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MEDICAL CONSEQUENCES OF THE RADIATION ACCIDENT IN THE SOUTHERN URALS IN 1957

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Abstract

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As a result of the radiation protection measures implemented after the accident causing radioactive contamination of the area, the maximum radiation dose received by 1150 people was 52 cSv; 9500 people received doses of 2.3–12 cSv. This portion of the population was evacuated. Another 270 000 people living in areas where the contamination density was less than 2 Ci/km^2 received doses of less than 1.4 cSv over 30 years. Monitoring of the health of evacuees and non-evacuees revealed no irregularities in the frequency with which somatic illnesses occurred, either during the earlier or later (30 years) monitoring period. No increase in the occurrence of malignant tumours was registered; no increase was found in infant mortality, stillbirths, congenital abnormalities or disturbances in the reproductive function, over the whole monitoring period; there was also no change in the birth rate. This was due to the low doses of radiation received.

On 29 September 1957, owing to a fault in the cooling system used for concrete tanks containing highly active nitrate–acetate wastes, a chemical explosion occurred in these materials and radioactive fission products were released into the atmosphere and subsequently scattered and deposited in parts of the Chelyabinsk, Sverdlovsk and Tyumensk provinces. The aggregate amount of activity released amounted to about 2×10^6 Ci (7.4×10^{16} Bq). The composition of the material released is indicated in Table I.

TABLE I. CHARACTERISTICS OF THE RADIONUCLIDE MIXTURE RELEASED IN THE ACCIDENT

Radionuclide	Contribution to total activity of the mixture (%)	Half-life	Type of radiation emitted	Nature of radiological hazard
^{89}Sr	traces	51 d	β, γ	
^{90}Sr + ^{90}Y	5.4	28.6 a	β	Internal irradiation (skeleton)
^{95}Zr + ^{95}Nb	24.9	65 d	β, γ	External irradiation
^{106}Ru + ^{106}Rh	3.7	1 a	β, γ	External
^{137}Cs	0.036	30 a	β, γ	External and internal
^{144}Ce + ^{144}Pr	66	284 d	β, γ	External
^{147}Pm	traces	2.6 a	β, γ	
^{155}Eu	traces	5 a	β, γ	
^{239}Pu	traces	–	α	

For the area with a ^{90}Sr contamination density of 0.1 Ci/km^2 (double the level of global fallout)[1], the maximum length of the deposition track under the radioactive plume formed reached 300 km; for ^{90}Sr contamination density of 2 Ci/km^2 it reached 105 km, with a width of 8–9 km. The area density distribution is shown in Table II.

The presence of gamma emitters among the contaminating nuclides was responsible for the external irradiation of the population and the environment. During the initial period the dose rate was about 150 μR/h in the area[2] with a ^{90}Sr contamination density of 1 Ci/km^2, with maximum values of 0.6 R/h at the head end of the track, where the contamination density (^{90}Sr) reached 4000 Ci/km^2.

Owing to radioactive decay of the short lived nuclides, contamination levels and gamma dose rates in the area of the accident fell off fairly rapidly during the first few years after formation of the deposition track (see Table III), and subsequently the radiation situation was governed entirely by the presence of ^{90}Sr and its

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[1] 1 Ci = 3.7×10^{10} Bq.

[2] 1 R = 2.58×10^{-4} C/kg.

TABLE II. AREA AND POPULATION OF THE CONTAMINATED REGION

Density of radioactive contamination, ^{90}Sr (Ci/km^2)	Area (km^2)	Population ($\times 10^3$)
0.1	15 000	270
including:		
2	1 000	10
100	120	1.5
1000	20	1.154

rate of radioactive decay. The exposure of the population in the contaminated territory was due in the first instance to external irradiation from the soil and from objects in their dwellings — including their own clothing — and also to internal irradiation due to the consumption of contaminated food and drinking water and inhalation of activity at the time when the cloud was being formed. Subsequently (after six months to a year) internal exposure from contaminated food was predominant.

The radiation protection measures adopted for the population were as follows:

- Evacuation of the population;
- Decontamination of some portions of the agricultural land;
- Monitoring of contamination levels in agricultural produce and rejection of produce with activity levels exceeding the accepted norms;
- Limitations imposed on the utilization of contaminated land;
- Reorganization of agriculture and forestry, with the creation of specialized state farms and forestry enterprises operating in accordance with the special recommendations worked out in the light of the accident.

The dynamics of the evacuation exercise for persons living in regions with a ^{90}Sr contamination density above 2 Ci/km^2 are shown in Table IV.

