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Impact of absorbed dose on the health status of lactating cows in the Bryansk region: comprehensive analysis of blood parameters in the long-term post-Chernobyl period

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The aim of this study was to assess the impact of the absorbed dose from chronic incorporated irradiation by ^{137}Cs on the hematological and biochemical parameters of blood in lactating cows during the long-term period after the Chernobyl accident. The study was conducted on 14 animals selected from two farms in the Bryansk region. These farms are located on radioactively contaminated territories within the zone of residence with the right to resettlement, where the current soil contamination density of ^{137}Cs is 185–555 kBq/m^2 (5-15 Ci/km^2). The study was carried out during the pasture period of 2023–2024. An assessment of the radiological conditions for keeping the study animals on the farms was performed. The whole-body absorbed dose from internal and external chronic exposure to ^{137}Cs was 0.57–1.72 mGy/y, which is significantly below the threshold for deterministic effects from acute external exposure. The complete blood count parameters corresponded to the physiological norm and were distributed within the reference values. Biochemical blood analysis showed a statistically significant decrease in urea levels in both experimental groups (2.77–2.85 mmol/L), as well as a decrease in total calcium (2.07 mmol/L) and inorganic phosphorus (1.05 mmol/L) levels in one experimental group. This may indicate pathological or compensatory processes occurring in the animals' bodies due to chronic incorporated irradiation during the long-term period of the consequences of radioactive contamination. The identified metabolic disorders have been confirmed by biochemical blood analyses conducted by veterinary laboratories from 2013 to 2025 and may be caused by the impact of ionizing radiation on both the macroorganism and the gastrointestinal tract microflora. The pathophysiological mechanism could be associated with a number of factors: altered protein metabolism, impaired liver function, suppression of ruminal fermentation, chronic exposure of radionuclides to the gastrointestinal mucosa, disrupted mineral metabolism and its hormonal regulation. These factors negatively affect animal health status.

Key words: *radiobiology, environmental health, complete blood count, blood biochemical analysis, absorbed dose, cattle, farm animals, radiation monitoring, low radiation doses, radioactively contaminated areas, Bryansk region.*

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Introduction

Livestock production in radioactively contaminated areas is associated with issues concerning the effects of ionizing radiation (IR) on animal viability and physiological functions. The study of the biological effects of incorporated chronic exposure in animals remains relevant for both fundamental and applied research. Assessment of the biological action of radionuclides should be based on a comprehensive approach that includes estimation of absorbed dose, evaluation of animals' health status, and consideration of feeding and housing conditions.

Hematological and biochemical blood analyses are among the principal methods used in studies of farm animals. Blood is a reactive internal system that responds sensitively to minor shifts in homeostasis. Deviations of blood parameters from physiological reference ranges indicate pathological or compensatory processes in the animal organism and may be attributable to the biological effects of IR resulting from the consumption of radioactively contaminated feed.

A number of scientific studies have addressed blood parameters in cattle raised on radioactively contaminated territories. These investigations were conducted at different stages of radioactive contamination: the acute period (up to 6 months after radioactive fallout), the period of early consequences (from 6 months to 2 years), and the period of late consequences (from 2 years to the present). In total, 10 studies have been reported: 2 in Japan, 2 in Belarus, 1 in Ukraine, and 5 in Russia. The reported effects were associated with the following technogenic events: the Southern Urals radiation accident at the Mayak Production Association [1], nuclear weapons testing at the Semipalatinsk Test Site from 1949 to 1989 [2], the accident at the Chernobyl Nuclear Power Plant (ChNPP) [3–8], and the Fukushima Daiichi Nuclear Power Plant accident [9, 10].

Among the observed alterations in cattle blood were dose-dependent eosinophilia and lymphopenia (gamma background in groups: 3–45 μSv/h); neutrophilic shifts, signs of anemia, hypo- and dysproteinemia, decreased calcium concentration, changes in acid–base balance, increased alanine aminotransferase (ALT) and aspartate aminotransferase (AST) activities, decreased urea, increased cholesterol, and impaired immune status. Dose-dependent changes in bone marrow hematopoiesis were also reported in cattle from areas differing in soil contamination density with ^{137}Cs (185–555 and 555–1110 kBq/m^2), including increased proportions of immature neutrophil forms, erythroblasts, and lymphocytes, along with decreased proportions of mature neutrophil forms.

