

Skeletal ^{90}Sr as a Marker of Migration Activity of Murine Rodents in the Zone of the Eastern Ural Radioactive Trace

V. I. Starichenko, N. M. Lyubashevskiy, M. V. Modorov, and M. V. Chibiryak

*Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences,
ul. Vos'mogo Marta 202, Yekaterinburg, 620144 Russia
e-mail: starichenko@ipae.uran.ru*

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Abstract—Analysis and generalization of long-term monitoring data on the accumulation of ^{90}Sr in the bone tissue of rodents inhabiting the East-Ural Radioactive Trace and the adjacent control area have shown that the skeletal content of ^{90}Sr depends on the level of radionuclide contamination of soil in animal habitats. An assessment of animal migration between contaminated and clean areas by this criterion has shown that the proportion of migrants does not exceed 10%. On this basis, the conclusion is drawn concerning relative isolation of rodent populations in the EURT zone.

Keywords: East-Ural Radioactive Trace (EURT), ^{90}Sr , bone tissue, rodents, migration

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Migration, or spatial dispersal of individuals is one of the basic characteristics of small mammal populations that is also a mechanism providing for their sustainable existence (Shvarts, 1969; Bol'shakov, 1972; Lidiker, 1985; Bol'shakov and Bazhenov, 1988; Luk'yanov and Luk'yanova, 2002). It is an accepted fact that the main function of migrants involves occupation of new areas and regulation of population spatial structure and density, whereas resident animals are responsible for reproduction and stabilization of population numbers. Analysis of specific features in the migration activity of small mammals in radioactively contaminated areas (the EURT, Chernobyl, Totsk, etc.) is of special significance in relation to the problem of their adaptation to radiation exposure (Raushebakh and Monastyrskii, 1966; Dubinin et al., 1972; Sokolov and Il'enko, 1980; Il'enko and Krapivko, 1989; Lyubashevskiy et al., 1995; Lyubashevskiy et al., 2002; Grigorkina et al., 2008; Meeks et al., 2009; Lyubashevskiy and Starichenko, 2010; Modorov and Pozolotina, 2011). The prevalence of resident animals over migrants in radioactively contaminated areas is a necessary condition for the acquisition and maintenance of hereditary radioadaptation, which develops in a series of generations exposed to chronic irradiation.

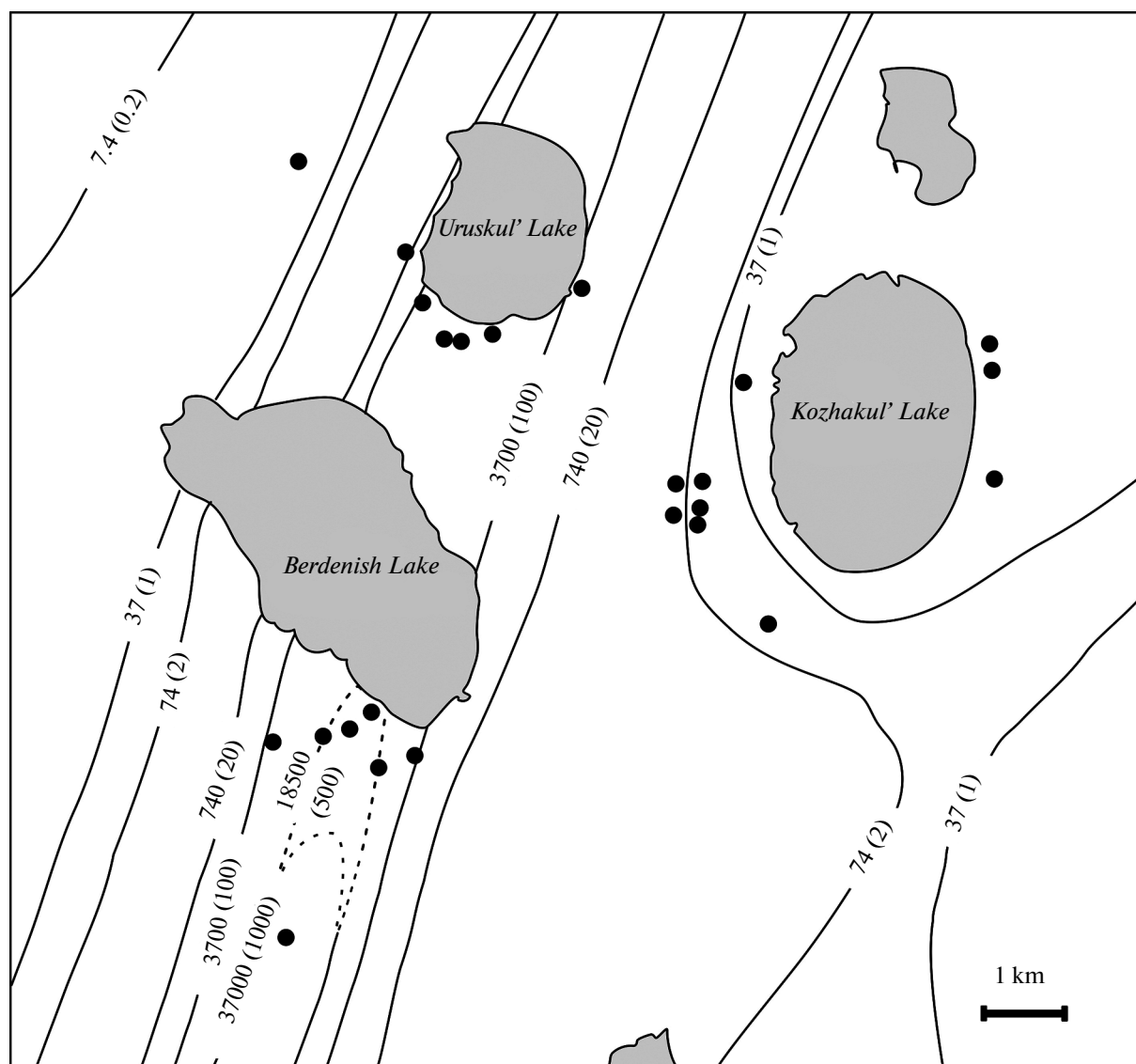
Although the assessment of migration processes in natural small mammal populations is obviously a difficult task, it is facilitated in radioactively contaminated areas due to the presence of emitters (radionuclides), which serve as natural markers entering animal bodies via food chains. In particular, ^{90}Sr is such a lifelong marker, since it is accumulated and retained in the skeleton for a long time. Significant deviations in

