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Dependence of Dose Loads on Bone Surfaces of Murine Rodents on the Level of ^{90}Sr Accumulation in the Skeleton

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Abstract—The relationship between ^{90}Sr accumulation in the skeleton after single injection and the resulting dose load on bone surfaces was studied in laboratory mice. Radiation doses were measured by a thermoluminescent method. A positive correlation was revealed between the surface dose rate on the skull and mandible and ^{90}Sr specific radioactivity in these bones. The possibility to calculate ^{90}Sr incorporation into the bone tissue from dosimetric data was evaluated as an analytical approach allowing preservation of the bone material for subsequent studies. Conversion coefficients relating surface doses to ^{90}Sr specific radioactivity in bones were calculated. However, their values have to be specifically defined for cases of chronic ^{90}Sr input and with regard to bone anatomy and species-specific and ecological features of test animals.

Keywords: ^{90}Sr, bone tissue, CBA mice, radiometry, thermoluminescent dosimetry, bone surfaces.

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Determination of radiation dose loads from incorporated ^{90}Sr is a key problem in assessing the viability of natural populations in radioactively contaminated areas, including the Eastern Ural Radioactive Trace (EURT) where ^{90}Sr deposited in the bone tissue is the main dose-forming radionuclide. There are two targets for β-radiation from ^{90}Sr and its daughter isotope ^{90}Y: the red bone marrow and bone surfaces coated by osteoblasts and connective tissue cell elements. The most serious consequence of bone marrow irradiation is leukemia; in the case of bones, this is osteosarcoma, which usually develops from cells covering the bone surface. In small mammals, the internal radiation dose received by the bone marrow is practically equal to dose per bone (Shishkina, 1998; Shvedov and Akleev, 2001), but estimation of dose loads on the bone surface is a special problem.

To develop approaches to its solution, we initially performed a model experiment on laboratory mice to analyze the relationship between ^{90}Sr accumulation in the skeleton and the resulting dose load on the bone surface. We also evaluated the possibility to calculate ^{90}Sr incorporation in the bone tissue from dosimetric data. Unlike routine methods for determining specific radioactivity of a certain radionuclide, such an approach excludes destruction of the test material, which in many cases is unique (e.g., the collection of the skulls of small mammals from the EURT area that is kept at the Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences). Measurements were made by the method of thermoluminescent dosimetry, which had been used for in vitro retrospective assessment of internal radiation doses (Shishkina, 1998; Shishkina and Tokareva, 2010) and for verification and adjustment of models for the metabolism of osteotropic radionuclides (Lyubashevsky et al., 1996). However, the mechanisms of formation of radiation doses were studied by this method mainly in dental tissues.

Our experiment was performed with adult CBA mice weighing 32.5 ± 0.6 g (n = 29) which received a single intraperitoneal injection of a ^{90}Sr Cl solution at a dose equivalent to 7.5 kBq per animal. At this dose, ^{90}Sr specific radioactivity in their bone tissue reached the level characteristic of animals from the EURT epicenter (Starichenko, 2004). These animals are exposed to chronic radionuclide input, but such a situation could not be simulated in the laboratory because of methodological difficulties.

The mice were euthanized on days 5 and 14 after the injection, and their skulls (crania and mandibles) were thoroughly cleaned of soft tissues, dried, and used to measure absorbed radiation doses. Measurements were made with highly sensitive Al_2O_3:C detectors TLD-500 and the recording equipment designed at the Ural State Technical University, as described (Shishkina, 1998). The detectors, shaped as tablets 5

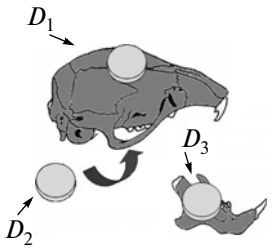

Fig. 1. Positions of thermoluminescent detectors on the cranium and mandible.

mm in diameter and 1 mm in thickness, were placed in two positions on the cranium and one position on the mandible (Fig. 1). After exposure for 7 days, they were removed to record the accumulated dose D (mGy) and calculate the dose rate DR (mGy/day).

It should be taken into account that these detectors are not intended for direct measurements of β-radiation doses: because of significant absorption of radiation in the bulk of the detector, its response is proportional to the radiation dose averaged over its volume. Since precise calibration of the dosimeter for β-sources is difficult, the recorded value should be regarded as a relative parameter proportional to ^{90}Sr specific radioactivity in the bone tissue rather than as the actual dose rate at the bone surface.

Radiometry of the samples was performed by the procedure tested previously (Starichenko, 2007). The recorded values were processed to calculate the mean, standard deviation, relative standard deviation, error of mean, and relative error of mean. Relationships between test parameters were evaluated by means of regression and correlation analyses in the Microsoft Excel 2002 and Statistica 6.0 program packages.

