РАДІОБІОЛОГІЯ ТА РАДІОЕКОЛОГІЯ
RADIOBIOLOGY AND RADIOECOLOGY

УДК [577.34:597.2/.5] (285.2/3) https://doi.org/10.15407/jnpae2022.01.057

O. V. Kashparova[1,2,*], S. E. Levchuk[2], Yu. V. Khomutinin[2], P. M. Pavlenko[2], M. O. Hrechaniuk[2], V. O. Kashparov[1,2]

[1] Center for Environmental Radioactivity, Norwegian University of Life Sciences, Ås, Norway
[2] Ukrainian Institute of Agricultural Radiology, National University of Life and Environment Sciences of Ukraine, Kyiv, Ukraine

*Corresponding author: elena.kashparova@gmail.com

THE UPTAKE AND EXCRETION RATE OF ^{137}Cs FROM THE SILVER PRUSSIAN CARP (*CARASSIUS GIBELIO*) AT DIFFERENT FEEDING ROUTINE

Throughout 2016 - 2021, a series of experimental studies on ^{137}Cs uptake and excretion rate constants for the silver Prussian carp (*Carassius gibelio*) were conducted in the Chornobyl exclusion zone (ChEZ) under natural conditions. To confirm the metabolic parameters of ^{137}Cs in the silver Prussian carp under strictly controlled conditions at different feed amounts real supporting laboratory experiments have been conducted. The excretion rate of the ^{137}Cs from the silver Prussian carp increased with increasing feed amount from 0.0068 ± 0.0003 day^{-1} to 0.0085 ± 0.0005 day^{-1} at water temperatures of 26 °C. The biological half-life of ^{137}Cs activity concentration in fish can be reduced by 2 times by increasing fish growth using clean feeding. The excretion rate of the ^{137}Cs from the silver Prussian carp agreed with data collected in natural conditions in the ChEZ during 2016 - 2020 at different water temperatures.

Keywords: ^{137}Cs, Chornobyl, freshwater fish, radioactive contamination, excretion rate, depuration rate, the concentration factor.

1. Introduction

Knowledge of the dynamic of radionuclides in the body of fish is necessary for the radiation protection of both humans and the environment [1, 2]. To date, the activity concentration of ^{137}Cs in fish in enclosed water reservoirs in the territories that were alienated after the Chornobyl (Ukraine) and Fukushima (Japan) nuclear accidents may reach thousands of Becquerel per kilogram and exceeds permissible levels in Ukraine and Japan [3 - 10].

The ^{137}Cs uptake and excretion from fish depend on many environmental and biological factors, such as chemical composition and temperature of water, oxygen and ammonium content in water, the season of the year, and radioactive contamination of feed, species, and size of the fish, and purification conditions, etc. [8, 11 - 19]. All this requires clarification of the parameters of models for predicting radioactive contamination of fish at different temperatures and feeding conditions [11, 20 - 22].

The ^{137}Cs excretion/decreasing rates from fish muscle tissue at different water temperatures and feed amount and composition vary widely (0.0002 - 0.12 day^{-1}) and are very controversial [8, 11, 16 - 18, 23 - 30]. It was found in a laboratory experiment [29] conducted for 270 days at room temperature that the mean value of the ^{137}Cs excretion rate from silver Prussian carp (*Carassius gibelio)* was 0.0067 day^{-1}. An increase in the body mass of fish was not observed in this experiment. In another aquarium experiment, the temporal decline of ^{137}Cs activity (Bq) in fish was the same for different feed, but the activity concentration of ^{137}Cs (Bq·kg^{-1}) in fish muscle tissue differed up to 1.8 times (0.0089 ± 0.0005 day^{-1} and 0.016 ± 0.002 day^{-1}) due to different mass gains at temperature 22 °C [19].

Recent studies of the ^{137}Cs excretion rates in the silver Prussian carp (*Carassius gibelio)* were performed under natural conditions in the Chornobyl exclusion zone (ChEZ) during 2016 - 2020 [8, 18]. It was found that the weighted average biological half-life of ^{137}Cs in muscle tissue in the summertime at a water temperature of about 19 °C was 75 ± 16 days while in the wintertime at a water temperature lower than 7 °C the value exceeded 230 days [8]. Data collected in experimental studies in the ChEZ showed that the values of the ^{137}Cs biological half-life in silver Prussian carp at a water temperature of 3.7 ± 0.9 °C were in the range of 193 - 495 days but at a water temperature of 22 ± 4 °C, the values varied from 63 to 92 days. Due to an increase in the mass of fish (biodilution) at water temperatures >13 °C, the half-life of the activity concentration of ^{137}Cs in the muscle tissue of fish decreased to 39 - 58 days^{-1} [18]. At the same time, some questions arise about the effect on the excretion rate of the ^{137}Cs from the fishes with a different diet. For example, does the absence of consumption of clean food affect the rate of excretion of ^{137}Cs from the body of freshwater fish?

