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Review

Consequences of the radiation accident at the Mayak production association in 1957 (the 'Kyshtym Accident')

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Abstract

This paper presents an overview of the nuclear accident that occurred at the Mayak Production Association (PA) in the Russian Federation on 29 September 1957, often referred to as 'Kyshtym Accident', when 20 MCi (740 PBq) of radionuclides were released by a chemical explosion in a radioactive waste storage tank. 2 MCi (74 PBq) spread beyond the Mayak PA site to form the East Urals Radioactive Trace (EURT). The paper describes the accident and gives brief characteristics of the efficacy of the implemented protective measures that made it possible to considerably reduce doses to the exposed population. The paper also provides retrospective dosimetry estimates for the members of the EURT Cohort (EURTC) which comprises approximately 21 400 people. During the first two years after the accident a decrease in the group average leukocyte (mainly due to neutrophils and lymphocytes) and thrombocyte count was observed in the population. At later dates an increased excess relative risk of solid cancer incidence and mortality was found in the EURTC.

Keywords: radiation accident, protective measures, exposure dose, radiation risk, solid cancers

(Some figures may appear in colour only in the online journal)

1. Introduction

The 'Kyshtym Accident', which happened on 29 September 1957 at the Mayak Production Association (PA) nuclear complex, located about 10 km to the east of the town of Kyshtym in Chelyabinsk Oblast, Russian Federation, although rated on the International Nuclear and Radiological Event Scale as one of the most severe nuclear accidents in the world, remained little known in the West until recently. Information about the causes of the accident and its consequences was unavailable for more than 30 years not only for the general population but also for the scientific community. Nevertheless, the health status of the population of radioactively contaminated territories of the East Urals Radioactive Trace (EURT) to the northeast of Mayak and which was formed as a result of the accident, has been and is regularly monitored, and radiological measurements of environmental media and people are performed on a regular basis. From 1957 until now the population of the EURT has been subjected to medical examination and treatment in the Clinic of the Urals Research Center for Radiation Medicine (URCRM) in the city of Chelyabinsk. Moreover, URCRM staff study the behavior of the radionuclide distribution in the environment, migration paths through trophic chains and intakes by human beings and animals.

The exposed population registry, individual doses of the exposed population as well as the medical-dosimetric database of the URCRM, which comprises the results of long-term dosimetric monitoring and medical follow-up of the population, form the basis for arranging medical assistance to the EURT population and for the analysis of the long-term health effects in the population.

The first papers on the causes and consequences of the accident were published outside the Russian Federation, and they were characterized by inaccurate statements of facts and had a large proportion of false stories [1, 2]. Although the first general conclusions concerning the consequences of the accident were made by URCRM staff in 1975, they were published in publicly available media only in 1990 [3]. A monograph published in 2001 provided information on radio-ecological and medical effects of the accident obtained over a longer period of follow-up [4].

The objective of the current paper is to provide an overview of radio-ecological, dosimetric and medical-biological consequences of the 1957 accident at Mayak PA over a 60 year period of follow-up.

2. Description of the accident and EURT formation

Starting in the earliest period of Mayak PA activities, large amounts of liquid high-level radioactive waste from the radiochemical facility were placed into long-term controlled storage in metal tanks installed in concrete vaults. Each full tank contained 70–80 tons of radioactive wastes, mainly in the form of nitrate compounds. The tanks were water-cooled and equipped with temperature and liquid-level measurement devices. In September 1957, as a result of a failure of the temperature-control system of tank #14, cooling-water delivery became insufficient and radioactive decay caused an increase in temperature followed by complete evaporation of the water, and the nitrate salt deposits were heated to 330 °C–350 °C. The thermal explosion of tank #14 occurred on 29 September 1957 at 4:20 pm local time. At the time of the explosion the activity of the wastes contained in the tank was about 740 PBq [5, 6]. About 90% of the total activity settled in the immediate vicinity of the explosion site

Table 1. Radionuclide composition of the release of 1957 [7].

Radionuclide	Contribution to the total activity, %
$^{90}Sr + ^{90}Y$	5.4
$^{95}Zr + ^{95}Nb$	24.8
$^{106}Ru + ^{106}Rh$	3.7
$^{144}Ce + ^{144}Pr$	65.8
$^{137}Cs + ^{137m}Ba$	0.35
^{89}Sr	Traces
^{147}Pm	Traces
^{155}Eu	Traces
^{239}Pu	0.002

(within distances less than 5 km), primarily in the form of coarse particles. The explosion gave rise to a radioactive plume which dispersed into the atmosphere. About 2×10^6 Ci (74 PBq) was dispersed by the wind (north-northeast direction with wind velocity of 5–10 m s^{-1}) and caused the radioactive trace along the path of the plume [5]. Table 1 presents the latest estimates of radionuclide composition of the release used for reconstruction of doses in the EURT area. The mixture corresponded to uranium fission products formed in a nuclear reactor after a decay time of about 1 year, with depletion in ^{137}Cs due to a special treatment of the radioactive waste involving the extraction of ^{137}Cs [6].

The formation of the EURT was complete after 10–11 h. Figure 1 shows a schematic map of ^{90}Sr soil deposition as reconstructed for 1957 [8]. The unit Ci km^{-2} (37 kBq m^{-2}) of ^{90}Sr was used in the official maps of radionuclide deposition and in the procedures of dose calculations for residents of the contaminated area. In addition, a level of ^{90}Sr deposition equal to 1 Ci km^{-2} (37 kBq m^{-2}) was historically established as the 'reference deposition'. Thus, the unit Ci km^{-2} is used in the present study.

The terrain in which the radioactive trace was formed is forest-steppe with a uniform relief. About one third of the EURT territory is occupied by forest, alternating with fields. There are also a few large virgin meadow tracts, and a number of lakes within the contaminated area (figure 1).

It was established during the first year after the accident that the total contaminated area bounded by 0.1 Ci km^{-2} for ^{90}Sr (a reliably detectable level equal to double the value of global background contamination as of the date of the accident) comprised 23 000 km^2. 217 settlements with a population of about 270 thousand people were located in this territory. Within the bounds of 2 Ci km^{-2} for ^{90}Sr, the contaminated area amounted to 1000 km^2. This territory acquired the official status of a contaminated area, and it is in this territory that the implementation of radiation protection measures for the population was considered indispensable. The territory of radioactive fallout also covered the facilities of the Mayak PA which had to continue its activities together with the implementation of countermeasures. Secondary transport of radioactive fallout to Ozyorsk city, adjacent to Mayak, required protective measures for the residents.

3. Radiation protection activity and monitoring

The first data on the levels of γ-radiation along the axis of the EURT for distances up to105 km from the epicenter were obtained by Mayak PA specialists on the night of 29–30 September 1957. Protective measures for the population comprised both emergency and

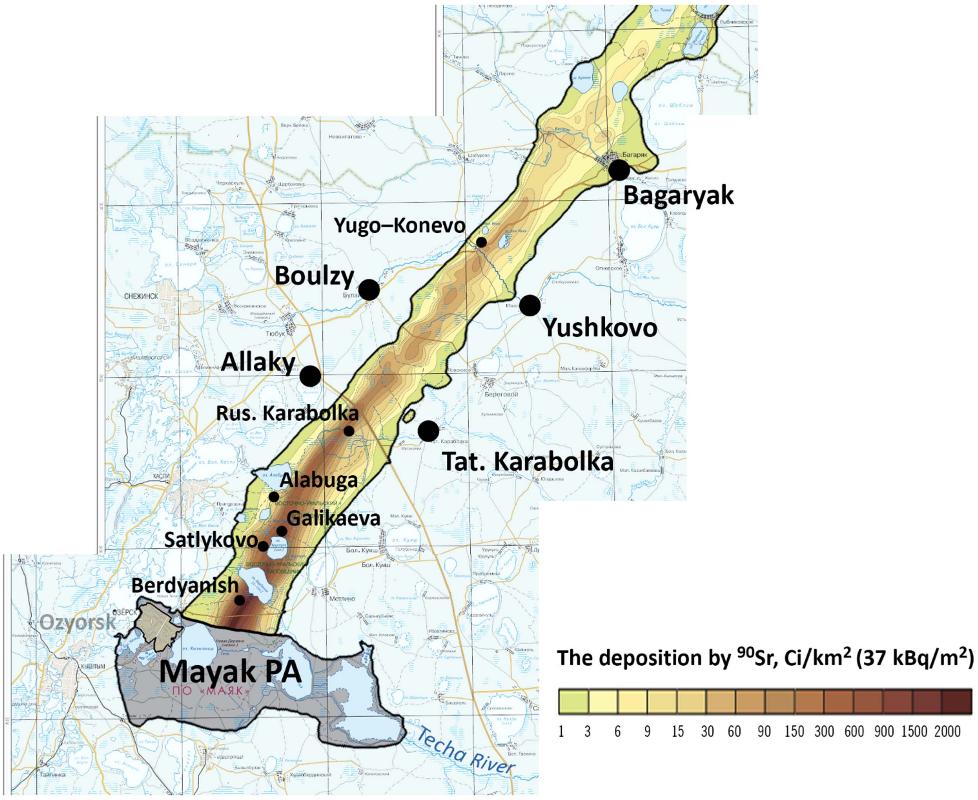

Figure 1. Schematic map of ^{90}Sr deposition in EURT territories in 1957 in Chelyabinsk Oblast (according to [8, 12]). Large circles indicate the reference non-evacuated settlements selected by URCRM for long-term monitoring; small circles indicate the evacuated settlements discussed in the present study.

scheduled activities. A program of emergency activities to mitigate the consequences of the explosion was approved on 2 October 1957. It included evacuation of the population from the nearest settlements, quality inspection of food products and fodder, and provision of 'clean' products, determination of the ^{90}Sr concentration per unit area and borders of the contaminated territory, and establishment of the sanitary-protected zone. Unfortunately, these measures were not taken in due time or to an adequate extent.

