explosion of conductors (superhigh magnetic fields, dense nonideal low-temperature plasma) and weak nuclear processes [6–9]. It has been shown in a number of experiments that the electric explosion of conductors is accompanied by an unknown type of radiation that leaves unusual traces on nuclear emulsions and X-ray films [10, 11]. It was hypothesized that taken together, these graphic characteristics of the tracks can characterize a new type of penetrating radiation of unknown nature (so-called "strange" radiation) [10].

In addition to the fundamental physical aspect of the problem, the question of the nature and mechanisms of interaction between matter and "strange" radiation has an additional aspect associated with the need to study the interaction between this radiation and biological systems. Biological systems can be considered one way of detecting radiation and a tool for assessing the danger of "strange" radiation for human health and other biological objects. In addition to "strange" radiation, the electric explosion of conductors is accompanied by the induction of a number of factors that can have biological effects: a light flash and a magnetic field pulse. In a number of experiments, changes were detected in the reaction of biological systems to the influence of physical factors of an electric explosion, including "strange" radiation [12, 13]. This work is an attempt to identify the biological effects of "strange" radiation among the active factors of an electric explosion.

The aim of this work was to assess the possibility of detecting factors associated with a high-current explosion of a tungsten wire in a vacuum, using such biological objects as human leukocytes, onion seeds (*Allium cepa*), lettuce seeds (*Lactuca sativa*), and unicellular algae (*Scenedesmus quadricauda*).

EXPERIMENTAL

In experiments to study the effect factors associated with the emergence of low-temperature plasma have on biological objects, the Helios facility was used to create the high-current electric explosion of a tungsten wire in a vacuum [14]. A detailed description of the experimental conditions for studying the effect electric explosions have on biological objects was given in [15]. It should be noted that the high-current electric explosion of wires was accompanied by a powerful flash of

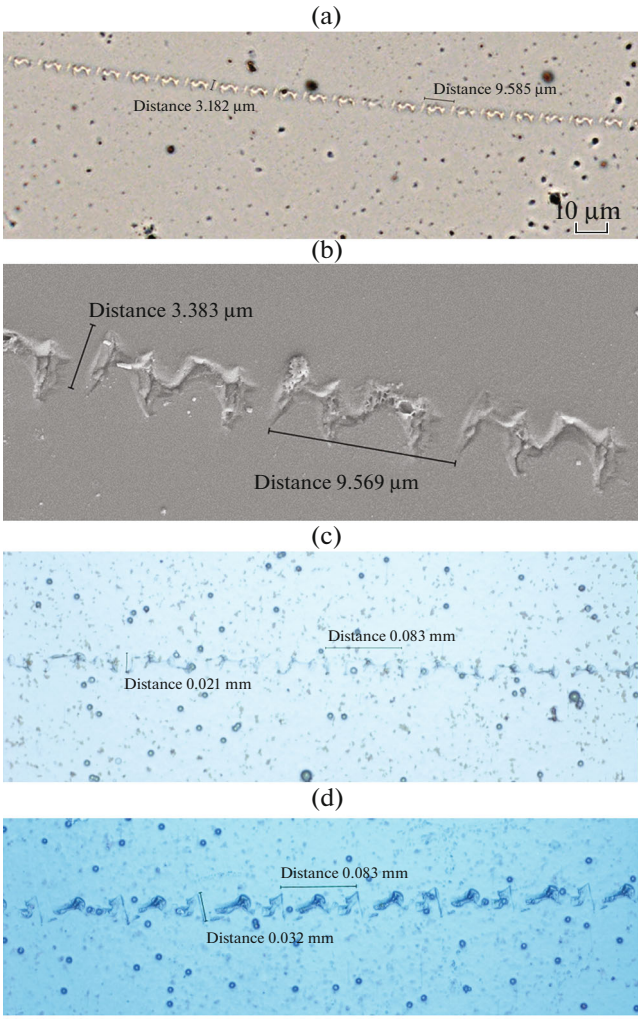

Fig. 1. (a) Track of "strange" radiation recorded on glass inside the discharge chamber during an electric explosion (optical microscopy); (b) track of "strange" radiation recorded on glass inside the discharge chamber during an electric explosion (scanning electron microscopy); (c, d) tracks of "strange" radiation recorded on Carestream D-Speed X-ray films at the place of biological objects during an electric explosion outside the discharge chamber (optical microscopy).

