The Measuring and Modelling of Strontium-90: an Integrated Retrospective Dosimetry Issue

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Introduction

Dose reconstruction for internal exposure is generally structured on a paradigm of release-transport-intake-uptake-dose. In some cases when it is necessary to reconstruct individual dose for the long time after intake and historical information on the releases is limited, bioassay measurements can be used for retrospective dosimetry of long-lived radionuclides with long biological residence times. Internal dose is related to the time integral of the body burden, therefore, individual measurements of body burden, metabolic model and some general suggestions on intake pattern are three necessary parts for dose reconstruction process in such cases.

^{90}Sr is long-lived bone-seeking radionuclide with a long biological residence time in the body. The world list of data on strontium in man was restricted to a few experimental findings with a single intake, information on global fallout and the measurements of dial painters. A large multitude of measurements of ^{90}Sr in human body for the residents of the Techa river (Southern Urals, Russia) contaminated by fission products in 1949-1956 has been published in open literature only recently (Kozheurov, 1994; Degteva et al., 1994). The necessity of dose reconstruction from long-lived radionuclides for the population living on the territories contaminated as a result of Chernobyl Accident calls the utilisation of the Urals experience to optimise the efforts. An analysis of a unique and abundant Urals data set on strontium in humans presents also a great interest for general purposes of retrospective dosimetry.

Population exposure in the Urals occurred as a result of failures in the technological processes at the Mayak plutonium facility in the 1950's. Construction of the Mayak facility began in 1945 and was completed in 1948. Initially this complex consisted of three main parts: Reactor plant, radiochemical facility, and waste-management facilities. The major sources of radioactive contamination were: (1) the discharges of 2.7×10^6 curies of liquid wastes into the Techa River (1949–1956); (2) an explosion in the radioactive waste storage facility in 1957 (the so-called Kyshtym Accident) that formed the East Urals Radioactive Trace (EURT) due to dispersion of $2 \times$

10^6 curies in the atmosphere; (3) the resuspension of 600 curies with dry silt from the shores of Karachay Lake during a heavy thunderstorm (1967); and (4) routine gaseous aerosol releases within the first decades of the facility's operation (Degteva et al., 1996). The significant portion of activity for the Techa River and EURT consists of long-lived radionuclides, mainly ^{90}Sr. These releases resulted in the long-lived contamination of surrounding territories. The activity released from Karachay Lake also consisted of ^{90}Sr and ^{137}Cs, and it superimposed on already existed EURT.

There are two cohorts of accidentally exposed population in the Urals: the residents of the Techa riverside communities and the residents of the area covered by EURT. The object of primary interest is Techa River population. The Techa River cohort is important because some of whose members have received relatively high doses and a significant increased risk of leukemia with increasing dose was observed (Kossenko and Degteva, 1994). The residents of the villages along the Techa were exposed to both external irradiation (from contaminated river water, sediments, flood plane soils) and internal irradiation due to ingestion of radionuclides (mainly ^{90}Sr) with drinking water and diet.

Whole-body counting system for measuring ^{90}Sr via bremsstrahlung

Since 1974 the large scale investigations of the ^{90}Sr content in the skeleton of Techa riverside residents with the whole body counting system SICH-9.1 were started. A detailed description of SICH-9.1, of the measurement procedure and results were given elswere (Kozheurov, 1994). The shielding for the whole-body counter was made of cast iron rings with a wall thickness of 200 mm. The inner surface has linings of lead (5mm), cadmium (1.5 mm), and copper (1 mm). Four Phoswich detectors are used for measuring. The geometry of measurement is as follows: the detectors are fixed in the central vertical plane with a 30° inclination towards the vertical. The distance between the axes of each pair of detectors is 35 cm at the base. On the bed frame, fabric is stretched which caves in under the weight of the body in such a way that the medium plane of the body is at a distance of 25 cm from the detectors. During the measurement the proband's bed is moved through the detector array. The scanning length is 2 m with stops at the ends lasting 10% each of the whole measurement time. The motion is controlled by impulses from the analyzer real-timer. The duration of the measurements is 20 min. The scanning device used in SICH-9.1 is discussed in (Zaitsev and Kozheurov, 1978), and the calibration technique of the whole-body counter is described in (Kozheurov et al., 1978). Minimum detectable activity (MDA) for SICH-9.1 is equivalent to 1.85 kBq of ^{90}Sr.

For the calibration of WBC two surrogate human structures were made by two different laboratories. Both phantoms were made of natural human skeletons, paraffin imitations of soft tissues and dry paper imitations of lung. Different methods of introducing ^{90}Sr into the bones of the phantoms were used. In one of the phantoms the isotope was introduced by being dripped into uniformly distributed holes drilled the bones. The bones of the other phantoms were impregnated with ^{90}Sr solution in a vacuum chamber. Each laboratory performed independent experiments aimed at determining bremsstrahlung yields relations and the influence of human soft tissues and the phantom paraffin on the absorption of the bremsstrahlung. Independent activity measurements were carried out on each phantom. After scanning the phantoms and making the appropriate corrections the difference in calibration coefficients was determined to be 6%. This value represents the estimate of the systematic error in ^{90}Sr counting by means of the spectrometer. Water-filled phantoms made of plastic tanks laid out in such a way as to imitate a human body were used for calibration of ^{137}Cs and ^{40}K. The length of the phantom could be changed by removing one or two tanks. Such calibration was done in 1974 and did not confirmed during twenty years period of WBC operating. It is highly desirable to ensure that the old measurement system is once again calibrated in depth on the basis of measurements of a special antropomorphic phantom.