In Japanese studies (gamma background in groups: 3–35 μSv/h), overall clinical and biochemical blood indicators remained within reference limits (with the exception of urea), and differences between control groups exceeded those between the control and contaminated zones, highlighting substantial natural variability in hematological parameters.

Such natural variability complicates the identification of deviations within the classical study design based on experimental and control groups, which underlies a number of published works. In this context, mutually contradictory findings have been reported, since statistically significant differences in blood indices may occur even within a single farm. Moreover, heterogeneity of results may reflect differences in the composition of contaminants across study areas and tissue-specific affinities of radionuclides. For example, ^{90}Sr and transuranium elements accumulate predominantly in bone tissue, whereas ^{137}Cs accumulates mainly in muscles and the liver.

The radiation situation in the Novozybkov district of the Bryansk region—the most contaminated area in Russia—is characterized by a considerable distance from the accident epicenter and predominance of ^{137}Cs in the contaminant mixture, making this territory a model area for investigating the biological effects of this radionuclide. Systematic studies of animal blood in the Novozybkov district were not conducted either during early periods of contamination or during the late-consequences period, which determines the scientific novelty of the present work as the first comprehensive observation of cattle in this area.

The aim of this study was to investigate the effect of absorbed dose due to chronic incorporated exposure to ^{137}Cs on hematological and biochemical blood parameters in lactating cows kept on radioactively contaminated territories of the Bryansk region during the late-consequences period after the ChNPP accident.

Materials and methods

The study was conducted in 2023–2024 on farms located in the Novozybkov district of the Bryansk region: Agricultural Production Cooperative (APC) “Udarnik”, Katashin village (Group 1), and APC “Kolkhoz im. Lenina”, Katichi village (Group 2). APC “Udarnik” is situated 195 km from Unit 4 of the Chernobyl Nuclear Power Plant (ChNPP), whereas APC “Kolkhoz im. Lenina” is located 183 km away. The farms are separated by 28 km (*Fig. 1*).