light with illumination of ~10^9 lx and a magnetic field pulse with an amplitude of $\lesssim$10 G at the place of the biological objects. No ionizing radiation was detected via TLD dosimetry [15]. In addition, visual artefacts similar to the tracks of "strange" radiation described in [10, 11] were recorded on glasses placed inside the discharge chamber (Figs. 1a, 1b), and on X-ray films at the place of biological objects (Figs. 1c, 1d).

Different types of shielding for biological objects during an electric explosion were used to determine the role played by exposure to light, a pulsed magnetic field, and "strange" radiation in the induction of biological effects. Biological objects with no shielding were exposed to the full range of factors. Shielding

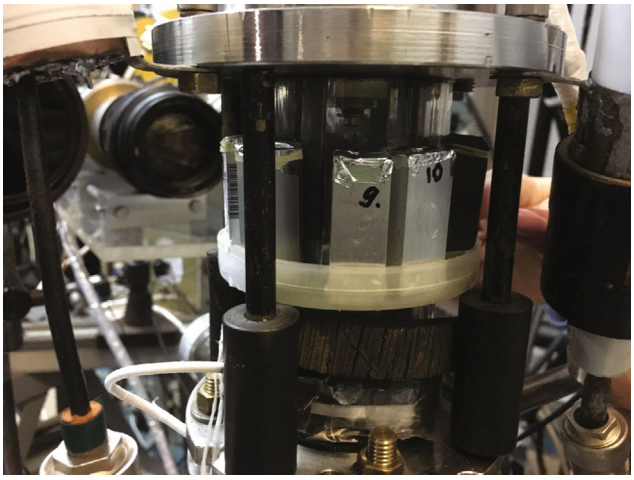

Fig. 2. Arrangement of the containers with biological objects around the quartz wall of the discharge explosion chamber.

with black lightproof paper 150 μm thick eliminated the effect of visible and ultraviolet light radiation. Shielding using aluminum foil 40 μm thick, a beryllium plate (100 μm), and a lead foil (200 μm) eliminated the effects of visible and ultraviolet radiation, along with that of a pulsed magnetic field.

As test systems for assessing the biological effect of electric explosion factors, we used human peripheral blood leukocytes (determination of genotoxic action by changing the level of damage to cellular DNA by the commet assay), onion seed seedlings (*Allium cepa*) (determining genotoxic action by estimating the frequency of chromosomal aberrations in proliferating seedling root cells), a laboratory culture of single-celled green algae *Scenedesmus quadricauda* (determining the effect on the growth rate of algae culture) and lettuce seeds (*Lactuca sativa*) (determining the effect on the germination and growth rate of seedling seeds).

The biological objects were placed in Eppendorf plastic test tubes. Before exposure, the tubes were placed in aluminum containers 10 × 10 × 40 mm in size, made from an aluminum channel with dimensions of 10 × 15 × 10 × 1 mm (40 mm long). One side of each container was open. On the open side, biological objects were shielded with black paper, aluminum foil, beryllium plate, and lead foil. Containers with the samples were placed on the outer side of a discharge explosion chamber close to a quartz wall, with the screened side facing a tungsten wire (Fig. 2).

