MATCHING OF DATA SETS OBTAINED WITH THE OLD AND NEW WBC SYSTEMS: SICH-9.1 (1974–1997) AND SICH-9.1M (2006–2011)

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TABLE OF CONTENTS

ABSTRACT

Techa River Dosimetry System (TRDS)-2009 approaches to ^{90}Sr-dose reconstruction are mainly based on in vivo ^{90}Sr measurements performed in 1974–1997 with whole body counter (WBC) SICH-9.1. Long-term in vivo monitoring of residents of the Urals has been conducted with this specifically designed WBC. Quantification of ^{90}Sr was achieved by measuring with a 'phoswich' detector the bremsstrahlung of ^{90}Y (daughter of ^{90}Sr) beta rays; for this purpose a scanning-bed geometry enclosed in a special shielding room was used. Analyses of ^{137}Cs and ^{40}K were accomplished at the same time with the same detectors by the measurement of their photopeaks. By 1997 the detector modules and electronic equipment of the old WBC had significantly deteriorated. As a result, the WBC system was upgraded in the framework of a joint US-Russian project and new system called SICH-9.1M was created. Individual measurements of Techa Riverside residents and other Urals residents were resumed in 2006 for monitoring purposes under the financial support of the Russian Federation. The comparison of data obtained with the old and the new WBC systems allows the pooled analysis of ^{90}Sr-body burdens measured in 1974–1997 and after 2006. Matching of the two ^{90}Sr data sets obtained with the old and the new WBC systems was performed using two approaches: (i) by comparison of individual data for 74 persons with high ^{90}Sr-body burdens (5–21 kBq in 2006; up to 100 kBq in 1974) repeatedly measured with the old and the new WBC; and (ii) via statistical analysis of 1,637 persons who have measurements on the old and new WBC. Good agreement between the two data sets was found. Comparison of data sets on naturally occurring ^{40}K shows similar results.

1. INTRODUCTION

The approaches used in Techa River Dosimetry System (TRDS)-2009 for reconstruction of dose from ^{90}Sr are mainly based on in vivo measurements of ^{90}Sr performed in 1974–1997 with whole body counter (WBC) SICH-9.1. During this long period more than 38,000 measurements were carried out on more than 20,000 persons by the WBC group under the direction of V. Kozheurov (Kozheurov, 1994). The original SICH-9.1 was designed by a group of scientists headed by Prof. Yu. Belle specifically for the exposure situation on the Techa River (Belle et al., 1975) for measurements of ^{90}Sr, ^{137}Cs and ^{40}K in people. Quantification of ^{90}Sr was achieved by measuring with four 'phoswich' detectors the bremsstrahlung of ^{90}Y (daughter of ^{90}Sr with a half-life of 64 h) beta rays; for this purpose scanning-bed geometry enclosed in a shielded room was used. Analyses of ^{137}Cs and ^{40}K were accomplished at the same time with the same detector system by the measurement of their photopeaks (photons with energy ranges 620–740 keV and 1400–1580 keV, respectively). The inventor of the first dual crystal used for direct measurement of internally deposited radionuclides was Dr. G. Laurer. This crystal design led directly to the development and use of 'phoswich' detectors. By 1997 the detector modules and electronic equipment of SICH-9.1 reached the end of their service life. The detection limit of the phoswich detectors increased from a starting level of 20 nCi (0.74 kBq) in 1974 to 100 nCi (3.7 kBq). The decrease in efficiency of the four detectors varied in a wide range that resulted in asymmetry of the summary spectrum recorded during measurements.

Therefore, in 1998, the question had been raised on improving the original SICH-9.1 within the framework of Project 1.1 in order to provide for the continuation of the individual-body-burden monitoring program. It was decided to use the same shielding room and the same geometry of measurements (scanning-bed), as well as the same type of detectors (phoswich). In 2002, Dr. G. Laurer and Dr. D. Hickman proposed a new modification of phoswich detectors to be used in the improved WBC. These detectors were purchased from Saint-Gobain Cristaux & Detecteurs (France). In 2002, Drs. Laurer and Hickman came to the URCRM to test these detectors. A new electronic scheme for the improved WBC was proposed and developed by V. Farafontov (Bougrov and Farafontov, 2004). Modular electronics for the improved WBC were produced by EG&G ORTEC (USA). Updating of the system of patient scanning was finished in 2005 with collaboration of the Department of Automation of Mechanoerecting Production (Southern Urals State University, Chelyabinsk, A. Sheremetiev and R. Abdullin).

The calibration and certification of SICH-9.1M was performed in 2006 by scientists of the URCRM Biophysics Laboratory and specialists of the "D.I. Mendeleyev Institute for Metrology" (Bougrov et al., 2008). The whole body counter SICH-9.1M has been certified by the Federal Technical Control and Metrology Agency and entered into the State registry of measuring instruments under №31185-06, on 14 March 14 2006 and approved for application in the Russian Federation. Since then, individual measurements of ^{90}Sr-body burdens have been performed continuously with financial support from the Russian Federation.

The task of further reduction in uncertainty of TRDS-based estimates of internal doses includes measurements of ^{90}Sr-body burdens from an additional number of Techa Riverside residents with the upgraded WBC. The comparison of data obtained with the old and the new WBC systems is important in order to ensure that the body burdens measured in 1974–1997 and after 2006 are sufficiently identical that the data sets can be combined. The specific tasks addressed in the current report are

1) description of the upgraded WBC system SICH-9.1M;
2) comparison of data on ^{90}Sr measurements obtained with the old and new WBC systems ; and
3) comparison of data on ^{40}K measurements obtained with the old and the new WBC systems.

2. DESCRIPTION OF SICH-9.1M

2.1. Spectrometer and calibration phantoms

The principal features of the WBC are illustrated in Fig. 1. The shielding room is made of cast-iron rings with a wall thickness of 200 mm. The inner surface has linings of lead (5 mm),