In the immediate aftermath of the accident — that is, within 7 to 10 days — six hundred persons were evacuated from the settlements in the most severely affected area; and about ten thousand persons were evacuated in the 18 months following the accident. Altogether 10 180 persons were evacuated. Maximum average exposure doses preceding evacuation reached 17 rem[3] in external exposure and 52 rem in effective dose equivalent (150 rem to the gastro-intestinal tract). These doses can be doubled in view of the non-uniformity of contamination density and the conditions in which the exposure occurred.

[3] 1 rem = 0.01 Sv.

TABLE III. DYNAMICS OF THE RADIATION SITUATION

Time after accident, (a)	Contamination density		Gamma dose rate (relative to initial value)
	Gross activity (relative units)	^{90}Sr (Ci/km^2)	
0	1	0.027	1
1	0.34	0.026	5.6×10^{-2}
3	0.10	0.025	8.3×10^{-3}
10	0.043	0.021	9.8×10^{-4} due to
25	0.029	0.014	3.8×10^{-4} ^{137}Cs

TABLE IV. DYNAMICS OF POPULATION EVACUATION AND OF EXPOSURE DOSE TO THE POPULATION BEFORE EVACUATION

Population group and size ($\times 10^3$)	Average contamination density, ^{90}Sr (Ci/km^2)	Time required for evacuation, (days)	Average dose received up to evacuation (rem)	
			External exposure	Effective dose eq.
A: 1.15	500	7–10	17	52
B: 0.28	65	250	14	44
C: 2.0	18	250	3.9	12
D: 4.2	8.9	330	1.9	5.6
E: 3.1	3.3	670	0.68	2.3
Total: 10.83				

Mass medical surveillance of the inhabitants of the affected region was arranged a year after the accident. It included examinations by paediatricians and therapists, by neuropathologists and gynaecologists, peripheral blood analysis, and determinations of body weight and height. Factors entailing a risk of cancer were assessed, as was cardiovascular pathology, and the presence of harmful habits; and urine tests for albumin and sugar were carried out. Serum cholesterol levels were determined and oto-laryngeal examinations were organized; all the individuals studied were given ECGs.

TABLE V. FREQUENCY OF ABNORMALITIES OF ARTERIAL BLOOD PRESSURE AND SYSTOLE FREQUENCY (PULSE RATE) AMONG EXPOSED INDIVIDUALS BELONGING TO POPULATION GROUP A

Index	Fraction of group affected (%)	(range)
Tachycardia (pulse >90)	5.5	(4–7.4)
Brachycardia (pulse < 60)	8.5	(0–14.1)
Hypertension (Blood pressure >160/95 mm Hg)	3.3	(1.7–4.0)
Borderline hypertension (blood pressure 140/90–159/94 mm Hg)	10	(7.5–14.5)
Hypotension (blood pressure <110/60 mm Hg)	16.4	(10.8–24.0)

The portion of the population most seriously affected by radiation (Group A) was comparatively young: persons 0–17 years of age accounted for 45%, 18–45 years of age 39% and above 50 only 16% of this group.

In the clinical studies carried out on this population no cases of radiation sickness were noted. During the early period of the investigations, 21% of the cases examined showed no decrease in the peripheral blood leucocyte count. However, the peripheral blood indices showed, in adults, average values for thrombocytes (236–280 $\times$ 10^9/L), leucocytes (7.2–7.5 $\times$ 10^9/L) and neutrophils (4.1–4.7 $\times$ 10^9/L) which were no different from those found in normal unexposed adults. The distribution function for these indices during the first examination period was the same, in terms of median values, for the irradiated group as for the references, but among the exposed persons a larger percentage showed two-sigma deviations from the average. Thus, the fraction of individuals with leucocyte counts above 9 $\times$ 10^9/L was 17–19%; with thrombocyte counts above 350 $\times$ 10^9/L it was 7–8%.

The reaction of the cardiovascular system was studied in all the individuals investigated on the basis of arterial blood pressure and systole frequency (pulse rate). The results among the essentially healthy members of Group A (Table V) indicated no regular increase in the frequency with which these indices departed from a normal distribution, nor any deviation as a function of radiation dose.

TABLE VI. NATURE AND FREQUENCY OF DISEASE IN THE INDIVIDUALS STUDIED

Class of illness, nosological units	Fraction of individuals affected (%)	
Parasitic infection, helminthiasis	0.6	
Nodular goitre and thyrotoxicosis	0.5	
Psychic disorders, neurasthenia	1.9	
Circulatory disorders:		
Rheumatic heart disease	1.8	13.7
Hypertension	2.5	
Ischaemia	3.3	
Coronary and cerebral atherosclerosis	5.1	
Varicose veins	1.0	
Respiratory disorders:		
Acute nasopharyngitis	5.3	8.3
Bronchitis	2.3	
Emphysema	0.7	

The population studies indicated that up to 75% were for all practical purposes healthy individuals. Twenty-five per cent of those investigated revealed general somatic problems of one kind or another. Among these, as can be seen from Table VI, more than half were suffering from cardiovascular disorders, and almost 30% had respiratory illnesses.