The genotoxic effect of the studied factors on human peripheral blood cells was estimated at the subcellular (molecular) level using the comet assay (by damage to the DNA molecule is related to an increase in the probability of malignant tumors). The peripheral blood of five healthy adult voluntary donors was used. Samples from each donor were exposed to sepa-

Table 1. Tail moments in human peripheral blood cells after experimental exposure in different experimental groups (comet assay)

Group	Experimental conditions	Tail moment	Relative to control
1	Control	144.0 ± 7.8	
2	EE, unshielded	139.2 ± 6.4	$t = 0.48$; $p = 0.63$
3	EE, shielding with black paper	135.7 ± 8.0	$t = 0.74$; $p = 0.46$
4	EE, shielding (Al)	131.8 ± 6.3	$t = 1.23$; $p = 0.22$
5	EE, shielding (Be)	83.0 ± 5.4	$t = 6.42$; $p = 3.0 \times 10^{-10}$
6	EE, shielding (Pb)	215.9 ± 9.8	$t = 5.73$; $p = 1.7 \times 10^{-8}$

Here and below, the tables give the mean value ± standard error. EE denotes the electric explosion of a wire in a vacuum.

rate explosions. The level of DNA damage was determined using the alkaline version of the comet assay [11]. This approach estimates the amount of damage to a DNA molecule based on the number and size of negatively charged DNA fragments migrating inside an electric field in an agarose gel: the more extensive the DNA damage, the greater the number of DNA fragments and the smaller their size (and thus the longer the tail of the comet and the higher the fraction of the migrated DNA). The state of the DNA in 70–100 individual blood cells was assessed for each donor in each experimental group. Except for the assessment using human cells, the genotoxic effect of the studied factors was determined from the change in the frequency of chromosomal aberrations (DNA damage visible as violations of the integrity, number, shape, or internal structure of chromosomes under a microscope during cell division) in dividing cells of the root of an onion seedling (*Allium cepa*) using the allium test [16]. We used onion seeds of the Zabiyaka variety (OOO The Gavrish Group of Companies, batch No. 25753, 2018). The frequency of chromosomal aberrations in at least 500 ana-telophases was analyzed for each group. The effect electric explosion factors had on the growth of unicellular green algae *Scenedesmus quadricauda* was determined according to the procedure described in [17], with which we can measure the toxic (growth suppression) or stimulating effect (growth stimulation under favorable conditions) the studied factors have on individual cells (which in this case represent a whole unicellular organism). Two independent series of experiments were performed. No fewer than 200 coenobia were counted to determine the relative number of different groups of cells (coenobia). The germination and growth rate of seedlings of lettuce seeds were studied in the same manner [18]. Lettuce seeds (GUP Semena OAO Flora, batch no. 1010, 2018) were used in this work. Seeds are multicellular organisms, and the germination stage is the one most sensitive to the action of different factors, allowing us to evaluate the effect the given factors have on the level of the entire multicellular organism. Three series of independent experiments were performed. The experimental group in each series had 95–120 seeds.

Statistical analysis [18, 19] included calculating the mean values of the analyzed biological parameters and determining the standard error. Differences between the mean values were determined using Student's *t*-test. A multivariate analysis was performed with the general linear model. The quality of the model was analyzed from the value of the coefficient of determination (R^2), and the statistical significance of the influence of the analyzed factors was determined using Fisher's *F*-test. The type of influence the analyzed factors had on the dependent indicator was judged from the coefficients in the equation in the general linear model. Differences were considered statistically significant upon probability $p < 0.05$ of the zero hypothesis.

RESULTS AND DISCUSSION

Indicators of the state of nuclear DNA of human peripheral blood leukocytes are given in Table 1. The table presents the tail moment index of a comet, which is considered to be optimal when assessing the degree of DNA degradation according to the comet assay [20]. The tail moment is a dimensionless indicator obtained from the product of the length of DNA migration and the percentage of DNA fragments that have migrated from the nuclear region. The greater the level of DNA damage, the longer the tail moment. In assessing the level of DNA damage according to the comet assay, it was shown that the background (initial) states of the nuclear DNA in the donors' peripheral blood leukocytes differed notably from one another, obviously reflecting the individual characteristics of donors. The tail moments in peripheral blood leukocytes that were not shielded during an electric explosion, and in the groups with shielding of lightproof black paper and aluminum foil, were slightly smaller than in the control group, but these deviations were not statistically significant (Table 1). In the group with screening by a beryllium plate, a statistically significant drop of 42% was observed in the parameter of DNA damage (the comet's tail moment), relative to