The residents of three settlements (Berdyanish, Satlykovo, and Galikaeva, figure 1), located in closest proximity to the site of the explosion (1100 persons), were quickly evacuated within 7–14 days after the accident, essentially because of high levels of external exposure. Residents underwent complete sanitization with their personal clothes being changed. The evacuated population was provided with new accommodation. Houses and outbuildings in these settlements were destroyed, private farm livestock were slaughtered and buried *in situ*.

Since autumn 1957, in the rest of the territory quality inspection of food products and fodder with partial replacement of contaminated products was started to decrease the absorbed dose from internal exposure sources. Within the first 2 years after the accident 1.3×10^5 kg of crops, 2.4×10^5 kg of potatoes, 1.0×10^5 kg of meat, 0.7×10^5 kg of milk were withdrawn—this amounted to 2%–3% of annual food and fodder supplies in the EURT households.

The efficacy of the quality inspection of agricultural products was low for a number of reasons. Quality inspection of food and fodder in the autumn of 1957 was difficult due to the absence of defined permissible levels of contamination at that time. Provisional maximum permissible levels of daily radionuclide intake for certain components of the daily ration and fodder were approved on 7 May 1958; the permissible annual intake of ^{90}Sr with food was 52 kBq/person. The large number of samples for examination (water, locally produced food products), absence of a regional radiological service and skilled personnel made quality inspection very difficult. Before the accident only one radiological laboratory at Mayak PA, which determined the radionuclide content in foodstuffs, was in operation in the Chelyabinsk and Sverdlovsk Oblasts. Consequently, dietary intake of radioactive substances for residents of certain settlements exceeded permissible levels.

On 10–20 October 1957 contaminated territories of the Chelyabinsk, Sverdlovsk, and Tyumen Oblasts up to 350 km from the explosion site were studied with exposure-rate measurements and parallel soil sampling. The following pathways of public exposure were distinguished: external exposure and inhalation of the radioactivity from the plume at the time of its passage; external exposure from radioactively contaminated soil and surfaces of buildings and trees; internal exposure due to ingestion of contaminated foodstuffs. An automobile survey in November–December 1957 and aircraft survey in February 1958 provided more complete information on the distribution of the radioactive contamination. The first schematic map of contamination levels and borders of contaminated territory was obtained after 3 months (25 January 1958) based on the results of radiological analysis of the contaminated area.

In early 1958, a sanitary protection zone (SPZ) was established with a restrictive regime (residence and economic activities were prohibited). The area of this zone was limited to an isoline of 2–4 Ci km^{-2} for ^{90}Sr. The area of the SPZ was 700 km^2. The East Ural Reserve, on the territory of which only scientific observations are allowed, was set up at the head part of the trace (i.e., closest to Mayak PA) with ^{90}Sr soil deposition of 100–600 Ci km^{-2}.

Although the territory of the SPZ was taken under protection by the police, the population continued to use part of the SPZ area due to the lack of 'clean' pastures and hayfields, and lack of official information about radioactive contamination.

^{90}Sr soil deposition equal to 2 Ci km^{-2} was recognized as maximum permissible for safe living of the population and was used as the official boundary of the EURT, within which there were 22 settlements, 19 were located on the territory of the Chelyabinsk Oblast, and 3 in the Sverdlovsk Oblast. For residents who continued living at their former place of residence, efforts were made to reduce external exposure doses and annual intakes of ^{90}Sr. Scheduled activities included: further relocation of the residents, decontamination of settlements and agricultural areas, development of a radiation monitoring system, including quality inspection of foodstuffs and fodder, as well as reorganization and reorientation of commercial farms.

The population of seven settlements (2280 persons in total) was evacuated 250 days after the accident. Relocation was due to high levels of ^{90}Sr deposition ($>$4 Ci km^{-2}) and high level of foodstuff contamination. Later (330–670 days after the accident) another 8300 persons from 12 settlements were removed from territories with ^{90}Sr deposition $>$2 Ci km^{-2} [1, 9–11]. By the end of 1959 after relocation of the residents, an exclusion zone where all economic activities were banned was established in the stated territory. In total, 22 settlements (including Berdyanish, Satlykovo, Galikaeva evacuated within 7–14 days) with the population over 10 000 people were relocated as a result of emergency and scheduled activities [4].

Table 2. Information on EURT monitoring contained in the URCRM Database.

Parameter (samples)	Number of measurements	Period of measurements
Environmental data		
Soil	6812	1958–2011
Grass	3840	1958–2011
Water	50	1960–2011
Foodstuffs		
Bread	460	1958–1982
Milk	6840	1958–2011
Potato	822	1958–2011
Vegetables	430	1958–2011
Meat	45	1962–1977
Human data		
Bone samples	2170[a]	1960–1989
Whole body *in vivo* measurements	369	1974–1997
Feces samples	226	1958–1959

[a] Samples from 1646 persons.

In 1958, 59 000 hectares of land in the Chelyabinsk Oblast were withdrawn from economic use. Then, in order to reduce the secondary contamination of the adjacent territory due to wind transfer, 20 hectares of alienated land were subject to decontamination by plowing. The plowing of land made it possible to move the upper layer of the earth contaminated with radionuclides down to a depth of 60–70 cm. However, decontamination of the EURT territory proved to be ineffective, since the windborne dust was important only for the head part of the EURT and only in 1957–1958.

In 1963, in order to reduce radionuclide intake with food products to the residents of the non-resettled villages, collective farms were reorganized. Instead of small farms, large farms specializing in meat-production with special conditions for keeping and feeding of animals were set up. The use of natural forage lands was limited. The production of grain and vegetables was banned, and the production of milk was limited. Enlargement of farms significantly facilitated radiation monitoring and resulted in a decrease in the dose to the population from the products with the greatest contribution to internal ^{90}Sr exposure: milk and grain. The content of ^{90}Sr in milk produced in specialized farms decreased by a factor of 3–4, and in meat by 2–7 [4].

Radioactive decay of radionuclides and various ecological factors also contributed to the improvement of the radiation situation on the territory of the trace, in addition to the protective measures that were undertaken. Thus, ^{90}Sr entry into plants and agricultural products from soil decreased with time mainly due to vertical migration of radionuclides along the soil profile [4].

Long-term monitoring of local foodstuffs and environmental samples was established in 1958, and five settlements (with ^{90}Sr deposition 0.7–2.0 Ci km^{-2}) located near the evacuation zone were selected for this purpose (figure 1). In addition, sampling of bone autopsies from deceased residents of the contaminated areas was organized. The information collected on the contamination of soil, water, grass, foodstuffs, and human data from the EURT is summarized in table 2.

As can be seen from table 2, a significant part of the data is the result of measurements of local foodstuffs; these measurements cover the period 1958–2011 and allow assessment of

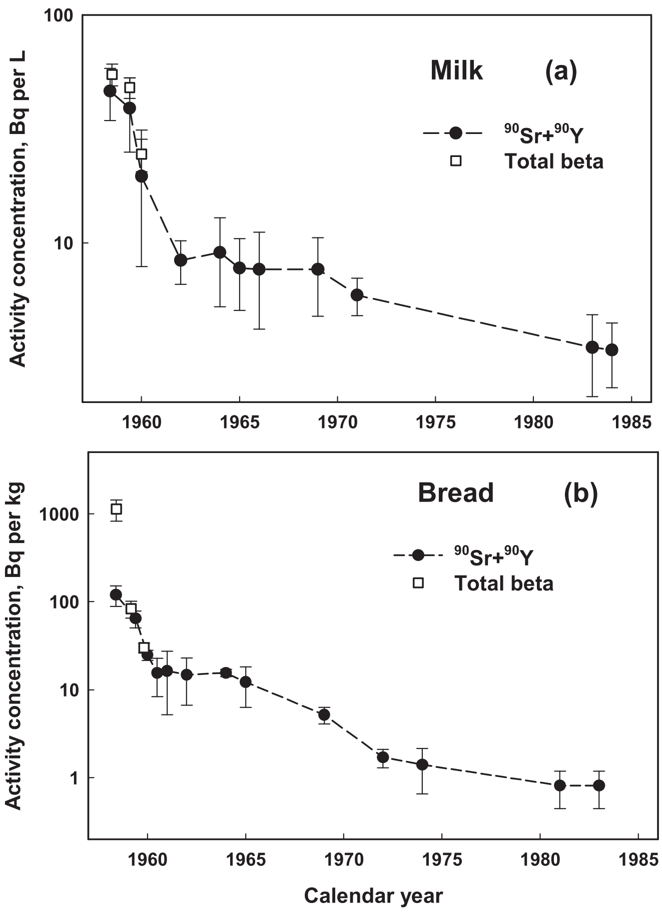

Figure 2. Radioactive contamination of milk (a) and bread (b) measured in 1957–1985 in reference settlements normalized per 1 Ci km^{-2} (37 kBq m^{-2}) of ^{90}Sr deposition.

radionuclide intakes with diet. The most important contributors in the diet were grain and grain products, dairy products, and potatoes [12]. Figure 2 presents the available data on the contamination of bread and milk. The data from the reference settlements were normalized per 1 Ci km^{-2} of initial ^{90}Sr in-soil deposition (the reference deposition). This allowed extrapolation of data from the reference villages to those villages where detailed studies have not been conducted.