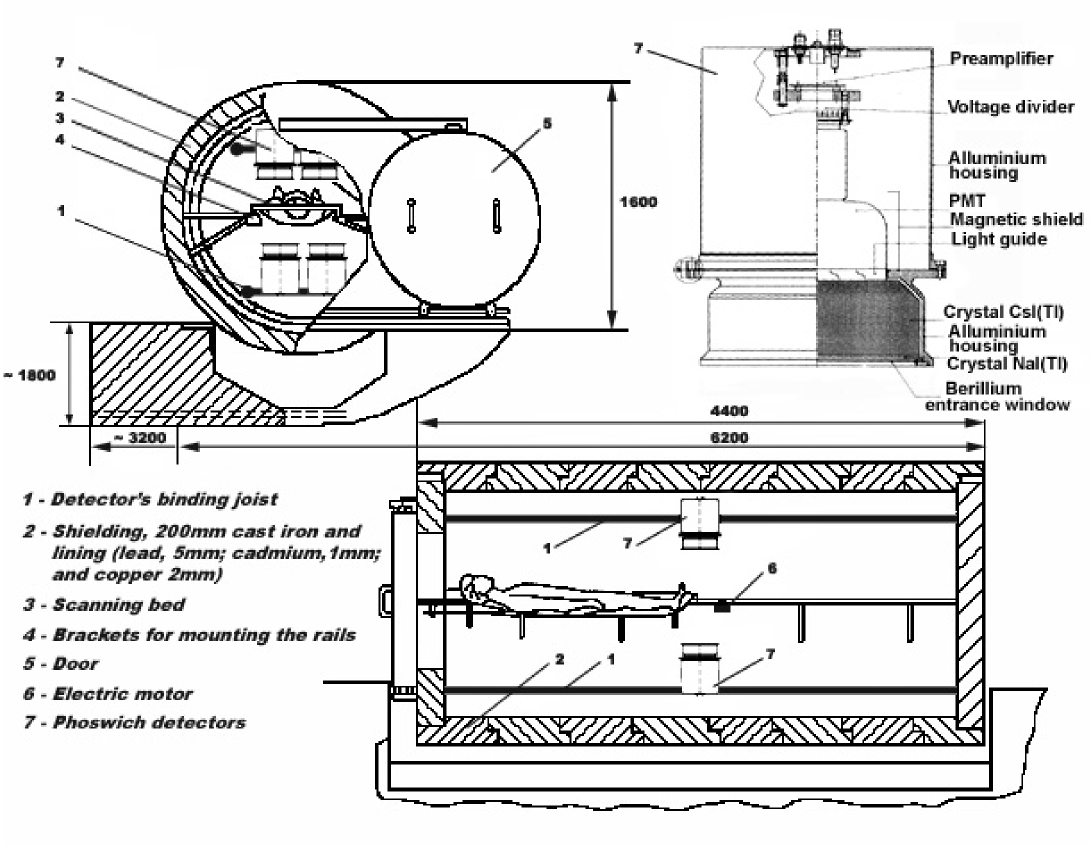


Fig. 1. A schematic sectional view of the SICH-9.1M whole body counter: 1 - a detectors' binding joist; 2 - shielding, 200-mm cast iron and lining (lead, 5 mm; cadmium, 1 mm; and copper, 2 mm); 3 - movable bed; 4 - brackets for mounting the rails; 5 - door; 6 - electric motor; and 7 - new phoswich detectors (all measurements in mm).

cadmium (1 mm), and copper (2 mm). Four phoswich detectors located in a central vertical plane are fixed on binding joists. During measurement the person lying on the bed is moved through the detector array over a scanning length of 2 m.

Currently, phoswich detectors are most applicable for detection of small quantities of pure beta-radiation nuclides (such as ^{90}Sr or ^{89}Sr) in the human body based on the detection of secondary bremsstrahlung radiation.

In phoswich detectors, a thin crystal (3 mm thick) of NaI (Tl) is backed by a thicker (80 mm) CsI (Tl) crystal. The light pulses from the two materials have significantly different shapes (decay constants for emission: 0.25 μs in NaI(Tl) and 1.00 μs in CsI(Tl)). The pulseshape discrimination method is used with modular electronic instruments from EG&G ORTEC (USA).

Fig. 2 shows a general view of the whole body counter: An exterior view of the WBC is shown on the left panel and an interior view with the array of four phoswich detectors placed in the central vertical plane is shown on the right panel.

The anthropomorphic phantom, FTS-06T(2), of an adult person was designed by Dr. A.V. Kovtun. This physical phantom is a model of an adult with a uniform distribution of ^{90}Sr (204 kBq in 2004) in the skeleton. The phantom imitates the body of an adult man with height of 172 cm; body weight of 71 kg, and skeletal mass of 9.2 kg (Fig. 3).

The phantom was constructed from plastic materials (cold-cured epoxy resin) imitating the density of main human tissues (bone - 1.3; lung - 0.26; and soft tissues - 1.04 g cm^{-3}) and also imitating by magnitude of the coefficient of linear attenuation of bremsstrahlung with an error of no more than 5%. A similar phantom FTS-06T(1) was used earlier for calibration of SICH-9.1; it contained 44 kBq of ^{90}Sr in 2004. Both phantoms contain trace amounts of naturally occurring

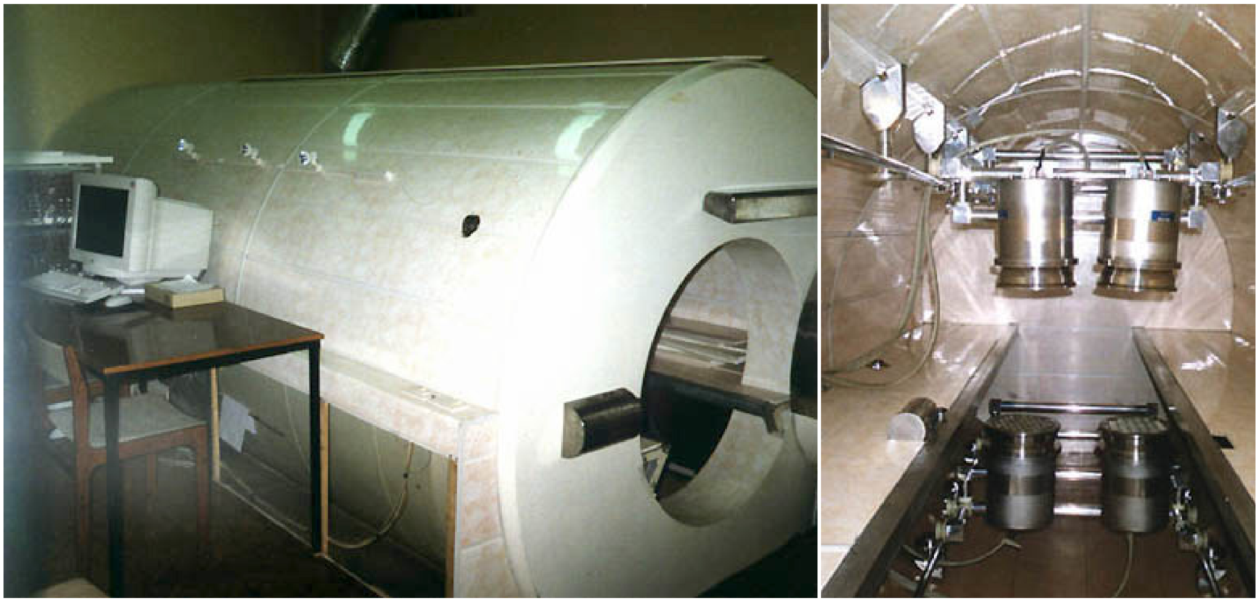


Fig. 2. General views of the whole body counter.

Fig. 3. Anthropomorphic phantom prepared to be measured.

radionuclides, and the earlier phantom [FTS-06T(1)] is used as a measure of "background" activity for radionuclides other than ^{90}Sr in phantom FTS-06T(2).

A solid whole-body phantom set assembled of right-angled polyethylene units and rod sources of ^{137}Cs and ^{40}K inserted into them were used for calibration for these radionuclides. This phantom set (UP-02T) simulates the body characteristics of children and of adults of different weights (Kovtun et al., 2000a); specifically the body characteristics of 2-, 6- and 14-year old children and three adults with nominal body masses of 70, 90, and 110 kg; rod sources containing standard activities of ^{137}Cs and ^{40}K are inserted into the phantom blocks (Fig. 4). Table 1 presents the main characteristics of the UP-02T phantom set.

Table 2 presents the common characteristics of SICH-9.1M.