The main goal of this work was to confirm the ^{137}Cs metabolic parameters in the silver Prussian carp (*Carassius gibelio)*, which were obtained in natural conditions in the ChEZ [8 - 10], under strictly controlled conditions at different daily feeding rates (0 - 1.5 % of fish biomass) in supporting laboratory aquarium experiments.

2. Material and methods

2.1. Objects and methods

Silver Prussian carps (*Carassius gibelio* (Bloch, 1782)) aged (1+) – (2+) years old weighing 16 ± 4 g and 41 ± 7 g were selected as objects of this study. Fish was taken from a floodplain lake in a suburb of Kyiv (N 50.663383°, E 30.722267°) [8 - 10, 16 - 19]. The initial activity concentration of ^{137}Cs in fish was less than 10 Bq·kg^{-1}. The rates of ^{137}Cs uptake and excretion at different temperatures (5 - 26 °C) at daily feeding rates (0 - 1.5 % of fish biomass) were determined in laboratory conditions in aquariums with a volume of 27 - 200 l. The water used in the experiment was similar in chemical composition to Glyboke Lake in the ChEZ: K^+ – 1.4 ± 0.5 mg·l^{-1}; Ca^{++} – 30 ± 1 mg·l^{-1}; ^{88}Sr – 0.11 ± 0.04 mg·l^{-1}; ^{133}Cs – 0.005 ± 0.003 mg·l^{-1} [8 - 10] and was always taken from the same natural floodplain lake (N50.224737°, E30.670096°) near the Dnipro River.

Aquariums of different volumes were used in the experiments: 27-liter aquariums (AF12 and AF13), 7 individuals per one aquarium with an average fish mass of 15 ± 3 g; a 54-liter aquarium (AF14), 7 individuals with an average mass of 17 ± 2 g, maximal daily feeding rate; a 200-liter aquarium (AF15), 5 individuals with an average mass of 41 ± 7 g.

Continuous monitoring and maintaining a constant temperature of water in aquariums was carried out using a temperature controller (DigiTOP TP-1, Ukraine) with a precision of 0.1 °C and immersion 50 - 300 W heaters (AquaEl Platinum, Poland) with a precision of 0.5 °C, as well as thermosmeters and automatic sensors Onset HOBO UA-001-64 Waterproof Pendant 64K Temperature Data Loggers (Onset Computer Corporation, USA).

Aquarium water was constantly filtered by submersible filters (AquaEl Fan Mini Plus, Poland for 27 and 54 l). An external filter (RESUN EF-800, China) was used for the 200-liter aquarium. Filters were cleaned once a week. Air was supplied to the water in the aquariums by compressors and sprayers (Tetra Tetratec APS 50-150 and Tetra AS50, Germany).

Replacement of water in aquariums was carried out every 7 - 30 days after controlling water transparency and chemical composition using a set of tests (Tetra Test 6in1, Germany): acidity (pH), stiffness (KH and GH), nitrite (NO_2^-), nitrates (NO_3^-) and chlorine (Cl_2).

Pelletized feed "Nutra Olympic" (Skretting, Norway) with a granule size of 1.2 mm contained 40 % of protein, and 8 % of fat was used in different daily feeding rates (Table).

The average daily intake of ^{137}Cs in fish (A_d, Bq·d^{-1}), the rate of excretion ($k_b^{'}$ and k_b, day^{-1}) of ^{137}Cs from fish and the biological half-life of the radionuclide from fish tissue/organism ($T_{1/2}^{'} = \ln(2)/k_b^{'}$ and $T_{1/2} = \ln(2)/k_b$) at water temperature 26 ± 1 °C and at different feeding rates (mean ± STD, n = 7)

Aquarium	Daily feeding rate, % of fish biomass	A_d, Bq·d^{-1}	$k_b^{'}$, day^{-1}	$T_{1/2}^{'}$, day	R^2	k_b, day^{-1}	$T_{1/2}$, day	R^2
AF12	0.15	8.5 ± 0.3	0.0061 ± 0.0008	114 ± 15	1.00	0.0073 ± 0.0003	95 ± 4	0.99
AF13	0.5	9.2 ± 0.2	0.0073 ± 0.0004	95 ± 5	0.99	0.0076 ± 0.0003	91 ± 4	0.98
AF14	1.5 - 0.8	7.5 ± 0.3	0.0084 ± 0.0007	83 ± 7	0.95	0.012 ± 0.001	58 ± 5	0.84
AF15	0.5 - 0.4	10.7±0.3	0.0073 ± 0.0004	95 ± 5	0.98	0.0081 ± 0.0005	86 ± 5	0.98

Before the start of all experiments, the fish had been adapted for 2 weeks under similar conditions (size of aquariums, water temperature, and feeding regime) for each planned experiment.

2.2. Investigation of ^{137}Cs uptake

Aquarium experiments with peroral contamination of silver Prussian carp with ^{137}Cs were carried out at different daily feeding rates and fish sizes at a temperature of 26 ± 1 °C for 155 days (see Table, Figs. 1 and 2).