the pattern of ^{90}Sr accumulation in some individuals, compared to that in the majority of animals inhabiting a given region, indicate that these individuals are migrants. In other words, the level of radionuclide accumulation may be used as a criterion for determining the proportions of migrant and resident animals, which are the main parameter of population mobility (Luk'yanov and Luk'yanova, 2002). This approach has been tested by many authors (Il'enko, 1978; Il'enko and Krapivko, 1989; Lyubashevskiy et al., 2002; Starichenko, 2002, 2004; Lyubashevskiy and Starichenko, 2010). It belongs to the category of indirect methods commonly employed in research on the relationship between the resident and nonresident components of small mammal populations; direct methods are used less frequently (for review, see Bol'shakov and Bazhenov, 1988).

The purpose of this study was to generalize the results of long-term studies on ^{90}Sr accumulation in the bone tissue of different rodent species from the EURT zone and control areas in order to indirectly evaluate their migration activity.

MATERIAL AND METHODS

Analysis of ^{90}Sr specific radioactivity was performed in the bone tissue of small mammals trapped in different years within the EURT zone in areas with ^{90}Sr contamination densities of 18.5 and 37 MBq/m² (500 and 1000 Ci/km²) in the epicenter and 74–3700 kBq/m² (2–100 Ci/km²) at the periphery and also in control areas with a contamination density of 7.4–74 kBq/m² (0.2–2 Ci/km²) located 0.5–4 km



Scheme of the study region and locations of small mammal capture sites in the EURT zone and the adjacent control area, scale 1 : 100 000 (Klimova et al., 2007), with modifications shown in dashed lines (Izuchenie..., 2005). Isolines of initial ^{90}Sr contamination density are in kBq/m^2 (Ci/km^2), $1 \text{ kBq}/\text{m}^2 = 2.7 \times 10^{-2} \text{ Ci}/\text{km}^2$.

from the EURT boundary (figure). Areas located beyond the EURT zone (in the vicinity of Kamensk-Uralsky, Orenburg oblast, and the Botanical Garden of the Institute of Plant and Animal Ecology, Yekaterinburg) were also used as control.

The species composition of small mammals was as follows: the common vole (*Microtus arvalis* s.l. Pall., 1778), narrow-skulled vole (*Microtus gregalis* Pall., 1779), root vole (*Microtus oeconomus* Pall., 1776), field vole (*Microtus agrestis* L., 1761), northern red-backed vole (*Clethrionomys rutilus* Pall., 1779), northern water vole (*Arvicola terrestris* L., 1758), pygmy wood mouse (*Sylvaemus uralensis* Pall., 1811), and striped field mouse (*Apodemus agrarius* Pall., 1771). On the whole, the bone tissue from 1583 rodents was

analyzed, including 1042 from the EURT zone, 378 ind. from the neighboring “clean” area, and 45 ind. from other control areas; in addition, 109 ind. from the EURT and neighboring area were trapped for special purposes and sacrificed after being kept in the vivarium and fed uncontaminated food for a period of 2 weeks to 1 year.