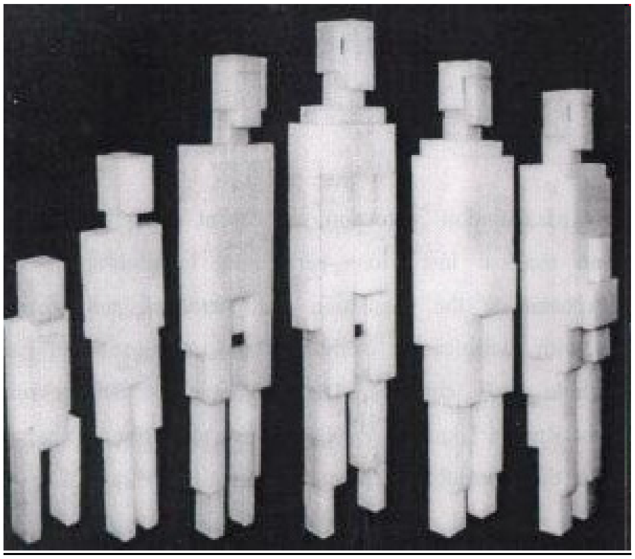


Fig. 4. Appearance of whole-body phantom set UP-02T.

Table 1. Main characteristics of the whole-body phantom set UP-02T with gamma-emitter sources.

Phantom type	Body mass, kg	Body length, cm	^{40}K content, Bq	^{137}Cs content, Bq
Ph1	12	82.5	840	1710
Ph2	24	121.0	1690	3420
Ph3	50	160.0	3530	7120
Ph4	70	170.5	4900	9960
Ph5	90	170.5	6340	12,800
Ph6	110	170.5	7750	15,700

Table 2. Common characteristics of SICH-9.1M.

Description		Value
Energy Range:	NaI(Tl) channel	20–200 keV
	CsI(Tl) channel	200–3000 keV
Integral nonlinearity (full scale) of SICH–9.1M		≤ 1%
Energy resolution of NaI(Tl) channel for ^{241}Am at 59.5 keV, %		≤ 20%
Energy resolution of CsI(Tl) channel for ^{137}Cs at 661.7 keV , %		≤ 12%
Detection sensitivity in the energy range 25–145 keV for measuring ^{90}Sr in the whole body		$\geq 4 \times 10^{-4}$ Bq$^{-1}\cdot$s^{-1}
Detection sensitivity in the energy range 560–760 keV for measuring ^{137}Cs in the whole body		$\geq 8 \times 10^{-3}$ Bq$^{-1}\cdot$s^{-1}
Detection sensitivity in the energy range 1310-1610 keV for measuring of ^{40}K in whole body		$\geq 8 \times 10^{-4}$ Bq$^{-1}\cdot$s^{-1}
Maximum Input count rate		3×10^3 s^{-1}
Warm-up time		≤ 30 min
Continuous operation		≤ 24 hr
Instability of energy characteristics during continuous operation		≥ 1%
Error of measurement of radionuclide activity (as measured by phantoms)		± 20%
Lower limit of detection (LLD) a counting time of 20 min:		
	- ^{137}Cs	≤ 40 Bq
	- ^{90}Sr	≤ 800 Bq
	- ^{40}K	≤ 300 Bq
Range of activity measured in the human body		
	- ^{137}Cs	$120–6 \times 10^5$ Bq
	- ^{40}K	$750–4 \times 10^6$ Bq
	- ^{90}Sr	$2600–2 \times 10^7$ Bq

2.2 Measurement procedure

The physical conditions during measurements include the following: air temperature from 15 to 35ºC; relative humidity up to 75% at 30ºC; atmospheric pressure from 84 to 107 kPa; and supply voltage of 220 VAC (plus 10%, minus 15% at 50 Hz.

The measurement procedure includes the following main steps:

1. Preparation of SICH-9.1M for measurements
    - Ventilate the shielded room for eight hours before the start of measurements in order to decrease the level of ^{222}Rn and decay products;
    - Calibrate the energy scale of the spectrometer with use of standard gamma sources ^{141}Am, ^{152}Eu, and ^{137}Cs. Calibration is performed for each phoswich detector in the NaI(Tl) channels with spectrum line 59.5 keV (^{241}Am) and 121.8 keV (^{152}Eu); in the CsI(Tl) channels with spectrum line 661.7 keV (^{137}Cs) and 1408 keV (^{152}Eu). The calibrations are kept in the computer code MAESTRO-32, which is the code for administration of spectrum parameters;
    - Check the detector sensitivity on the basis of the count rates from standard gamma-emitting sources; and
    - Measurement of background levels based on spectrum measurements of the empty shielding room. Data on background counts in the ranges 25–145 keV; 560–760 keV; and 1310–1610 keV are kept in MAESTRO-32 and compared with previously obtained values.
2. Measurement of patient
    - Measure the patient's height and weight. Individual data are recorded into the computer code SICHDB which records the measurement procedure,
    - The patient lies on his/her back on the movable bed in standard position. Scanning occurs inside the shielded room with following standard parameters: scanning starts from the patient's head; scanning is uniform on the entire length of the body, time of scanning is 20 min. The code SICHDB controls the time of start and finish of measurement, performs some quality checks, and processes the primary spectrum.

- The code SICHDB automatically passes the obtained spectrum to the computer code ASW_SICH, which calculates the following parameters for each radionuclide: body burden, relative error (%) of body burden; statistical estimation of minimal measurable activity for a specific patient (spectrum); and statistical estimation of detection threshold. If the relative error (%) of radionuclide-body burden is higher than 90%, the radionuclide body burden is assumed to be undetected, i.e., <minimal measurable activity.
- The data on radionuclide characteristics are returned to the code SICHDB, where they are accumulated into the data base of SICH-9.1M measurements and can be presented in standard paper form, if desired.

2.3 Quality assurance

Analysis of the empty shielding-room background. Data on 73 measurements of the empty shielding room, performed form 1 June 2006 to 6 July 2010 were analyzed. The empty shielding room background essentially depends on the quantity of natural radon and its progeny. In order to improve the quality of measurements, the ventilation system was improved in 2007, which reduced the variations in background values. Table 3 presents the values of total count rate for 20 min for different energy ranges. As can be seen, the differences are most pronounced at low energies, where the bremsstrahlung of the ^{90}Sr-^{90}Y spectrum is detected.

Stability of registration. According to the *technique of measurement* the spectrum (count rates) of the UP-02T phantom set, measured without the radioactive source, is used as the background spectrum to be subtracted from the patient's spectrum. So, the spectrum of the UP-02T phantom is an important component for estimation of radionuclide body burden.

Analysis of the stability of phantom measurements (without radioactive sources) is shown for the example of phantom Ph-4 from the UP-02T set, which corresponds to the anthropometric characteristics of more than 40% of the patients. Table 4 presents the daily coefficients of variation of the total count rate in selected energy ranges for Ph-4, which is measured several times during the day.

Table 3. Total count rate and coefficients of variation (CV) during 20 min for different energy ranges during measurement of the empty shielded room.

Energy range of spectral scan, keV	Before ventilation improvements, N = 41		After ventilation improvements, N = 32	
	Average	CV, %	Average	CV, %
40–150[a]	**180**	**8**	**161**	**4**
400–560	105	8	99	4
560–650	95	8	89	5
585–730[b]	**77**	**10**	**71**	**7**
1050–1200	31	7	29	5
1350–1560[c]	**21**	**7**	**20**	**5**
1650–1850	15	8	14	8
2500–2720	6	11	4	18

[a] range of ^{90}Sr detection;
[b] detection of ^{137}Cs; and
[c] detection of ^{40}K.