Fish was contaminated by a chronic intake of ^{137}Cs with "Nutra Olympic" feed contained the radionuclide. Feed was previously contaminated with ^{137}Cs as follows. 5 ml of ^{137}CsCl solution with the activity concentration of 1.1 ± 0.1 kBq·ml^{-1} was added to 35 ml of 96 % ethanol. The resulted solution was uniformly added to 20 g of feed (1 : 2 ratio) and dried on a Petri dish in an oven at a temperature of 45 °C with periodic mixing for 3 h. Mean ^{137}Cs activity concentration of dry feed, averaged by results of 14 aliquots measurements, was 270 ± 15 Bq·g^{-1}. A 0.25 g portion of the feed was presented to fish in each aquarium (AF12-AF15) twice a week on Monday and Friday morning for 155 days. In water, in the process of being eaten by fish, ^{137}Cs quite fast washes out of feed pellets. The dynamic of the process was experimentally estimated. It was found that 30 ± 8 % of ^{137}Cs activity was washed out in the water in the first minute. The value increased with

time: 5 min – 65 ± 11 %; 10 min – 90 ± 10 %; 15 min – 100 ± 15 %. Consequently, ^{137}Cs oral intake depends on the time during which a presented feed portion will be consumed. The balance of ^{137}Cs activity was permanently controlled by gamma-spectrometric intravital measurement of fish and water.

An additional portion of 0.25 g of "clean" feed (only 1 g per week or 0.14 g·day^{-1}, which is 0.15 ± 0.02 % of fish biomass) was presented to the AF12 aquarium in the evening after consumption of radioactively contaminated feed (see Table). Total amounts of feed daily presented to aquariums AF13 and AF14 were 0.48 g (0.5 % of fish biomass) and 2.03 g (1.5 % of fish biomass), respectively. The portions take into account 0.25 g of radioactivity contaminated feed, which was fed twice a week. In the AF14 experiment, the feed was presented to the aquarium in equal parts twice per day and the portion was the maximum amount of feed that fish could consume in 30 min. In the AF15 experiment, the daily feeding rate was 1.02 g of feed (0.5 % fish biomass). 30 min after feeding remains of uneaten feed were removed from aquariums.

2.3. Investigation of ^{137}Cs excretion

A study of ^{137}Cs excretion from the fish had been started after the contamination stage for 155 days and has been conducted under the same environmental and feeding conditions for 105 days. Portions of the radioactively contaminated feed were substituted by the same amount of "clean" feed.

2.4. A sampling of water and fish tissues

Activity concentrations of ^{137}Cs in the fish groups (AF12-AF15) were measured in-vivo in 1 l Marinelli vessels approximately every two weeks. At the same time, a water sample of 100 ml was collected from each aquarium for ^{137}Cs activity measurements. The water samples were filtered through 0.45 μm membrane filters and acidified (0.1 % HNO_3) before measurements.

When the experiment was finished fish tissue samples were taken for direct determination of ^{137}Cs activity concentration in each individual. Fish were sacrificed by a blow to the head, mass, and the total body length were measured, followed by dissection of the body and collection of muscle samples. Dissection of the fish was carried out in accordance with the EMERGE sampling protocol [31]. Muscle tissue was collected after removing the skin. Small tissues after homogenization were transferred to 5 or 20 cm^3 plastic tubes for measuring ^{137}Cs activity in samples. All samples were stored cold before being kept in the freezer at –20 °C before analysis. The mass of each fish was determined regularly during measurements until the fish were dissected at the end of each series of experiments with an accuracy of 0.1 g. Fish tissue samples before measurements of radionuclide activity were measured on a balance (KERN pfb) with an accuracy of 0.01 g and AXIS AD200 (Poland) with an accuracy of 0.001 g.

2.5. Measurement of ^{137}Cs activity in samples

Measurements of ^{137}Cs activity in water samples and fish/muscle tissues samples were carried out using low background γ-spectrometric complex with a multi-channel analyzer ASPEC-927 (software GammaVision 32) and a high purity germanium detector GEM-30185 "EG & G ORTEC" (USA) with an energy resolution of 1.78 keV along the ^{60}Co line of 1.33 MeV. The minimum detectable activity of ^{137}Cs was 0.1 Bq. Marinelli vessel (1 l) and plastic vials (5 or 20 cm^3) were used for measurements of ^{137}Cs activity in water and fish tissues, respectively [8, 16, 17, 32].

Whole-body measurements of ^{137}Cs activity in fish groups from each aquarium were carried out in a Marinelli vessel (1 l) containing "clean" water, with a total mass of 1000 g [8, 16, 17, 33]. Measurement of the net count rate of gamma quanta in the photopeak of total absorption at energy 661.6 keV (im/s) was carried out for 600 - 1000 s using a scintillation gamma-ray spectrometer (SEG-05, Ukraine) with NaI(Tl) 63 × 63 mm detector in passive shield (lead 5 cm). The correction coefficient was calculated for numerous in-vivo measurements in the laboratory [16, 17] and as well as in the field experiments [8 - 10].