Today, the main dose-forming radionuclides in the EURT zone are β -emitters ^{90}Sr and its daughter ^{90}Y and β - γ -emitter ^{137}Cs , with its specific radioactivity in the soil being two orders of magnitude lower than that of $^{90}\text{Sr} + ^{90}\text{Y}$. In the animal body, 90–95% of $^{90}\text{Sr} + ^{90}\text{Y}$ is deposited in the bone tissue, and the amount of β -radioactivity in the skeleton can therefore be equated to the content of these radionuclides in it. For

Table 1. Statistical parameters of ⁹⁰Sr accumulation (Bq/g) in the bone tissue of rodents from the EURT zone and the adjacent control area

Soil ⁹⁰ Sr contamination density		<i>n</i>	<i>M</i> (min–max)	<i>SD</i>	<i>m</i>	Per 10	Quar 1	Med	Quar 3	Per 90
EURT	37 MBq/m ² (1000 Ci/km ²)	12	1454 (417–2839)	793	229	556	891	1287	2084	2528
	18.5 MBq/m ² (500 Ci/km ²)	561	169 (0.2–1198)	148	6	51	80	127	205	331
	Periphery 74–3700 kBq/m ² (2–100 Ci/km ²)	469	44 (0.2–853)	58	3	0.2	9	32	58	111
	Total area: 74 kBq/m ² –37 MBq/m ² (2–1000 Ci/km ²)	1042	127 (0.2–2839)	210	7	6	31	78	144	269
Control	7.4–74 kBq/m ² (0.2–2 Ci/km ²)	387	2.2 (0.2–249)	15	0.7	0.2	0.2	0.2	0.9	2.3
		Without ⁹⁰ Sr specific radioactivity of ≥4 Bq/g, <i>n</i> = 27)	0.5 (0.2–3.4)	0.6	0.03	0.2	0.2	0.2	0.6	1.4

Designations: *M*, arithmetic mean; min–max, range of values; *SD*, standard deviation; *m*, standard error; Med, median; Per, percentile (10th and 90th); Quar 1 and Quar 3, the first and third quartiles, respectively.

brevity, the radioactivity of ⁹⁰Sr + ⁹⁰Y is referred to below as ⁹⁰Sr radioactivity.

Radiometric analysis was performed using an RFT 10 MHz-Zähler VAG-120 instrument. To calculate specific ⁹⁰Sr radioactivity of the samples (Bq/g fresh bone weight), the instrument was calibrated relative to a series of potassium reference standards (Starichenko and Lyubashevskiy, 1998).

In each population sample, the average specific ⁹⁰Sr radioactivity was taken as 100%, and individual animals were classified as migrants if the radioactivity of their skeleton differed from this value by an order of magnitude (<10% or >1000%). This “order-of-magnitude” criterion is based on the results of statistical analysis of whether or not an animal belongs to a given population and is similar to that used in the study by Il’enko (1978).

It is known that the frequency distribution of specific ⁹⁰Sr radioactivity values in animals from the natural environment is usually lognormal (Starichenko and Lyubashevskiy, 1998; Tarasov, 2000; Chesser et al., 2000). However, parameters of an asymmetric data distribution (the median, quartiles, and percentiles) fail to take into account the greater part of information and have no algebraic expression. Therefore, in addition to these parameters, we calculated the mean, standard deviation, and standard error to characterize the entire data set and the mean with standard error for

intraspecific characteristics (migrants were excluded from averaging).

The data were processed statistically using licensed program packages Microsoft Excel 2002 and Statistica 6.0 (StatSoft Inc.).

RESULTS AND DISCUSSION

Table 1 shows statistical parameters of skeletal ⁹⁰Sr accumulation in pooled heterospecific samples of rodents trapped over many years in different zones of the EURT and in the neighboring control area. It can be seen that the average level of ⁹⁰Sr accumulation has a distinct tendency to decrease in the direction from the EURT epicenter to the periphery (from 1454 to 169 and to 44 Bq/g). This is in good agreement with current views on correlation between ⁹⁰Sr deposition in the skeleton and the level of soil radioactive contamination (Il’enko, 1968; Tarasov, 2000; Chesser et al., 2000) and indicates that the rodent population is actually resident. The above correlation has been revealed even in highly mobile animals such as hares in zones contaminated after nuclear tests in Nevada (Neel and Larson, 1968). It has been noted that a dynamic equilibrium between the level of environmental ⁹⁰Sr and its intake into the body is established within 20 days after the start of radioactive fallout.

However, although the correlation between the ⁹⁰Sr levels in the skeleton and soil is clearly manifested in

statistical comparisons of animal groups, this does not exclude wide variation in the level of radionuclide deposition in the animal body. Some of these features can be explained without addressing the phenomenon of migration.

Even in laboratory experiments with pure-line mice, individual differences in the kinetics of ^{90}Sr and stable fluorine within even-aged animal groups may be as great as two- to eightfold (Starichenko, 2010). The range of this variation in the natural environment is markedly wider. For example, Panteleev et al. (1970) concluded that, with a probability of 10^{-3} to 10^{-6} , the skeletal ^{90}Sr content in some people may exceed the population average level by a factor of 6–15.