In the autumn of 1957 (just after the explosion), the grain was contaminated because it was in the open or in poorly covered storage. The rapid radioactive decay of short- and medium-lived radionuclides from the releases resulted in a sharp increase in the ^{90}Sr contribution to the total β-activity of bread samples. Cow's milk was mainly contaminated due to the transfer soil→grass (cow's forage)→milk, and the ^{90}Sr + ^{90}Y contribution to the total activity of milk exceeded 80%.

Averaged values of ^{90}Sr body burdens derived from measured bone samples obtained postmortem in residents of reference settlements decreased from 1 kBq in 1960 to 0.5 kBq in 1975 [12]. The ^{90}Sr body burdens of residents evacuated from the EURT were measured in

1974–1994 using a whole body counter [13]. Measurement results showed that ^{90}Sr body burdens for those who were in their teens at the time of the accident were about 1–5 kBq.

The monitoring has determined major exposure pathways and provided data for the reconstruction of radionuclide intakes on the EURT [12].

4. Reconstruction of external and internal doses

A unified dosimetry system Techa River Dosimetry System (TRDS) [12, 14, 15] was used for the calculation of individual doses. The TRDS calculates doses from the major exposure pathways: external exposure in the areas along the Techa River and in the region of the EURT; and internal exposure from intakes acquired in the Techa River and EURT villages. The TRDS relies on extensive databases to compute the doses for each person. The system databases include time-dependences of exposure parameters normalized per 1 Ci km^{-2} of ^{90}Sr deposition and deposition densities for 83 EURT settlements covering the range from 0.1 to 650 Ci km^{-2}. These data provided the basis for dose reconstruction by use of the classical 'deposition density-to-dose-conversion-factor' approach. Individual doses for the cohort members were calculated by use of individual residence histories within the contaminated areas (Techa River and EURT).

Methods and parameters used for reconstruction of external doses in the EURT were described in detail in [16]. Time dependencies of dose rate in air per unit ^{90}Sr deposition for the EURT area were evaluated using the approach of Eckerman and Ryman [17] and the ratios of different gamma-emitting radionuclides to ^{90}Sr in the fallout (table 1). Absorbed doses in human organs were calculated by combining dose rates in air per unit deposition density, typical life patterns and shielding, as well as conversion factors from dose in air to dose in organs. Dose accumulation is considered for only two calendar years, because dose-rate values decreased rapidly due to radioactive decay of the short-to-intermediate-lived radionuclides.

The reconstruction of radionuclide intakes for EURT residents was recently conducted based on the results of ^{90}Sr measurements in humans, and the dataset on ^{90}Sr in foodstuffs was used only to evaluate the relative intakes in the period of interest [12]. The reference intake function for ^{90}Sr is shown in table 3, and table 4 presents the values of non-strontium radionuclide intakes (which were important only in the early period after the accident).

Total radionuclide intakes in the period 1957–1980 estimated in terms of kBq for reference deposition were: ^{90}Sr-32.8; ^{144}Ce-49.4; ^{95}Zr-4.4; ^{95}Nb-7.8; ^{106}Ru-3.1, and ^{137}Cs-0.8. For the most contaminated settlements evacuated during the first two weeks after the explosion, the values of intakes (kBq) were significantly higher: ^{90}Sr-50; ^{144}Ce-6040; ^{106}Ru-340; ^{95}Zr-1690; ^{95}Nb-2870; ^{137}Cs-32 [12].

Dose-conversion factors representing absorbed doses in tissues and organs per unit intake for non-strontium radionuclides were based on the models from ICRP Publication 67 [18]. A special age- and sex-dependent biokinetic model described in [19] was used for ^{90}Sr.

Breakdown of internal dose and their values for the residents who lived in the area with reference deposition and for those who were evacuated within 7–14 days are shown in figure 3 (similar breakdown of internal dose is obtained for all non-evacuated EURT settlements). Stomach dose was used for the analysis of solid cancers as a group. The dose to the stomach was similar to absorbed doses to the lung and other soft tissues other than intestines. As can be seen, doses to bone marrow were dominated by bone-seeking ^{90}Sr (contribution >97%). Doses to extra-skeletal tissues were significantly less so, and mainly due to intakes of ^{144}Ce (contribution 60%–70%).

Table 3. Reference values of ^{90}Sr intake Bq for EURT settlements (according to [12]).

Calendar period	^{90}Sr dietary intake in calendar period (Bq)	Calendar period	^{90}Sr dietary intake in calendar period (Bq)
29 September 1957–April 1958	3395	1971	634
May 1958–October 1958	4095	1972	692
November 1958–April 1959	2760	1973	634
May 1959–October 1959	2749	1974	634
November 1959–April 1960	1758	1975	634
May 1960–December 1960	1717	1976	577
1961	1730	1977	519
1962	1442	1978	519
1963	1153	1979	461
1964	1326	1980	461
1965	923	1985	306
1966	865	1990	210
1967	865	1995	183
1968	750	2000	156
1969	807	2005	145
1970	721	2011	135

Table 4. Reference values of non-strontium radionuclide intakes in different calendar periods, Bq (according to [12]).

Calendar period	^{144}Ce	^{95}Zr	^{95}Nb	^{106}Ru	^{137}Cs
29 September 1957–April 1958	31 772	4002	7029	1905	222
May 1958–October 1958	16 639	367	791	1121	272
November 1958–April 1959	490	2.33	4.33	37	81
May 1959–October 1959	319	0.33	0.553	26	82
November 1959–April 1960	94	0.021	0.036	8.7	77
May 1960–December 1960	70	0.003	0.005	7.2	54
Sum	49 384	4371	7825	3105	788

Individual doses were calculated for 21 427 members of the EURTC based on their residence histories. It should be noted that 1431 members of the cohort were exposed both in the EURT area and from the contaminated Techa River (which was taken into account). Maximum values of dose for the whole EURTC reached 0.6 Gy for stomach and 1.9 Gy for bone marrow. The cohort-average values of dose were low: 28 mGy for stomach and 78 mGy for bone marrow. The average contribution of external exposure to the total absorbed dose was: 83% for stomach, and 35% for bone marrow.

The uncertainty in individual radiation doses from exposures within the EURT is due to several factors including: uncertainty in the radionuclide composition of the release; variability in deposition across each village; individual variability in intakes; individual variability