As follows from Table 1, the distribution of ^{90}Sr and resulting dose rates at the bone surface was uneven, and its specific radioactivity decreased with time. These results well agree with published data (Engström et al., 1962; *Metabolizm strontsiya*, 1971; Bazhenov et al., 1990; Zhuravlev, 1990; Shvedov and Akleev, 2001; Stover, 1959; *ICRP Publication...*, 1973, 1995; Lloyd et al., 1976).

A positive correlation was revealed between the surface dose rate and ^{90}Sr specific radioactivity in skull bones (Fig. 2). It is noteworthy that the statistical significance of this correlation sharply increased when dose rated for the cranium were calculated from measurements in two geometries (from $r = 0.33–0.36$, $p = 0.088–0.115$ to $r = 0.31$, $p = 0.032$). This can be explained by an increase in sample size as well as by the uneven distribution of ^{90}Sr over the bone volume due to differences in the specific surface area of bones (Starichenko, 2007). These differences are better manifested between different regions of the cranium than within the mandible. Thus, the specific surface area (and, hence, ^{90}Sr specific radioactivity) in flat bones of the dorsal cranium is significantly smaller than in bones of its ventral region containing a well-developed trabecular network.

To evaluate the possibility to use the results of dosimetry for nondestructive verification of data on the level of ^{90}Sr deposition in individual bones, experimental group "14 days" was randomly separated into two subgroups (Table 2). In subgroup "14 days-1," we calculated conversion coefficients k relating dose rates to ^{90}Sr specific radioactivity and estimated their variation range (Table 3).

It should be noted that experimentally determined k values are fairly close to the value computed using the program VARSKIN 3 (Durham, 2006) designed for assessing skin doses of β-radiation. The radiation source in this model was taken to be a disk with a diameter of 15 mm, thickness of 0.5 mm, and density of 1.8 g/cm^3 (the density of cortical bone); ^{90}Sr / ^{90}Y specific radioactivity was 1000 Bq/g; the absorbent had a density of 3.9 g/cm^3 (the density of Al_2O_3). Under these conditions, we calculated dose rates of β-radiation behind the absorbent, with its thickness increasing from 0 to 1 mm in 0.1-mm steps. On this basis, we obtained the value of β dose rate averaged over the detector thickness. This value proved to be commensurate with that experimentally determined in measurements on skull bones: 0.949 vs. 0.468 (μGy/day)/(Bq/g), respectively. The difference may be explained by noncoincidence between model and experimental geometries of irradiation, difficulties in

Table 1. Specific ^{90}Sr radioactivity (C_{Sr}) and dose rate (DR) on the bone surface, $M \pm m$

Skull part	C_{Sr}, Bq/g		DR, mGy/day	
	Time after ^{90}Sr injection, days			
	5 ($n = 5$)	14 ($n = 24$)	5 ($n = 5$)	14 ($n = 24$)
Cranium	855 ± 49 (774–1045)	652 ± 21 (385–823)	0.263 ± 0.058** (0.074–0.385)	0.282 ± 0.014 (0.144–0.584)
Mandible*	1904 ± 155 (1400–2659)	1730 ± 48 (1206–2499)	0.322 ± 0.040 (0.216–0.495)	0.472 ± 0.019 (0.242–0.800)

Notes: * Sample size = 2n (both bones were included in analysis).
** Measurements in the same geometry (DR_1).

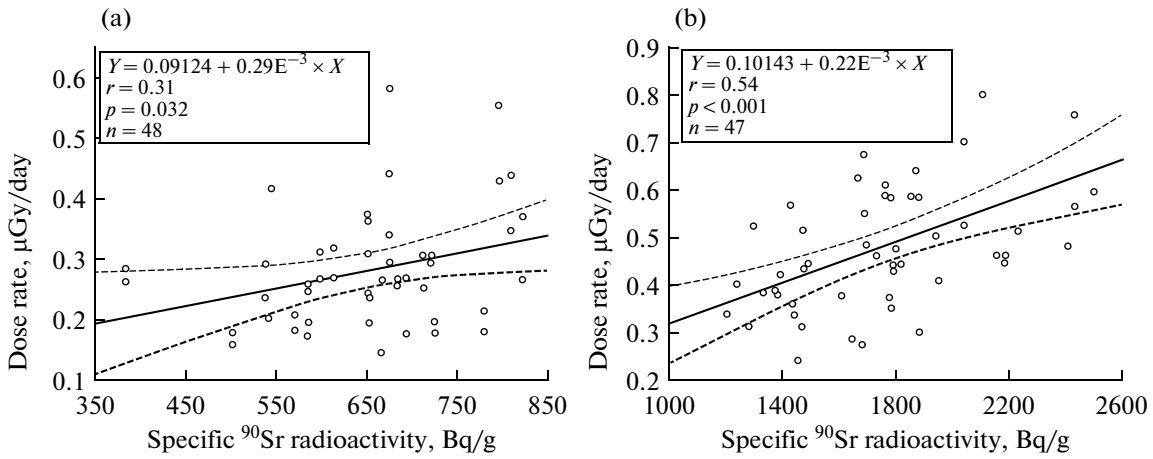

Fig. 2. Dose rates on the (a) cranium and (b) mandible surface as a function of ^{90}Sr specific radioactivity in the bone (group "14 days"). Dotted lines delimit 95% confidence interval.

calibrating detectors for β-radiation, and approximations inherent in the VARSKIN 3 program.