As can be seen from Table 4, the daily coefficients of variation insignificantly changed during 2006–2010 and vary from 2 to 12% depending on energy range. Some increase in the coefficient of variability on 24 December 2007 can be explained by instability of the ventilation system or background fluctuation during this day. The best reproducibility was observed in the range of ^{137}Cs detection (560–730 keV). Maximal dispersion was observed in the high energy range, 2500–2720 keV.

Fig. 5 shows the total count rate during 20 min (monthly average relative to the total average obtained for all time of observation) in ranges of spectral scan corresponding to ^{90}Sr, ^{137}Cs and ^{40}K. As can be seen in Fig 5, good reproducibility (about 10%) of measurements of Ph-4 is observed during the period of 2006–2011. A trend with time was not observed. That allowed the averaging of the results of Ph-4 background measurements (126 spectra) and to

Table 4 Daily coefficient of variation of total count rate in different energy ranges for Ph-4.

Date of measure-ments	N	Coefficient of variation (%)of total count rate in different energy ranges of spectral scan, keV							
		40–150[a]	400–560	560–650	**585–730**[b]	1050–1200	**1350–1560**[c]	1650–1850	2500–2720
25.05.2006	5	**6**	2	2	**3**	4	**5**	7	8
29.06.2006	7	**5**	2	3	**3**	4	**6**	7	11
26.09.2007	3	**5**	3	2	**2**	3	**4**	5	17
01.10.2007	5	**6**	2	4	**3**	4	**6**	7	9
24.12.2007	7	**12**	4	12	**9**	10	**8**	11	10
25.12.2007	10	**5**	3	3	**2**	5	**5**	7	14
27.12.2007	23	**6**	3	5	**4**	5	**5**	8	14
04.03.2008	15	**6**	3	6	**5**	5	**5**	7	12
11.03.2008	3	**5**	2	3	**3**	4	**4**	5	13
12.03.2008	3	**5**	1	2	**2**	3	**5**	4	10
07.07.2008	7	**5**	2	3	**2**	4	**5**	7	12
09.07.2008	17	**5**	2	3	**3**	5	**5**	8	10
29.06.2010	2	**5**	2	5	**4**	4	**5**	7	9
30.06.2010	5	**5**	2	2	**2**	4	**5**	5	15
02.07.2010	5	**6**	2	4	**4**	6	**5**	6	11
Average	117	**6**	2	4	**3**	5	**5**	7	12

[a] range of ^{90}Sr detection;
[b] detection of ^{137}Cs; and
[c] detection of ^{40}K.

receive the so called "average background spectrum" that was used in the SICHDB-1 code for derivation of radionuclide-body content in individuals.

The efficiency of activity detection is the important characteristic of SICH-9.1M. It was described in terms of the sensitivity coefficient (SC) calculated with use of data on calibration phantoms. The calculation was performed according to the standard method from the certified

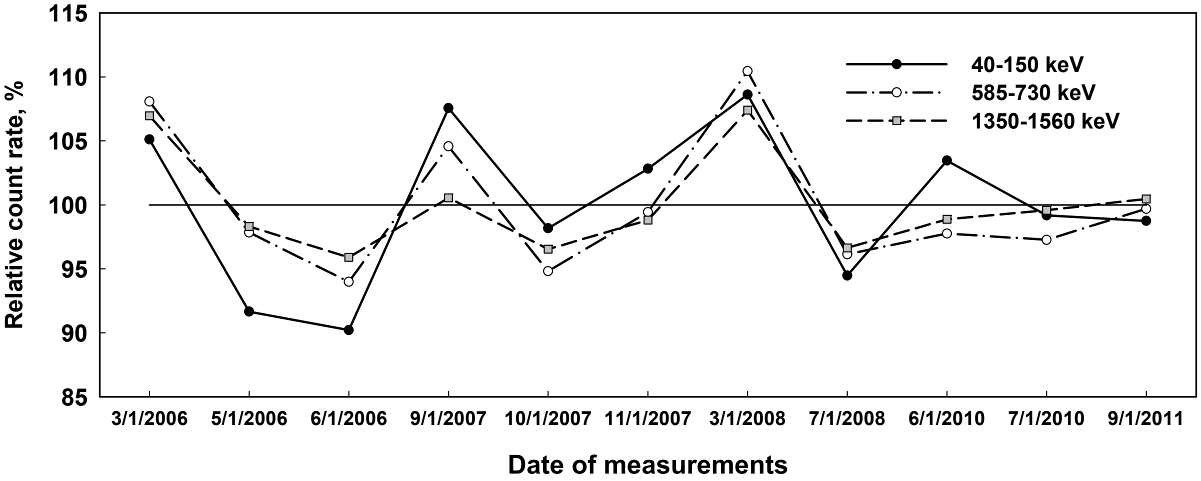


Fig. 5 Monthly average relative count rate (%) reflected monthly average obtained over the all-time of observation in energy ranges of spectral scan corresponding to ^{90}Sr, ^{137}Cs and ^{40}K

technique of measurements using equation (1):

$$c_{ijl} = \frac{\overline{n}_{ijl} - \overline{n}_{\phi jl}}{A_{0i}} \quad , \tag{1}$$

where

c_{ijl} = sensitivity of recording of ***i*** radionuclide in ***j*** energy range at measurements of *l* phantom (imp s^{-1} Bq^{-1});

$\overline{n}_{ijl}$ = average count rate in *j*-energy range, obtained by measurement of *i* radionuclide in *l* phantom, s^{-1};

$\overline{n}_{bjl}$ = average count rate in j-energy range, obtained by measurement of l phantom without radionuclide (background (b) phantom), s-1.

A_{0i} = value of activity in *l* phantom at the time of measurement (calculated on the basis of value from certificate), Bq.

Table 5 presents the results of calculations of the CS for ^{90}Sr.

Table 5. ^{90}Sr sensitivity coefficient for SICH-9.1M in 2006–2011.

Date of measurements	Activity of FTS-06T(1), kBq	SC, Imp s^{-1} Bq^{-1} (number of spectrum)	^{90}Sr in FTS-06T(2), kBq	SC, Imp s^{-1}Bq^{-1} (number of spectrum)	Difference of ^{90}Sr activity FTS-06T(2)-FTS-06T(1), kBq[a]	SC, Imp s^{-1} Bq^{-1} (number of spectrum)
09.06.2006	36.6	0.001 (3)	194.3	0.0010 (3)	157.7	0.00096 (3)
11.10.2007	35.4	0.00098 (7)	188.2	0.00097 (12)	152.7	0.00096 (7)
21.03.2008	35.1	0.00099 (7)	186.2	0.00097 (7)	151.1	0.00097 (7)
06.07.2010	33.2	0.00098 (7)	176.2	0.00098 (7)	143.0	0.00098 (7)
09.07.2010	33.1	0.001 (10)	175.9	0.00098 (10)	142.8	0.00097 (10)
19.10.2011	32.2	0.001 (5)	170.0	0.00099 (5)	157.7	0.00096 (5)
	Average	0.001	Average	0.001	Average	0.001

[a] calibration on the basis of two phantoms, FTS-06T(1) is used as background.

