ISSN 1067-4136, Russian Journal of Ecology, 2011, Vol. 42, No. 1, pp. 64–70.

Accumulation of ^{90}Sr in the Bone Tissue of Northern Mole Voles in the Head Portion of the East Ural Radioactive Trace

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Received January 14, 2010

Abstract—The accumulation of ^{90}Sr in the bone tissue of northern mole voles (*Ellobius talpinus* Pallas, 1770) living under chronic exposure to ^{90}Sr in the center of the Eastern Ural Radioactive Trace (EURT) with a ^{90}Sr contamination density of 37 MBq/m^2 or 1000 Ci/km^2 has been evaluated. Northern mole voles live underground and are characterized by family organization of populations and an extremely weak tendency toward dispersal. While there are no sex- or age-related differences in ^{90}Sr accumulation, sevenfold interindividual differences have been found. Hereditary (familial) determination of the variability of ^{90}Sr accumulation has been demonstrated. The probable causes of the difference in the familial component from the results of laboratory experiments on inbred mice are considered. The age-related inversion of ^{90}Sr accumulation previously found in other mammalian species in the EURT area has been confirmed. A possible mechanism of its formation is suggested.

Keywords: northern mole vole, Eastern Ural Radioactive Trace (EURT), ^{90}Sr, bone tissue, family analysis, intrafamilial correlation coefficient.

DOI: 10.1134/S1067413611010115

The northern mole vole (*Ellobius talpinus* Pallas, 1770) is a specialized vole species characterized by predominantly underground life and a complex population structure. Although many studies have dealt with the ecology of the northern mole vole, the radioecology of this species has not been studied sufficiently. For example, there are no experimental data on the kinetics of osteotropic radionuclides (such as ^{90}Sr, one of the most common dose-forming radionuclides in the Ural region) in the skeleton of northern mole voles; the characteristics of their accumulation in voles living in radioactively contaminated areas as dependent on the endogenous parameters of the animals also remain unknown. Stable family groups, which are characteristic of the northern mole vole (and of very few species of aboveground rodents) and a low migration activity provide a unique possibility for evaluating the hereditary (familial) component of the variation of ^{90}Sr accumulation in animals living in the natural environment (Glotov, 1983). Experimental studies using the method of interstrain comparison (Shvedov and Akleev, 2001) did not confirm hereditary determination of the ^{90}Sr metabolism. On the other hand, there is evidence (Shagina et al., 2006) that, in humans living in the EURT under chronic exposure to ^{90}Sr, the variance of its body content within individual families is smaller than the mean variance in a settlement.

The purpose of this study was to analyze the pattern of ^{90}Sr accumulation in the bone tissue of northern mole voles living in the head portion of the EURT as dependent on their sex, age, and family.

MATERIALS AND METHODS

Northern mole voles live in underground burrows and dig complex systems of galleries with a total area of as much as several hectares. They mainly travel underground and very rarely appear on the surface. The distance daily traveled by a northern mole vole may be as long as 200–280 m (Khlyap et al., 1980). Northern mole voles feed on underground organs and green parts of plants as well as on worms, and insects.

Colonies of these rodents consist of relatively isolated families living in a limited area for many generations. Usually, one female (the "dam") and one or two males participate in reproduction in each family. Young females do not began reproduction until the "dam" dies (youngs of the year never take part in reproduction). Females produce four litters a year, a litter consisting of two to four newborns. Seasonal dispersal of young animals results in the formation of new (young) families (mainly at the periphery of the colony), which also may "bud off" from old ones. After the third winter, the voles that remain in families lead sedentary life. The northern mole vole is considered a long-lived rodent; its maximum life span is six years (Evdokimov, 2001; Shevlyuk and Elina, 2008).

The accumulation of ^{90}Sr (the summary β activity of $^{90}Sr + ^{90}Y$) was measured in the bone tissue of northern mole voles living in a ~300 × 500 m grassy clearing in the head portion of the EURT, where the ^{90}Sr contamination density was 37 MBq/m^2 (1000 Ci/km^2). The control group consisted of northern mole voles captured in an area with a contamination density of 7.4 MBq/m^2 (0.2 Ci/km^2) (the Aminevo village, Kunashak raion, Chelyabinsk oblast). We determined to which family each animal captured in the EURT belonged; this was not made in the control group. A total of 60 EURT voles from eight families and 34 control voles were studied.

