SECTION «MEDICAL SCIENCES»

HOMOCYSTEINE AND ^{137}CS DECORPORATION IN CHILDREN LIVING NEAR THE CHORNOBYL EXCLUSION ZONE

Yuri Bandazheuski[1]
Nataliia Dubovaya[2]

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Abstract. Living near the Chornobyl Exclusion Zone (ChEZ) and consuming local foods containing radionuclides causes damage to vital organs and systems in children. ^{137}Cs, as well as its decay product ^{137}Ba, negatively impact energy processes, inducing oxidative stress. One marker of metabolic disturbances is elevated blood levels of the sulfur-containing amino acid homocysteine (H_{cy}). Hyperhomocysteinemia has been detected in the majority of children living near the ChEZ. Therefore, it is important to determine the relationship between the radiation factor, which constantly affects children, and H_{cy}. *The purpose* of this study was to determine the relationship between the concentration of the sulfur-containing amino acid H_{cy} in the blood and the specific activity of ^{137}Cs in the body of children living near the ChEZ. *Research methods.* Laboratory and instrumental examinations were conducted on 67 children aged 8-17 years from rural communities located near the ChEZ before and after a summer health trip to France organized by the French NGO "Children of Chernobyl". Specific activity of ^{137}Cs in the body, blood H_{cy} levels, and the state of the folate cycle were assessed. Statistical analysis of the results was performed using IBM SPSS Statistics 22 (USA). *Results.* In the group of children living near the ChEZ, after a 3-week health trip to France, the specific activity

[1] Doctor of Medical Sciences, Professor,
Chairman of the Board of the Coordination Analytical Center "Ecology and Health", Ukraine
[2] Candidate of Medical Sciences, Associate Professor,
Deputy Chairman of the Board of the Coordination and Analytical Center "Ecology and Health," Ukraine

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of ^{137}Cs in the body decreased in 97.0 % of cases, while the level of H_{cy} in the blood increased in 82.1 % of cases. The maximum value of the specific activity of ^{137}Cs in the children's body before the trip to France was 63.45 Bq/kg, after the trip – 37.21 Bq/kg. The interquartile range (IQR) of H_{cy} concentrations in the blood of the examined children was determined before the trip in the range of 8.60-11.68 μmol/l, after the trip in the range of 9.40-12.60 μmol/l. An inverse correlation was revealed between the values of the specific activity of ^{137}Cs in the body and the concentration of H_{cy} in the blood, which was more pronounced after the children's return from France. Based on the obtained data and the results of previously conducted studies, the mechanism of H_{cy} participation in the natural decorporation of ^{137}Cs from the body is presented. *Conclusions.* Sulfur-containing amino acids methionine (Met) and H_{cy}, by stimulating energy processes in the cells of vital organs, participate in the decorporation of ^{137}Cs radionuclides from the child's body. This activates the antioxidant system, eliminating and preventing the development of radiation-induced oxidative stress. An increase in the H_{cy} level in the blood of children exposed to constant radiation indicates both a disruption of metabolic processes and the activation of adaptive reactions aimed at restoring the physiological functions of the body. The ability of the sulfur-containing amino acids Met and H_{cy} to enhance the decorporation of ^{137}Cs radionuclides from the body should be taken into account when implementing health measures for populations living in radiation-exposed areas. Therefore, health trips for children to European Union countries should be considered in terms of restoring, at the physiological level, the oxidation-reduction processes disrupted as a result of constant radiation toxicity. Forty years after the Chornobyl accident, radiation protection measures in the affected area must include regular monitoring of children's levels of the sulfur-containing amino acid H_{cy} and ^{137}Cs. Furthermore, ^{137}Cs and Ba must also be measured in locally sourced food and water.

INTRODUCTION

The population living near the ChEZ is constantly exposed to radiation. ^{137}Cs radionuclides were detected in the bodies of all children from the Ivankivsky and Polessky districts of the Kyiv region, examined in 2013-2017 as part of the European Commission project

"Health and Ecological Programmes around the Chernobyl Exclusion Zone: Development, Training, and Coordination of Health-Related Projects" [1, p. 12].

Moreover, electrocardiographic changes were recorded in 81.9 % of children [1, p. 23], an increase in the activity of serum aspartate aminotransferase (AST) above the physiological level was detected in 37.5 % of cases, while an increase in alanine aminotransferase (ALT) activity was detected in 1.21 % of cases [1, p. 28].

A direct correlation between the specific activity of ^{137}Cs in the body and AST activity in the blood [1, p. 31], as well as the values of the de Ritis coefficient [1, p. 32], identified in the group of examined children, indicates, taking into account previous studies [2, p. 71], a negative impact of incorporated ^{137}Cs radionuclides on the mitochondria of cardiomyocytes and the energy supply of cardiac activity.