The sensitivity coefficients for detection for ^{40}K and ^{137}Cs were estimated on the basis of phantom Ph-4 (Table 6). As can be seen, there have not been systemic biases in the SC values for ^{40}K and ^{137}Cs in 2006–2011. As a whole the WBC system SICH-9.1M has remained stable.

Table 6. Sensitivity coefficients for ^{137}Cs and ^{40}K for SICH-9.1M in 2006–2011.

Date of measurements	Number of spectra	^{137}Cs activity, kBq	SC, Imp s^{-1} Bq^{-1}	^{40}K activity, kBq	SC, Imp s^{-1} Bq^{-1}
08.06.2006	3	9.52	0.0102	4.9	0.00094
09.10.2007	5	9.23	0.0102	4.9	0.00092
21.03.2008	5	9.14	0.0101	4.9	0.00099
05.07.2010	7	8.66	0.0104	4.9	0.00096
19.10.2011	5	8.42	0.0103	4.9	0.00095
	Average		0.0102	Average	0.00096

2.4 Individual anthropometric characteristics

Individual anthropometric characteristics (height and mass) are used to select an adequate phantom from the UP-02T set for analysis of individual spectra. An anthropometric index is calculated as $\sqrt{h/M}$, where h is height in cm and M is mass in kg. Table 7 shows the values of anthropometric index (A) for each phantom; and the average thickness of tissue characterizing the absorption of gamma emissions from the anthropomorphic phantom. Table 7 also presents the number of individuals for which the specific phantom was selected. As can be seen, most individuals corresponded to Ph-4 and Ph-5 (more than 80% of measurements).

Analysis of anthropometric characteristics of measured individuals has shown that A values were obtained at other values of height and mass than are shown in Table 7. Persons whose A values corresponded to Ph-4 had an average height of 160 cm and mass of 67 kg. If A values corresponded to Ph-5, the average height was equal to 161 cm and mass of 82 kg. Obviously, the anthropometric characteristics essentially depend on age and gender. Table 8 presents the characteristics of measured persons. As seen, most of people are older than 40 y (80%). and women are a large fraction of the group.

Table 7. Characteristics of the UF-02T phantom set and the number of individuals with corresponding A values.

Phantom	Anthropometric characteristic of phantoms						Number of individuals (%)
	Age, y	Mass (M), kg	Height (h), cm	Average thickness of tissue, cm	$A = \sqrt{h/M}$	Ranges of A values for phantom choice	
Ph-1	2	12	82.5	8.8	2.62	≥2.434	0
Ph-2	6	24	121.0	10.9	2.24	2.017≤A<2.434	6 (0.1)
Ph-3	14	50	160.0	11.8	1.79	1.675≤A<2.017	411 (8)
Ph- 4	≥18	70	170.5	14.3	1.56	1.469≤A<1.675	2093 (41)
Ph-5	≥18	90	170.5	15.7	1.38	1.311≤A<1.469	2130 (41)
Ph-6	≥18	110	170.5	19.4	1.24	<1.311	521 (10)

Table 8. Anthropometric characteristics of persons measured with SICH-91M in 2006–2011.

Gender	Age, years	Height, cm, M±SD	Weight, kg, M±SD	$A=\sqrt{h/M}$ M±SD	Number of person (%)
Men	<20	168.0 ± 12.6	59.6 ± 13.2	1.71 ± 0.15	49 (2.7)
	20-29	172.8 ± 6.8	71.9 ± 15.5	1.57 ± 0.14	113 (6.1)
	30-39	172.9 ± 5.9	80.4 ± 14.7	1.48 ± 0.12	130 (7.1)
	40-49	170.9 ± 6.9	79.5 ± 15.4	1.48 ± 0.13	272 (14.8)
	50-59	169.3 ± 6.0	80.7 ± 14.2	1.46 ± 0.12	557 (30.3)
	60-69	167.4 ± 6.3	78.0 ± 14.8	1.48 ± 0.13	429 (23.3)
	70-79	163.6 ± 6.0	74.7 ± 13.2	1.50 ± 0.12	272 (14.8)
	>80	163.5 ± 4.3	69.0 ± 9.7	1.55 ± 0.10	17 (0.9)
Total					*1839 (100)*
Women	<20	160.1 ± 6.89	56.3 ± 13.3	1.72 ± 0.19	36 (1.1)
	20-29	160.8 ± 6.48	57.4 ± 10.6	1.69 ± 0.14	127 (3.8)
	30-39	160.1 ± 6.02	67.0 ± 14.1	1.57 ± 0.15	213 (6.4)
	40-49	158.4 ± 5.88	72.9 ± 14.4	1.49 ± 0.14	579 (17.4)
	50-59	156.7 ± 5.48	76.3 ± 14.9	1.45 ± 0.13	983 (29.6)
	60-69	154.6 ± 5.37	76.0 ± 14.6	1.45 ± 0.13	815 (24.5)
	70-79	151.6 ± 5.22	71.9 ± 13.1	1.47 ± 0.13	525 (15.8)
	>80	149.0 ± 4.81	66.2 ± 12.4	1.52 ± 0.14	44 (1.3)
Total					*3322 (100)*

3. MATCHING OF DATA OBTAINED WITH THE OLD AND THE NEW WBC SYSTEMS (SICH-9.1 AND SICH-9.1M)

3.1. Comparison of SICH-9.1 and SICH-9.1M in terms of efficiency of detection (sensitivity coefficient)

Calculations of sensitivity coefficients for the old and new WBC systems were performed according to the corresponding techniques of measurements (equation 1). Standard energy ranges of spectral scans that should be used for calculation are not quite identical in the old and the new techniques but are very close. For SICH-9.1M the following energy ranges are used for standard calculation: 40–150 keV; 585–730 keV; 1350–1560 keV. For SICH-9.1 these ranges are 30–160 keV, 620–740 keV, and 1400–1580 keV (Belle et al., 1973; Belle et al., 1975; Kozheurov 1994). Data on measurements on the same phantoms performed with the two WBC systems were compared. For ^{90}Sr it was phantom FTS-06T(1) (Kovtun et al., 2000b); for ^{40}K and ^{137}Cs phantom Ph-4 was used. It should be noted that the count rates of Ph-4 without radionuclide sources were used as background count rates for anthropomorphic phantom FTS-06T(1). Table 9 presents the results of ^{137}Cs and ^{40}K measurements with the two WBC systems; Table 10 shows the data on ^{90}Sr.

As can be seen from Table 10, the sensitivity coefficient of SICH-9.1M is higher than that for SICH-9.1 by a factor of 3–5 depending on energy range. It should be noted that the energy scale resolution of SICH-9.1M is significantly better than that of SICH-9.1: 512 detecting channels versus 256. Integral nonlinearity (characteristic of accuracy of energy scale graduation) for SICH-9.1 was estimated as 6.7%; for SICH-9.1M this value was considerably lower at 0.25%.

Table 9. Efficiency of detection of ^{137}Cs and ^{40}K with SICH-9.1 and SICH-9.1M (phantom Ph-4).

WBC	Year	^{137}Cs, imp s^{-1} Bk^{-1} (energy range, keV)		^{40}K, imp s^{-1} Bk^{-1} (energy range, keV)	
SICH-9.1	1998	0.0027 (620–740)	0.0016 (30–160)	0.006 (1400–1580)	0.008 (30–160)
SICH-9.1M	2006	0.0103 (585–730)	0.0057 (40–150)	0.03 (1350–1560)	0.027 (40–150)

Table 10. Efficiency of detection of ^{90}Sr with SICH-9.1 and SICH-9.1M [phantom FTS-06T(1)].