Specific ^{90}Sr radioactivity in rodents from the control area near the EURT averages 2.2 ± 0.7 Bq/g. Its values recorded in animals from control areas beyond the EURT are as follows: in the vicinity of Kamensk-Uralsky, 0.4 ± 0.02 Bq/g ($0.3\text{--}0.6$ Bq/g) (*A. agrarius*, $n = 15$; *M. gregalis*, $n = 8$); in Orenburg oblast, 0.3 ± 0.1 Bq/g ($0.2\text{--}0.6$ Bq/g) (*M. arvalis*, $n = 8$); in the botanical garden (Yekaterinburg), 0.5 ± 0.1 Bq/g ($0.2\text{--}1.7$ Bq/g) (*S. uralensis*, $n = 11$; *A. agrarius*, $n = 3$). Although the southern and western surroundings of Kamensk-Uralsky are within the EURT boundaries, including the zone with a soil contamination density (by ^{90}Sr) of 2 Ci/km² or higher, radiometric measurements of bone tissue in rodents from this area do not exceed background values. The level of ^{90}Sr accumulation in northern mole voles (*Ellobius talpinus* Pall., 1779) from Kunashak raion of Chelyabinsk oblast is similar, 0.2 ± 0.05 Bq/g ($0.1\text{--}0.7$ Bq/g) (Starichenko, 2011). Thus, it may be assumed that the background level of ^{90}Sr accumulation in the bone tissue of rodents is within a range of $0.2\text{--}0.5$ Bq/g, averaging 0.4 Bq/g. If we exclude from analysis obvious migrants from the contaminated territory (with a specific skeletal ^{90}Sr radioactivity of $10\text{--}20$ Bq/g or higher) and potential migrants (according to the order-of-magnitude criterion, with a radioactivity ten times higher than 0.4 Bq/g, i.e., ≥ 4 Bq/g; $n = 27$), then the specific skeletal ^{90}Sr radioactivity in the control groups decreases to 0.5 ± 0.03 Bq/g, which does not differ from the background levels. Animals with a specific skeletal ^{90}Sr radioactivity of less than 4 Bq/g (10% of 44 Bq/g) were classified as migrants from the control area to the EURT periphery.

Table 2 shows radiometric data on individual species trapped in different years (migrants were excluded from averaging). The absence of sex-related differences in ^{90}Sr among conspecific animals allowed us to pool the data on males and females into a single sample. Published data also show that sex-related differences in the pattern of accumulation and metabolism of most bone-seeking radionuclides are relatively small (for review, see Starichenko et al., 1993; Makyuk et al., 2006). Exceptions concern the breeding period (Il'enko, 1967; Il'enko and Krapivko, 1989),

when changes take place in female mineral metabolism, and the period of rapid growth, when the skeleton is formed: the rate and amount of radionuclide deposition—removal in this period differ between males and females because of sexual dimorphism in body (skeleton) size.

Specific ^{90}Sr radioactivity in the bone tissue of rodents from the EURT head part is two to four orders of magnitude higher than in the control. In some cases, there are conspicuous interspecific differences in radionuclide accumulation and individual variation in its specific radioactivity among conspecific animals. Differences in radionuclide accumulation between conspecific animals trapped in different years may be due to changes in climatic conditions between these years, as has been repeatedly noted in the literature (Il'enko and Krapivko, 1989). However, the question concerning their causes has not yet been resolved unequivocally. Another probable factor that may be responsible for these differences is an uneven age composition of the sample. Age-depending differences in ^{90}Sr accumulation are related primarily to seasonal changes in the animal diet (Il'enko, 1968). Seasonal variations of specific ^{90}Sr radioactivity in animals of different species inhabiting the same area usually have comparable patterns (Chesser et al., 2000; Baryakhtar et al., 2003).

In addition to the aforementioned factors, interspecific differences in ^{90}Sr accumulation may be explained by variation in the radionuclide content of the animal diet, which, in turn, depends on the pattern of soil contamination. Closely related small rodent species that live in the same area but eat different kinds of food differ from each other in the level of ^{90}Sr accumulation (Il'enko, 1968; Il'enko and Krapivko, 1989).

Bats are a good example illustrating the dependence of ^{90}Sr accumulation on animal diet and mobility (Starichenko, 2004). For example, among bats living in clean areas (namely, in human buildings on the shore of Akakul' Lake), specific skeletal ^{90}Sr radioactivity in the northern bat (*Eptesicus nilssonii*) was only 185 ± 84 Bq/g ($n = 13$), whereas that in the pond bat (*Myotis dasycneme*) reached 3197 ± 694 Bq/g ($n = 23$). To explain such a significant difference ($p < 0.01$), Tarasov (2000) formulated the hypothesis of trophic contamination, which was confirmed by Smagin et al. (2000). Although these bat species inhabit clean areas, both of them forage at radioactively contaminated lakes and ponds located at distances of several tens of kilometers. However, pond bats hunt over the water surface, mainly on insects developing in lakes (in particular, in bottom sediments of technological ponds on PO Mayak Radiochemical Plant), whereas northern bats forage over land and can supplement their diet with uncontaminated insects. Specific skeletal ^{90}Sr radioactivity in bats from Kamenskii raion does not exceed the background level.