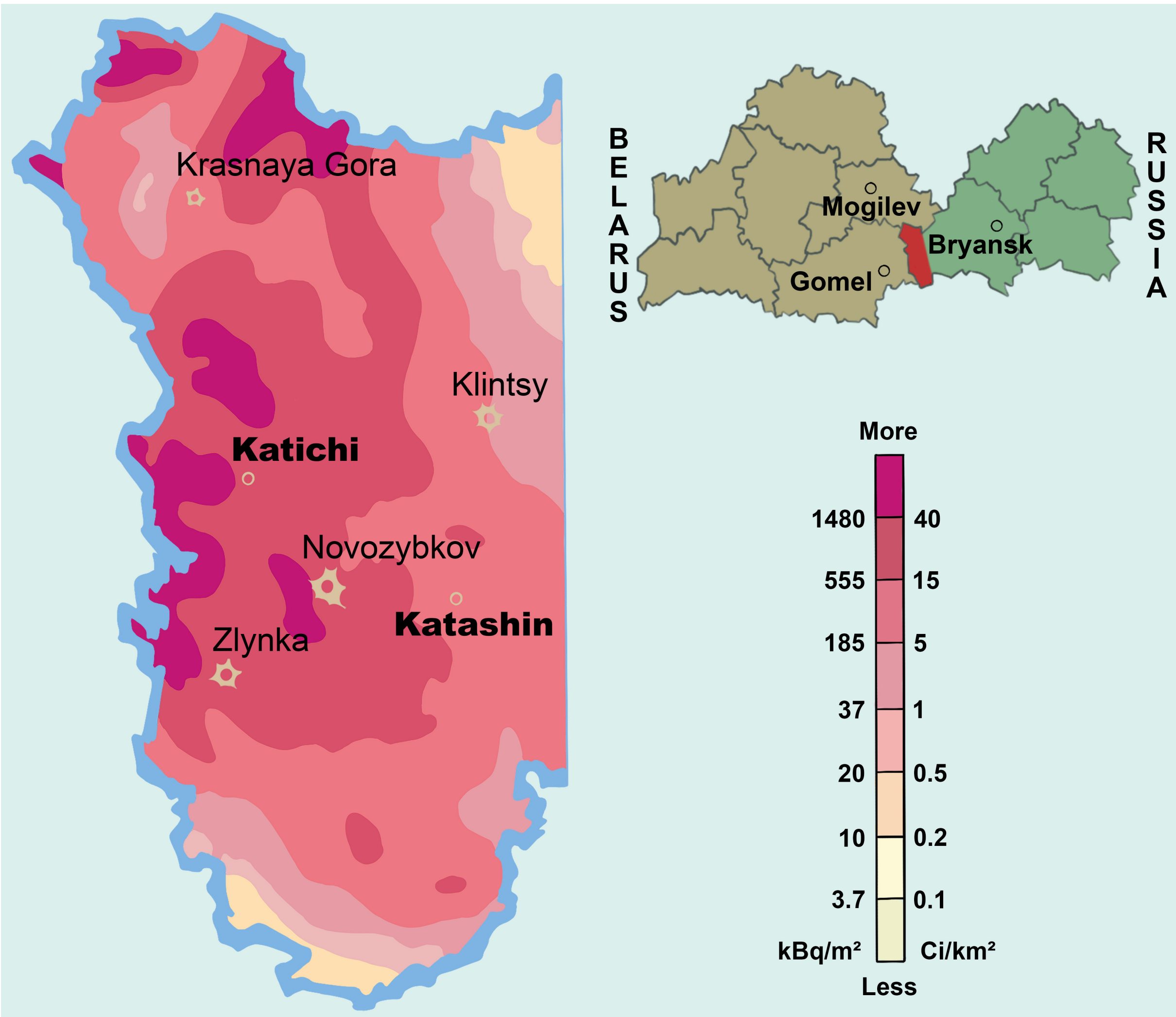

Fig. 1. ^{137}Cs soil contamination in the Bryansk region in 1986.

Fig. 1 was prepared using graphical software in accordance with published data [11]. The study settlements belong to the zone of residence with the right to resettlement, within which the current ^{137}Cs deposition density is 185–555 kBq/m^2.

At the time of the study, the livestock complex of APC “Udarnik” comprised 300 dairy cows of the Brown Swiss breed, and APC “Kolkhoz im. Lenina” maintained 210 dairy cows of the Black-and-White breed. Both farms were free from infectious and invasive diseases; the animals received standardized feeding and appropriate husbandry.

The gamma absorbed dose rate in air was measured on pastures using the scintillation dosimeter–radiometer SRP-68-01 (conversion factor: 0.0087 μGy/h per 1 μR/h). Soil and green forage samples were collected directly from grazing plots. Soil (surface layer, 10 cm) was sampled during the grazing season using the envelope method at five points within a 1-ha area with a soil sampler, from the floodplain of the Iput River (Group 2) and from meadows adjacent to the farms.

Plants cleaned of soil and soil samples were dried in a drying oven at 105 °C to constant dry mass, then ground and homogenized. Dried soil was sieved through a laboratory sieve for homogenization and removal of stones. Hay, straw, silage, and haylage were sampled on the farms during the housing period in winter and were ground during sample preparation. The activity concentration of ^{137}Cs was determined by gamma spectrometry using an SKS-99 “Sputnik” NaI(Tl) spectrometer with the “Progress” software package (Russia).

The hematological assessment included the following parameters: hematocrit (Ht, PCV), hemoglobin (Hb), red blood cells (RBC), mean corpuscular hemoglobin (MCH), mean corpuscular hemoglobin concentration (MCHC), erythrocyte sedimentation rate (ESR), mean corpuscular volume (MCV), red cell distribution width (RDW), white blood cells (WBC), band neutrophils, segmented neutrophils, eosinophils (EOS), monocytes (MONO), basophils (BAS), lymphocytes (LYM), and platelets (PLT).