As a result, there is a decrease in myocardial contractility and a decrease in blood pressure [3, p. 352].

The functional reserve and adaptive capacity of the cardiovascular system also decrease [4, p. 168].

Under these conditions, children's physical development is impaired. The Rohrer index, which reflects children's physical development, is inversely related to the specific activity of ^{137}Cs in the body [1, p. 15].

The disruption of cellular energetics induced by ^{137}Cs incorporation leads to disruption of transmembrane ion exchange and Ca retention in cells, as evidenced by the inverse correlation between the specific activity of ^{137}Cs in the body and serum Ca [3, p. 342].

Thus, as the specific activity of ^{137}Cs in the body increases, the level of Ca in the blood serum should decrease.

However, the results of studies indicate that the level of Ca in the blood serum of children does not decrease, but, in most cases, corresponds to the physiological level, and even exceeds it [3, p. 348].

In our opinion, this is related to the sulfur-containing amino acid H_{cy}, the concentration of which in the blood is elevated in most children living near the ChEZ [1, p. 33].

Forest fires in the ChEZ contributed to the development of hyperhomocysteinemia in these children [5, p. 24].

A direct correlation has been established between H_{cy} and Ca values [3, p. 346], indicating that hyperhomocysteinemia is associated with increased serum Ca levels.

This may be due to the effect of H_{cy} on the skeletal system, particularly osteoclasts [6, pp. 1008, 1009], as well as its stimulating effect on cellular energy processes via triiodothyronine (T_3) [7, p. 65].

Given the above scientific data, it is advisable to study the metabolic transformations of H_{cy} under conditions of changing ^{137}Cs specific activity in the body.

The aim of this study was to determine the relationship between the concentration of the sulfur-containing amino acid H_{cy} in the blood and the specific activity of ^{137}Cs in the body of children living near the ChEZ.

1. Material and Methods

A laboratory and instrumental examination was conducted on children from rural settlements in the Ivankivsky and Polessky districts of the Kyiv region located near the ChEZ before and after a health trip to France organized by the French public organization "Children of Chernobyl."

The specific activity of ^{137}Cs in the bodies of 67 children, aged 8-17 years, was measured using a 3-detector human radiation spectrometer "SICH-AKP-3" (LLC NPP "ATOMKOMPLEKSPRIBOR", Ukraine).

The specific activity of ^{137}Cs in the bodies of 67 children aged 8–17 years was measured using the SICH-AKP-3 three-detector whole-body counter (Atomkomplekspribor NPP LLC, Ukraine).

The measurement time was 10 minutes. The spectrometer ensures measurement accuracy for ^{137}Cs body content levels up to 5 Bq/kg (with a measurement uncertainty not exceeding 30 %).

Automatic spectrum processing, calculation of the specific activity of radioactive elements, and data storage were performed using the instrument's "AKWin" software.

The first dosimetric measurement was performed on July 4-5, 2018, immediately before the children's trip to France. The second dosimetric measurement was performed on July 28-29, 2018, immediately after the children's return from France.

During the individual dosimetry period, blood was collected from the cubital vein of each child to determine the sulfur-containing amino acid H_{cy} content and assess the state of the folate cycle (FC) system.

The determination of H_{cy} in blood and the genetic study of FC were carried out in a laboratory certified according to the quality standards of the European Union using the immunochemical method with chemiluminescent detection (ECLIA). Analyzer and test system: Architect 1000 (ABBOT Diagnostics (USA)).

The genetic testing included determination of the C677T and A1298C allelic variants of the MTHFR gene (associated with the enzyme methylenetetrahydrofolate reductase), A2756G of the MTR gene (associated with the enzyme B_{12}-dependent methionine synthase), and A66G of the MTRR gene (associated with the enzyme methionine synthase reductase). Real-time PCR was used.

The radiometric study, determination of H_{cy} levels in the blood, and determination of folate-rich proteins genetic polymorphisms in children were all agreed upon with their parents.

Statistical processing of the obtained results was performed using IBM SPSS Statistics 22 (USA). The median (Me), interquartile range (IQR), minimum and maximum parameter values were calculated for the analyzed parameters. Percentiles.

A hypothesis test regarding the distribution type was conducted (Kolmogorov-Smirnov test).

It was found that the distribution of values deviated from normality, so the Wilcoxon signed-rank Z-test was used to assess the statistical significance of differences in the indicators; the significance level (p) was determined using a statistical program.