Table 2. Specific ⁹⁰Sr radioactivity (Bq/g, $M \pm m$) in the bone tissue of small mammals from the EURT zone and the adjacent control area

Species	Soil ⁹⁰ Sr contamination density			
	EURT epicenter		EURT periphery	control
	37 MBq/m ² (1000 Ci/km ²)	18.5 MBq/m ² (500 Ci/km ²)	74–3700 kBq/m ² (2–100 Ci/km ²)	7.4–74 kBq/m ² (0.2–2 Ci/km ²)
Common vole (<i>Microtus arvalis</i>)	1910 ± 263 ($n = 7$) ⁰¹ (1055–2839)	335 ± 79 ($n = 7$) ⁹² (114–599) 82 ± 7 ($n = 5$) ^{92/21} (64–104)	–	0.5 ± 0.1 ($n = 20$) ⁹² (0.3–1.6) 12 ($n = 1$) ⁹² 0.3 ± 0.01 ($n = 10$) ^{92/21} (0.3–0.4)
		392 ± 101 ($n = 6$) ⁹⁴ (152–724)	–	0.3 ± 0.02 ($n = 37$) ⁹⁴ (0.2–0.6)
		532 ± 124 ($n = 5$) ⁰¹ (64–795) 28 ($n = 1$) ^{01/100}	8, 12, 262 ($n = 3$) ⁰¹	0.6 ± 0.2 ($n = 12$) ⁰¹ (0.2–1.6) 0.2 ($n = 1$) ^{01/100}
		823 ($n = 1$) ⁰³	–	0.2, 0.2, 0.6, 6 ($n = 4$) ⁰³
		901 ($n = 1$) ⁰⁴		0.7 ± 0.2 ($n = 16$) ⁰⁴ (0.2–2.9) 6, 100 ($n = 2$) ⁰⁴
		250 ± 57 ($n = 4$) ⁰⁵ (99–358)	0.2 ($n = 1$) ⁰⁵	–
		412 ($n = 1$) ⁰⁹	37, 48 ($n = 2$) ⁰⁹	–
Root vole (<i>Microtus oeconomus</i>)	–	216 ± 12 ($n = 72$) ⁰¹ (21–600) 170 ± 37 ($n = 9$) ^{01/100} (44–318)	45, 155, 853 ($n = 3$) ⁰¹	0.2, 0.3, 0.5 ($n = 3$) ⁰¹ 168 ($n = 1$) ^{01/100}
	–	206 ± 38 ($n = 5$) ⁰² (137–348) 152 ± 24 ($n = 9$) ^{02/40} (61–234)	3, 4 ($n = 2$) ⁰²	–
	–	125 ± 14 ($n = 24$) ⁰³ (51–323)	3, 4 ($n = 2$) ⁰³	0.2, 0.2, 1.0, 249 ($n = 4$) ⁰³
	–	216 ± 17 ($n = 24$) ⁰⁴ (69–394)	106 ± 38 ($n = 4$) ⁰⁴ (47–213)	0.2 ± 0.0 ($n = 5$) ⁰⁴ (0.2–0.2)
	–	100, 124 ($n = 2$) ⁰⁵	0.2, 0.2 ($n = 2$) ⁰⁵	–
	–	231 ± 28 ($n = 4$) ⁰⁹ (172–307)	42 ± 5 ($n = 6$) ⁰⁹ (26–62)	–
	–	124 ± 38 ($n = 4$) ¹⁰ (35–219)	59 ± 4 ($n = 82$) ¹⁰ (10–141)	–
Narrow-skulled vole (<i>Microtus gregalis</i>)	–	537 ± 52 ($n = 19$) ⁹² (244–1198) 103 ± 18 ($n = 8$) ^{92/21} (31–174)	–	0.5, 0.5 ($n = 2$) ⁹²
	–	–	–	0.9 ($n = 1$) ⁰¹
	–	297, 326, 580 ($n = 3$) ⁰⁵	–	0.7 ± 0.3 ($n = 8$) ⁰⁵ (0.2–2.3) 14 ± 5.3 ($n = 4$) ⁰⁵ (4.7–25)
	–	–	8 ($n = 1$) ⁰⁹	–
	–	–	60 ± 5 ($n = 43$) ¹⁰ (17–127)	–

Table 2. (Contd.)