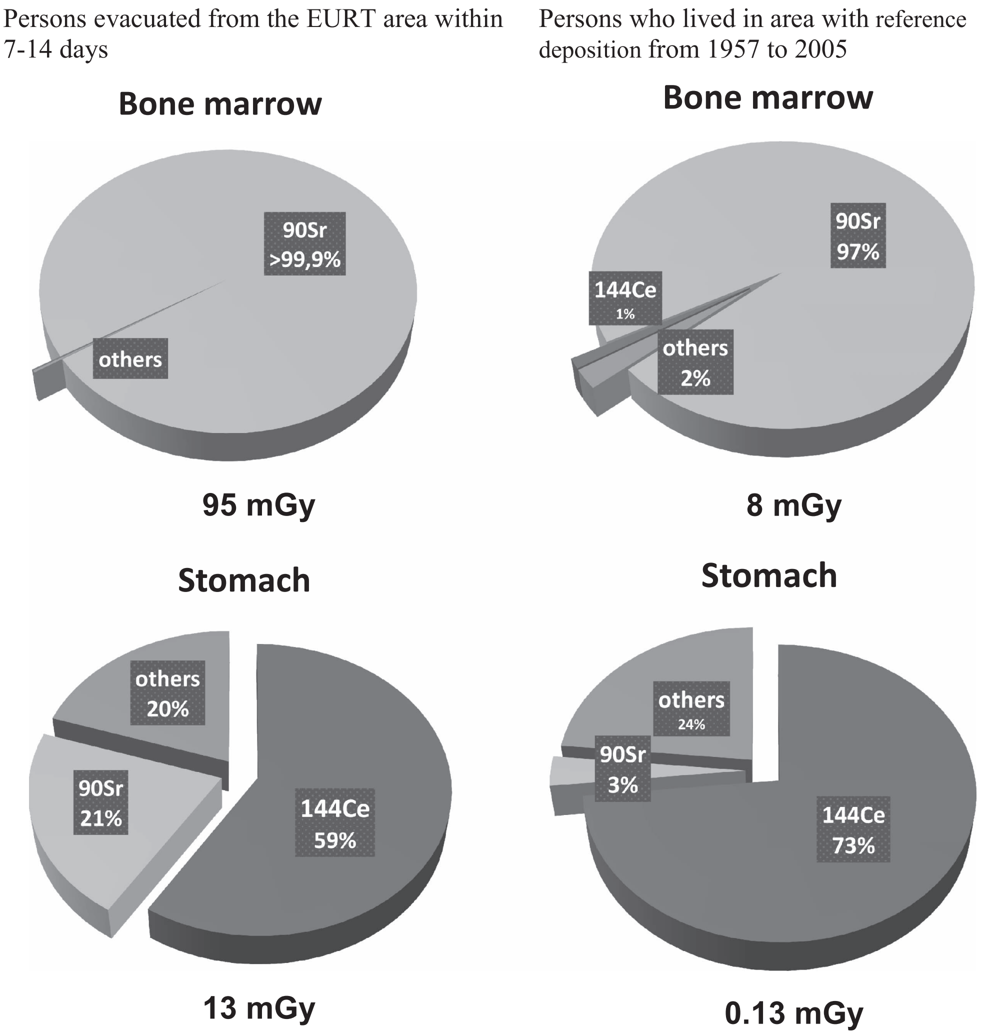

Figure 3. Breakdown of internal doses to bone marrow and stomach for persons evacuated from the EURT within 7–14 days (left column) and permanent residents of the area with reference deposition (right column). Stomach dose was used as an analog of organ dose for the group of all solid cancers because dose accumulated in the majority of organs is very similar to stomach dose.

in biokinetics and dosimetry etc. Aside from minor measurement errors, these parameters have Berkson character. The composite of these factors is a lognormal distribution for reference adults with geometric standard deviation of about 2.7, of which a portion is shared and a portion unshared between members of the cohort [12].

5. Health status of the exposed population and their offspring

The first medical examinations of the residents of the settlements of Berdyanish, Satlykovo and Galikaeva located in closest proximity to the explosion site, were conducted during the first days and weeks after the accident by the physicians from the Mayak PA hospital in the course of visiting medical examinations. Examination of the adult population involved a checkup by a general practitioner and a neuropathologist. Women were also examined by a gynecologist, children by a general pediatrician. The following analyses were performed: complete blood count, electrocardiography, and analysis of some biochemical parameters of the blood. Moreover, within 10 months of the accident specialists from the URCRM Clinic examined another 2055 residents of various EURT settlements (Igish, Gusevo, Melnikovo, Krivosheino, Fadino, Yugo-Konevo and Boevskoye), relocated from the EURT territory. No case of acute radiation syndrome was found in the examined people. However, group estimates of thrombocyte, leukocyte, and neutrophil number in exposed persons were lower relative to those in unexposed people. In a number of cases, absolute lymphopenia and increased percentage of band neutrophils were registered in the cellular composition of the peripheral blood, which was viewed as the hematopoietic reaction to radiation exposure [4].

A second examination of the 491 residents of the settlements of Berdyanish, Satlykovo and Galikaeva, performed 1–2 years after the accident, demonstrated that the mean values of thrombocyte, leukocyte and neutrophil counts did not differ from those of the control. The increase in the proportion of persons with higher leukocyte ($>9.0 \times 10^9\,l^{-1}$) and thrombocyte ($>350.0 \times 10^9\,l^{-1}$) number among exposed people testified to the onset of the hematopoiesis recovery stage, and resulted from compensatory proliferation of the hematopoietic stem cells and bone marrow progenitor cells. Neurological disorders and internal organ diseases (most often those of respiratory organs and the circulatory system) typical of the attained age were registered in exposed persons. Their frequency in the exposed population did not exceed that in the unexposed population. Symptoms of the diseases were not unique. The level of arterial tension (frequency of arterial hypertension and hypotension) did not differ between exposed and unexposed persons. Further follow-up (3–5 years after the accident) allowed us to note the recovery of the peripheral blood cellular composition [10, 20].

Ten to twelve years after the accident (1967–1969) the analysis of the prevalence of diseases in 12 372 EURT residents (including 3961 persons aged under 15) and 12 723 unexposed people, out of whom 4071 were children and teenagers aged under 15, confirmed the absence of an influence of exposure on somatic health status. In the course of clinical examinations it was registered that residents of the settlements with the most adverse conditions in terms of radiation exposure had common somato-neurological disorders that did not differ significantly (in terms of frequency) from those in persons from the control group. Prevalence of diseases of the respiratory organs (chronic bronchitis, pneumonia, bronchial asthma and tuberculosis of the lungs) in exposed adults and children was comparable with that in unexposed people, whereas prevalence of acute pneumonia in exposed adults in that period was significantly lower ($p < 0.05$) than that in unexposed adults [4].

Twenty-eight years after the accident no deviations in the health status of the residents of the settlements Satlykovo, Galikaeva, Alabuga and Russkaya Karabolka, who were exposed at the highest doses, was noted relative to unexposed people. Diseases of internal organs were diagnosed in exposed persons as frequently as in unexposed persons living in the same region. The cellular composition of the peripheral blood was within agreed standards [4].

Taking into account the fact that children are more sensitive to the effects of ionizing radiation, special attention was paid to the assessment of their health status. Over the period 1958–1960, 952 children aged under 14 were examined in the course of visiting medical examinations. Children 5–9 years of age at the time of the accident formed the main part of the examined group. Increased infectious disease incidence was observed in the group with the highest exposure dose. The following diseases were registered most frequently: pertussis, measles, mumps, acute upper respiratory infections, bronchitis, pharyngitis, tonsillitis, as well as acute skin infections (pyoderma and furunculosis).

Among diseases of the endocrine system, nutritional deficiencies and metabolic disorders (ICD-9 class 3) rachitis or its residual effects were most often diagnosed. Among diseases of the nervous system and sense organs (ICD-9 class 6) mainly conjunctivitis, blepharitis and otitis were registered. The following diseases of the digestive system (ICD-9 class 9) were observed: caries, gastritis, cholecystitis and colitis. The prevalence of the above-mentioned diseases did not depend on dose, and it was difficult to associate their development in exposed children with radiation exposure. Most of the parameters of peripheral blood cellular composition in visually healthy children, examined during the first 4–10 months after the accident, were within the expected range for their age. However, leukocytosis in the absence of any inflammatory diseases was more frequently registered among children with the highest exposure dose.

Mortality rates, including infant mortality, were assessed over the period 1958–1989 in offspring of the population that was not resettled, but continued living on the EURT territories with low deposition density. The infant mortality rate (per 1000 person years) for the offspring of the population residing on the territories with ^{90}Sr deposition 0.1–1.0 Ci km^{-2} was 52.4 (95% CI: 42.0–64.6), for the offspring of the population residing on the territory with ^{90}Sr deposition <0.1 Ci km^{-2} it was 55.7 (95% CI: 50.4–61.3) and 57.2 (95% CI: 51.7–63.1) for offspring of the unexposed population. The infant mortality structure did not differ radically from that in offspring of unexposed persons. Most often babies died of pneumonia. The percentage of this cause of death as a proportion of all deaths during the first years after the accident reached 52.9%–62.4%, and then it decreased greatly. Another common cause of death was intestinal infectious diseases (for example, dysentery). Rather a large percentage of deaths was of perinatal diseases due to immaturity of the fetus and occurrence of a hypoxic state. No significant increase in mortality rates (including mortality from endogenous causes, for example congenital abnormalities) was observed in the course of the mortality analysis among persons exposed in utero [4].

6. Assessment of radiation risk of solid cancer mortality

The first analysis of solid cancer mortality risk among 14 589 residents of the EURT covering the period 1957–1987 was conducted 30 years after the accident [21]. The EURT cohort included people born before the accident, both resettled and those who continued living on the contaminated territories of the Chelyabinsk Oblast. Analysis was performed using both external and internal controls. The external control group, 19 375 persons in number, was formed from the population residing on non-contaminated territories of the same administrative raions of the Chelyabinsk Oblast as the exposed population, and was comparable to the main group in terms of sex, age, and ethnicity. The EURTC members affected by chronic radiation exposure in the dose range of external gamma radiation 0.3–43 mGy, and absorbed dose to red bone marrow ranging from 6 to 2100 mGy, were noted to have a significant increase in solid cancer mortality rate (ICD-10 codes C00-C80, D43) relative to the external control group. However, no statistically significant dose dependence of solid cancer mortality risk was found. Leukemia mortality rates over a 30-year period after the accident did not differ from those in the group of unexposed people.