Thus the examinations conducted on individuals living in settlements at the head end of the deposition track showed no clinical evidence of radiation pathology. It is fair to assume that certain distortions in the distribution of blood indices are associated with the haematological reaction to irradiation observed in the early period: leucopenia, relative lymphoplasia and a leftward shift in the neutrophil formula.

Long after the accident medical studies were performed on individuals who could be said to belong to the critical group: these were people whose exposure to radiation had occurred during the period of body formation and development and in whom the exposure levels had been highest (Groups A and B). Of these individuals, one third were, for all practical purposes, healthy. In the rest careful investigation showed chronic infection of one kind or another (in 18% chronic otitis, in 13% chronic tonsilitis, and in another 16% chronic gastritis and cervicitis). The frequency of osteochondrosis increased with the age of the individual. Three persons had epilepsy associated with alcoholism and cranial trauma. The morbidity of the exposed individuals revealed no special characteristics in comparison with the control contingent. Peripheral blood indices were in the normal range. With increasing age the frequency of dystrophic changes in the ECG increased (classes 4, 5 and 9 in the Minnesota code). The frequency of ECGs in the zero class (with no changes) was no less in the irradiated persons than in the controls.

Serum cholesterol concentrations (mm/L) were the same among the irradiated contingent as among the controls: under 29 years of age 4.78 ± 0.1; up to 39 years of age 5.25 ± 0.06; up to 49 years 5.41 ± 0.06; and above 50 years 5.69 ± 0.06.

Certain disorders thought to be cancer risk factors were recorded no more frequently among irradiated persons than among the controls. Thus, in the 28-year-olds, chronic gastritis, endocervicitis and cervical erosion were encountered in 2.3, 11.1 and 11.1% of cases, respectively, whereas in the 50-year-olds they were found in 9, 20 and 0% of cases. One of the sensitive criteria for damage caused by ionizing radiation is infant mortality and intra-uterine developmental anomalies. Over the 35 year period, 35 cases of death due to congenital anomalies have been found among the offspring of the population living on land covered by the radioactive deposition track. In the first group, consisting of 10 270 individuals living in areas with a ^{90}Sr concentration of 1–2 Ci/km^2, there were 10 cases, and in the second group, consisting of 23 230 individuals living in an area with a ^{90}Sr density of 0.1–1 Ci/km^2 there were 25 cases. In the control group, consisting of 21 537 individuals living in an area with less than 0.1 Ci/km^2 (^{90}Sr), there were 39 cases of death due to congenital anomalies. In the overall mortality structure we found that mortality due to developmental defects accounts for 0.36–0.67% of all cases (see Table VII).

As can be seen from Table VII, the differences between the groups are statistically unreliable; nor did any significant differences emerge during the first two years following the accident.

The figures in Table VIII demonstrate the absence of any statistically significant difference in infant mortality although they are higher for the settlement closest to the radiation source. The reason for these higher figures still needs further clarification.

Highly instructive data were obtained from analyses of infant mortality during the years after the accident (Table IX). As can be seen from this table, there is no appreciable difference in infant mortality between the three groups compared, even against the background of the rather high infant mortality prevailing during those years. Here, too, the cases of infant mortality are apparently not associated so much with the levels of radiation exposure as with inequalities in the medical treatment accorded to newly born infants.

TABLE VII. EXTENSIVE (%) AND INTENSIVE INDICES OF MORTALITY DUE TO CONGENITAL DEVELOPMENTAL ANOMALIES

Population group	Extensive indices	Intensive indices after 35 years	
		per 10^5 population	per 10^3 newborn infants
1 - 10 270 individuals	0.36	4.2	1.02
2 - 23 230 individuals	0.38	4.2	1.93
K - 21 537 individuals	0.67	7.4	2.66
Chelyabinsk province			
- 1965	0.53	3.6	2.3
- 1986	0.23	2.2	1.3

TABLE VIII. MORTALITY OF NEWBORN INFANTS WITH CONGENITAL DEVELOPMENTAL DEFECTS BETWEEN 1980 AND 1987 (PER 1000 LIVE BIRTHS)

In the entire affected zone	At the nearest settlement	In Chelyabinsk province	In Sverdlovsk province
0.95 ± 0.08	1.7 ± 0.4	1.0 ± 0.08	1.1 ± 0.07

The remote (long term) effects of radiation exposure were studied in parallel among the irradiated population and the control contingent, and also in a zone where the effects of a nuclear facility might be expected to make themselves felt. In this way, more than 100 000 persons were surveyed.