Species	Soil ⁹⁰ Sr contamination density			
	EURT epicenter		EURT periphery	control
	37 MBq/m ² (1000 Ci/km ²)	18.5 MBq/m ² (500 Ci/km ²)	74–3700 kBq/m ² (2–100 Ci/km ²)	7.4–74 kBq/m ² (0.2–2 Ci/km ²)
Field vole (<i>Microtus agrestis</i>)	1167 (n = 1) ⁰¹	218 (n = 1) ^{01/100}	61, 97 (n = 2) ⁰¹	–
		–	162 (n = 1) ⁰³	0.3 (n = 1) ⁰³
		–	–	0.2, 0.2, 1.0 (n = 3) ⁰⁴
		69 (n = 1) ⁰⁵	37, 47, 294 (n = 3) ⁰⁵	–
		–	76, 81 (n = 2) ⁰⁹	–
Voles (<i>Microtus</i>)*	–	375 ± 105 (n = 5) ⁰¹ (118–639)	–	–
Northern water vole (<i>Arvicola terrestris</i>)	1208 (n = 1) ⁰¹	22 (n = 1) ⁰¹	3, 4, 9 (n = 3) ⁰²	0.5, 1.0 (n = 2) ⁰¹
		210 ± 34 (n = 4) ⁰² (153–296)		
		422 (n = 1) ⁰³		
		20 (n = 1) ⁰⁹		
Northern red-backed vole (<i>Clethrionomys rutilus</i>)	417 (n = 1) ⁰⁸	126, 268, 470 (n = 3) ⁰¹	–	0.6 (n = 1) ⁰¹
		8, 342 (n = 2) ⁰³		0.4 ± 0.1 (n = 15) ⁰² (0.2–1.2)
		–		0.7 ± 0.2 (n = 26) ⁰³ (0.2–2.7) 6 (n = 1) ⁰³
		–	51, 95, 103 (n = 3) ⁰⁴	0.8 ± 0.2 (n = 10) ⁰⁴ (0.2–2.4) 6 (n = 1) ⁰⁴
		88, 105 (n = 2) ⁰⁵	55, 56, 60 (n = 3) ⁰⁵ 0.2, 0.2 (n = 2) ⁰⁵	0.2 ± 0.0 (n = 6) ⁰⁵ (0.2–0.2) 95 (n = 1) ⁰⁵
		105, 175 (n = 2) ⁰⁹	101 ± 24 (n = 8) ⁰⁹ (27–197)	–
Striped field mouse (<i>Apodemus agrarius</i>)	–	54 (n = 1) ⁰¹	0.2, 10 (n = 2) ⁰¹	0.5 ± 0.1 (n = 14) ⁰¹ (0.2–1.6)
		123, 136, 330 (n = 3) ⁰²	8, 8, 51, (n = 3) ⁰² 2.0 ± 0.2 (n = 11) ⁰² (1.3–3.2)	1.4 ± 0.3 (n = 7) ⁰² (0.2–2.5)
		108 ± 43 (n = 8) ⁰³ (6–299) 0.2, 1.5, 1.8 (n = 3) ⁰³	0.2, 7, 10 (n = 3) ⁰³	0.6 ± 0.1 (n = 29) ⁰³ (0.2–3.4) 0.2, 0.2, 0.6 (n = 3) ^{03/180}
		175 ± 38 (n = 10) ⁰⁴ (68–490)	–	0.2 ± 0.0 (n = 4) ⁰⁴ (0.2–0.2)
		112 ± 5 (n = 133) ⁰⁵ (19–285) 4 (n = 1) ⁰⁵	30 ± 7 (n = 49) ⁰⁵ (5–226) 0.4 ± 0.1 (n = 44) ⁰⁵ (0.2–4.3)	0.4 ± 0.1 (n = 20) ⁰⁵ (0.2–3.0) 6.0 ± 0.3 (n = 4) ⁰⁵ (5.0–6.4)
		6 (n = 1) ⁰⁹	10 ± 2 (n = 4) ⁰⁹ (6–15) 3, 3, (n = 2) ⁰⁹	–

Table 2. (Contd.)

Species	Soil ⁹⁰ Sr contamination density			
	EURT epicenter		EURT periphery	control
	37 MBq/m ² (1000 Ci/km ²)	18.5 MBq/m ² (500 Ci/km ²)	74–3700 kBq/m ² (2–100 Ci/km ²)	7.4–74 kBq/m ² (0.2–2 Ci/km ²)
Pygmy wood mouse (<i>Sylvaemus uralensis</i>)	556, 728 (n = 2) ⁰⁸	176 ± 58 (n = 12) ^{99/15} (42–772)	–	0.9 ± 0.1 (n = 11) ^{99/15} (0.7–1.5)
		161 ± 29 (n = 26) ⁰¹ (45–627)	33 ± 17 (n = 6) ⁰¹ (6–118)	0.7 ± 0.1 (n = 10) ⁰¹ (0.2–1.5)
		59 ± 10 (n = 12) ^{01/365} (22–117)		0.4 ± 0.1 (n = 7) ^{01/365} (0.2–1.0)
		103 ± 17 (n = 11) ⁰² (24–217)	7, 17, 24 (n = 3) ⁰²	0.7 ± 0.1 (n = 17) ⁰² (0.2–2.3)
		60 ± 6 (n = 9) ^{02/28} (37–95)		6 (n = 1) ⁰² 0.6 ± 0.2 (n = 10) ^{02/28} (0.2–2.4)
		79 ± 12 (n = 24) ⁰³ (17–208)	41 ± 32 (n = 4) ⁰³ (6–136)	0.6 ± 0.1 (n = 28) ⁰³ (0.2–1.9)
		129 ± 14 (n = 43) ⁰⁴ (6–465)	72 ± 16 (n = 6) ⁰⁴ (35–116)	0.6 ± 0.2 (n = 21) ⁰⁴ (0.2–2.3)
		117 ± 7 (n = 84) ⁰⁵ (16–372)	35 ± 8 (n = 28) ⁰⁵ (5–194) 0.4 ± 0.2 (n = 18)⁰⁵ (0.2–3.6)	0.4 ± 0.1 (n = 36) ⁰⁵ (0.2–2.8) ⁰⁵ 11 ± 4 (n = 10)⁰⁵ (4.5–50) ⁰⁵
66 ± 11 (n = 9) ⁰⁹ (11–139)	48 ± 3 (n = 87) ⁰⁹ (10–197)			
	–	70 ± 10 (n = 21) ¹⁰ (5–147)	–	