The relationship between the analyzed indicators, ^{137}Cs and H_{cy}, was determined using Spearman's rank correlation coefficient (r_{xy}). The strength of the correlation was assessed using a traditional scale: weak – from 0 to 0.299; moderate – from 0.3 to 0.699; strong – from 0.7 to 1.0.

2. Research Results and Discussion

Radiometric testing conducted July 4-5, 2018, revealed that the specific activity of ^{137}Cs in the bodies of 60 of the 67 children examined (89.6 %) was less than 5.0 Bq/kg.

Moreover, specific activity of ^{137}Cs equal to or greater than 5 Bq/kg was detected in 8 cases (11.9 %), compared to 5 cases (7.5 %) during the July 28-29, 2018, examination.

A decrease in specific activity of ^{137}Cs was recorded in 65 of the 67 children examined (97.0 %) after their return from France on July 28-29, 2018.

The maximum specific activity of ^{137}Cs in the children's bodies before the trip to France was 63.45 Bq/kg, and after the trip, it was 37.21 Bq/kg.

An increase in blood H_{cy} levels after the trip to France was detected in 55 children (82.1 %).

An assessment of the statistical significance of the differences in the analyzed parameters, using the Wilcoxon signed-rank Z-test, showed that in children from settlements located near the ChEZ, immediately after a short-term (3-week) health trip to France, the specific activity of ^{137}Cs in the body decreased ($Z = -6.706$, $p = 0.0001$; $n = 67$), while the level of H_{cy} in the blood increased – $Z = -4.520$, $p = 0.0001$, $n = 67$ (Table 1).

Table 1

Statistical characteristics of the ^{137}Cs and H_{cy} levels in the bodies of the examined children

Study	^{137}Cs, Bq/kg		H_{cy} µmol/l	
	Me	IQR	Me	IQR
No. 1	2.78	2.35 - 3.45	9.90	8.60 - 11.68
No. 2	2.35	1.98 - 3.00	10.50	9.40 - 12.60

Note. No. 1 – examination on July 4-5, 2018, before the trip to France; No. 2 – examination on July 28-29, 2018, after returning from France. Me – median; IQR – interquartile range.

Correlation analysis revealed an inverse relationship between ^{137}Cs and H_{cy} levels in this group of children, which became more pronounced after their return from France (Table 2). Furthermore, four cases with a homozygous variant of the TMTHFR:677 allele, which has a direct and significant effect on H_{cy} level in the blood, were excluded from the analyzed group [8, p. 12].

Conducted studies indicate a link between ^{137}Cs incorporation and the metabolism of the sulfur-containing amino acids Met and H_{cy} in the bodies of children living near the ChEZ.

The penetration of ^{137}Cs radionuclides into the cells of internal organs and the brain (Fig. 1) [9, p. 489] disrupts the formation of energy carriers in mitochondria [2, p. 71].

Table 2

Results of correlation analysis in the group of children examined

Study group of children	Correlation coefficient	^{137}Cs - H_{cy}	
		No. 1	No. 2
No cases with the genotype T/T MTHFR:677	Spearman's	- 0.314*	- 0.358**
	Sign. (2-tailed), p	0.012	0.004
	n	63	63

Note: No. 1 – examination on July 4-5, 2018, before the trip to France; No. 2 – examination on July 28-29, 2018, after returning from France.

Radiation exposure to the body causes mitochondrial dysfunction and the formation of reactive oxygen species, which have a destructive effect on intracellular structures [10, pp. 3, 4].

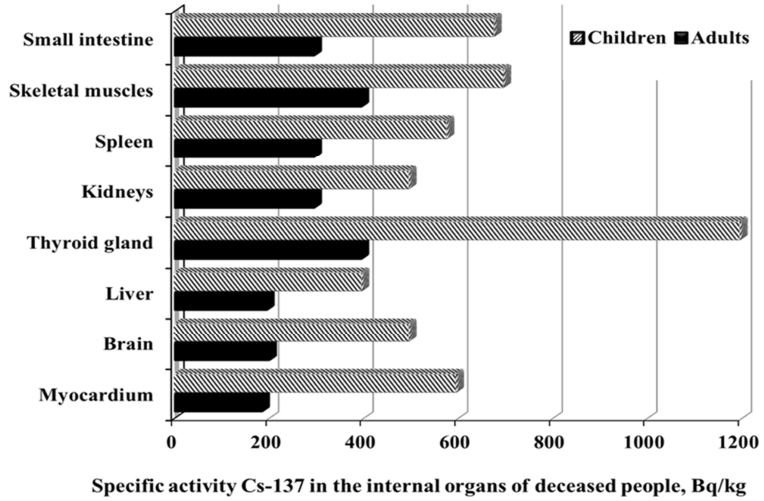


Figure 1. Specific activity of ^{137}Cs (Bq/kg) in the internal organs of adults and children – residents of the Gomel region of the Republic of Belarus who died in 1997 [9, p. 489]

The greatest pathological changes occur in organs that intensively accumulate ^{137}Cs radionuclides: the heart, kidneys, and endocrine glands [9, p. 489].