All results of measuring the activity concentration of radionuclides in fish tissues are given for wet mass (WM).

2.6. Data statistical analysis

A standard set of MS Excel 2016 tools was used for statistical analysis of the experimental data. The significance of the differences between samples was analyzed using the Mann - Whitney test. In the Figures and Table, mean ± STD values are given for 5 or 7 samples (n = 7 for AF12-14 or n = 5 for AF15). Statistical significance was established at the $p < 0.05$ level.

2.7. Mathematical description of uptake and excretion of ^{137}Cs

The changes in the ^{137}Cs activity concentration in the body of fish $C_f(t)$ could be described by the linear differential equation [8, 11]:

$$\frac{dC_f}{dt} = \left(k_f + k_w\right)C_w - \left(k_b + \lambda\right)C_f, \qquad (1)$$

where $C_w(t)$ and $C_f(t)$ are the ^{137}Cs activity concentrations in water and whole-body/muscle tissue (Bq·kg^{-1}), respectively, at time t (days); k_f and k_w are the ^{137}Cs uptake rates in fish by feed and water (day^{-1}); k_b is the ^{137}Cs excretion/decreasing rate (day^{-1}); while the ^{137}Cs biological half-life is equal to $T_{1/2} = \ln(2)/k_b$, day; λ is decay constant $6.3\cdot10^{-5}$ day^{-1} for ^{137}Cs. Whole-body tissue ratios for freshwater fishes are given in the review [34].

Dynamic of ^{137}Cs activity in the body of fish ($A_f(t)$, Bq) can be described by a similar linear differential equation:

$$\frac{dA_f}{dt} = A_d - \left(k_b^{'} + \lambda\right) A_f, \qquad (2)$$

were A_d is the ^{137}Cs daily uptake (Bq·d^{-1}); $k_b^{'}$ is the ^{137}Cs activity excretion rate (day^{-1}). If the mass of fish does not change significantly during experiments $\left(m_f(t) \approx const\right)$, then $k_b^{'} \approx k_b$. In the case of the zero initial condition ($A_f(0) = 0$ and $C_f(0) = 0$) solutions of Eq. 2 can be expressed by Eqs. 3 and 4:

$$A_f(t) = \frac{A_d}{(k_b^{'} + \lambda)}\left(1 - \exp\left(-\left(k_b^{'} + \lambda\right)t\right)\right), \qquad (3)$$

$$C_f(t) = \frac{A_f(t)}{m_f(t)} = \frac{\left(k_f + k_w\right)C_w}{(k_b + \lambda)}\left(1 - \exp\left(-\left(k_b + \lambda\right)t\right)\right). \qquad (4)$$

Consequently, fish-water ^{137}Cs concentration factor (CF) from water to fish for $t >> (k_b + \lambda)^{-1}$ will be equal:

$$CF = \frac{C_f}{C_w} \approx \left(k_f + k_w\right) / \left(k_b + \lambda\right). \qquad (5)$$

Equilibrium fish-feed ^{137}Cs transfer coefficient F_m (Bq·kg^{-1})/(Bq·d^{-1}) for fish with mass m (kg) will be equal [35]:

$$F_m = C_f\left(t >> \left(k_b + \lambda\right)^{-1}\right) / A_d = 1 / \left[\left(k_b + \lambda\right) \cdot m\right]. \qquad (6)$$

When radioactively contaminated fish is transferred into an aquarium with "clean" water ($C_w = 0$) the ^{137}Cs uptake rates with "clean" feed and from the water will be equal to 0 ($k_f = 0$ and $k_w = 0$). The solution of Eq. (1) for ^{137}Cs initial activity concentration $C_f(0)$ (Bq·kg^{-1}) can be expressed by an exponential decline function:

$$C_f(t) = C_f(0) \cdot \exp\left(-\left(k_b + \lambda\right)t\right),$$

$$C_f(t) / C_f(0) = \exp\left(-\left(k_b + \lambda\right)t\right). \qquad (7)$$

In the case of a change in fish mass over time, the solution of Eq. (2) for ^{137}Cs initial activity concentration $C_f(0)$ (Bq·kg^{-1}) and initial mass $m_f(t)$ can be expressed by a function (Eq. 8):

$$A_f(t) / A_f(0) = C_f(t) \cdot m_f(t) / \left(C_f(0) \cdot m_f(0)\right) = \exp\left(-\left(k_b^{'} + \lambda\right)t\right). \qquad (8)$$

Eqs. 3, 4 and 7, 8 were used to determine the excretion rates ($k_b^{'}$ and k_b, day^{-1}) of ^{137}Cs from whole-body/muscle tissue of fish at water temperatures 26 ± 1 °C and different feeding rates (0.15, 0.5 and 0.7 % of fish biomass) (see Table). In this case, the biological half-life of the radionuclide in fish tissue or whole organism was $T_{1/2} = \ln(2)/k_b$, and the effective half-life was $\ln(2)/(k_b + \lambda)$.