WBC	Year	^{90}Sr, imp s^{-1} Bk^{-1} (energy range, keV)
SICH-9.1	1998	0.00028 (30–160)
SICH-9.1M	2006	0.001 (40–150)

3.2. Strontium-90 measurements

The total number of measurements performed with use of SICH-9.1M in the period from 15 June 2006 to 30 September 2011 was 5161; the number of persons measured was 4364. Characteristics of people measured according to their involvement in different radiation accidents are presented in Table 11. The members of epidemiological cohorts [Extended Techa River Cohort (ETRC) and Techa River Offspring Cohort (TROC)] are specially indicated. As follows from Table 11, about 80% of persons lived in the radioactive contaminated territories (Techa River and EURT settlements). Twenty five per cent of measured ETRC members and 55% of TROC members were measured for the first time.

Other people belong to the following groups: the control group (specially invited for background measurements; not present in database "Man" of URCRM); persons who worked/served in the Semipalatinsk testing area; Chernobyl liquidators; persons who requested a measurement on their own initiative; and employees of URCRM.

Table 11. Characteristic of data set obtained with use SICH-9.1M (measurements of 15 June 2006–30 September 2011).

Characteristics of individuals	Number of persons
Total measured	4364
Lived in Techa Riverside settlements in different periods of time	2665
ETRC members	1025
Measurements of ^{90}Sr >Detection limit	331
TROC members	1421
Measurements of ^{90}Sr > Detection limit	36
Lived in EURT settlements in different periods of time	781
Were measured with SICH-9.1 in the period 1974-1997	1637
ETRC members	760
TROC members	634

EURT – East Urals Radioactive Trace

Two approaches were used for matching data sets obtained with the new and the old WBC systems:

- Comparison of individual data for persons with high ^{90}Sr-body burden (most reliable data); and
- Statistical analysis based on pairwise comparison of individual data for all persons measured with both the new and the old WBC.

3.2.1. Comparison of individual data for persons with high ^{90}Sr-body burdens

Persons were selected according to the following conditions:

1) High ^{90}Sr-body burden; in 2006–2011 the values should be $\geq$5 kBq; and
2) The person has to have three or more measurements performed in 1974–1997 with use of SICH-9.1; that allows for a reliable estimate of the rate of biological elimination of ^{90}Sr from the body (λ_b).

Data for 74 persons satisfied the above-listed requirements. The total number of SICH-9.1 measurements was equal to 851, and the number of SICH-9.1M measurements was 74. Two kinds of calculations were performed for these persons: (1) estimation of biological rate of ^{90}Sr elimination from the body on the basis of SICH-9.1 data and (2) estimation of biological rate of ^{90}Sr elimination on the basis of combined data of SICH-9.1 and SICH-9.1M. The term "biological rate" (λ_b) means the value of ^{90}Sr-diminution rate after subtraction of the rate of ^{90}Sr radioactive decay (2.38% y^{-1}).

Table 12 presents the statistical characteristics of two sets of λ_b. As seen, the additional data of 2006–2011 leads to insignificant changes in the rates of ^{90}Sr elimination. However, the tendency for an increase in the strontium elimination rate in the case of joint analysis is obvious. Comparison of the two distributions with use of parametric and nonparametric tests have not shown differences between them (p = >0.1). Because the values of elimination rates for specific persons should be considered as independent parameters, the Wilcoxon test was applied: this

Table 12. Statistical characteristics of biological rate (λ_b) of strontium elimination from the body based on SICH-9.1 data set and joint data of SICH-9.1 and SICH-9.1M.

Sample	Minimum (% year^{-1})	Percentiles of λ_b (% year^{-1})					Maximum (% year^{-1})
		5%	25%	50%	75%	95%	
SICH-9.1	0.4	1.6	2.4	2.8	3.9	4.9	9.7
SICH-9.1+ SICH-9.1M	1.5	1.8	2.6	3.3	4.2	5.1	9.1

test analyzes only the differences between the paired measurements for each subject. It was found that the differences should be assumed as significant ($p = 0.0003$).

The increase in strontium-elimination rates after the extension of the time period of observation is understandable and expected. As shown earlier (Shagina et al., 2011), the rate of ^{90}Sr elimination increases with age, and this is explained by the age-related increase of bone loss both in men (after 60 years) and women (after 50 years).

Fig. 6 illustrates the data on individual-WBC measurements. As can be seen, individual joint data sets can be described by a single exponential function that characterizes the rate of strontium elimination.

3.2.2. Statistical approach

The statistical approach involved the comparison of expected (calculated) values of ^{90}Sr-body-burden on the basis of SICH-9.1 measurement (1974–1997) and results of direct measurements of SICH-9.1M (2006–2011). For this purpose data for all persons measured with both WBC systems were used (n = 1637). For calculations, the result of last-time measurement with SICH-9.1 and the first-time measurement with SICH-9.1M were selected for each person. In order to extrapolate the result of SICH-9.1 measurement to the date of SICH-9.1M measurement, the average value of strontium biological elimination rate (3% y^{-1}) and the rate of ^{90}Sr radioactive decay (2.38% y^{-1}) were taken into account.