Superscript indices show the year of capture/captive period, days; figures in bold italic refer to migrants (bone ⁹⁰Sr radioactivity ≤4 Bq/g in EURT and ≥4 Bq/g in control), excluded from calculations of mean values; (*) voles of the genus *Microtus* without species identification.

Another relevant example concerns increased ⁹⁰Sr accumulation in the bodies of narrow-skulled voles, compared to common voles from the same area, as found by analyzing the radionuclide contents of the digestive tract with chyme (Starichenko and Lyubashevskiy, 1998). Taking into account the wide variation range of radioactivity concentrations in plant samples (grasses, fungi, and meadow herbage)—2600–45000 Bq/kg dry weight for ¹³⁷Cs and 9000–260000 Bq/kg for total β-radioactivity—it may be justly assumed that the observed differences in radionuclide accumulation are indeed explained by differences in the animal diet.

It should be noted that variation in specific skeletal ⁹⁰Sr radioactivity is the lowest at a ⁹⁰Sr contamination density of 37 MBq/m² (CV = 55% at the lowest sample size) but increases at contamination densities of 18.5 MBq/m² and 74–3700 kBq/m² (CV 88 and 132%, respectively). Increased variation in radionu-

clide accumulation level in areas with lower densities of radioactive contamination has also been observed by other authors (Il'enko, 1968). The variation coefficient for the entire EURT zone is 165%, while that for the control area (⁹⁰Sr contamination density 7.4 kBq/m²) is 682%, decreasing to 163% when migrants are excluded from analysis.

The occurrence of individuals with increased skeletal ⁹⁰Sr radioactivity among control (uncontaminated) animals may have several explanations. In particular, it may be that (a) they are migrants from the radioactive area, with the bulk of radionuclide having been removed from their bodies as a result of feeding on uncontaminated foods; (b) they are the offspring of contaminated mothers that moved to the clean area before giving birth to them; however, this appears unlikely, taking into account that when the natural diet of pregnant females is replaced by a standard vivarium

diet, the level of ^{90}Sr in the first litter already becomes so low that it cannot be detected by radiometric methods (Il'enko and Krapivko, 1989; our own unpublished data); (c) the home range of a rodent is in a “hot spot” with locally increased contamination density, and therefore specific ^{90}Sr radioactivity in its skeleton is higher than in its neighbors; finally, (d) it cannot be excluded that uncontaminated animals make short-term stays in the neighboring radioactive area.

Differences in ^{90}Sr accumulation among rodents trapped in the radioactive area are more difficult to interpret. Assuming that animals with a specific skeletal ^{90}Sr radioactivity of ≤ 4 Bq/g or lower are migrants from the control area to the EURT periphery and those with a higher skeletal radioactivity are migrants from the EURT to the control area (see above), we obtain that the proportion of migrants in the EURT periphery is more than 10% but less than 25% (Per 10 = 0.2 Bq/g, Quar 25 = 9 Bq/g). Analysis of lower percentiles in the Per 10–Quar 25 range shows that this proportion **at the EURT periphery** decreases to 10–20%. In the control area, migrants account for less than 10% of the total sample (27 out of 387 ind.).

It should be noted that a major contribution to the estimated level of migration at the EURT periphery is made by the sample of animals trapped in 2005, when their abundance reached a peak (Grigorkina et al., 2008). If the 2005 sample is excluded from analysis, the estimated proportion of migrants in this area drops to the control level (<10%). This is expectable, since the level of migration sharply increases at a peak of abundance (Luk'yanov and Luk'yanova, 2002).

Since migration flows pass through the EURT periphery, the level of ^{90}Sr accumulation in animals in this area (≤ 4 Bq/g) may be taken as the reference point **for the entire EURT zone**. In such a case, we obtain that the proportion of migrants is less than 10% (Per 10 = 6 Bq/g). Migrations within the EURT (from the periphery to the center and vice versa) are less intensive: for example, we have found only four animals with a specific skeletal ^{90}Sr radioactivity of ≤ 4 Bq/g in the zone with a contamination density of 18.5–37 MBq/m², and one animal with a radioactivity of ≥ 440 Bq/g in the zone contaminated to 74–3700 kBq/m². This is additional evidence for a decreased mobility of animals exposed to radiation.