The ^{90}Sr and ^{137}Cs (a mixed β and γ emitter) isotopes are the main artificial contaminants in the EURT. Both radionuclides accumulate in the bodies of animals living there. However, radiochemical analysis of tissue samples from animals living in the EURT showed that $^{90}Sr + ^{90}Y$ accounted for 90–95% of the β activity of their skeletons (Betenekov et al., 1996). A study on the radionuclide accumulation in rodents and large mammals from the EURT yielded similar results: the specific activity of ^{137}Cs in their skeletons was two to three orders of magnitude lower than that of ^{90}Sr, and the ^{137}Cs content of the skeletons varied from several tenths of a percent to several percent (Tarasov, 2000). In humans living near the EURT, this ratio is about the same (Degteva et al., 1998). This gives us grounds to consider the β activity of the skeleton to be equivalent to its $^{90}Sr + ^{90}Y$ content.

In contrast, the total β activity of soft tissues, chyme, and vegetation is determined by both $^{90}Sr + ^{90}Y$ and ^{137}Cs. Therefore, when comparing the radionuclide accumulation in the skeleton and other tissues, we will speak of β activity for the sake of unification.

The accumulation of ^{90}Sr was estimated in long tubular bones. Radiometry was performed by means of an RFT 10 MHz–Zahler VAG-120 device with the use of potassium reference samples (Starichenko and Lyubashevskii, 1998). Samples for analysis of soil contamination in the area of EURT inhabited by northern mole voles were taken from the soil that the animals threw onto the ground surface when digging their burrows. ^{90}Sr was radiochemically assayed by daughter ^{90}Y with the use of the oxalate method (*Metodicheskie rekomendatsii* ..., 1980).

The method of statistical analysis of the data was selected after the distribution type was determined. The data were described using the arithmetic mean, standard error of the mean, median, and quartiles. The significance of differences between samples was estimated using Student's *t* test. The differences were considered significant if the confidence probability was no lower than 95% ($p \leq 0.05$).

To estimate the degree of hereditary (familial) determination of the variability of quantitative parameters, we used a component model of ANOVA, namely a *hierarchical* pattern with mixed effects where the *sex* and *age* factors were taken to be fixed and the *family* factor, random.

The distribution of the body weight of northern mole voles is close to a normal one, and that of the specific activity of ^{90}Sr is log-normal. Therefore, we used logarithmic transformation of the specific activity of ^{90}Sr to meet the condition of a normal distribution. For simplicity, however, we use below the expression "specific activity of ^{90}Sr" to mean both the specific activity itself and its logarithm. We analyzed the variation of the body weight and the specific activity of ^{90}Sr in bone tissue.

To obtain the F statistics in the mixed model of ANOVA, we used synthesis of the denominator (Sheffe, 1963; Sokal and Rohlf, 1995). The *intraclass correlation coefficient* (*R*) calculated as the ratio of the variance component for the corresponding random factor to the total variance (Sokal and Rohlf, 1995) (the *variance component* is equal to $R \times 100\%$) served as an estimate of the hereditary determination of the traits studied.

Data were analyzed using the Microsoft Excel 2002 and Statistica 6.0 (StatSoft) software.

RESULTS AND DISCUSSION

The specific activity of ^{90}Sr in the bone tissue of northern mole voles from the control area was low (0.2 ± 0.05 Bq/g wet tissue) and corresponded to the background ^{90}Sr content of mammalian skeletons in "pure" areas. In the contaminated are, it was 765 ± 54 Bq/g (varying from 225 to 1652 Bq/g in individual animals) (Table 1). This level of accumulation of the radionuclide is comparable to that in other small mammals living in areas with a contamination density of 18.5–37.0 MBq/m^2 (500–1000 Ci/km^2) that were captured during the same season (Starichenko, 2002, 2004). The individual variation of the specific activity of ^{90}Sr in northern mole voles ($CV = 54\%$, max/min = 7.3) was comparable with that in aboveground rodents, e.g., common voles, from the center of the EURT ($CV = 50\%$, max/min = 5.3) (Starichenko and Lyubashevskii, 1998).