3. Results and discussion

Statistically significant changes in acidity (pH), stiffness (KH and GH), and chemical composition of water in the aquariums were not observed during the experiments ($p > 0.05$). Concentrations of major elements in water were characterized by the following values: Na – 11 ± 3 mg·l^{-1}, Mg – 7 ± 1 mg·l^{-1}, K – 2 ± 1 mg·l^{-1}, and Ca – 34 ± 2 mg·l^{-1}. The content of nitrites (NO_2^-), nitrates (NO_3^-), and chlorine (Cl_2) in water did not exceed permissible levels.

The values of the arithmetic average of fish masses in AF12 and AF13 experiments (Fig. 1) with different daily feeding rates did not differ significantly ($p > 0.05$). The daily feeding rate of 0.5 % of fish biomass (14 g) in AF13 experiment was insufficient for fish growth. The weight of the fish in AF12 experiment with a daily feeding rate of 0.15 % of fish biomass (14 g) tended to decrease and the species of the fish by the end of the experiment was anorexic. The statistically significant increases in fish mass were observed in the AF14 ($p < 0.001$) and AF15 ($p < 0.001$) experiments. Average fish growth rates were 0.08 g·day^{-1} ($R^2 = 0.94$) and 0.04 g·day^{-1} ($R^2 = 0.95$) in AF14 and AF15 experiments, respectively. The daily feeding rate of 0.5 % of fish biomass 14 g in AF13 and 40 g in AF15 experiments was the same, but weight gains of smaller fishes were not observed. One may assume it is due to the different metabolic rates of different size fish. Different initial sizes of fish and daily feeding rates applied in the experiment resulted in different fish growth.

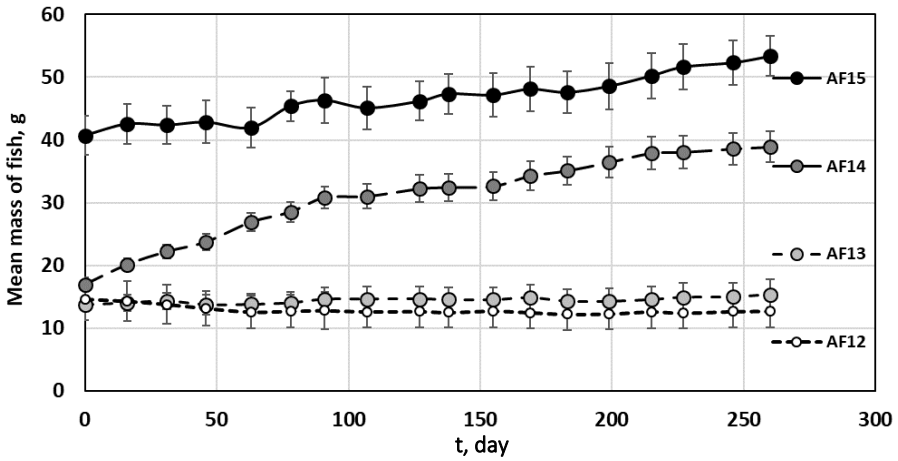
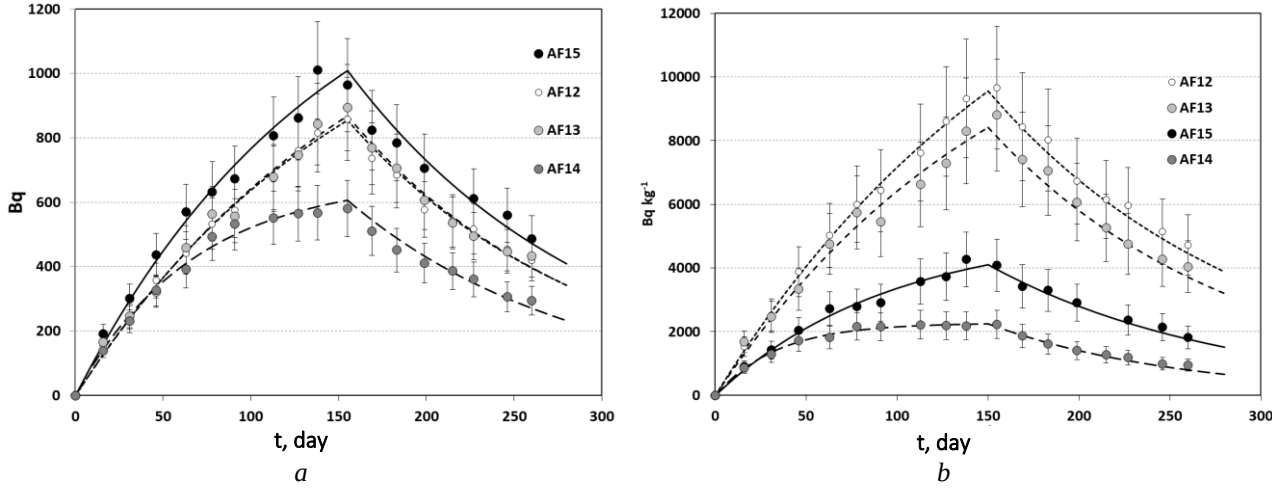


Fig. 1. Dynamics of the average mass of fish during experiments AF12-AF15.