Table 2. Results from multivariate analysis of the effects different electric explosion factors have on the tail moment in human peripheral blood cells after experimental exposure (comet assay)

Factors	F	p	GLM coefficient
Donor	510.1	$\ll 0.001$	donor 1: 45.3 ± 6.6 donor 2: 2.2 ± 6.5 donor 3: 233.2 ± 6.2 donor 4: 146.8 ± 6.1 donor 5: 0
"Strange" radiation	45.0	2.8×10^{-11}	-42.2 ± 6.3
Light exposure	28.9	8.7×10^{-8}	39.8 ± 7.4
PMF	1.1	0.30	0
Shielding material	317.6	5.0×10^{-65}	0.557 ± 0.031
$R^2 = 0.596$			

Here and below, GLM is the general linear model and PMF is a pulsed magnetic field.

the indicator in the control group: $t = 6.42$; $p = 3.0 \times 10^{-10}$. When screening blood samples with lead foil, a statistically significant increase of 50% was noted in the level of DNA damage, relative to the parameter of the comet's tail moment in the control group: $t = 5.73$; $p = 1.7 \times 10^{-8}$.

In performing a multivariate analysis of variance in the general linear model, it was found (Table 2) that the level of nuclear DNA damage depended on the individual characteristics of donors ($F = 825.8$; $p \ll 0.001$). The coefficient for the exposure to light factor (39.8 ± 7.4) in the general linear model shows that this component of the impact of electric explosion factors produces a statistically significant increase in the level of nuclear DNA damage ($F = 28.9$; $p = 8.7 \times 10^{-8}$). The pulsed magnetic field had no statistically significant effect on the level of DNA damage ($F = 1.1$; $p = 0.3$), while "strange" radiation with a high level of significance ($F = 45.0$; $p = 2.8 \times 10^{-11}$) reduced the level of DNA damage (the coefficient for this factor in the general linear model was -42.2 ± 6.3). At the same time, it was found that the shielding material modified the effects of "strange" radiation appreciably ($F = 317.6$; $p = 5.0 \times 10^{-65}$). The level of nuclear DNA damage grew with a coefficient of 0.557 ± 0.031 per atomic mass unit, depending on the atomic mass of the shielding material. It should be noted that our model describes the experimental data well ($R^2 = 0.596$).

Among other factors of an electric explosion, exposure to light can damage DNA, due mainly to the ultraviolet component in its spectrum [21]. Two hypotheses explain the drop in the level of DNA damage under the influence of "strange" radiation: (1) "strange" radiation strongly stimulates processes of nuclear DNA repair so that even the background level of thermal DNA damage is lowered, and (2) "strange" radiation modified by interacting with materials of low atomic mass induces DNA–DNA and DNA–protein crosslinks, which can also manifest in a drop in the background level of nuclear DNA damage in human peripheral blood cells. It was shown in a number of studies that agents capable of inducing DNA–DNA and DNA–protein crosslinks lower the level of DNA damage induced by hydrogen peroxide or gamma irradiation [22].

The increase in the level of nuclear DNA damage depending on the atomic mass of the shielding material suggests that "strange" radiation interacts differently with matter, depending on its atomic mass. As a result of such interaction, there is either a substantial change in the physical properties of the "strange" radiation or the induction of secondary radiation. This depends on the atomic mass of the shielding material either quantitatively or qualitatively, and thus induces different types of biological effects in biological systems.

In addition to assessing the influence of the given factors on the integrity of the nuclear DNA of human peripheral blood leukocytes, an experiment was performed to determine the effect factors associated with an electric explosion have on the induction of chromosomal aberrations using the allium test (determination of the mutagenic effect of factors according to altering the frequency of chromosomal aberrations in onion root cells).