In this connection, considerable differences between families with respect to ^{90}Sr accumulation are noteworthy (Table 1, Fig. 1). The variation within families was substantially smaller than in the sample as a whole(CV = 5–32%, max/min = 1.2–2.3). A proportion of the difference between families could be attributed to sex- or age-related characteristics of ^{90}Sr accumulation making different contributions to the resultant value for each particular family. However, most families, as well as the sample as a whole, exhibited no effect of the sex on ^{90}Sr accumulation. The absence of the sex effect on the accumulation of osteotropic radionuclides has been shown in many studies (Bazhenov et al., 1990; Zhuravlev, 1990; Momeni et al.,

Table 1. Accumulation of ^{90}Sr in the bone tissue of northern mole voles living in the head portion of the EURT (analysis in individual families)

Family no.	n	Body weight, g			Specific ^{90}Sr radioactivity, Bq/g		
		Males	Females	Mean	Males	Females	Mean
1	12 (7/5)*	36.9 ± 1.6 (32.0–42.6)	39.4 ± 1.2 (36.6–43.0)	37.9 ± 1.1 (32.0–43.0)	298 ± 35 (225–503)	317 ± 51 (252–517)	306 ± 29 (225–517)
2	11 (6/5)	43.1 ± 1.0 (40.0–46.0)	45.8 ± 1.0 (42.8–48.6)	44.3 ± 0.8 (40.0–48.6)	580 ± 20 (487–623)	599 ± 19 (539–645)	589 ± 13 (487–645)
3	11 (4/7)	49.2 ± 1.8 (46.9–54.3)	44.5 ± 2.2 (34.2–48.9)	46.2 ± 1.6 (34.2–54.3)	445 ± 52** (388–601)	653 ± 49 (510–900)	577 ± 47 (388–900)
4	5 (2/3)	38.3 ± 7.6 (30.7–45.9)	43.0 ± 1.7 (39.6–45.0)	41.1 ± 2.8 (30.7–45.9)	957 ± 37** (920–994)	765 ± 30 (716–820)	842 ± 51 (716–994)
5	5 (1/4)	37.0	44.4 ± 2.0 (39.7–48.8)	42.9 ± 2.1 (37.0–48.8)	1249	1238 ± 38 (1140–1323)	1240 ± 29 (1140–1323)
6	6 (4/2)	48.1 ± 2.3 (44.4–53.6)	48.8 ± 0.0 (48.8–48.8)	48.3 ± 1.4 (44.4–53.6)	1390 ± 64** (1207–1482)	1590 ± 22 (1567–1612)	1457 ± 59 (1207–1612)
7	6 (4/2)	47.0 ± 3.5 (38.0–53.4)	49.2 ± 1.8 (47.4–50.9)	47.7 ± 2.3 (38.0–53.4)	1370 ± 107 (1152–1652)	1265 ± 34 (1231–1299)	1335 ± 72 (1152–1652)
8	4 (2/2)	47.7 ± 0.8 (46.8–48.5)	45.0 ± 9.3 (35.7–54.2)	46.3 ± 3.9 (35.7–54.2)	508 ± 39 (469–547)	599 ± 141 (458–740)	554 ± 65 (458–740)
Sample mean	60 (30/30)	43.4 ± 1.2 (30.7–54.3)	44.3 ± 0.9 (34.2–54.2)	43.9 ± 0.7 (30.7–54.3)	752 ± 82 (225–1652)	777 ± 70 (234–1612)	765 ± 54 (225–1652)

Notes: * Numerator, males; denominator, females.
** Significant differences between males and females ($p \leq 0.05$, Student's t test).