Because the oral way of ^{137}Cs uptake into fish is predominant, before experiments AF12-AF15 to study the rate of excretion (k_b, day^{-1}) of radionuclide from fish preliminary contamination of fish was carried out using specially prepared feed (Sec. 2.2). It was shown that ^{137}Cs was rather quickly washed out in the water from the prepared feed during its consumption by fish (Sec. 2.2) and to assess the losses dynamics of activity concentration of the radionuclide in aquarium water and in fish were measured. The results showed that about 60 % of ^{137}Cs activity was washed out of the contaminated feed at a water temperature of 26 ± 1 °C. Consequently, the oral uptake of ^{137}Cs activity can be estimated on average as 40 ± 5 % of its initial value or A_d = 8 ± 2 Bq·kg^{-1}.

Obtained on the basis of growth dynamics of ^{137}Cs activity in silver Prussian carp in experiments AF12-AF15 the daily uptake of ^{137}Cs in fish (Eq. 4) was in the range of 7.5 - 10.7 Bq·kg^{-1} (see Table), which is consistent with the above experimental estimates. In experiments AF14 and AF15, there was an increase in fish mass due to feeding uptake (see Fig. 1), which led to the biological dilution of ^{137}Cs. The dilution resulted in a smaller increase in the ^{137}Cs activity concentration in fish in these experiments compared to experiments AF12 and AF13, where the mass of the fish decreased slightly or remained constant due to the smaller amount of feed consumed (Fig. 2, *b*).



a *b*

Fig. 2. Dynamics of ^{137}Cs activity (*a*) and ^{137}Cs activity concentration (*b*) in fish due to oral contamination (t = 0 - 155 day) and following excretion of radiocaesium with clean feeding (t = 155 - 260 day). Lines are the best fit of experimental data on dynamics of ^{137}Cs content in fish by Eqs. 3, 8 (*a*), and 4, 7 (*b*).

The least-squares method was used to estimate values of the ^{137}Cs excretion rates from fish ($k_b^{'}$ and k_b, day^{-1}). The values were found as the best fit of experimental data (see Fig. 2) on dynamics of ^{137}Cs content in fish by Eqs. 3, 4, and 7, 8. The rate of ^{137}Cs activity excretion from fish at the temperature of 26 °C did not depend on the mass of the fish and their feeding regime $k_b^{'}$ = 0.006 - 0.008 day^{-1} ($T_{1/2}$ = = 83 - 114 day). Wherein, the rate of ^{137}Cs activity concentration excretion/decreasing (k_b = 0.012 ± ± 0.001 day^{-1}; $T_{1/2}$ = 58 ± 5 days) in the experiment with maximal feeding and fish growth rates (AF14)

was almost 2 times as high as that in other experiments (k_b = 0.007 - 0.008 day^{-1}; $T_{1/2}$ = 86 - 95 days) due to biodilution (see Table). The results agree with other experiments performed at a temperature of 22 °C [16]. Authors found that biological dilution can reduce the biological half-life of the ^{137}Cs activity concentration in fish by up to 2 times.

The rate of ^{137}Cs excretion from fish ($k_b > 7.3 \times 10^{-3}$ day^{-1}) was higher than decay constants of ^{137}Cs ($\lambda = 6.3 \cdot 10^{-5}$ day^{-1}) and ^{134}Cs ($\lambda = 9.2 \cdot 10^{-4}$ day^{-1}).

Values of the ^{137}Cs excretion rate (see Table) from the silver Prussian carp (*Carassius gibelio*) are in line with the recent observations by Kaglyan et al. [29] (k_b = 0.0067 day^{-1}).

4. Conclusions

The ^{137}Cs activity biological half-life in the fish at the water temperature of 26 °C decreased from $T_{1/2}^{'}$ = 114 ± 15 days ($k_b^{'}$ = 0.0061 ± 0.0008 day^{-1}) to $T_{1/2}^{'}$ = 83 ± 7 days ($k_b^{'}$ = 0.0084 ± 0.0007 day^{-1}) with an increase in the amount of food from 0.15 to 1.5 % of the fish mass. The biological half-life of the ^{137}Cs activity concentration in muscle tissue decreased faster with an increase in the amount of food from $T_{1/2}$ = 95 ± 14 days (k_b = 0.0073 ± 0.0003 day^{-1}) to $T_{1/2}$ = 58 ± 5 days (k_b = 0.012 ± 0.001 day^{-1}) due to the biological dilution.

The biological half-life of ^{137}Cs activity concentration in fish can be reduced by 2 times by increasing fish growth using clean feeding.

Values of the ^{137}Cs excretion rate ($k_b^{'}$ and k_b, day^{-1}) from fish and the biological half-life of the radionuclide in the fish tissue/organism agree with data previously obtained in natural conditions in the ChEZ [8, 17].