In our experiments, it was found that in all groups where the roots of an onion seedling were exposed during an electric explosion, a statistically significant increase was registered in the frequency of chromosomal aberrations (Table 3). This effect was strongest in the group where onion seedlings were screened with black paper during an electric explosion (an increase of 6.7 times in the frequency of chromosomal aberrations) and weakest in the group with aluminum screening (an increase in the frequency of chromosomal aberrations by a factor of 3).

Multivariate analysis of variance in the frequency of chromosomal aberrations showed that it depended

Table 3. Frequency of chromosomal aberrations in meristem cells of the root of an onion seedling 1 day after experimental exposure in different experimental groups.

Group	Experimental conditions	Frequency of cells with chromosomal aberrations, %	Relative to control
1	Control	1.39 ± 0.52	
2	EE, unshielded	7.6 ± 1.2	$t = 4.75$; $p = 2.3 \times 10^{-6}$
3	EE, shielding with black paper	9.3 ± 1.3	$t = 5.65$; $p = 2.1 \times 10^{-8}$
4	EE, shielding (Al)	4.17 ± 0.89	$t = 2.70$; $p = 7.5 \times 10^{-3}$
5	EE, shielding (Be)	6.5 ± 1.1	$t = 4.20$; $p = 2.9 \times 10^{-5}$
6	EE, shielding (Pb)	5.46 ± 0.99	$t = 3.64$; $p = 2.9 \times 10^{-4}$

Table 4. Results from multivariate analysis of the effects different electric explosion factors have on the frequency of chromosomal aberrations in cells of the roots of onion seedlings (allium test)

Factors	F	p	GLM coefficient
"Strange" radiation	9.73	0.002	4.0 ± 1.3
Exposure to light	1.42	0.23	0
PMF	9.50	0.002	3.9 ± 1.3
Shielding material	0.005	0.94	0
$R^2 = 0.011$			

on the effect of "strange" radiation ($F = 9.73$; $p = 0.002$), manifested in an average $4.0 \pm 1.3\%$ increase in the indicator, and the action of a pulsed magnetic field ($F = 9.50$; $p = 0.002$), which produced an effect comparable to that of "strange" radiation: a $3.9 \pm 1.3\%$ increase in the frequency of chromosomal aberrations (Table 4). There was no statistically significant effect from the exposure to light factor ($F = 1.42$; $p = 0.23$) or the shielding material ($F = 0.005$; $p = 0.94$) on the given indicator.

The results from our allium test allow us to confidently reject the hypothesis that "strange" radiation sharply increases the efficiency of repair, and thus does not contradict the hypothesis of "strange" radiation inducing such DNA damage as DNA–DNA and DNA–protein crosslinks.

The effect of factors associated with high-current explosions of conductors in a vacuum at the cellular level was determined using the growth model of the single-celled green algae *Scenedesmus quadricauda*. These algae can exist as unicellular organisms and at the same time form groups (coenobia) of 4, 8, and 16 cells [23]. The effect electric explosion factors have on unicellular algae was assessed according to the growth rate of the algae culture (the number of *Scenedesmus quadricauda* cells on the fourth day of cultivation) and the proportion of 1-, 2-, 4-, and 8-celled cenobia (%). Their impact was assessed in two series of experiments.