The biochemical assessment included total bilirubin, direct bilirubin, AST, ALT, urea, creatinine, alkaline phosphatase, alpha-amylase, glucose, LDH, GGT, cholesterol, triglycerides, creatine phosphokinase (CPK), potassium, sodium, inorganic phosphorus, total calcium, iron, magnesium, chloride, acidity, total protein, albumin, and globulin. Blood analyses were performed using a BioSystems A-25 biochemical analyzer (Spain) and an Abacus Junior Vet veterinary hematology analyzer (Austria).

In each group, blood sampling was performed during the grazing period in summer from seven clinically healthy lactating cows aged 3–8 years. Blood was collected from the jugular vein in the morning before feeding into vacuum tubes containing K_2-EDTA (2 mL) and a clot activator (6 mL). Immediately after collection, samples were placed in an electrically powered portable car cooler and delivered to the laboratory within 8 h under a temperature regime of 2–8 °C.

The results were compared with veterinary diagnostic reference values for cattle because analysis of published data [9, 10] indicated that control groups are not a significant factor due to normal variability of blood parameters within reference ranges. Reference intervals were established by laboratories and are consistent with published sources [12–14].

The absorbed dose from chronic exposure to ^{137}Cs was calculated according to the ICRP (2017) methodology using the BiotaDC and ERICA Tool software and a differentiated approach accounting for the duration of the grazing and housing periods (180 and 185 days, respectively), daily intake of dry and succulent feeds, and the time spent by the animals on pasture during the grazing period (11 h), as expressed by Eq. (1):

$$D = \sum_{p} \underbrace{k_{d,internal}\, C_{body,p}\, t_p}_{D_{internal}} + \underbrace{k_{d,external}\, A_{soil,p}\, t_p\, k_{shield}}_{D_{external}}, \tag{1}$$

where t is the housing period (days); $k_{d,internal}$ is the dose coefficient for internal exposure (β, γ); $k_{d,external}$ is the dose coefficient for external exposure to ^{137}Cs; k_{shield} is the external exposure attenuation factor; A_{soil} is the activity concentration of ^{137}Cs in the upper 10-cm soil layer of the pasture/barn for the period (Bq/kg); C_{body} is the equilibrium (steady-state) concentration of ^{137}Cs in the body for the period (Bq/kg), calculated using Eq. (2):

$$C_{body,p} = \frac{f_1\, A_{feed,p}}{m\, \lambda_{eff}}, \tag{2}$$

where f_1 is the absorption fraction of ^{137}Cs; A_{feed} is the daily intake of ^{137}Cs with feed during the period (Bq/day); m is body mass (kg); and λ_{eff} is the effective elimination constant calculated using Eq. (3):

$$\lambda_{eff} = \frac{ln2}{\alpha T_1 + (1 - \alpha) T_2}, \tag{3}$$

where α is the fraction of the fast component; T_1 is the biological half-life of the fast component (days); and T_2 is the biological half-life of the slow component (days).

Statistical analysis included descriptive and parametric methods implemented in computational statistics packages. Results are presented as the mean and 95% confidence interval (CI). The Shapiro–Wilk test indicated a normal distribution of blood parameters in both groups. To identify statistical differences between sample means and the bounds of the reference intervals, the Two One-Sided Tests (TOST) approach based on Student's t-tests was applied:

H_0: $L_{RI} \le \mu \le H_{RI}$,
H_1: $\mu < L_{RI}$ or $\mu > H_{RI}$,

where L_{RI} and H_{RI} are the lower and upper bounds of the interval, respectively. Family-wise error control was performed using the Bonferroni correction; with this adjustment, the critical significance level was set at 0.025.

Results and discussion

Table 1 presents radiation monitoring parameters for the pastures of the investigated farms: the absorbed dose rate (ADR) of gamma radiation in air and the activity concentration (AC) of ^{137}Cs in soil, feeds, and milk. The mean body mass of the cows was 500 kg, and the annual milk yield was approximately 5000 L.