This work was supported by the National University of Life and Environmental Sciences of Ukraine, the Ministry of Education and Science of Ukraine (Project No. 110/1-pr-2022), and the Norwegian Center for International Cooperation in Education (SiU) «Joint Ukrainian-Norwegian education programme in Environmental Radioactivity» NMBU, Norway (CPEA-2015/10108).

REFERENCES

1. *Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience*. Report of the Chernobyl Forum Expert Group 'Environment' (Vienna: IAEA, 2006). 180 p.
2. *Environmental Protection - the Concept and Use of Reference Animals and Plants*. ICRP Publication 108. Ann. ICRP 38(4-6) (ICRP, 2008).
3. D. Gudkov et al. Dynamics of the Content and Distribution of the Main Dose Forming Radionuclides in Fishes of the Exclusion Zone of the Chornobyl NPS. Hydrobiological Journal 44(5) (2008) 87.
4. Yu. Khomutinin, V. Kashparov, A. Kuzmenko. Dependence of ^{137}Cs and ^{90}Sr uptake rates by fish on potassium and calcium in a freshwater reservoir. Radiation Biology. Radioecology 51(3) (2011) 374. (Rus)
5. A. Kaglyan et al. Radionuclides in native fish species of the Chornobyl exclusion zone. Yaderna Fizyka ta Energetyka (Nucl. Phys. At. Energy) 13(3) (2012) 306. (Rus)
6. M. Balonov et al. Harmonization of standards for permissible radionuclide activity concentrations in foodstuffs in the long term after the Chornobyl accident. Journal of Radiological Protection 38 (2018) 854.
7. T. Wada et al. Strong contrast of caesium radioactivity between marine and freshwater fish in Fukushima. Journal of Environmental Radioactivity 204 (2019) 132.
8. H.-C. Teien et al. Seasonal changes in uptake and depuration of ^{137}Cs and ^{90}Sr in silver Prussian carp (*Carassius gibelio*) and common rudd (*Scardinius erythrophthalmus*). Science of the Total Environment 786 (2021) 147280.
9. P. Pavlenko et al. Effect of additional "clean" feeding on ^{90}Sr and ^{137}Cs content in Prussian carp (*Carassius gibelio*) in the Chornobyl exclusion zone. Yaderna Fizyka ta Energetyka (Nucl. Phys. At. Energy) 22(3) (2021) 272. (Ukr)
10. O. Kashparova et al. Clean feed as countermeasure to reduce the ^{137}Cs and ^{90}Sr levels in fish from contaminated lakes. Journal of Environmental Radioactivity (2022). (Submitted).
11. J.T. Smith. Modelling the dispersion of radionuclides following short duration releases to rivers Part 2. Uptake by fish. Science of the Total Environment 368 (2006) 502.
12. J.E. Pinder et al. Caesium accumulation by fish following acute input to lakes: a comparison of experimental and Chornobyl-impacted systems. Journal of Environmental Radioactivity 100 (2009) 4560.
13. N.A. Beresford et al. A new approach to predicting environmental transfer of radionuclides to wildlife: A demonstration for freshwater fish and caesium. Science of the Total Environment 463-464 (2013) 284.
14. M.E. Haque et al. Developing a food web-based transfer factor of radiocaesium for fish, whitespotted char (*Salvelinus leucomaenis*) in headwater streams. Journal of Environmental Radioactivity 172 (2017) 191.
15. M. Metian, S. Pouil, S.W. Fowler. Radiocesium accumulation in aquatic organisms: A global synthesis from an experimentalist's perspective. Journal of Environmental Radioactivity 198 (2019) 147.
16. O.V. Kashparova et al. Dynamics of the ^{137}Cs excretion from Prussian carp (*Carassius gibelio*) at different water temperatures. Yaderna Fizyka ta Energetyka (Nucl. Phys. At. Energy) 20(4) (2019) 411. (Rus)