Subsequent analysis conducted 50 years after the accident involved 21 427 EURT residents, who lived in 19 relocated settlements of the Chelyabinsk Oblast (excluding three Sverdlovsk Oblast villages) before the resettlement took place, and residents who lived in 14 non-resettled villages of the Chelyabinsk Oblast adjacent to the head part of the EURT from 29 September 1957 until 1 January 1960 [22]. The follow-up period was 50 years (1957–2006). Thus, this second analysis of solid cancer mortality risk in EURTC members was performed in a cohort larger in size and over a period which was 20 years longer. These contributed to an increase in statistical power of the study; the number of person-years at risk increased by more than 100 000, and the number of deaths from solid cancer among the cohort members was twice as large as in the previous study. With due account for migration of the EURT population, the catchment area for mortality analysis in EURTC members comprised the whole Chelyabinsk and Kurgan Oblasts.

Women predominate in the EURTC population (56%), which is due to the fact that the cohort was formed in the post-war period. Slavs account for 60% of the cohort members, the other 40% are Tartars and Bashkirs. During the initial period of the follow-up (as of 01.01.1960) people of a young age (under 20) comprised a large part of the cohort, 43%. By the end of the follow-up period (31.12.2006) 5731 (27%) out of 21 427 cohort members were alive and resided in the catchment area, 8016 cohort members (37%) had died, and 4169 (19%) had migrated from the catchment area. Vital status was unknown for 3512 (16%) cohort members. Mortality risk analysis comprised only those cases that were confirmed by medical certificates of death, which made up 89% of the total deaths. Most common causes of death were cardio-vascular diseases (51%), neoplasms (16%), and deaths from injury and poisoning (12%). Among solid cancers, the most common were cancers of trachea, bronchi, and lung (21%), stomach cancer (21%), and cancers of other organs of the digestive system (23%); uterine cancer and cervical cancer accounted for more than 7% of all cases. The distribution of causes of death is given in table 5 [22].

In 2011–2012 for the first time ever individualized doses, including external and internal dose components, accumulated in organs over the whole follow-up period, were calculated for EURTC members on the basis of the dosimetry system TRDS [14, 15]. Due to the fact that the dose accumulated in the majority of organs excluding colon, bone tissue, blood and lymph, is very similar to the dose to the stomach (mean dose to the uterus, lungs, and stomach is 0.03 Gy, maximum is 0.60–0.69 Gy) and as the number of stomach, lung and uterine cancer cases in total accounts for half of all cancer cases in the EURTC, dose to the stomach was chosen for the solid cancer mortality analysis. Colon and bone cancer were included in the analysis of mortality risk from all solid cancers taken together. Recognizing the potential influence of the peculiarities of dose to these organs, we have also performed analyses of solid cancer mortality risk excluding colon cancer (33 cases) and bone cancer (7 cases).

The cohort study has been conducted by using an internal control formed by the cohort members with the lowest dose. Mortality risk was estimated with the use of regression analysis; its significance was assessed using a maximum-likelihood method. Software DATAB and AMFIT of the statistical package EPICURE were used for calculations with the use of a simple parametric model of excess relative risk (ERR) [23]. The software makes it possible to perform multiple factor analysis of the mortality rate dependence on radiation and non-radiation factors, and to determine the shape of the dose dependence curve. Similar methods of analysis were used in estimating cancer incidence and mortality in the Techa River Cohort (TRC) [24, 25]. Characteristics of solid cancer cases, person-years and crude mortality rates depending on sex, age, ethnicity, resettlement, and follow-up period are given in table 6.

Table 5. Cancer mortality structure in the EURTC members as of 31.12.2006.

ICD-10 codes, sites of malignant neoplazms	N	%
(C00-C14) Lip, oral cavity, throat	18	1.6
(C15) Oesophagus	76	6.9
(C16) Stomach	230	20.8
(C17-C26) Intestine, colon, rectum and other sites within the digestive organs	161	14.5
(C30-C32) Nasal cavity, ears, sinuses, larynx	19	1.7
(C33-C34) Trachea, bronchus, lung	231	20.9
(C37-C39) Other sites of respiratory system, thymus, heart, mediastinum, pleura	4	0.4
(C40-C41) Bones, articular cartilage	7	1.1
(C43-44) Melanoma 7 cases, other skin	14	1.2
(C45-C49) Connective tissue	5	1.1
(C50) Breast (including 2 cases of male breast)	36	3.3
(C53-C55) Cervix, corpus uteri and unspecified part	82	7.40
(C51-C52, C56-C68) Other genital organs and urinary tract	71	6.4
(C69-C80) Other and unspecified sites, including brain tumor D43;	85	7.7
(C00- C80) Total solid, including brain tumor of uncertain behavior (D 43)	1039	93.9
(C81-C90) Malignancies of lymphoid tissue	21	1.9
(C91-C96) Leukemias	31	2.8
(D37-D48) Neoplazms of uncertain/unknown behavior, excluding D43	16	1.4
Total	1107	100.0

When comparing crude mortality rates, one can see that in the EURTC there is a tendency to higher cancer mortality rates among males in comparison with females, among Slavs in comparison with Tartars and Bashkirs, among non-resettled residents in comparison with resettled ones, among the older exposed population in comparison with the younger exposed population, and that mortality rates increase with increasing follow-up period. The same trends can be observed among the residents of the Techa riverside villages living in the South Urals [26].

In the dose-response model, baseline levels of solid cancer mortality were adjusted by sex, ethnicity, fact of evacuation, follow-up period (3 categories) and sex-specific log of attained age or square of the log of attained age. In order to determine which function best described the dose-effect relationship, we tested linear, linear-quadratic, and quadratic models. The point value of the ERR per 100 mGy for solid cancer mortality for the members of the EURTC based on the linear model with 5- and 10-year latent periods was 0.057/100 mGy (95% CI: 0.001; 0.125) and 0.067/100 mGy (95% CI: 0.006–0.141), respectively. The significance was slightly higher with a 10-year latent period ($p = 0.046$ and $p = 0.03$, respectively). Analysis based on maximum-likelihood ratio test did not indicate that a linear-quadratic model fits any better than a simple linear model ($p > 0.5$). Also, a pure quadratic model fits the data as well as the linear model, point value of ERR at 100 mGy for the quadratic model was 0.013; (95% CI: 0.001; 0.028; $p = 0.03$) [22]. It should be noted that the upward slopes of the linear and quadratic fits are driven entirely by the highest dose and that there are still huge uncertainties in the low dose range.

Table 6. Crude rates of cancer mortality in the EURTC (with most common cancer sites).

Parameters		Persons	Person-years	Solid cancer	Lung cancer	Stomach cancer	Colon cancer
Total,	number	21 427	458 131	1039	231	230	77
	CMR[a]			22.7	5.0	5.0	1.7
Sex							
Males,	number	9509	197 707	566	207	123	32
	CMR			28.6	7.3	6.2	2.2
Females,	number	11 918	260 425	473	24	107	45
	CMR			18.2	0.9	4.1	1.7
Ethnicity							
Slavs,	number	12 929	232 576	668	169	144	52
	CMR			28.7	7.3	6.2	2.2
Tartars and Bashkirs,	number	8498	225 555	371	62	86	25
	CMR			16.4	2.7	3.8	1.1
Resettlement							
Resettled,	number	8478	319 502	658	142	139	55
	CMR			20.6	4.4	4.4	1.7
Non-resettled,	number	12 949	138 630	381	89	91	22
	CMR			27.5	6.4	6.6	1.6
Calendar follow-up period							
1957–1969,	number		157 392	227	31	82	9
	CMR			14.4	2.0	5.2	0.6
1970–1989,	number		181 501	381	90	89	21
	CMR			21.0	5.0	4.9	1.2
1990–2006,	number		119 238	431	110	59	47
	CMR			36.1	9.2	4.9	3.9
Age at the onset of exposure							
<20 years old,	number	9937	235 551	151	36	22	8
	CMR			6.4	1.5	0.9	0.3
20–39 years old,	number	6510	156 019	452	111	75	45
	CMR			29.0	7.1	4.8	2.9
40 years and older,	number	4980	66 560.3	436	84	133	24
	CMR			65.5	12.6	20.0	3.6

[a] CMR—crude mortality rate by 10^5 person-years.

Figure 4 presents the plots describing the dose dependence of solid cancer mortality using linear and quadratic models, as well as point estimates of ERR in dose groups with confidence intervals.

Over the 50-year period, 26 solid cancers in the EURTC could be associated with radiation exposure (based on a linear dose-response model). This amounts to 2.5% of all observed solid cancer cases in the cohort in the catchment area over the period of interest.