Comparative verification of the results of skull bone radiometry in group "5 days" and subgroup "14 days-1" and computed data showed good agreement between them (Table 4). This agreement improved when calculations were made with the coefficient k for the group of animals with the same period of exposure. For example, the conversion coefficient for subgroup "14 days-1" allowed estimation of ^{90}Sr specific radioactivity in the bones of animals from group "5 days" with an error of 25–40%, whereas the error of this estimation for subgroup "14 days-2" was only 15–20%.

Radiation dose rates for the bone surfaces and bone marrow were calculated on the basis of radiometric data using the equations from previous studies (Shibkova, 2000; Shishkina and Lyubashevsky, 2008). The results showed that dose load on the bone surfaces was many times smaller than that on the bone marrow. In studies on human subjects exposed to ^{90}Sr deposited in the skeleton over several decades, conversely, the dose load on the bone surfaces was found to be higher than on the bone marrow (*ICRP Publication...*, 1996). Differences in the formation of radiation doses between species largely depend on the size of bones and specific features of their geometry.

We have revealed a positive correlation between ^{90}Sr specific radioactivity in bones and dose rates on their surfaces, which is evidence for the principal possibility of using nondestructive methods to assess ^{90}Sr accumulation in animal skeletons. The numerical values of coefficients k relating ^{90}Sr radioactivity in the skeleton to dose rates for organs and tissues can be computed using a model simulating the geometry and relative arrangement of the radiation-source organ and the target organ. Ultrathin detectors (mass thickness 10–20 mg/cm^2) make possible such experiments in nature, provided ^{90}Sr radioactivity in the skeleton is sufficiently high.

However, the values of these coefficients have to be specifically defined for cases of chronic ^{90}Sr input and with regard to bone anatomy and species-specific and ecological features of test animals. When data on ^{90}Sr specific radioactivity are available, such conversion coefficients can be used to assess the structure of morbidity and mortality among small mammals inhabiting radioactively contaminated areas. In particular, irradiated populations may be characterized by a relatively

Table 2. Specific ^{90}Sr radioactivity (C_{Sr}) and dose rate (DR) on the bone surface in "14 days" subgroups, $M \pm m$

Skull part	Subgroup			
	"14 days-1" ($n = 12$)		"14 days-2" ($n = 12$)	
	C_{Sr}, Bq/g	DR, mGy/day	C_{Sr}, Bq/g	DR, mGy/day
Cranium DR_1	640 ± 18	0.264 ± 0.025	665 ± 24	0.227 ± 0.016
DR_2		0.341 ± 0.030		0.296 ± 0.030
DR_{1+2}		0.303 ± 0.021		0.261 ± 0.018
Mandible*	1656 ± 50	0.448 ± 0.022	1807 ± 80	0.496 ± 0.030

* Sample size = $2n$ (both bones were included in analysis).

Table 3. Numerical values of conversion coefficients k in subgroup "14 days-1," (μGy/day)/(Bq/g)

Skull part	Ratio	Mean	Standard deviation	Standard error	Relative standard deviation	Relative standard error
Cranium	DR_1/C_{Sr}	0.407	0.092	0.026	0.226	0.064
	DR_2/C_{Sr}	0.529	0.128	0.037	0.242	0.070
	DR_{1+2}/C_{Sr}	0.468	0.125	0.026	0.267	0.056
Mandible	DR_3/C_{Sr}	0.272	0.059	0.012	0.217	0.044

Table 4. Specific ^{90}Sr radioactivity (C_{Sr}) in bones as determined (A) by calculations and (B) radiometrically, $M \pm m$

Bone	TLD position	DR, mGy/day	k for subgroup "14 days-1," (μGy/day)/(Bq/g)	C_{Sr}, Bq/g			
				Group "5 days"		Subgroup "14 days-2"	
				A	B	A	B
Cranium	DR_1	0.263 ± 0.058 0.227 ± 0.016	0.407 ± 0.026	646 ± 184	855 ± 49	558 ± 75	665 ± 24
	DR_2	– 0.296 ± 0.030	0.529 ± 0.037	–		560 ± 96	
	DR_{1+2}	– 0.261 ± 0.018	0.468 ± 0.026	–		558 ± 69	
Mandible	DR_3	0.322 ± 0.040 0.496 ± 0.030	0.272 ± 0.012	1184 ± 199	1904 ± 155	1824 ± 191	1807 ± 80

high frequency of skeletal tumors, which is known to increase in environments with high levels of radioactive contamination.

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