This creates an emergency situation in the body, activating adaptive processes involving the sulfur-containing amino acids Met and H_{cy} [11, p. 70].

Met, interacting with ATP, under the influence of methionine adenosyltransferase, forms S-adenosylmethionine (S-AM), which is the main donor of methyl groups in the body [12, p. 3].

By donating a methyl group (CH_3), in protein, lipid, and neurotransmitter methylation reactions, S-AM is sequentially converted to S-adenosylhomocysteine (S-AH) and H_{cy}.

H_{cy} undergoes remethylation, forming internal Met, with the help of FC enzymes and methyl group carriers.

In the transsulfuration cycle, H_{cy} is converted into cysteine and glutathione, an intracellular tripeptide with antioxidant properties [12, p. 3].

The regulation of H_{cy} metabolic transformations is associated with the activity of FC enzymes and the transsulfuration cycle, which depends on the state of their genes and the influence of environmental factors.

The combined influence of internal and external factors determines the nature of H_{cy} metabolic transformations.

In children carrying the GMTR:2756 allele and living near the ChEZ under conditions of constant radiation exposure,

H_{cy} remethylation is impaired, and therefore it is utilized in the transsulfuration cycle to form cysteine and glutathione [13, p. 251].

In the studied group of girls carrying the G allele of MTR:2756, elevated blood levels of the adrenal cortex hormone cortisol were recorded, and a direct correlation between H_{cy} and cortisol was determined [11, p. 69].

Thus, decreased activity of the enzyme B_{12} methionine synthase, which is involved in the methylation of H_{cy} and the formation of internal Met, stimulates the synthesis of a hormone with antioxidant properties.

H_{cy}, at elevated blood concentrations, activates the formation of the active form of thyroid hormone, T_3, which affects mitochondrial function and stimulates energy metabolism.

This also leads to increased methylation of H_{cy} and the formation of internal Met (Fig. 2) [7, p. 65].

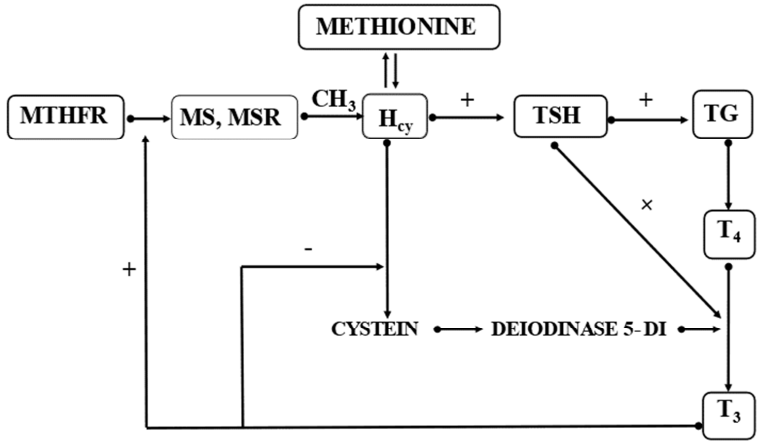


Figure 2. The effect of T_3 on H_{cy} methylation processes [7, p. 65]

S-AM is known to suppress methylenetetrahydrofolate reductase (MTHFR) activity and enhance the activity of enzymes in the transsulfuration cycle [14, p. 5].

Therefore, if S-AM levels increase, 5-methyltetrahydrofolate levels decrease, and, accordingly, the intensity of H_{cy} methylation decreases.

In this situation, blood H_{cy} concentrations increase, which are utilized in the transsulfuration cycle, followed by the formation of cysteine and glutathione, which plays an important role in the body's antioxidant defense.

The inverse correlation between H_{cy} and ^{137}Cs indicates that the elimination of ^{137}Cs from the body is enhanced.

The increased blood H_{cy} concentration in the children studied may be due to increased

Met intake in their diet during their stay in France.

Given the above, it can be assumed that Met and its metabolic product, H_{cy}, as activators of cellular energy restoration, help eliminate the negative impact of ^{137}Cs and its decay product, ^{137}Ba, on the body.

At the same time, the functioning of organs involved in radionuclide decorporation and the removal of ^{137}Ba from the body is improved.