No statistically significant influence of electric explosion factors on the growth rate of one-celled algae *Scenedesmus quadricauda* was observed during our study. Under favorable conditions, the green algae *Scenedesmus quadricauda* mainly forms 4-celled coenobia. Conditions unfavorable to the life of the algae raises the proportion of single-celled coenobia in a culture, and the proportion of 4-, 8-, and even 16-celled coenobia grows under more favorable conditions. In our experiments, the proportion of single-celled coenobia in the control group was $20.9 \pm 7.3\%$ (Table 5). Changes in the proportion of single-celled coenobia in all experimental groups did not reach statistical significance. However, multivariate analysis of the variance using the general linear model showed the proportion of single-celled coenobia depended on the experimental series ($F = 84.25$; $p = 4.6 \times 10^{-10}$), while "strange" radiation produced a statistically significant ($F = 6.2$; $p = 0.015$) drop in the indicator by an average of $11.8 \pm 5.5\%$ (Table 6). In addition, a pulsed magnetic field had a statistically significant effect ($F = 4.66$; $p = 0.039$) on the biological effect of "strange" radiation. The effect of this factor raised the proportion of one-celled coenobia by $11.5 \pm 5.4\%$.

The effect of factors associated with a high-current explosion of conductors in a vacuum at the level of an organism was evaluated using a model of lettuce seed germination. The influence of the studied factors on lettuce seeds was assessed according to seed germination (%), seedling root length (mm), and the length of a seedling sprout (mm). Three independent series of experiments were performed. No statistically significant effect of electric explosion factors on germination

Table 5. Proportion of one-celled coenobia in the culture of *Scenedusmus quadricauda* algae 3 days after experimental exposure in different experimental groups

Group	Experimental conditions	Proportion of one-celled coenobia, %	Relative to control
1	Control	20.9 ± 7.3	
2	EE, unshielded	11.8 ± 7.2	$t = 0.89$; $p = 0.39$
3	EE, shielding with black paper	20.9 ± 8.9	$t = 0$; $p = 1.0$
4	EE, shielding (Al)	11.5 ± 6.6	$t = 0.95$; $p = 0.36$
5	EE, shielding (Be)	7.7 ± 5.0	$t = 1.49$; $p = 0.17$
6	EE, shielding (Pb)	14.1 ± 5.5	$t = 0.75$; $p = 0.47$

Table 6. Results from multivariate analysis of the effects different electric explosion factors have on the proportion of one-celled coenobia in the culture of *Scenedusmus quadricauda* algae 3 days after experimental exposure

Factors	F	p	GLM coefficient
Series of experiments	45.85	1.65×10^{-7}	Series 1: 24.0 ± 3,5 Series 2: 0
EE, "strange" radiation	4.66	0.039	−11.8 ± 5.5
EE, exposure to light	2.06	0.16	0
EE, PMF	4.62	0.040	11.5 ± 5.4
EE, shielding material	0.78	0.38	0
$R^2 = 0.64$			

Table 7. Lengths of lettuce seedling sprouts in different experimental groups

Group	Experimental conditions	Sprout length, mm	Relative to control
1	Control	14.60 ± 0.54	
2	EE, unshielded	13.28 ± 0.52	$t = 1.76$; $p = 0.08$
3	EE, shielding with black paper	12.89 ± 0.51	$t = 2.3$; $p = 0.022$
4	EE, shielding (Al)	12.16 ± 0.53	$t = 3.23$; $p = 0.0013$
5	EE, shielding (Be)	13.09 ± 0.53	$t = 2.0$; $p = 0.046$
6	EE, shielding (Pb)	13.67 ± 0.52	$t = 1.24$; $p = 0.22$

and root length of lettuce seed seedlings was observed. The average length of a lettuce seedling's sprout in the control group when analyzing data from the three series of the experiment was 14.60 ± 0.54 mm. When analyzing the length of lettuce sprouts in different experimental groups, a statistically significant drop in the indicator relative to the control was recorded in the groups where the seeds were shielded with black paper (a 12% reduction in sprout length), a beryllium plate (a 13% reduction), and aluminum foil (a 17% reduction) during an electric explosion (Table 7).

When performing a multivariate analysis of the variance in the influence of the given factors on the length of lettuce seed sprouts, it was found that the length of the sprout differed considerably in different series of the experiment ($F = 7.56$, $p = 0.001$) (Table 8). A statistically significant effect of "strange" radiation ($F = 7.27$, $p = 0.007$) on this indicator was also revealed that manifested in shortening of the length of a sprout by an average of 1.60 ± 0.59 mm. Other factors of the electric explosion had no statistically significant effect on the lengths of lettuce seedling sprouts.