Strontium Registry

The measurements of ^{90}Sr in humans for the residents of the Techa river were started in 1951. The first findings were ^{90}Sr concentrations in different bones received from autopsies (Table 1). Since 1960 the surface beta-activity on the teeth has been measured; this was made possible with the detectors suitable to perform such measurements in the mouth of a person (Kozheurov, 1994). From 1962 through 1979 daily urinary excretion was estimated by radiochemical methods. And since 1974 the Techa river residents have also been examined for their body burdens with the whole-body counter (Kozheurov, 1994). In parallel with whole-body counting the measurements of beta-count of forehead bone are carried out. About 30,000 measurements have been performed on more than 14,000 persons from the contaminated. Both men and women of all ages have been measured. This has given a unique experience of the arrangement of individual monitoring of ^{90}Sr human body contamination. A list of available data is given in Table 1.

Table 1. Techa River Strontium Registry.

Measured values	Number of measurements	Number of subjects measured	Period of observation
Sr-90 whole-body content	28,500	14,200	since 1974
Tooth beta-count	30,200	15,300	since 1960
Forehead beta-count	23,100	12,300	since 1976
Sr-90 urinary excretion	2,910	1,564	1962-1979
Sr-90 concentration in bone	350	160	1951-1973

The results of the multitude of measurements showed a clear dependence of the ^{90}Sr body burden on the year of birth, and formed the basis for the elaboration of age-dependent model for strontium retention in human skeleton.

Metabolic Modelling of Strontium

Our age-dependent model of strontium retention in human bone is descridbed in detail elsewere (Degteva and Kozheurov, 1994). This model represents mathematical function similar to ICRP-20 retention function (in a simplified form), in which parameters are dependent on age at intake. The main task for the model development was to estimate the parameters and to validate the model under different conditions of strontium intake. The approach to the validation of metabolic models established in ICRP Publication 20 and accepted now, was the following: to collect all available sets of data on the metabolism of a particular radionuclide in humans which are suggested to reflect Reference Man (ICRP-23) under various schedules of intake; to fit model calculations for available schedules of intake based on the metabolic parameters of Reference Man to the sets of data. Thus, checking of model fitness and parameter verification are carried out.

As a starting point for parameter fit the general view of some age-dependent functions was identified by combining relatively extensive information concerning the development of the human body with the findings of experiments on different species of animals. Then the available sets of human data were determined for the more precise estimates using empirical fitting technique. Besides the Techa river data, the information on strontium in human bone from global fallout (Leggett et al., 1982; Loutit, 1967; Papworth and Vennart, 1984; Warren, 1972) and experimental findings with single injection (Bishop et al., 1960; Kereiakes et al., 1968; Kohn et al., 1962; Likhtarev et al., 1975; Woodard and Dwyer, 1972) were involved in parameter estimation and the validation of our model. Such approach has allowed to derive the model which takes into account changes in metabolic parameters throughout the entire life beginning from bone formation and growth in childhood and including loss of skeleton calcium in old age. The model gives reliable description of ^{90}Sr retention from one month to thirty years from the moment of intake.

Another possibility of the model verification was given by a set of data on direct assessments of individual strontium excretion rates dated 25-35 years after the basic intake for persons aged 30-70. Excretion rate was estimated by two different methods: using radiochemical analysis of bioassay samples and on the basis of repeated whole-body counter measurements (Table 2). The latter approach made it possible to receive the most detailed information concerning age- and sex-dependencies of the late phase of excretion, in comparison with earlier studies (Muller, 1970). The comparison of model prediction with experimental results has shown that our model overestimates excretion rate for the ages 30-45 years and does not take into account distinct sex differences in excretion rates for the elderly persons. This fact give us reasons to continue our studies and to improve our new model for strontium metabolism. Nevertheless, the model presented served to bring together into a relatively simple framework the majority of experimental data on strontium in humans and can be useful as workable age-dependent model in radiation protection.

Table 2. The comparison of strontium excretion rate estimates in late phase of retention for humans.

Study description	Muller, 1970	Present paper	Kozheurov, 1994
Sample information - sex - age, yr - ^{90}Sr body burdens, kBq	9 luminizers 1 M + 8 F 22 - 41 1.85 - 70.3	40 residents of the Techa riverside 21 M + 19 F 37 - 50 7.4 - 145.0	717 residents of the Techa riverside 367 M + 350 F 30 - 76 3.0 - 164.5
Methods of measurements	Radiochemical analysis of bioassay	Radiochemical analysis of bioassay in parallel with whole-body counting	Repeated WBC measurements made within 5-10-year intervals
Time since exposure, yr	2.2 - 8.2	29 - 30	25 - 35
Statistical evaluation techniques	Model extrapolation using additional data on stable Sr	Direct assessment	Direct assessment
Resultant excretion rate estimates	$(7.7\pm1.0)\ 10^{-5}$ per day 0.028 ± 0.004 per year	$(8.3\pm3.6)\ 10^{-5}$ per day 0.030 ± 0.013 per year	Distinct age- and sex-dependence. Mean value for ages 30-40 years: 0.025 ± 0.016 per year

Conclusions

The results of a long-term investigation of the Techa river population have given a unique experience in the arrangement of individual monitoring of ^{90}Sr human body contamination for the purposes of retrospective dosimetry. Techa River Strontium Registry data base can serve for the development of age-dependent metabolic models for long-lived bone-seeking radionuclides. The data of concern are of major interest to the reconstruction of dose to the red bone marrow and bone surfaces of the members of the Techa river cohort which could give a possibility of direct radiation risk assessments for long-term chronic exposure conditions.

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