^{137}Ba, formed as a result of the decay of radioactive ^{137}Cs, both in the body's cells and in the environment, is a toxicant that reduces the activity

of catalase, glutathione peroxidase, and glutathione, and causes oxidative stress [15, p. 964].

The specific activity of ^{137}Cs and the concentration of Ba in oat grain grown in the Ivankivsky district 25 years after the Chornobyl Nuclear Power Plant (ChNPP) accident were significantly higher than in oat grain grown in areas not exposed to radiation [5, p. 29; 16, p. 48].

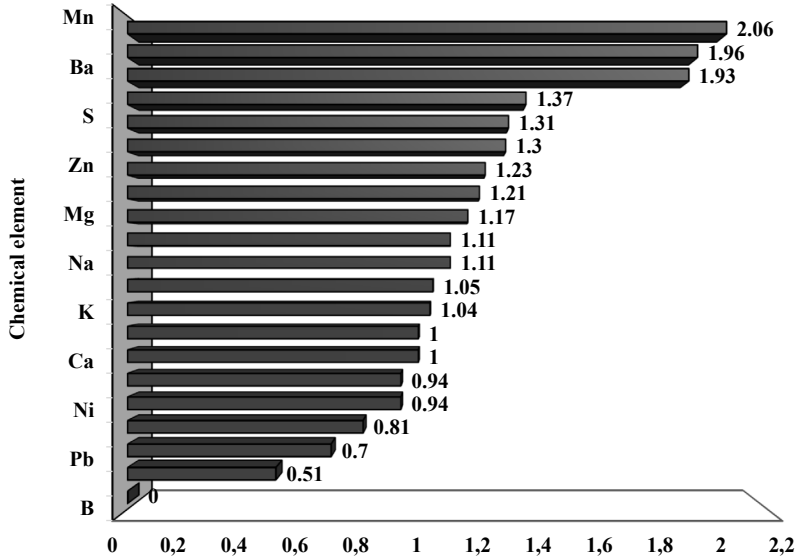


Figure 3. The content of chemical elements in the studied sample of oats from the Ivankivsky district in relation to the sample of oats from the district with the absence of ^{137}Cs in the soil [16, p. 48]

Feeding experimental animals this grain during pregnancy resulted in congenital malformations (Fig. 4) [5, p. 30].

Congenital malformations of the brain and facial skull – such as anencephaly, exencephaly, craniocerebral hernia, cleft lip and hard palate, micrognathia, microgenia, microphthalmia, and anophthalmia – were observed in Syrian hamsters [2, p. 105].

These malformations belong to the group of multifactorial defects resulting from the interplay of genetic predisposition and environmental factors.



Figure 4. Congenital malformations in Syrian hamster embryos (bilateral cleft lip) when females were fed oat grain during pregnancy (^{137}Cs concentration 49.8 Bq/kg), grown in the Ivankovsky district of the Kyiv region in 2011 [5, p. 30]

Although ^{137}Cs is largely retained by placental structures, under certain conditions it penetrates embryonic cells, causing pathological changes at the cellular, organ, and organismal levels.

The mean specific activity of ^{137}Cs in the placentas and fetuses of humans with multifactorial congenital malformations was recorded as 61.50 ± 13.50 Bq/kg and 25.40 ± 3.20 Bq/kg, respectively [2, p. 103].

An increase in the specific activity of ^{137}Cs in the placenta was associated with a rise in cortisol levels in maternal blood and a decrease in the hormone's levels in fetal blood (Fig. 5) [2, p. 103].

Undoubtedly, this reduces the overall resistance and adaptive capacity of the developing organism during the postnatal period.

This may explain the pathological changes observed in children and adults living in areas at risk of radiation exposure resulting from the Chernobyl accident.

Noteworthy findings include cardiovascular dysfunction in more than 80% of the children examined [1, p. 23], as well as susceptibility to various infectious agents (tuberculosis, viral hepatitis, and acute respiratory

infections) and allergic reactions to components of common food products.

In children with a body burden of ^{137}Cs of 128.38 ± 13.38 Bq/kg, a strongly positive allergic reaction to cow's milk protein was recorded in more than 50 % of cases [2, p. 96].