Table 1

Radiological conditions of keeping the studied animals

Parameter	n	Group 1	Group 2	
Gamma radiation ADR in air	10	0.27 ± 0.01 μGy/h	0.52 ± 0.07 μGy/h	
Soil (top layer, 10 cm), ^{137}Cs AC	5	360 ± 50 Bq/kg (pasture, farm)	2270 ± 620 Bq/kg (pasture)	500 ± 40 Bq/kg (farm)
Green forage from pastures (dry matter), ^{137}Cs AC	20	153 ± 10 Bq/kg	910 ± 90 Bq/kg	
Hay, ^{137}Cs AC	10	45 ± 4 Bq/kg	68 ± 6 Bq/kg	
Straw, ^{137}Cs AC	10	33 ± 3 Bq/kg	55 ± 5 Bq/kg	
Silage, ^{137}Cs AC	10	21 ± 2 Bq/kg	30 ± 2 Bq/kg	
Haylage, ^{137}Cs AC	10	30 ± 3 Bq/kg	38 ± 2 Bq/kg	
Milk, ^{137}Cs AC	20	21 ± 4 Bq/kg (summer) 12 ± 2 Bq/kg (winter)	65 ± 12 Bq/kg (summer) 19 ± 4 Bq/kg (winter)	

During the housing period, the diet at both farms was based on silage and haylage and also included hay, compound feed, and straw. During the grazing period, the diet consisted of herbage from pastures and compound feed. *Table 2* summarizes the feeding ration of the studied animals based on the farms' seasonal feed consumption.

Table 3 presents the calculated absorbed dose of lactating cows attributable to internal and external exposure to ^{137}Cs. To determine whole-body dose coefficients for cattle, the following parameters were used: body mass 500 kg, height 1.3 m, width 0.44 m, and length 1.6 m. The dose coefficient for internal exposure was 8.76 × 10^{-3} μGy day^{-1} Bq kg^{-1}, and for external exposure 1.64 × 10^{-3} μGy day^{-1} Bq kg^{-1}.

Table 2

Feeding ration of the studied cattle (as-fed basis)

Diet component	kg/day	Period
Herbage	55	Grazing
Hay	6	Housing
Straw	1	
Silage	20	
Haylage	20	
Compound feed (concentrates)	3–6	All
Feed additives	vitamin–mineral	
Salt, buffer mixture	according to standards	

Table 3

Absorbed dose from ^{137}Cs in cows (mGy/year)

Absorbed dose	Group 1	Group 2
Internal	0.50	1.36
External	0.07	0.36
Total	0.57	1.72

When calculating the external dose, the following shielding (attenuation) factors were applied: 1 for pastures (no shielding) and 0.1 for cowsheds equipped with concrete walls and bedding (maximum shielding). For internal dose calculations, the following biokinetic parameters of ^{137}Cs excretion were used: $\boldsymbol{f_1}$ = 0.8, $\boldsymbol{\alpha}$ = 0.3, $\boldsymbol{T_1}$ = 3.6 days, and $\boldsymbol{T_2}$ = 56 days.

Published data indicate that biokinetic parameters for calves are α = 0.41, T_1 = 3.6 days, and T_2 = 85 days [15]. When selecting parameters for the present study, the duration of juvenile growth and the period until first calving (up to 3 years), as well as the lifespan of adult cows in dairy production (up to 8 years), were taken into account. In young animals, α is higher due to accelerated metabolism, whereas T_2 is relatively long. In contrast, in adult cows T_2 decreases due to active elimination of ^{137}Cs with milk. Moreover, T_2 depends directly on daily milk yield: in high-producing cows it is shorter, whereas in dry cows it approaches the upper limit. In this study, a mixed population (young stock and adults) was considered; cows of moderate productivity during lactation and the dry period were assessed assuming proportional feed intake relative to body mass. Under these assumptions, the calculated effective half-life (T_{eff}) of 40 days represents a median value for cattle (30–50 days).

It has been reported that cattle may ingest up to 600 kg of soil together with herbage over a grazing season. However, under sod–podzolic soil conditions during the late-consequences period, ^{137}Cs intake into the organism is provided predominantly by plants, because ^{137}Cs in soil occurs mainly in a chemically bound form [16]. Since the contribution of the soil component to the total body activity is minor, whole-body absorbed dose should be calculated without accounting for soil ingestion. Nevertheless, this factor becomes relevant when estimating local dose to different segments of the gastrointestinal tract (GIT) and to its microbiota. For example, at an activity concentration of the topsoil layer on pastures of 360–2270 Bq/kg in the studied groups, the daily ^{137}Cs activity in the soil–forage mass will be 1.5–2 times higher than the daily activity in forage mass alone. At the same time, in early periods after radioactive contamination, soil particles may contribute substantially to the whole-body absorbed dose due to the high bioavailability of ^{137}Cs.