Table 2. Accumulation of ^{90}Sr in the bone tissue of northern mole voles of different ages living in the head portion of the EURT (analysis in individual families)

Family no.	Body weight, g					Specific ^{90}Sr radioactivity, Bq/g				
	Age, months									
	2–4	14–16	26–28	38–40	50–52	2–4	14–16	26–28	38–40	50–52
1 (9/2/1/0/0)*	37.2 ± 1.3	39.5 ± 1.1	41.0	–	–	298 ± 27	236 ± 11	517	–	–
2 (9/1/1/0/0)	44.6 ± 0.8	46.0	40.0	–	–	597 ± 10	487	623	–	–
3 (6/1/2/1/1)	45.9 ± 2.4	47.0	46.7 ± 7.6	48.4	43.5	627 ± 26	395	454 ± 56	388	900
4 (4/1/0/0/0)	41.5 ± 3.6	39.6	–	–	–	847 ± 66	820	–	–	–
5 (3/2/0/0/0)	42.9 ± 3.4	42.9 ± 3.1	–	–	–	1269 ± 27	1197 ± 58	–	–	–
6 (4/1/0/1/0)	49.2 ± 1.9	44.4	–	48.8	–	1411 ± 77	1482	–	1612	–
7 (4/2/0/0/0)	49.4 ± 1.8	44.5 ± 6.4	–	–	–	1360 ± 111	1285 ± 13	–	–	–
8 (2/2/0/0/0)	45.0 ± 9.3	47.7 ± 0.8	–	–	–	599 ± 141	508 ± 39	–	–	–

* The ratio between the numbers of animals of different ages.

1976; Parks et al., 1978). Some researchers (Il'enko and Krapivko, 1989) have reported that sex-related differences in ^{90}Sr accumulation occur in the reproduction and lactation periods because of changes in mineral metabolism in females. Another exception is the period of rapid growth, when the bone mass forms. Males and females differ from each other in the radionuclide accumulation/excretion rate and its amount in this period because of the sexual dimorphism in the skeleton (body) size (Tolstykh et al., 2001).

Nor did estimation of age-related differences in ^{90}Sr accumulation showed a significant increase in the radionuclide accumulation with age either in individual families or in the entire sample (Table 2), in contrast to experiments on chronic intake of the radionuclide (beginning from early postnatal ontogeny), when the specific activity of ^{90}Sr is higher in adult than in young animals because of its longer accumulation (*Metabolizm strontsiya*, 1971; *Ot radiobiologicheskogo eksperimenta ...*, 1976). The absence of this difference

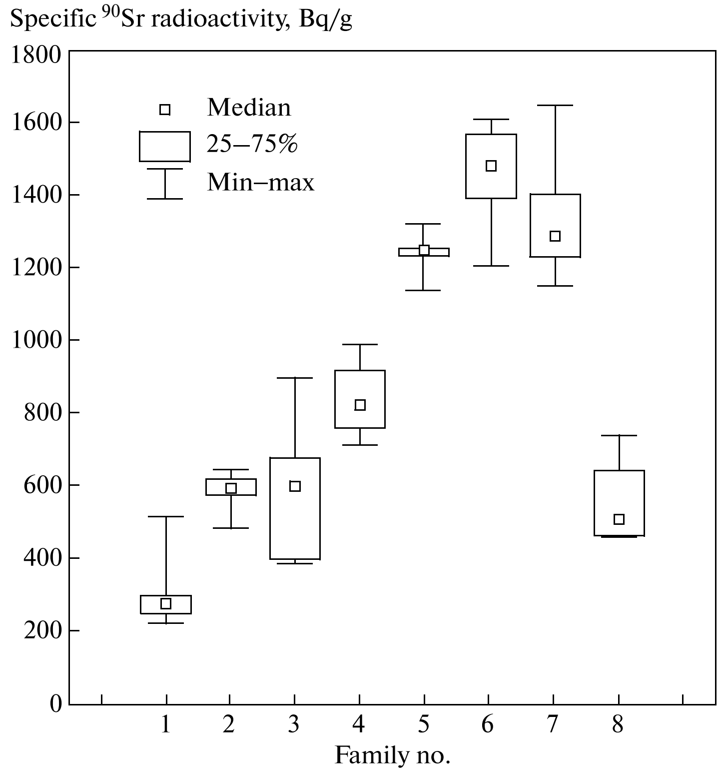

Fig. 1. Specific ^{90}Sr radioactivity in the bone tissue of northern mole voles living in the center of the EURT.

in northern mole voles confirms the age-related inversion of ^{90}Sr accumulation that was earlier found in other mammals in the EURT, when the specific activity of ^{90}Sr in the skeletons of some young animals was considerably higher than in those of old animals (Tarasov, 2000).