Among the factors of a high-current electric explosion in a vacuum, the only biologically significant factor at the level of the organism (the biological model of germination of lettuce seeds) was thus "strange" radiation. Sprouts were most sensitive to the action of this factor. The type of the biological effects (a reduction in length of growth and the entire seedling) does not contradict the data on genotoxic effects recorded using the comet assay and the allium test, and could be a sign of the induction of macromolecule (protein and DNA) crosslinks in cells.

Earlier studies to determine the biological effects of factors associated with electric explosions of a con-

Table 8. Results from multivariate analysis of the effects different electric explosion factors have on the length of lettuce seeds sprouts

Factors	F	p	GLM coefficient
Series of experiment	7.56	0.001	Series 1: 3.48 ± 0.96
			Series 2: 1.24 ± 0.53
			Series 3: 0
EE, "strange" radiation	7.27	0.007	-1.60 ± 0.59
EE, exposure to light	0.24	0.62	0
EE, PMF	0.62	0.43	0
EE, shielding material	1.46	0.23	0
$R^2 = 0.018$			

ductor (titanium foil) in condensed media (a 40% aqueous solution of glycerol) showed that when mice were exposed to 14 electric explosions over 4 days, they developed an adaptive response that lowered the frequency of bone marrow erythrocytes with micronuclei (a result of gross chromosomal aberrations) induced by additional testing with external gamma radiation at doses of 2 Gy [19]. It was also shown that shielding mice with aluminum and iron modified the biological effects of electric explosion factors [19]. It should be noted that it was difficult in earlier studies to separate the effects from exposure to light, sound, and a pulsed magnetic field, and reasonably associate the identified biological effects with the action of "strange" radiation.

CONCLUSIONS

Experiments with different shielding materials and statistical analysis allowed us to separate the biological effects of exposure to light, pulsed magnetic fields, and "strange" radiation, making it possible for the first time to obtain results that can be interpreted as biological effects of "strange" radiation.

The results from our experiments showed that using biological systems to index "strange" radiation confirm that it is penetrating. It also indicates that shielding material modifies "strange" radiation, depending on the atomic mass of the shielding material. Our results, obtained in the form of a drop in the level of nuclear DNA damage in human peripheral blood cells and an increase in the frequency of chromosomal aberrations in dividing cells of an onion seedling's root, allowed us to determine the effects "strange" radiation have on human health when exposed to levels typical of electric explosions in a vacuum close to a discharge chamber.

Several factors associated with a high-current explosion of a conductor in a vacuum were considered: exposure to light, a pulsed magnetic field, and "strange" radiation, as was confirmed by recording tracks on glass inside the explosion chamber and on X-ray films at the place of biological objects. A multivariate analysis of the variance in the general linear model showed the biological effect of penetrating "strange" radiation was present in all four biological models (human peripheral blood leukocytes, onion and lettuce seeds, and single-celled green algae *Scenedesmus quadricauda*). This action manifested in (1) a drop in the level of DNA damage in the leukocytes of human peripheral blood, (2) an increase in the frequency of chromosomal aberrations in onion root cells, (3) a reduction in the length of lettuce seed sprouts, and (4) a drop in the proportion of one-celled coenobia in a culture of green algae *Scenedesmus quadricauda*.

The materials used for shielding (beryllium, paper, aluminum, lead) modified the biological effect of "strange" radiation: the level of nuclear DNA damage grew along with the atomic mass of the shielding material, suggesting that the physical interaction between "strange" radiation and a substance depends on the atomic mass of the latter. The results from our study indicate the biological effect of "strange" radiation is due to DNA damage caused by the induction of DNA–DNA and DNA–protein crosslinks.

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