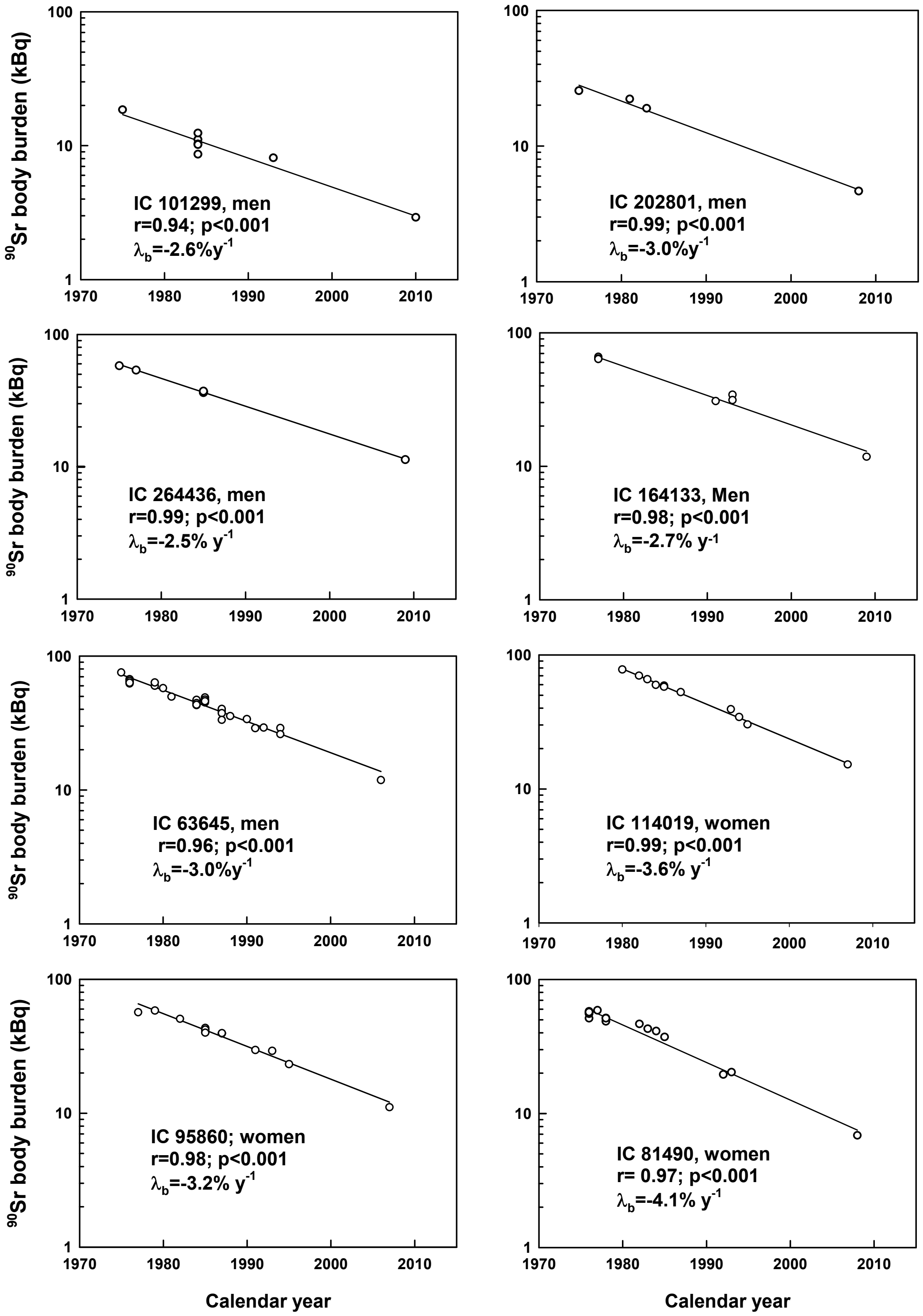


Fig. 6. Examples of individual data sets on ^{90}Sr measurements with use of SICH-9.1 (data of 1974–1997) and SICH-9.1M (data of 2006–2011). Individual data sets were described by a single exponential function (lines) with a high level of reliability. IC –individual identification code maintained in URCRM databases.

Fig. 7 shows good agreement between data of the old and the new WBC systems. The slope of the regression line is close to unity (0.97). The dispersion of the ^{90}Sr-body-burden values around the regression line can be explained by significant variability of individual rates of strontium elimination (Table 12).

3.3. Potassium-40 measurements

Potassium-40 is a naturally occurring radionuclide. Its quantity in adult men of 70 kg weight is about 4–5 kBq (ICRP-23, 1977), which is explained by the significant mass of stable potassium in the human body (about 140 g). Because the relative content of ^{40}K in the mix of natural potassium isotopes is constant, the WBC measurements allow estimation of potassium-body content based on the measurement of ^{40}K. As has been shown (Gallagher et al., 1997; Silva et al., 2010), a significant part of body potassium is accumulated in muscles; its quantity is relatively low in skeletal and adipose tissue. So, the value of potassium-body-content is proportional to muscles mass, which in turn, depends on age, gender, and physical activity. Furthermore, muscular mass also depends on ethnicity in terms of constitutional features

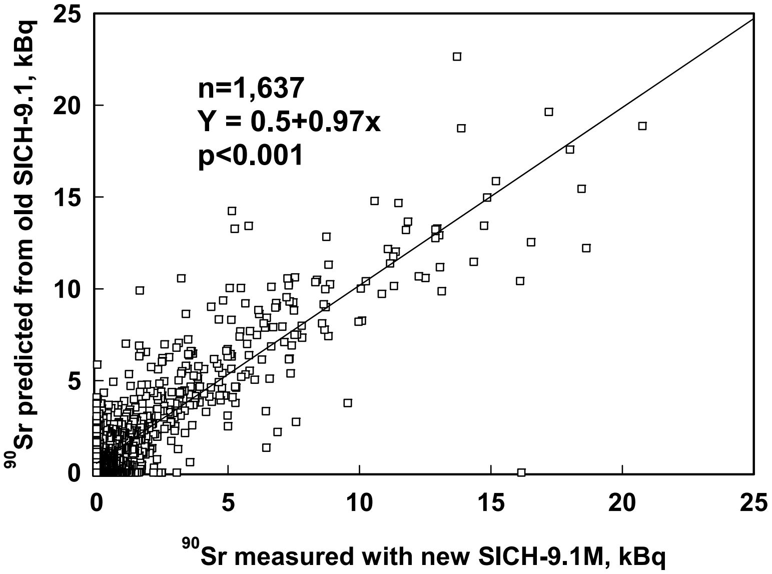


Fig. 7. Comparison of data on direct SICH-9.1M measurements (X-axis) and values calculated on the basis of SICH-9.1 data (Y-axis); the regression line and its characteristics are shown.

(percent of muscular mass, height, and body proportions) (Flynn et al., 1989; Gallagher et al., 1997; Silva et al., 2010; He et al., 2003). In the present study it is assumed that the specific activity of natural ^{40}K is equal to 2.652 × 10^5 Bq g^{-1}, in accordance with the natural abundance of ^{40}K of 0.0118%. Therefore, the value of potassium-body-content (g) was calculated according to following equation (2):

$$K = \frac{A_{40K}}{31.29}, \tag{2}$$

where

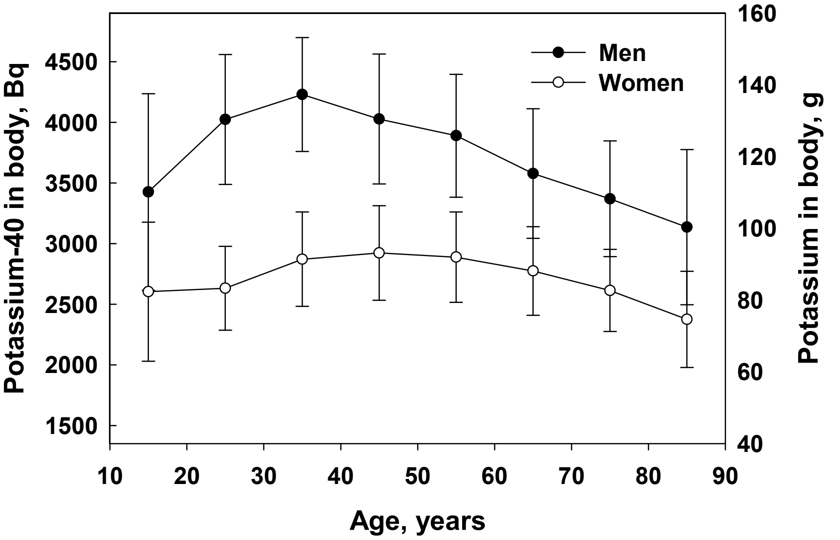
A_{40K} = value of ^{40}K in the body measured with the SICH (Bq); and

31.29 = conversion factor obtained as 2.652 × 10^5 × 1.18 × 10^{-4} (Bq g^{-1}).

If the relative error of specific measurement of ^{40}K was higher than 90% (it is possible due to fluctuation of radon concentration in the shielding room), such measurements were not used for estimates of ^{40}K body content. The data on ^{40}K- and potassium-body content obtained with SICH-9.1M are presented in Table 13. Fig. 8 shows average values depending on age and gender. As whole, the data measured with SICH 9.1M are in agreement with published results (Table 14).

Table 13. Results of SICH-9.1M measurements of ^{40}K and potassium in Urals residents in 2006–2011.