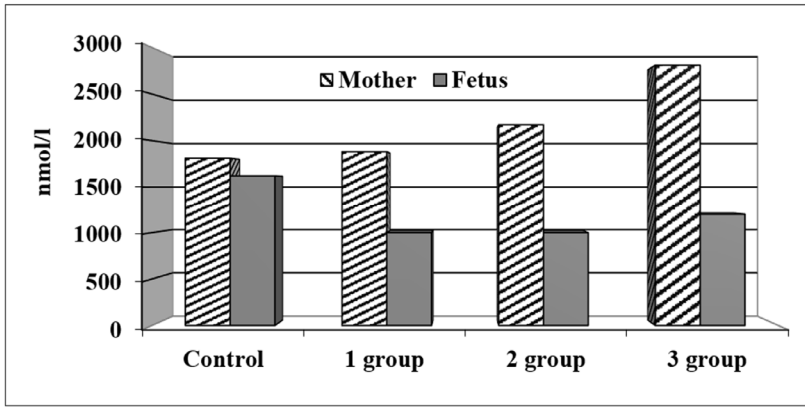


Figure 5. Cortisol concentration in maternal and fetal blood in the control and experimental groups*. (Note. * - ^{137}Cs concentration in the placenta: group 1 (1.0 – 99.0 Bq/kg), group 2 (100.0 – 199.0 Bq/kg), group 3 (more than 200.0 Bq/kg)) [2, p. 103]

Experimental studies have revealed that, upon transitioning to independent feeding (on the 30th day after birth), rat pups exposed to ^{137}Cs during prenatal development incorporate this radionuclide from food sources more intensively than females and control-group animals (Table 3) [2, p. 63].

The effectiveness of the decorporation process, activation of the antioxidant system, and restoration of metabolic processes is due to the fact that ^{137}Cs and its decay product Ba do not enter the children's bodies, or enter in very small quantities, during their stay in France.

^{137}Cs is excreted from the body primarily by the kidneys; however, a number of agents can eliminate this radionuclide through the digestive tract with feces.

^{137}Cs decorporation is an effective means of reducing the radiation toxicity of children living near the ChEZ.

Table 3

Specific activity of ^{137}Cs in the body of female and young rats (Bq/kg) [2, p. 63]

Days after childbirth	Experimental group		Control group	
	Female rats	Baby rats	Female rats	Baby rats
1st	128.30 ± 6.52	36.64 ± 7.46	12.10 ± 7.59	3.95 ± 1.00
10th	34.46 ± 10.44	7.80 ± 1.53	8.53 ± 1.73	4.29 ± 1.36
20th	22.06 ± 6.23	9.69 ± 4.05	10.95 ± 4.20	6.29 ± 2.88
30th	19.32 ± 4.34	35.55 ± 5.92	18.74 ± 4.01	16.71 ± 2.49

Currently, the officially recommended agent for removing ^{137}Cs from the bodies of humans and animals is Prussian blue (insoluble iron hexacyanoferrate $Fe_4[Fe(CN)_6]_3$), the effectiveness of which depends on the pH of the gastrointestinal contents [17, p. 2].

Apple pectin has been shown to reduce ^{137}Cs levels in the bodies of children living in areas affected by the Chornobyl accident [18, p. 728].

However, as our research shows, the natural decorporation of ^{137}Cs from children's bodies involves Met and H_{cy}.

This property of sulfur-containing amino acids should be considered when implementing measures aimed at improving the health of children and adults suffering from radiation exposure.

Thus, metabolic disturbances caused by ^{137}Cs incorporated into the body cause impaired H_{cy} methylation.

The resulting hyperhomocysteinemia activates metabolism, thereby stimulating the decorporation of ^{137}Cs and Ba at the cellular, organ, and systemic levels.

This process can be enhanced by the intake of Met in food products.

However, when H_{cy} metabolism is impaired, it binds to protein molecules, causing their modification and functional alteration.

This leads to the development of an autoimmune process and increased thrombus formation.

Oxidative stress results in the formation of hydrogen peroxide (H_2O_2) and the superoxide anion radical, which stimulate lipid peroxidation processes [1, p. 36].

At high concentrations, H_{cy} undergoes spontaneous oxidation to form homocysteine acid, which induces cell apoptosis even upon brief exposure [1, p. 36].

H_{cy}-induced hypercoagulability leads to cerebral tissue ischemia.

Elevated blood levels of H_{cy} promote the excessive activation of ion-channel-linked glutamate receptors. This results in an influx of calcium ions into cells, the formation of free radicals, and mitochondrial damage [1, p. 38].

Thus, impaired H_{cy} metabolism can lead to serious pathological changes in the cells of vital organs.

In light of this, attention should be paid to the metabolism of the sulfur-containing amino acids Met and H_{cy} in the population exposed to radiation long after the ChNPP [19, p. 250].

Medical monitoring is required for individuals (both children and adults) with genetic defects affecting the activity of enzymes involved in the FC and the transsulfuration pathway.

This primarily applies to the homozygous MTHFR:C677T variant, which suppresses MTHFR activity [20, p. 13], as well as the homozygous MTR: A2756G variant; the latter is associated with reduced B_{12}-methionine synthase activity but leads to the activation of enzymes in the transsulfuration pathway [21, p. 32].