We evaluated potential modification of the dose response by various non-radiation factors, with the use of a linear model of ERR. Assessment of the influence of factors such as sex, ethnicity, fact of evacuation, calendar period, age at the beginning of exposure, and attained age demonstrated that the ERR value per unit dose changes significantly only with

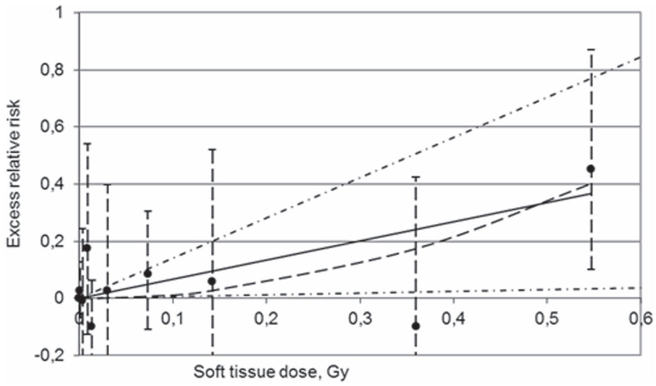

Figure 4. Dose-response for solid cancer mortality in the EURTC. Solid line—linear model, bold dashed line—quadratic model, dots—risk values in different dose groups. Dashed vertical lines—confidence intervals for categorical risks and dash-dot—confidence intervals for linear model [22].

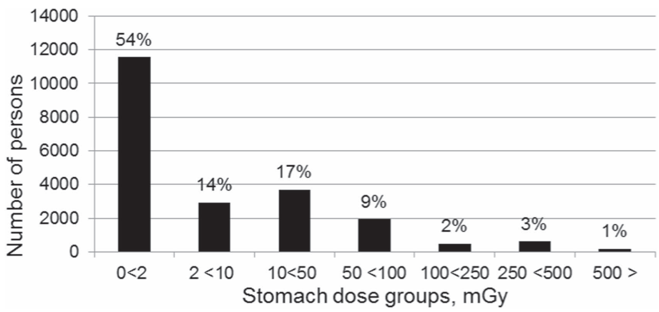

Figure 5. Dose distribution of EURTC members by stomach dose.

attained age: risk increased proportionally to the increasing age raised to the power of 4.14 ($p = 0.024$).

7. Assessment of radiation risk of solid cancer incidence in EURTC members

Solid cancer incidence in the EURTC was studied over a 53-year period (1957–2009). The cohort included in the incidence analysis numbered 21 394 persons [27]. The catchment area for the incidence analysis was limited to 5 of 27 administrative-territorial raions of the Chelyabinsk Oblast, Chelyabinsk City and Ozyorsk City, where there was access to malignant neoplasm incidence data. Approximately 1.5 out of 3.5 million residents of the whole Chelyabinsk Oblast live in this catchment area. The number of person-years at risk was 437 719. Risk analysis was performed with the use of individualized estimates of absorbed doses to organs over the whole follow-up period, calculated based on the improved TRDS [12, 14, 15].

The dose distribution of the cohort members by stomach dose is given in figure 5. It can be seen that only 6% of cohort members received a dose >100 mGy.

The vital status of the cohort members as of 31.12.2009 was as follows: 4333 people (20%) were alive and resided in the catchment area, 7920 people (37%) were deceased by the end of the follow-up; 6007 (28%) people migrated from the catchment area, and for 3134 residents of the catchment area (15%) vital status as of 31.12.2009 was unknown. For 90% of deceased persons, the cause of death was known based on medical death certificates. Cohort members were included in the analysis from the date of the accident (29 September 1957), or from the date of birth on contaminated territory before resettlement (during 1957–1959). The number of person-years at risk for EURTC members was calculated up to the date of cancer diagnosis in the catchment area, and for those who did not have malignant neoplasms till the end of the follow-up period in the catchment area (31.12.2009), or date of death in the catchment area, or date of migration from the catchment area if it happened before the end of follow-up.

The main sources of cancer information were cancer notification forms from the Chelyabinsk Regional Oncological Dispensary. An additional source of information were death certificates which were gathered from a larger territory (the whole Chelyabinsk and Kurgan Oblasts) and allowed for the assessment of the completeness of data on malignant neoplasm cases, especially in the early years after the accident. All cancer cases (ICD-10 codes C00-C 80) were included in the analysis except hematological malignancies and non-melanoma skin cancers (ICD-10 code C44). The latter are excluded from the analysis of cancer incidence in the majority of international studies due to the fact that cancer registries may have incomplete data on non-melanoma skin cancers as patients with basalioma are excluded from the follow-up and the cancer registry after a 5-year remission. It is important to note that neoplasms of unspecified behavior of the brain (ICD-10 code D43) were included in the analysis as the course of this disease was similar to a malignant one. Cancer incidence data by site are provided in table 7 [27].

The cancer incidence structure of EURTC members corresponds to the cancer mortality structure; the most frequent cancer sites are lung cancer and stomach cancer (18.7% and 18%, respectively). The percentage of lung cancer in men is rather high and exceeds 32%. The percentage of breast cancer in total cancer incidence is significantly higher than that in mortality (as not all the cases lead to death) and makes up 7%. In the cancer incidence structure of females, the most frequent were cancer of the reproductive organs, 25.7%. Cancer of stomach (16.8%) and cancer of intestine, colon, liver and other digestive organs rank next to reproductive organs. Breast cancers were also quite frequent, 13.5% (table 7). As for hematological malignancies, over the period 1957–2009 there were 76 incidence cases among EURT cohort members: 31 lymphomas, 8 myelomas, and 37 leukemias (including 12 chronic lymphatic leukemias). Leukemia incidence risk analyses for EURT cohort members over the period mentioned above are now in progress and are not available in this paper.

Over the whole follow-up period, morphological confirmation is available for 43% of cancer cases, instrumental (radiographic examination, ultra-sound, computed tomography, magnetic resonance tomography, endoscopy) for 10%. In 20% of cases, the cancer diagnosis was only clinically confirmed or confirmation is unavailable (this refers mainly to the data which were obtained retrospectively). For 27% of cancer cases only death certificates are available. The quality of data is constantly improving; the percentage of morphological and instrumental cancer diagnosis confirmation increased from 33% (in 1957–1989) to 77% (in 1990–2009), and the percentage of cancer diagnosis confirmation based on death certificates only decreased from 39% to 14%. As incompleteness of data for the first years was not related to the dose received by the cohort members, there should not be a large bias in cancer incidence risk estimates in the cohort.

Methods of cancer incidence risk analysis were similar to those used for the mortality analysis. The dose dependence of solid cancer incidence in the EURTC (linear and quadratic models, as well as ERR estimates in specified dose groups with confidence intervals) is given

Table 7. Cancer incidence structure by sites in EURTC members.

Cancer sites (ICD-10 codes)	Male		Female		Total	
	cancer number	%	cancer number	%	cancer number	%
(C00-C14) Lip, oral cavity, throat	60	8.5	18	2.5	78	5.5
(C15) Oesophagus	45	6.4	45	6.3	90	6.3
(C16) Stomach	135	19.1	121	16.8	256	18.0
(C18) Colon	23	3.3	32	4.4	55	3.9
(C17, C19-C26) Other sites within the digestive organs	66	9.3	89	12.4	155	10.9
(C33-C34) Trachea, bronchus, lung	229	32.4	38	5.3	267	18.7
(C30-C32, C37-C39) Other organs of respiratory tract	26	3.7	3	0.4	29	2.0
(C40-C41) Bones, articular cartilage	1	0.1	2	0.3	3	0.2
(C43) Melanoma	7	1.0	6	0.8	13	0.9
(C45-C49) Connective tissue	7	1.0	3	0.4	10	0.7
(C50) Breast	2	0.3	97	13.5	99	6.9
(C53-C54) Corpus uteri and unspecified sites	0	0.0	53	7.4	53	3.7
(C51, C52, C55-C58) Other female genital organs	0	0.0	132	18.3	132	9.3
(C60-C63) Male genital organs	26	3.7	0	0.0	26	1.8
(C64-C68) Bladder and other urinary organs	39	5.5	18	2.5	57	4.0
(C73) Thyroid	2	0.3	20	2.8	22	1.5
(C69-C72, C74-C80) Other not specified sites and brain tumor D43	38	5.4	43	6.0	81	5.7
(C00-C43, C45-80) Total solid, including brain tumor D43	706	100.0	720	100.0	1426	100.0

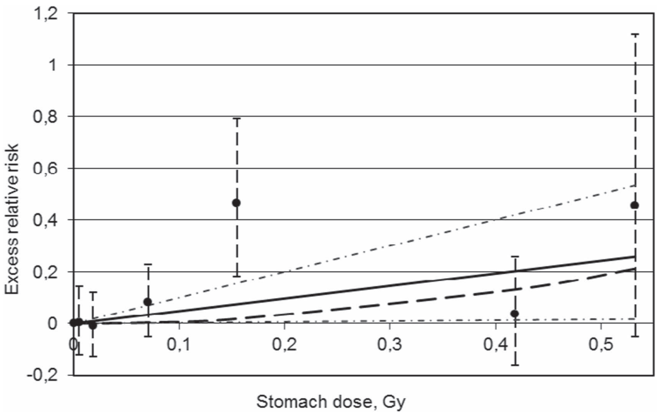

Figure 6. Dose-response for solid cancer incidence in the EURTC: solid line—linear model, dashed line—quadratic model, points—ERR values in dose groups, dash-dot line—90% bounds for linear model, vertical dashed line—90% bounds for points.

in figure 6 [27]. The ERR estimate on the basis of a linear model and with 5-year lag period showed a statistically significant dose dependence with 90% probability: 0.049/100 mGy; CI: 0.003; 0.10. Adding a quadratic component to the linear model did not improve the model fit ($p > 0.05$) (not shown in the figure). The use of the quadratic model did not reveal a statistically significant dose dependence of the risk ($p = 0.2$), ERR at 100 mGy = 0.008; 95% CI: −0.004; 0.021. It is clear from the figure that point estimates of the risk have great uncertainty due to low statistical power. For dose groups, a significant increase in ERR is observed only in the dose range 100–200 mGy.