A complete blood count (CBC) in lactating cows from both groups did not reveal statistically significant deviations of hematological parameters from normal values; instead, the results fell within the reference ranges, which is consistent with several previously published studies [2, 7, 9].

Table 4 presents the biochemical blood test results for lactating cows as sample mean values for those indicators that showed statistically significant deviations from the reference ranges. The findings indicate decreased urea concentrations in Group 1 in 5/7 cows and in Group 2 in 7/7 cows. In Group 1, decreased total calcium and inorganic phosphorus were observed in 6/7 and 7/7 cows, respectively. The remaining parameters were within reference limits or did not show statistically significant deviations.

Table 4

Biochemical blood profile of lactating cows (mmol/L)

Parameter	**Reference range**	**Group 1**	**Group 2**
Urea	3.39–7.14	2.77 (95% CI: 2.23–3.31) ↓	2.85 (95% CI: 2.65–3.05) ↓
Total calcium	2.50–3.10	2.07 (95% CI: 1.92–2.22) ↓	2.61 (95% CI: 2.37–2.85)
Inorganic phosphorus	1.45–1.94	1.05 (95% CI: 0.85–1.25) ↓	1.75 (95% CI: 1.48–2.02)

In adult lactating and dry cows, blood urea concentration normally ranges from 3.39 to 7.14 mmol/L. The present study demonstrated a decrease in urea below the reference range in both experimental groups. This is consistent with reports by several authors who described urea concentrations below physiological norms in cattle kept on radioactively contaminated territories [1, 7, 10] and also in areas contaminated with heavy metals [1]. In contrast, biochemical blood testing of cows from five breeding farms located in environmentally favorable regions of the Northwestern Federal District [17] showed that urea concentrations in the grazing period were within the reference range in all cases.

The present results indicate decreased total calcium and inorganic phosphorus in experimental Group 1, whereas these indicators remained within reference limits in experimental Group 2. The observed hypocalcemia is consistent with findings from two earlier studies [2, 6]. Systematic hypophosphatemia and disturbances of calcium–phosphorus metabolism in the investigated groups are further supported by archival biochemical blood test data obtained in veterinary laboratories, summarized in *Table 5* as the mean and standard error of the mean. Hypophosphatemia has not been previously reported in the literature.

Analysis of biochemical indicators over 2013–2025 suggests a systematic decrease in calcium in Group 1 (12 of 17 examinations). Across both groups, systematic decreases were observed for inorganic phosphorus (13 of 21 examinations), alkaline reserve of blood (14 of 21 examinations), beta-carotene (16 of 21 examinations), and total protein (8 of 21 examinations). Ketone bodies were absent (19 of 19 examinations). Blood urea was not assessed in the archival dataset.

Table 5

Biochemical blood testing of cows and calves (farm archives)