17. O.V. Kashparova et al. Dynamics of ^{137}Cs uptake from water to Prussian carp (*Carassius gibelio*). Yaderna Fizyka ta Energetyka (Nucl. Phys. At. Energy) 21(1) (2020) 64. (Rus)
18. O. Kashparova et al. The excretion of ^{137}Cs from silver Prussian carp (*Carassius gibelio*) with different water temperature under nature conditions in the Chornobyl exclusion zone. Sci. Reports of the Nat. Univ. of Life and Environ. Sci. of Ukraine 6(88) (2020) 1. (Ukr)
19. O. Kashparova et al. Excretion of ^{137}Cs from silver Prussian carp (*Carassius gibelio*) at 5 °C water temperature. Sci. Reports of the Nat. Univ. of Life and Environ. Sci. of Ukraine 4(86) (2020) 1.
20. J.T. Smith et al. The "Aquascope" simplified model for predicting ^{89,90}Sr, ^{131}I, and ^{134,137}Cs in surface waters after a large-scale radioactive fallout. Health Physics 89(6) (2005) 628.
21. J.T. Smith et al. Uptake and elimination of radiocaesium in fish and the "size effect." Journal of Environmental Radioactivity 62 (2002) 145.
22. J.T. Smith et al. A review and test of predictive models for the bioaccumulation of radiostrontium in fish. Journal of Environmental Radioactivity 100 (2009) 950.
23. J. Garnier-Laplace, E. Vray, J.P. Baudin. A dynamic model for radionuclide transfer from water to freshwater fish. Water, Air, and Soil Pollution 98 (1997) 141.
24. O. Ugedal et al. Effects of temperature and body size on radiocaesium excretion in brown trout, *Salmo trutta*. Freshwater Biology 28(2) (1992) 165.
25. T. Forseth et al. Radiocaesium elimination in fish: variation among and within species. Journal of Applied Ecology 35 (1998) 847.
26. O.I. Nasvit, N.I. Buyanov, M.I. Kuzmenko. Determination of kinetic parameters of the process of uptake of radionuclides by ecosystem components from the equilibrium values of the hydrobiology concentration factors. Hydrobiological Journal 26(1) (1990). (Rus)
27. A.I. Kryshev. Modelling the accumulation of ^{137}Cs by age-structured fish population. Radioprotection - Colloques 37(C1) (2002) 627.
28. M. Sundbom et al. Long-term dynamics of Chornobyl ^{137}Cs in freshwater fish: quantifying the effect of body size and trophic level. Journal of Applied Ecology 40 (2003) 228.
29. O.E. Kaglyan et al. Method of cleaning silver carp (*Carassius gibelio* Bloch) from ^{137}Cs radionuclide to hygienic radiation-safe levels. Patent UA No. 132603. Published on Sept. 25, 2018, bull. No. 18/2018. (Ukr)
30. K. Niizeki et al. Estimating biological half-lives of ^{137}Cs in a cyprinid fish Tribolodon hakonensis by a one-compartment model considering growth dilution effect. Fisheries Science 86 (2020) 861.
31. B. Rosseland et al. Fish Ecotoxicology. The EMERGE Fish Sampling Manual for Live Fish (European mountain lake ecosystems: regionalisation, diagnostic & socio-economic evaluation, 2001) 7 p.
32. Standard Practice for High-Resolution Gamma-Ray Spectrometry of Water. ASTM D3649-06 (American Society for Testing and Materials, 2014) 8 p.
33. T. Cresswell et al. Aquatic live animal radiotracing studies for ecotoxicological applications: Addressing fundamental methodological deficiencies. Journal of Environmental Radioactivity 178-179 (2017) 453.
34. T.L. Yankovich et al. Whole-body to tissue concentration ratios for use in biota dose assessments for animals. Radiation and Environmental Biophysics 49 (2010) 549.
35. *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments.* Technical Reports Series No. 472 (Vienna: IAEA, 2010). 194 p.

О. В. Кашпарова[1,2,*], С. Є. Левчук[1], Ю. В. Хомутінін[2], П. М. Павленко[2], М. О. Гречанюк[2], В. О. Кашпаров[1,2]

[1] Український науково-дослідний інститут сільськогосподарської радіології Національного університету біоресурсів і природокористування України, Київ, Україна
[2] Центр радіоактивності навколишнього середовища Норвезького університету природничих наук, Ос, Норвегія

*Відповідальний автор: elena.kashparova@gmail.com

ШВИДКІСТЬ НАДХОДЖЕННЯ ТА ВИВЕДЕННЯ ^{137}Cs З ОРГАНІЗМУ КАРАСЯ СРІБЛЯСТОГО (*CARASSIUS GIBELIO*) ЗА РІЗНОЇ ГОДІВЛІ

Протягом 2016 - 2021 рр. було проведено серію експериментів з вивчення швидкості надходження та виведення ^{137}Cs з організму карася сріблястого (*Carassius gibelio*) в природних умовах Чорнобильської зони відчуження (ЧЗВ). Для підтвердження отриманих параметрів надходження та виведення^{137}Cs з організму карася сріблястого було проведено лабораторні експерименти у строго контрольованих умовах за різних режимів годівлі. Швидкість виведення ^{137}Cs з карася сріблястого зростає зі збільшенням споживання додаткового штучного корму з 0.0068 ± 0.0003 доба$^{-1}$ до 0.0085 ± 0.0005 доба$^{-1}$ за температури води 26 °C. Завдяки збільшенню швидкості росту риб з використанням додаткового штучного «чистого» корму через біологічне розбавлення, біологічний період напіввиведення питомої активності ^{137}Cs з риби може бути зменшений у 2 рази. Швидкість виведення ^{137}Cs з карася сріблястого за різної температури води збігається з результатами отриманими в природних умовах ЧЗВ протягом 2016 - 2020 рр.

Ключові слова: ^{137}Cs, Чорнобиль, прісноводна риба, забруднення радіонуклідами, швидкість виведення, коефіцієнт накопичення.

Надійшла/Received 22.02.2022