The attributable risk (AR) of solid cancer incidence in the EURTC, which gives the proportion of excess cancer cases out of the sum of excess and baseline cases, calculated according to the linear model, made up 1.9% over the whole follow-up period. Therefore, only 27 cancer cases out of 1426 could be associated with accidental radiation exposure of the EURT population. AR is highest in the highest dose groups (250–500 mGy and >500 mGy) and exceeds 17%.

To estimate the potential effect of differences in doses accumulated in bone and colon on the incidence risk value for all solid cancers taken together, we performed the analysis of solid cancer incidence risk excluding cases of bone and colon cancer. The value of ERR/100 mGy obtained in the analysis of 1368 cancer cases with the linear model (with 5-year lag-period) was 0.054 (90% CI: 0.007; 0.107), and did not differ from the one obtained without the exclusion of these sites [27].

There was no significant effect modification (based on the linear model), which was evaluated with AMFIT software of the statistical package EPICURE [23], depending on sex, ethnicity, age at the beginning of exposure, attained age, fact of evacuation, calendar period, or year of birth (table 8). It was noted that the ERR value per unit dose tends to be higher ($p = 0.085$) in Tartars and Bashkirs as compared with Slavs. Absence of a clear dependence of the risk value on the stated factors could be due to the small numbers of cancer cases in certain groups.

Table 8. Solid cancer incidence ERR modification by non-radiation factors in the EURTC.

Parameters	ERR/100 mGy, (95% CI)[a]	Ratio, (95% CI), P-value
Sex		F/M ratio
Male	0.008 (−0.060; 0.096)	9.77 (0.32—nf[b])
Female	0.083 (0.007; 0.176)	$p = 0.2$
Ethnicity		Ratio Tatars and Bashkirs/ Slavs
Slavs	0.029 (<−0.026; 0.093)	6.83 (0.55; nf > 100),
Tatars and Bashkirs	0.200 (0.020; 0.426)	$p = 0.085$
Age at exposure		Increase per decade
10 years	0.023 (nf <−0.007; 0.112)	1.31 (0.52; 107.1)
40 years	0.051 (nf < −0.001; 0.116)	$p = 0.3$
Attained age		Power of age
50 years	0.009 (nf < −0.01; 0.111)	5.46 (−2.21; 26.32)
70 years	0.055 (nf < −0.003; 0.136)	$p = 0.2$
Evacuation		nonevac/evac ratio[c]
Evacuated	0.240 (0.038; 0.618)	0.16 (0; 4.56)
Non-evacuated	0.039 (−0.014; 0.102)	$p = 0.2$
Calendar period		<1986/>1985 ratio
Before 1986	0.054 (−0.016; 0.140)	1.28 (0; >100)
After 1985	0.042 (nf < −0.028; 0.129)	$p > 0.5$
Birth cohort		<1932/>1931 ratio
Before 1932	0.050 (−0.014; 0.126)	1.1 (0; >100)
After 1931	0.047 (−0.035; 0.150)	$p = 0.2$

[a] Based on linear model.
[b] Not found; confidence interval bound cannot be calculated with given significance.
[c] Non-evacuated/evacuated.

8. Conclusion

As a result of a thermochemical explosion in the storage tank for liquid high-level waste at the Mayak PA on September 29 1957, 20 million Ci (740 PBq) of radionuclides were released into the air up to an altitude of 1 km, and 2 MCi (74 PBq) was deposited beyond the Mayak PA perimeter. The radioactive plume dispersed in the direction of the wind flow, and the radioactive substances deposited from it contaminated the terrain and formed the EURT along the path of the plume. As a result of the accident, settlements, forests, pastures, arable lands, and water bodies were radioactively contaminated. The accident caused surface contamination of food and fodder. Houses, outbuildings, household items, agricultural equipment, people and animals that were not sheltered during the passage of the plume were contaminated. The favorable factors (as compared with the Chernobyl accident) were the following: formation of the EURT was limited in time (11 h), the wind was uniform in direction, and major fallout (about 90%) occurred on a limited area immediately adjacent to the explosion site within the Mayak PA boundary.

During the first year after the accident, external γ-radiation predominated. In 2–3 years the radiation situation changed significantly, and internal exposure started to prevail, mainly due to ^{90}Sr intake with contaminated food products. Maximal levels of radioactive contamination of the environment, as well as doses of external γ-radiation, were noted in the first

1.5–2 years after the accident. Doses due to external and internal exposure of the population decreased significantly with time after the accident.

The dose averted due to countermeasures was regarded as a criterion for assessing the effectiveness of protective measures. Protective measures (emergency evacuation of the residents of the settlements closest to the EURT, scheduled resettlement of residents of settlements where ^{90}Sr intake levels exceeded the permissible levels, formation of a SPZ, etc) made it possible to considerably decrease exposures of the population. Emergency resettlement was the most effective measure which significantly reduced the potential dose of external γ-exposure of the population.

However, evacuation of the population was delayed due to the difficulties in providing resettled people with the minimum necessary living conditions in new places of residence. Expected dose estimates for people resettled in a pre-planned manner allow us to conclude that resettlement of residents at a later date was not justified from the radiological protection point of view, since the population has already received virtually the entire exposure dose, and resettlement only caused a sharp decline in the living conditions of the people.

During the first few years after the accident, medical examination was piecemeal and could not cover all exposed persons, which was explained by the large number of people exposed due to the accident, the sudden development of the radiation situation, and inadequate preparedness of medical institutions for a radiation accident. Visiting medical examinations were limited to general medical examinations and mainly to analyses of peripheral blood. Should pathology be suspected, patients as a rule were hospitalized for in-depth examination and treatment at the URCRM Clinic. The emergency nature of the situation did not allow the timely formation of control groups, which made it difficult to interpret the results obtained while observing people affected by radiation exposure. Another unfavorable factor was the poor quality of medical records that were available before the accident and that were required to describe the initial health status of exposed persons. Finally, lack of information on radiation doses complicated greatly the work of physicians in the early period after the accident.

Medical examinations of the exposed people showed that none of the exposed had signs of radiation syndrome. Within the first few weeks to months after the accident, some deviations in the peripheral blood counts (moderate leukopenia, thrombocytopenia, lymphopenia, and increase in the proportion of band neutrophils) that could not be associated with any of the concurrent diseases were noted. Within 3–5 years after the accident, blood counts in exposed people returned to normal levels.

A solid cancer mortality study showed a statistically significant linear dose response using 5 and 10 year minimal latent period. The ERR of solid cancer mortality for the members of the EURTC based on the linear model with 5- and 10-year latent period was 0.057/100 mGy, $p = 0.046$ and 0.067/100 mGy, $p = 0.03$, respectively. ERR estimates for the cohort members depending on sex, ethnicity, fact of evacuation, age at the onset of exposure and follow-up period did not show any statistically significant differences between these groups. However, a significant increase in ERR value was observed with increase in attained age. A similar pattern was registered in studies of the TRC [24, 25].

A study of solid cancer incidence risk in the EURTC using doses calculated with unified dosimetry system TRDS showed a significant increase of ERR over 53 years of follow-up [27]. The dose-response relationship was consistent with linearity. According to a linear model with a 5-year lag period, the ERR of solid cancer incidence per 100 mGy is 0.049 (90% CI: 0.003; 0.010). Exclusion of solid cancer cases in organs that accumulated a larger dose or a dose that differed from that to the stomach (colon, bone tissue, and skin) from the analysis did not result in significant changes in the risk value, ERR/100 mGy was 0.054 (90% CI:

0.007; 0.107). No significant effect modification by non-radiation factors was revealed. Nevertheless, it was observed that ERR values in women tend to be higher than those in men, and the same tendency was observed in Tartars/Bashkirs relative to Slavs.