These results agree with published data. According to Il'enko (1978), for example, the average proportion of migrants in the contaminated and control areas (determined by the same radionuclide method) were as follows: 6.5–9.0% in forest and field mice, about 2% in root voles, 14.3% in narrow-skulled voles, and 17.4% in northern red-backed voles. In another study (Il'enko and Krapivko, 1989), the proportion of migrant rodents in the same region was estimated in a range of 4–18%.

Of basic interest are the results of comparing these estimates with those made in nonradioactive areas.

According to publications that provide quantitative characteristics of migration depending on population types and the degree of habitat inoptimality (Nikitina, 1970; Mukhacheva and Luk'yanov, 1997; Luk'yanov and Luk'yanova, 2002), the proportion of migrants in the undisturbed zone ranges from 0 to 25%.

Our estimates are also in line with interesting observations by Chesser et al. (2000) in the Chernobyl zone, which these authors do not discuss from the standpoint of migration. They note that there are microgroups of rodents sharply differing in the amount of accumulated radionuclides that inhabit contaminated sites arranged in a mosaic pattern at distances of no more than 100 m from each other, which is evidence for low mobility of these animals. In other words, migration activity of rodents is also reduced in the Chernobyl zone, where the pattern of radioactive contamination is completely different from that in the EURT.

Evidence that resident animals prevail in small mammal communities of radioactively contaminated areas also comes from the fact that they form stable combinations of phenotypic characters (phenetic complexes) that differentiate them from control animals (Vasil'ev et al., 2003; Vasil'ev, 2005). For example, the shape of the mandible in the impact samples of pygmy wood mice from technogenic areas differ from that in control mice at a statistically significant level (Bol'shakov et al., 2012). Such morphological characters are formed in a series of generations.

The opposite view on rodent migration in the EURT zone, i.e., that this process is markedly enhanced, compared to that in the control area (the authors designate this by the term “flowing population”), is based on the results obtained using chromosome aberrations as a marker (Grigorkina et al., 2009). Individuals without such a marker may indeed be migrants from the clean area (this could have been determined from the level of ^{90}Sr accumulation). However, a decrease in chromosome aberration frequency may well be a consequence of radioadaptation, as follows from the study by Nizhnik et al. (1978). Among animals living in a radioactive environment, individuals that have no cytogenetic disturbances are by heredity best adapted to radiation exposure. An illustrative example are northern mole voles, rodents with a subterranean mode of life (Gileva, 2002).

Naturally, the question arises as to whether the long-term (though incomplete) functional apartness of adapted populations may not lead to their genetic isolation. In the context of the synthetic theory of evolution (STE), the answer is obvious: genetic isolation is inevitable. However, studies by Meeks et al. (2009) and Modorov and Pozolotina (2011) performed in the Chernobyl zone (on bank voles) and in the EURT (on pygmy wood mice) using different markers (mtDNA and allozyme variation) have revealed no differences in the frequencies of haplotypes or allozyme alleles

between inhabitants of radioactive and control areas. This is evidence for the absence of their genetic isolation, contrary to the views on genetic radioadaptation developed over the past 50 years (Raushenbakh and Monastyrskii, 1966; Dubinin et al., 1972; Sokolov and Il'enko, 1980; Il'enko and Krapivko, 1989; Lyubashevskiy et al., 1995; Glazko et al., 2008; Lyubashevskiy and Starichenko, 2010). At the same time, these results do not contradict but even indirectly support the epigenetic nature of radioadaptation. The epigenetic character of shifts in rodent populations of radiation biogeocenoses has been revealed (Vasil'ev et al., 2003; Vasil'ev, 2005). The results of our studies (Lyubashevskiy et al., 2009; Lyubashevskiy and Starichenko, 2010) show that both ⁹⁰Sr metabolism at the organismal level and radioadaptation of rodents at the population level are highly probable to be epigenetic processes. Apparently, different rodent genotypes available prior to the accidents have transformed in an adaptive direction, and the EURT and Chernobyl zones are currently populated by their descendants. This is why these rodents do not differ genetically from their neighbors inhabiting clean areas, taking into account that both of them belonged to the same populations before the accidents. Such an interpretation eliminates contradictions incompatible with the STE and is in line with current epigenetic concepts (Vasil'ev, 2005; Jablonka, 2012).

Table 2 also includes data on rodents that were kept after capture in the vivarium and fed uncontaminated food for a long period of time (2 weeks to 1 year). It should be noted that specific skeletal ⁹⁰Sr radioactivity in all the animals from the EURT zone was no less than 20 Bq/g. With regard to these data, migration is estimated at a still lower level.

Thus, the results of long-term monitoring of ⁹⁰Sr accumulation in the bone tissue of small mammals provide evidence for significant intraspecific variation in this parameter. A considerable amount of material has been analyzed to estimate the level of rodent migration (regardless of species-specific features) in the EURT zone and neighboring control area. As follows from statistical parameters of ⁹⁰Sr accumulation, the approximate proportion of migrants is no more than 10% in the EURT zone and less than 10% in the control area. On this basis, the conclusion is drawn concerning relative isolation of rodent populations in the EURT zone.

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