An analysis of the results of long-term scientific studies on children living near the ChEZ leads to the conclusion that H_{cy} serves as an indicator reflecting both the development of a pathological process and the activation of adaptive responses aimed at stabilizing cellular energy potential.

In each specific case, it is necessary to consider both internal factors (genes controlling metabolic cycles) and environmental influences (in this instance, radiation exposure).

CONCLUSIONS

Consumption of foods grown in areas contaminated with Cs and Ba isotopes causes damage to vital organs and systems in developing organisms.

^{137}Cs, as well as its decay product, ^{137}Ba, negatively impact energy processes, inducing oxidative stress in the bodies of children living near the ChEZ.

^{137}Cs decorporation helps reduce the radiation-toxic effects on the bodies of children living near the ChEZ.

The sulfur-containing amino acids Met and H_{cy}, by stimulating energy processes in the cells of vital organs, participate in the decorporation of ^{137}Cs radionuclides from the child's body. This activates the antioxidant system, eliminating and preventing the development of radiation-induced oxidative stress.

In a group of children living near the ChEZ, after a three-week health trip to France, the specific activity of ^{137}Cs in the body decreased, while the level of H_{cy} in the blood increased.

A decrease in the specific activity of ^{137}Cs was recorded in 97 % of cases, while an increase in the blood H_{cy} level occurred in 82.1 %.

Moreover, an inverse correlation was found between the specific activity of ^{137}Cs in the body and the concentration of H_{cy} in the blood, which became more pronounced after the children returned from France.

An increase in the H_{cy} level in the blood of children exposed to constant radiation indicates both a disruption of metabolic processes and the activation of adaptive reactions aimed at restoring the physiological functions of the body.

The ability of the sulfur-containing amino acids Met and H_{cy} to enhance the decorporation of ^{137}Cs radionuclides from the body should be taken into account when implementing health measures for populations living in radiation-exposed areas.

In this regard, health trips for children to European Union countries should be considered in terms of restoring, at the physiological level, the oxidation-reduction processes disrupted by constant radiation toxicity.

Forty years after the Chornobyl accident, radiation protection measures in the affected area must include regular monitoring of children's levels of the sulfur-containing amino acid H_{cy} and ^{137}Cs. Furthermore, ^{137}Cs and ^{137}Ba must also be measured in locally sourced food and water.

References:

1. Bandazhevsky Yu. I., Dubovaya N. F. (2022). Chernobyl catastrophe and childrens health. 35 years of world tragedy. Ivankov: PI Coordination and Analytical Center «Ecology and health», - Kyiv: «Alyant» LLC, 158 p.

2. Badazhevsky Yu., Dubovaya N., Bandazhevskaya G., Kadun O., Perepletchikov A., Zherbo L. (2015). Chernobyl 25 years: incorporated radionuclides Cs-137 and human health. Tokyo, 132 p.

3. Bandazheuski Yu., Dubovaya N. (2025). Participation of homocysteine in the regulation of calcium-phosphorus metabolism and cardiovascular function in children living in areas affected by the Chernobyl Nuclear Power Plant accident // Modern science: theory, practice, innovative technologies : Scientific monograph. Part 1. Riga, Latvia : Baltija Publishing, pp. 331-356. DOI: https://doi.org/10.30525/978-9934-26-602-7

4. Dubovaya N., Bandazheuski Yu. (2023). Adaptation resources of the cardiovascular system of schoolchildren living near the Chernobyl nuclear power plant // Scientific space: integration of traditional and innovative processes : Scientific monograph. Riga, Latvia : Baltija Publishing, pp. 147-170. DOI: https://doi.org/10.30525/978-9934-26-310-1-5

5. Bandazhevsky Yu. I., Dubovaya N. F. (2021). Forest fires in the Chernobyl exclusion zone and children's health. Ivankov : PI Coordination and Analytical Center «Ecology and health». Kyiv : «Aliant» LLC, 44 p.

6. Koh JM, Lee YS, Kim YS, Kim DJ, Kim HH, Park JY, Lee KU, Kim GS. (2006). Homocysteine enhances bone resorption by stimulation of osteoclast formation and activity through increased intracellular ROS generation. *J Bone Miner Res*. Jul;21(7):1003-11. DOI: 10.1359/jbmr.060406. PMID: 16813521.

7. Bandazhevsky Yu. I., Dubovaya N. F. (2025). Regulation of thyroid gland function in children living in areas affected by the Chernobyl nuclear power plant accident. Ivankiv: PI Coordination and Analytical Center «Ecology and Health». Kyiv, FOP Samchenko A. M., 80 p.