It is important to note that the results of the analysis of this cohort are in good agreement with the data obtained for the TRC. Despite the difference in the exposure pathways (the EURTC was exposed via air and the TRC by water-mediated pathways), members of both cohorts were affected by long-term exposure at cumulative doses of mainly below 1 Gy. The ERR value for solid cancer mortality in the TRC with 5-year latent period over the 58-year follow up period was 0.061/100 mGy (95% CI: 0.004–0.127) [25], and for solid cancer incidence the smoking-adjusted ERR was 0.077/100 mGy (95% CI: 0.013–0.15) over a 52 year period [26]. The findings of the studies presented here demonstrate that the solid cancer mortality and incidence risks per unit dose in case of chronic exposure at cumulative doses of <1 Gy are comparable to those for exposure to higher doses. The risk estimates for solid cancer incidence and mortality in the EURTC (and the TRC) were comparable not only to those for the Chernobyl nuclear accident clean-up workers (0.74/Gy; 95% CI: 0.29; 1.25 for all ages) [28], but also to those for the Japanese A-bomb survivors cohort (ERR = 0.47/Sv; 95% CI: 0.37–0.57) [29, 30].

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References

[1] Medvedev Z A 1980 *Nuclear Disaster In The Urals* (New York: W W Norton)
[2] Stratton W, Stillman D, Barr S and Agnew H 1979 Are portions of the Urals really contaminated? *Science* **206** 423–5
[3] Burnazyan A I (ed) 1990 *Itogi Izucheniya I Opyt Likvidatsii Posledstviy Avariynogo Zagryazneniya Territorii Produktami Deleniya Urana (Overall Results and History of Mitigation of Consequences of Accidental Exposure of the Territory with Uranium Fission Products)* (Moscow: Energoatomizdat) p 144 (In Russian)
[4] Akleyev A V and Kisselyov M F (ed) 2001 *Ecological and Health Effects of the Radiation Accident of 1957 at the Mayak PA* (Moscow: Medbioekstrem) p 294 (In Russian)

[5] Avramenko M I, Averin A N, Drozhko E G, Glagolenko Yu V, Loboiko B G, Mokrov Yu G, Romanov G N, Kotov E S and Filin V P 1997 Accident of 1957 and East Urals radioactive trace *Vopr. Radiatsionnoy Bezopasnosti* **3** 18–28 (in Russian)

[6] Joint Norwegian-Russian Expert Group for Investigation of Radioactive Contamination in the Northern Areas (JNREG) 1997 *Sources Contributing to Radioactive Contamination of the Techa River and Areas Surrounding the Mayak Production Association, Urals, Russia* (Østerås: JNREG) p 47

[7] Khokhryakov V V *et al* 2002 Characteristics of anthropogenic radiation impact on territory and population *Consequences of an Anthropogenic Radiation Incident and Rehabilitation Problems of the Urals Region* (Moscow: Comtehprint Publisher) pp 8–77 (in Russian)

[8] Izrael Y A (ed) 2013 *Atlas of the East Ural and Karachay radioactive trace including forecast up to 2047* (Moscow: IGCE Roshydromet and RAS) (In Russian) (http://downloads.igce.ru/publications/Atlas/CD_VURS/about.html)

[9] Nikipelov B V, Romanov G N, Buldakov A A, Babayev N S, Kholina Yu B and Mikerin Ye I 1989 Radiation accident in the Southern Urals in 1957 *At. Energ.* **67** 74–80 (In Russian)

[10] Buldakov L A, Demin S N, Kosenko M M, Kostyuchenko V A, Koshurnikova N A, Krestinina L Y, Saurov M M, Ternovskij I A, Tokarskaja Z B and Shvedov V L 1990 Medicinskie posledstvija radiacionnoj avarii na Juzhnom Urale v 1957 g (Medical consequences of the radiation accident in the Southern Urals in 1957) *Medicinskaja Radiologija* **12** 11–6 (In Russian)

[11] Kostyuchenko V A and Krestinina L Y 1994 Long-term irradiation effects in the population evacuated from the East Urals radioactive trace area *Sci. Total Environ.* **142** 119–25

[12] Tolstykh E I, Peremyslova L M, Degteva M O and Napier B A 2017 Reconstruction of radionuclide intakes for the residents of East Urals radioactive trace (1957–2011) *Radiat. Environ. Biophys.* **56** 27–45

[13] Kozheurov V P, Zalyapin V I, Shagina N B, Tokareva E E, Degteva M O, Tolstykh E I, Anspaugh L R and Napier B A 2002 Evaluation of uncertainties in ^{90}Sr-body-burdens obtained by whole-body count: application of Bayes' rule to derive detection limits by analysis of *a posteriori* data *Appl. Radiat. Isot.* **57** 525–35

[14] Degteva M O, Shagina N B, Tolstykh E L, Vorobiova M I, Anspaugh L R and Napier B A 2009 Individual dose calculations with use of the revised Techa River Dosimetry System TRDS-2009D *Final Report for Milestone 22 of JCCRER project 1.1* Chelyabinsk and Salt Lake City, Urals Research Center for Radiation Medicine and University of Utah (in Russian and English)

[15] Napier B A, Degteva M O, Shagina N B and Anspaugh L R 2013 Uncertainty analysis for the Techa river dosimetry system *Med. Radiol. Radiat. Saf.* **58** 5–28

[16] Vorobiova M I, Degteva M O, Peremyslova L M, Safronova N G, Shagina N B, Anspaugh L R and Napier B A 2006 Methodological approaches to external dose reconstruction and validation for the EURT and Karachay trace areas *Final report for milestone 13 of JCCRER Project 1.1* Chelyabinsk and Salt Lake City, Urals Research Center for Radiation Medicine and University of Utah (in Russian and English)

[17] Eckerman K F and Ryman J C 1993 *External exposure to radionuclides in air, water, and soil Federal Guidance Report No.* 12 Oak Ridge National Laboratory and U.S. Environmental Protection Agency; Washington, D.C. EPA 402-R-93-081

[18] ICRP 1993 Age-dependent doses to members of the public from intake of radionuclides–part 2: ingestion dose coefficients. ICRP Publication 67 *Ann. ICRP* **23** (3–4)

[19] Shagina N B, Tolstykh E I, Degteva M O, Anspaugh L R and Napier B A 2015 Age and gender specific biokinetic model for strontium in humans *J. Radiol. Prot.* **35** 87–127

[20] Kosenko M M, Kostyuchenko V A and Shvedov V L 1991 Consequences of the population exposure in the head part of the East Urals radioactive trace *At. Energ.* **71** 444–8 (In Russian)

[21] Krestinina L Y and Akleyev A V 2005 Cancer mortality in EURT cohort members exposed of chronic irradiation with low and intermediate doses *Bjulleten' Sibirskoj Mediciny* **4** 36–44 (In Russian)

[22] Krestinina L Y, Silkin S S and Epifanova S B 2014 Analysis of solid cancer mortality risk for the population exposed in the territory of East Urals radioactive trace over a 50 year period *Radiats. Gygiena* **7** 23–9 (In Russian)

[23] Preston D L, Lubin J H and Pierce D A 1993 *Epicure Users Guide* (Seattle, WA: Hirosoft International Corporation)

[24] Krestinina L Y, Preston D L, Ostroumova E V, Degteva M O, Ron E, Vyushkova O V, Startsev N V, Kossenko M M and Akleyev A V 2005 Protracted radiation exposure and cancer mortality in the Techa River Cohort *Radiat. Res.* **164** 602–11

[25] Schonfeld S J, Krestinina L Y, Epifanova S, Degteva M O, Akleyev A V and Preston D L 2013 Solid cancer mortality in the Techa River Cohort (1950–2007) *Radiat. Res.* **179** 183–9

[26] Davis F G, Krestinina L Y, Preston D L, Epifanova S B, Degteva M O and Akleyev A V 2015 Solid cancer incidence in the Techa River Incidence Cohort: 1956–2007 *Radiat. Res.* **184** 56–65

[27] Silkin S S, Krestinina L Y, Tolstykh E I and Epifanova S B 2017 Analysis of solid cancer incidence risk among the population exposed in the East Urals Radioactive Trace over 1957–2009 *Radiats. Gygiena* **10** 36–46 (In Russian)

[28] Kashcheev V V, Chekin S Y, Maksioutov M, Tumanov K A and Ivanov V K 2009 Dependence of radiation risk of solid cancers in emergency accident workers of the Chernobyl accident on their age at exposure *Radiaciya I Risk* **8** 48–53 (in Russian)

[29] Preston D L, Shimizu Y, Pierce D A, Suyama A and Mabuchi K 2003 Studies of mortality of atomic bomb survivers. Report 13: solid cancer and noncancer diseases mortality: 1950–1997 *Radiat. Res.* **160** 381–407

[30] Preston D, Ron E, Tokuoka S, Funamoto S, Nishi N, Soda M, Mabuchi R and Kodama K 2007 Solid cancer incidence in atomic bomb survivors: 1958–1998 *Radiat. Res.* **168** 1–64