Since the mechanism of ^{90}Sr accumulation in the skeleton of vertebrates does not depend on the route or rhythm of the radionuclide intake, it is conceivable that the level of ^{90}Sr accumulation under natural conditions is modified by both exogenous and endogenous factors. Exogenous factors may include some dietary characteristics of young voles as compared to adult ones. However, the physiological age of the bone tissue of some young voles may be younger than the chronological age (i.e., bones are undercalcified) for a number of reasons; in this case, ^{90}Sr may more rapidly accumulated in the skeleton of these animals owing to the effect of the mineral density of bones (Starichenko, 2007).

Table 3 shows the results of multiway ANOVA of the sex, age, and family of northern mole voles on the ^{90}Sr accumulation in the skeleton. As evident from these data, the contributions of the sex and age to the specific activity of ^{90}Sr is insignificant, which agrees with the data shown in Tables 1 and 2. The effects of these factors on the body weight are also insignificant, which is not unexpected. It is known that the body weight is weakly correlated with the sex and age in northern mole voles of the age groups studied (Evdokimov, 2001).

Conversely, the effect of the *family* factor was strong and significant ($p < 0.001$). This factor determines the body weight and ^{90}Sr accumulation level by 32.5 and 91.9%, respectively. The degree of hereditary variation of the weight parameters agrees with data reported by other authors (Mina and Klevezal', 1976; Falconer, 1960; etc.) who, having studied the hereditary variation of the body weight and size in animals and humans, concluded that, although its estimates widely varied, it was as high as 50% or even higher in some cases, the differences between different taxa of vertebrates being small.

The substantially higher "familial" component of ^{90}Sr accumulation may be determined not only by family specificity of the radionuclide metabolism (e.g., different dietary preferences in different families), but also by the spatial heterogeneity of soil contamination (which was not taken into account) and, hence, a wide variation of the radionuclide content of plants.

The relationship between the contamination of the soil and plant covers, dietary characteristics, and the degree of radionuclide accumulation in living organisms is well known (Il'enko and Krapivko, 1993; Tolstykh, 2006). For example, we earlier demonstrated that the specific β radioactivity of plants growing in the EURT area with a ^{90}Sr contamination density of

Table 3. Intrafamilial correlation coefficient of the body weight and specific activity of ^{90}Sr in the bone tissue of northern mole voles living in the head portion of the EURT ($n = 60$, eight families)

Source of variance	Effect			Residue		F	$p \leq$	R
	Type	df	MS	df	MS			
Body weight								
Sex	Fixed	1	11.88	46.32	30.42	0.39	0.5350	–
Age	Fixed	4	11.96	40.69	32.13	0.37	0.8270	–
Family	Random	7	104.19	47.00	24.20	4.31	0.0009	0.325
Logarithm of the specific activity of ^{90}Sr								
Sex	Fixed	1	0.12	9.24	0.22	0.56	0.4723	–
Age	Fixed	4	0.11	8.69	0.27	0.39	0.8098	–
Family	Random	7	2.47	47.00	0.03	78.59	0.0001	0.919

18.5 MBq/m^2 varied from 9 to 260 kBq/kg dry weight (Starichenko et al., 1995). Study of two species of common voles living there showed a correlation of the total β radioactivity accumulation in the skeleton and chyme of the animals ($r = 0.60$, $p < 0.05$) (Fig. 2).