Parameter	Men			Women		
	Age, years	^{40}K in the body, kBq	Body potassium, g	Age, years	^{40}K in the body, kBq	Body potassium, g
Minimum–maximum	9–84	1.6–5.6	52–178	10–90	1.0–4.3	31–136
90% range	23–75	2.8–4.7	88–151	30–74	2.2–3.5	70–111
Median	56	3.8	121	57	2.8	89



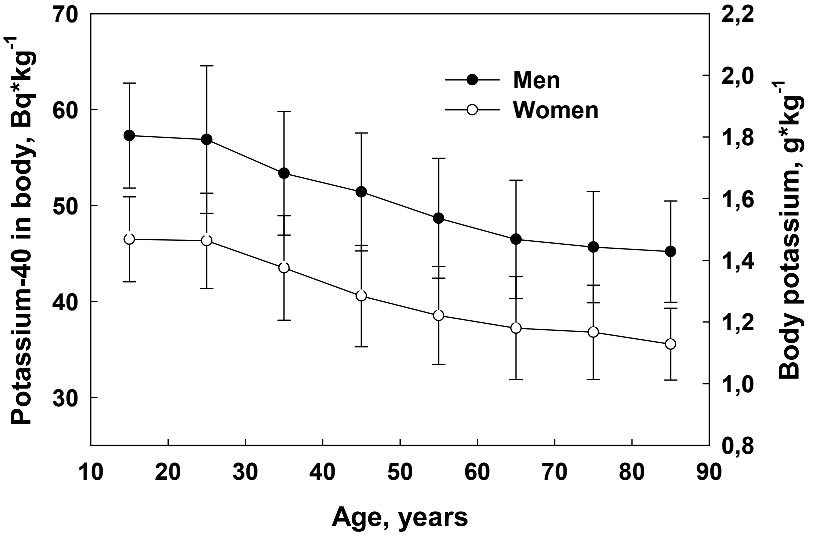


Fig. 8. Total body potassium and ^{40}K (a) in men (n = 1769) and women (n = 3117); and values normalized to body mass (b). Vertical lines represent the range of standard deviations.

In order to compare the results of ^{40}K measurements obtained with the new and the old SICH WBCs, persons of appropriate age (30–39 years old) and genders were selected. Table 15 shows the results of the comparison. It was found that the total potassium content in body, height, and mass are higher in men measured with SICH-9.1M in 2006–2011 than in the corresponding group measured in 1974–1997. For women such differences were not found: the

Table 14. Comparison of published data on ^{40}K measurements and data obtained with SICH-9.1M.

Group	Gender	Age	^{40}K, kBq	K, g kg^{-1}	Source
Hanford workers	W	Adults	3.1±0.02	1.4±0.3	Lynch et al., 2004
	M		4.2±0.01	1.7±0.3	
Workers of Egyptian nuclear plants	W	Adults	4.1±0.03	2.0±0.5	Gohary et al., 2010
	M		5.2±0.02	2.1±0.4	
Urals residents	W	30-49	2.9±0.03	1.3±0.2	Present study
	M		4.1±0.01	1.7±0.2	

Table 15. Comparison of anthropometric parameters and potassium body contents in men and women of 30-39 years measured by SICH-9.1 and SICH-9.1M.

Gender	Parameter	Old SICH-9.1 Average ±standard deviation		New SICH-9.1M Average ±standard deviation	
Men	Potassium. g	119 ± 22	N=504	135 ± 15[a]	N=128
	Body height. cm	171 ± 6		173 ± 6[b]	
	Body mass. kg	74 ± 12		81 ± 15[a]	
Women	Potassium. g	90 ± 21	N=713	92 ± 12	N=202
	Body height. cm	160 ± 6		160 ± 5	
	Body mass. kg	69 ± 14		67 ± 15	

[a] the difference is significant at p = <0.001

[b] the difference is significant at p = <0.05.

similar aged groups of women differed neither on anthropometric parameters nor on ^{40}K contents. This implies that the differences observed for men are not a systematic bias due to technical features of equipment and/or calibration. The differences can be explained by changes in men's physique during the last 20 years. Therefore, it is concluded that there is good agreement between SHICH-9.1 and SICH-9.1M measurements of potassium.

It should be noted that another conversion factor, equal to 30.23 Bq g^{-1} (Belle et al., 1973), was used for conversion of the ^{40}K value to potassium content in 1974–1997. This conversion factor corresponded to data on ^{40}K radioactive decay rate available in that time period. Therefore the results obtained with SICH-9.1 should be assumed as overestimated by 3.5%. This does not influence the results of the above data comparison.

4. DISCUSSION

The analysis of SICH-9.1M measurements has shown that the spectrometer was stable during 2006–2011. Efficiency of detection, derived from the calibration-phantom measurements, did not change significantly during this period; the variability of efficiency did not exceed 1% (Tables 5 and 6). The variability of background level estimated with use of the UP-02T Ph-4 phantom without insertion of the core sources did not exceed 10%; that corresponds to ordinary fluctuation of background levels. The coefficient of variation of empty-room background levels was also close to 10% (Table 4).

Comparison of SICH-9.1 and SICH-9.1M in terms of efficiency of detection has shown that the sensitivity of SICH-9.1M is higher than that of SICH-9.1 by a factor of about three. It should be noted that the energy scale resolution of SICH-9.1M is better than that of SICH-9.1 by a factor of two. In the period from 15 June 2006 to 30 September 2011, 5161 measurements of 4364 persons were performed. Matching of data sets obtained with SICH-9.1 and SICH-9.1M was performed for ^{90}Sr and ^{40}K.

Strontium-90. About 12% of the ^{90}Sr measurements made with SICH-9.1M were higher than the detection limit. Reliable levels of ^{90}Sr-body burden were mainly detected (90%) among the members of the ETRC. They had ingested ^{90}Sr due to residence on the Techa River and use of Techa River water and local foodstuffs in the 1950s. The maximal measured value was equal to 24 kBq. Isolated cases of reliable levels of ^{90}Sr-body contents were observed for members of the TROC and for residents on the EURT. Data from persons measured both with SICH-9.1 and SICH-9.1M were used for matching of data sets on ^{90}Sr. The comparison has shown good agreement between the two data sets (Table 12; Figs. 6 and 7). Therefore, the two data sets (data of 1974–1997 and 2006–2011) can be analyzed together. This increases the number of measurements and allows investigation of age-dependents features of strontium metabolism over the combined time interval.

Potassium-40 is a naturally occurring radionuclide. According to SICH-9.1M data (2006–2011), the levels of ^{40}K-body contents depend upon gender, age, and body mass. As a whole, they are in agreement with published data for other populations. It was found (Table 15) that for persons with similar body characteristics (gender, age, body mass, and height) both SICH WBCs detected similar values of ^{40}K in the body; thus, it is concluded that there is good agreement between two data sets on ^{40}K measurements.

5. CONCLUSION

The comparison of data sets obtained with the old and the new WBC systems have shown good agreement for measured data on ^{90}Sr and ^{40}K.

The results obtained in 1974–1997 and 2006–2011 can be analyzed together; this increases the statistical power of the measurements and provides the opportunity to derive more accurate estimates of internal dose. The pooled data set on ^{90}Sr-body burdens provides the basis for further investigation of ^{90}Sr metabolism over an period of time and of age of the measured persons.

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