8. Bandazhevskyi Yu. I., Dubova N. F. (2018). MTHFR:677TT genotype and state of hyperhomocysteinemia in the children of regions suffered as a result of the accident at the Chornobyl nuclear power plant. *Environment&Health*. No 2(86), pp. 10-15.

9. Bandazhevsky Yu. I. (2003). Chronic Cs-137 incorporation in children's organs. *Swiss Medical Weekly*. Vol. 133, pp. 488-490. DOI: https://doi.org/10.4414/smw.2003.10226

10. Nuszkiewicz J, Woźniak A, Szewczyk-Golec K. (2020). Ionizing Radiation as a Source of Oxidative Stress-The Protective Role of Melatonin and Vitamin D. *Int J Mol Sci.* Aug 13;21(16):5804. DOI: 10.3390/ijms21165804. PMID: 32823530; PMCID: PMC7460937.

11. Bandazhevskyi Yu. I., Dubova N. F. (2025). Folate cycle genes, hyperhomocysteinemia, and stress response in children living near the Chernobyl exclusion zone. *Environment&Health*. № 4(117), pp. 62-71. DOI: https://doi.org/10.32402/dovkil2025.04.062

12. Škovierová H., Vidomanová E., Mahmood S. et al. (2016). The molecular and cellular Effect of homocysteine metabolism imbalance on human health. *Int J Mol Sci.* Oct 20; 17(10): 1733. DOI: 10.3390/ijms 17101733

13. Bandazheuski Yu., Dubovaya N. (2025). Folate cycle genes and adaptation processes in children living near the Chernobyl Exclusion Zone // Transformation of the scientific area in the context of contemporary challenges : Scientific monograph. Riga, Latvia : Baltija Publishing, pp. 242-260. DOI: https://doi.org/10.30525/978-9934-26-631-7-10

14. Fernández-Ramos D, Lopitz-Otsoa F, Lu SC, Mato JM. (2025). S-Adenosylmethionine: A Multifaceted Regulator in Cancer Pathogenesis and Therapy. *Cancers (Basel)*. Feb 5; 17(3):535. DOI: 10.3390/cancers17030535. PMID: 39941901; PMCID: PMC11816870.

15. Elwej A, Ben Salah G, Kallel C, Fakhfakh F, Zeghal N, Ben Amara I. (2016). Protective effects of pomegranate peel against hematotoxicity, chromosomal aberrations, and genotoxicity induced by barium chloride in adult rats. *Pharm Biol.*; 54(6):964-74. DOI: 10.3109/13880209.2015.1087035. Epub 2016 Mar 12. PMID: 26971618; PMCID: PMC11133871.

16. Bandazhevsky Yu. I., Dubovaya N. F. (2026). Pathological processes and adaptive reactions in children's bodies after the Chornobyl nuclear power plant accident. Ivankiv: PI Coordination and Analytical Center «Ecology and Health». Kyiv, FOP Samchenko A. M., 60 p.

17. Martínez-Alonso, B.; Torrado Durán, G.; Pardo Laurel, H.; Guarnizo-Herrero, V.; Peña Fernández, M.Á. (2025). Prussian Blue Tablets for Cesium Decorporation: pH-Dependent Performance Under Normogastric and Hypochlorhydric Conditions in an In Vitro Gastrointestinal Model. *Pharmaceuticals*, 18, 1702. DOI: https://doi.org/10.3390/ph18111702

18. Bandazhevskaya G. S., Nesterenko V. B., Babenko V. I., Yerkovich T. V., Bandazhevsky Yu. I. (2004). Relationship between caesium (Cs-137) load cardiovascular symptoms, and source of food in "Chernobyl" children-preliminary observations after intake of oral apple pectin. *Swiss Medical Weekly*. Vol. 134, pp. 725-729.

19. Labunska I., Kashparov V., Levchuk S. et al. (2018). Current radiological situation in areas of Ukraine contaminated by the Chernobyl accident: Part 1. Human dietary exposure to Caesium-137 and possible mitigation measures. *Environment International*, no 117, pp. 250–259.

20. Bandazhevskyi Yu. I., Dubova N. F. (2018). MTHFR: 677TT genotype and state of hyperhomocysteinemia in the children of regions suffered as a result of the accident at the Chornobyl nuclear power plant. *Environment&Health*. No 2(86), pp. 10-15.

21. Bandazhevskyi Yu. I., Dubova N. F. (2025). Regulation of thyroid hormone metabolism in hyperhomocysteinemia in children living near the Chornobyl exclusion zone. *Environment&Health.* No. 2(115), pp. 29-34. DOI: https://doi.org/10.32402/dovkil2025.02.029