Date	Group	n	Beta-carotene (μmol/L)	Total protein (g/L)	Total calcium (mmol/L)	Inorganic phosphorus (mmol/L)	Alkaline reserve (mmol/L)
05.02.2013	1	7	7.0 ± 1.6 ↓	70.3 ± 1.9 ↓	2.14 ± 0.1 ↓	1.58 ± 0.1	20.5±0.5
25.04.2013	1	17	–	–	1.90 ± 0.1 ↓	1.35 ± 0.1 ↓	–
09.10.2013	1	15	6.3 ± 0.2 ↓	76.5 ± 1.3	2.57 ± 0.1	–	19.8±0.6 ↓
26.02.2014	1	25	7.4 ± 0.3 ↓	67.9 ± 2.5 ↓	2.37 ± 0.1 ↓	1.47 ± 0.1	19.5±0.4 ↓
09.10.2014	1	20	7.2 ± 0.2 ↓	59.8 ± 0.4 ↓	2.22 ± 0.1 ↓	1.44 ± 0.1 ↓	20.8±0.8
05.02.2015 *	1	10	7.2 ± 0.2 ↓	76.3 ± 1.6	2.36 ± 0.1 ↓	1.43 ± 0.1 ↓	20.7±0.2
04.03.2015	1	12	7.3 ± 0.1 ↓	61.8 ± 3.5 ↓	1.86 ± 0.1 ↓	1.62 ± 0.1	21.6±0.3
26.11.2015	1	20	3.4 ± 0.3 ↓	71.5 ± 1.4 ↓	2.45 ± 0.1 ↓	0.77 ± 0.1 ↓	19.7±0.1 ↓
03.02.2016 *	1	10	5.1 ± 0.5 ↓	67.5 ± 1.3 ↓	2.54 ± 0.1	1.19 ± 0.1 ↓	20.4±0.2 ↓
01.03.2016	1	30	8.4 ± 0.1	78.6 ± 1.0	2.39 ± 0.1 ↓	2.00 ± 0.1 ↑	20.8±0.2
14.07.2016	1	11	25.0 ± 0.5	73.9 ± 1.7	2.47 ± 0.1 ↓	1.21 ± 0.1 ↓	19.9±0.3 ↓
14.11.2016	1	30	3.5 ± 0.2 ↓	74.9 ± 1.1	2.44 ± 0.1 ↓	0.71 ± 0.1 ↓	19.8±0.1 ↓
06.02.2017	1	15	5.4 ± 0.3 ↓	74.4 ± 2.1	1.89 ± 0.1 ↓	1.35 ± 0.1 ↓	20.0±0.2 ↓
01.03.2017	1	16	4.5 ± 0.2 ↓	68.2 ± 1.9 ↓	2.45 ± 0.1 ↓	1.20 ± 0.1 ↓	19.4±0.2 ↓
26.03.2018	1	36	6.3 ± 0.3 ↓	78.7 ± 0.9	2.69 ± 0.1	1.17 ± 0.1 ↓	17.5±0.2 ↓
06.09.2018	1	38	10.0 ± 0.4 ↓	78.0 ± 0.7	2.84 ± 0.1	1.08 ± 0.1 ↓	21.1±0.1
12.03.2019	1	40	6.0 ± 0.1 ↓	78.5 ± 0.8	2.65 ± 0.1	1.47 ± 0.1	20.4±0.1 ↓
16.03.2021	2	20	4.0 ± 0.1 ↓	75.9 ± 1.0	2.93 ± 0.1	1.27 ± 0.1 ↓	20.3±0.2 ↓
14.03.2022	2	10	6.9 ± 0.1 ↓	70.6 ± 1.0 ↓	2.55 ± 0.1	1.36 ± 0.1 ↓	20.4±0.2 ↓
18.04.2023	2	20	9.4 ± 0.3	78.2 ± 1.0	2.86 ± 0.1	1.45 ± 0.1	19.5±0.2 ↓
19.04.2024	2	10	7.8 ± 0.1	78.3 ± 0.8	2.63 ± 0.1	1.46 ± 0.1	20.0±0.1 ↓
03.04.2025	2	10	11.9 ± 1.0	84.1 ± 0.4	2.56 ± 0.1	1.48 ± 0.1	20.8±0.1
Reference ranges		winter	7.5–18.6	72.0–86.0	2.50–3.10	1.45–1.94	20.5–29.4
		summer	16.8–52.1				

Note: * indicates calves.

The literature describes threshold dose values for acute external exposure at which reversible hematological changes are observed in laboratory animals: lymphopenia occurs at a dose of 250 mGy, whereas a dose of 500 mGy induces anemia, leukopenia, and other hematopoietic shifts [9].

In the present study, the whole-body absorbed dose in cows was markedly below the thresholds associated with the onset of deterministic effects, which is consistent with the CBC findings. At the same time, the metabolic alterations identified may be related to the influence of chronic oxidative stress under internal exposure, affecting both the host organism and the gastrointestinal (GI) microbiota. Community structure and microbiota profiles may shift under the action of lipid peroxidation–associated factors. The ecological niche of bacteria, protozoa, and fungi inhabiting the GI tract may change under IR exposure; however, this mechanism of radionuclide action has not yet been investigated in ruminants.