We did not study the diet of northern mole voles; however, different levels of soil contamination in the plots inhabited by the animals could be used for indirect estimation of their feeding. To determine the effect of the spatial heterogeneity of soil contamination on the accumulation of ^{90}Sr in their bone tissue, we analyzed soil samples collected near the openings of vole burrows on the ground surface. The sol contamination with ^{90}Sr in the plot inhabited by northern mole voles varied by a factor of four (29.2–118.8 kBq/kg dry weight). This scatter of the specific radioactivity of the radionuclide in the soil may partly explain the observed differences between families in ^{90}Sr accumulation. However, when collecting the soil samples, we did not take into account the ordinal numbers of the families; therefore, it was impossible to estimate the dependence of the level of ^{90}Sr accumulation in bones of northern mole voles on the soil contamination, i.e., to determine the proportion of the resultant variance that was accounted for by the heterogeneity of soil contamination. On the other hand, it is unlikely that each family lives within a "spot" with the same contamination level, because the underground galleries usually branch over an area of several hundreds of square meters, crossing "spots" with different contamination levels. Therefore, there are no grounds to assume that the heterogeneity of soil contamination plays an exclusive role in the differences in radionuclide accumulation. Note that aboveground rodents living in the same plot accumulate radionuclides almost homogeneously; northern mole voles also rather actively move along their underground galleries and eat food from different parts of the studied area.

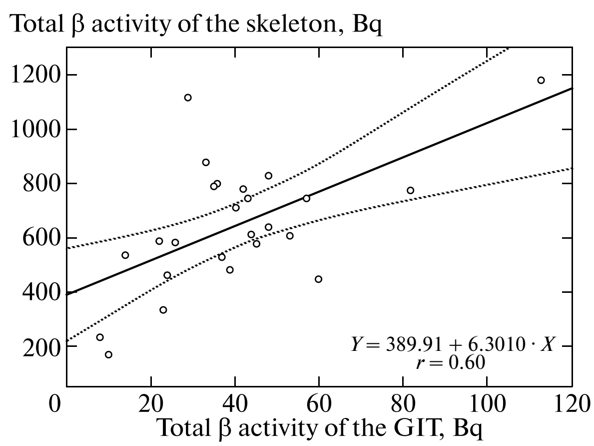

Fig. 2. Dependence of the specific β radioactivity of the skeleton on the β radioactivity of the gastrointestinal tract (GIT) in two species of common voles living in the EURT ($n = 25$). Dashed lines show the boundaries of the 95% confidence interval (Starichenko, 2007).

High intrafamilial correlations of the accumulation of ^{90}Sr (0.513, $p < 0.001$) and stable fluorine, another osteotropic substance (0.417, $p < 0.001$) have also been found in a laboratory experiment on inbred mice (Starichenko and Kshnyasev, 2004; Starichenko, 2005). In northern mole voles, the intrafamilial correlation coefficient for the ^{90}Sr kinetics is also two times higher. However, if we assume that half of the variation of the ^{90}Sr accumulation in bone tissue of northern mole voles is determined by heterogeneity of soil contamination and animal feeding and the other half, by true familial variation of skeletal metabolism, than the correlation coefficient will be 0.460 (0.919 : 2). This is close to the results of laboratory experiments and allows the "familial proper" component of ^{90}Sr accumulation in northern mole voles living in the EURT to be estimated (as a first approximation) at 40–50%.

Thus, northern mole voles living in the radioactively contaminated area of the EURT and characterized by underground way of life, family-based organization of local populations, and low migration rates exhibit the rates of ^{90}Sr accumulation in bone tissue comparable with those for other vertebrates. The sex and age of the animals little affected the skeletal accumulation of the radionuclide, whereas the effect of the family was significant ($p < 0.001$). The comparable levels of intrafamilial accumulation of ^{90}Sr in the case of chronic exposure in the natural environment and in laboratory experiments on inbred mice confirm hereditary (familial) determination of the accumulation of osteotropic substances. In practical terms, the estimate of the contribution of heredity to the variation of their metabolism may be useful for the evaluation of the dose of the affecting osteotropic factor and prediction of the toxicant metabolism in individual animals and population as a whole.

ACKNOWLEDGMENTS

I am grateful to O.V. Tarasov, N.G. Evdokimov, N.V. Sineva, V.P. Guseva, and I.A. Kshnyasev for their assistance with the study.

This study was partly supported by the Ural Division of the Russian Academy of Sciences, interdisciplinary project no. 09-M-24-2001.

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