It should also be noted that statistical analyses of farms located in radioactively contaminated territories (the East Ural Radioactive Trace) indicate that mortality of newborn offspring is 3–4 times higher than average values [1]. Radionuclides such as ^{137}Cs and ^{90}Sr readily cross the placental barrier; in the case of ^{137}Cs, the fetus is additionally exposed to gamma radiation emitted from maternal tissues and the GI tract. Thus, during intrauterine development the fetal dose is comparable to the maternal dose, while the developing fetus exhibits high radiosensitivity. This ecological aspect also remains insufficiently studied and requires detailed investigation. An effect of 50–100 mGy of X-ray exposure on mitochondrial activity in sheep oocytes has been reported without observable impairment of embryonic development [18].

An important direction is the assessment of potential transgenerational effects of chronic exposure on animal organisms. APC “Udarnik” (Group 1) was established in 1929 and operated until 2024, whereas APC “Kolkhoz im. Lenina” (Group 2) was established in 1951 and remains in operation at present. In both farms, the hereditary line of the animals was not interrupted throughout the entire period of their operation; genetic material was renewed in a planned manner by inseminating cows with semen from bulls originating from uncontaminated settlements. After the ChNPP accident, the cattle were not replaced and continued to graze under routine management, having received an incomparably higher dose in the early period. Since the deposition of radioactive fallout, four animal generations have changed, creating conditions for potential accumulation of epigenetic changes. Therefore, a combined scenario is possible, in which metabolic disturbances are driven by adaptive changes transmitted to offspring. The GI microbiome may likewise have undergone long-term restructuring following the initial radiation impact, with subsequent vertical transmission of an altered microbial profile. APC “Kolkhoz im. Lenina”, which preserves an uninterrupted history of cattle husbandry on contaminated territory, is of scientific interest for studying late radiation effects at molecular and ecosystem levels.

In addition to the chronological and geographical factors of radioactive contamination that influence the biological effects of radionuclides, it is necessary to consider the impacts of heavy metals and other xenobiotics on animal organisms, as these agents can affect the hematological and biochemical composition of blood [1, 19]. Agricultural lands are typically subject to combined technogenic contamination by multiple toxicants, among which complex interactions occur when they jointly participate in animal metabolic processes [20]. The health status of animals, as well as features of their diet and husbandry, should also be taken into account.

Veterinary examination of lactating cows did not reveal infectious, invasive, or internal non-contagious diseases that could have affected the outcomes of the present study, which is also supported by the current CBC and biochemical blood test results. The grazing feeding regime may be regarded as a model for such investigations, because the diet consists predominantly of pasture herbage, compound feed, and vitamin–mineral supplements and is well controlled.

Conclusion

The whole-body absorbed dose in cattle attributable to chronic internal and external exposure to ^{137}Cs was 0.57–1.72 mGy/year, which is markedly below the thresholds for deterministic effects under acute external irradiation. CBC results in lactating cows revealed no deviations of hematological parameters from the reference ranges. Biochemical blood testing demonstrated a statistically significant decrease in urea concentration in both experimental groups (2.77–2.85 mmol/L), as well as a decrease in total calcium (2.07 mmol/L) and inorganic phosphorus (1.05 mmol/L) below physiological norms in one experimental group. For all of these indicators, the 95% confidence intervals lay entirely below the corresponding reference intervals.

The obtained results may indicate pathological or compensatory processes occurring in the animal organism under chronic incorporated exposure during the late-consequences period of radioactive contamination. The identified metabolic disturbances may be associated with the effects of IR on both the host organism and the microbiota inhabiting the gastrointestinal tract of ruminants, leading to shifts in the ecological niches of the microflora and changes in microbial community composition.

Potential mechanisms underlying decreased blood urea concentration in cattle may be related to alterations in protein metabolism, impaired liver function, and suppression of ruminal fermentation. The mechanisms of hypocalcemia and hypophosphatemia may involve changes in protein metabolism, impaired liver function, reduced gastrointestinal absorption of calcium and phosphorus, endogenous vitamin D deficiency, chronic radionuclide effects on the gastrointestinal mucosa, and dysregulation of calcium–phosphorus homeostasis via effects on calcitonin secretion, parathyroid hormone production, and the synthesis of 1,25-$(OH)_2$D.

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