Table X shows the effects of exposure to radiation on the most severely irradiated contingent. Among these persons, intensive mortality indices in Groups 1, 2, 3 and K were 272, 2760, 6578 and 5873 cases, respectively, and the corresponding mortality coefficients were 9.5, 11.5, 11.0 and 10.9 $\times 10^{-3}$. It will be seen that there are no differences as compared with the control contingent.

At the same time, age-related mortality indices show substantial deviations from the control contingent in individuals under age 4 and older than age 60. Nevertheless, it has proved impossible to find any link with the radiation dose. Thus, in Groups 1, 2, 3 and K the mortality coefficients for children aged up to one year

TABLE IX. MORTALITY OF INFANTS AGED UP TO 1 YEAR (PER 1000 LIVE BIRTHS)

Causes of death	Territory covered by deposition track	Control No. 1 on track boundary	Control No. 2 far from track boundary
All causes	27.7	31.4	38.6
Nutritional disorders	15.2 ± 2.8	12.3 ± 3	5 ± 1
Pneumonia	1.7 ± 1.0	3.1 ± 1.5	16.1 ± 1.8
Infectious diseases	1.6 ± 0.9	2.3 ± 1.3	3.0 ± 0.8
Disease of the newborn	8.7 ± 2.2	13.8 ± 3.2	14.5 ± 1.7

TABLE X. SIZE OF THE EXPOSED POPULATION AND AVERAGE DOSES RECEIVED

Group	Number of inhabitants	Duration exposure	Average doses (cSv)						
			External gamma irradiation	Internal irradiation				Effective dose eq.
				G.I. tract	Lungs	Red bone marrow	Bone surfaces	
1	1 054	10 d	17	150	2.7	0.5	0.7	52
2	10 720	30 a	0.4	2	0.2	3.8	5.2	2
3	23 230	30 a	0.1	0.7	0.1	0.7	1.0	0.4
K	21 537	30 a	–	–	–	–	–	–

were 91, 32, 63 and 52, for children between one and four years of age 13.7, 1.7, 5.0 and 3.3, and for individuals over 60 years of age, 39.2, 50.4, 43.1 and 46.9, respectively. In all other age groups the mortality indices and coefficients reflected no differences between the groups and the control contingent.

A fact to be noted is that among the 272 individuals from Group 1 who died, cancer is not in second place but in third place as a cause of death after heart disease, injuries and accidents. Another peculiarity is the predominance of death from infectious diseases over that from respiratory disorders.

TABLE XI. EXTENSIVE (%) AND INTENSIVE ($\times 10^{-5}$) INDICES OF MORTALITY DUE TO MALIGNANT TUMOURS

Population group	Number of cases	%	10^{-5}	Confidence intervals 95%
1	25	11.7	115.9	75–165
2	376	13.6	157.4	142–174
3	775	11.8	129.2	120–142
K	707	12.0	131.9	122–142

TABLE XII. STRUCTURE OF MORTALITY DUE TO MALIGNANT NEOPLASMS (PER 100 000 POPULATION)

Principal tumour sites	International classification number	Irradiated individuals			
		1	2	3	K
Oesophagus	150	26.5	8.2	11.3	12.1
Stomach	151	35.3	45.1	32.4	44.3
Other organs of the digestive system	152–159	8.8	30.7	20.9	22.4
Respiratory organs	160–163	17.7	29.5	24.9	26.4
Bones	170	0	3.1	0.9	2.4
Skin, oral cavity	140–147 172–173	0	7.5	1.4	4.5
Mammary gland	174	4.4	4.4	2.1	4.2
Corpus et cervix uteri	180–182	0	13.1	9.6	10.8
Other urogenital organs	183–189	4.6	9.4	6.6	7.6
Lymphatic and haematopoietic tissue	200–209	13.2	5.0	5.2	4.7

TABLE XIII. MORTALITY DUE TO MALIGNANT NEOPLASMS

	In the whole of the affected zone	At the nearest settlement	In Chelyabinsk province	In Sverdlovsk province
1970-1980	145.8	-	146.6	-
1980-1987	160.7 ± 2.5	105 ± 12.7	167.6 ± 3.2	159.4 ± 6.6

Particularly interesting is the analysis of mortality due to malignant tumours since these are the principal later manifestation of the effects of irradiation. The highest mortality indices — on the boundary of reliable statistical significance — were noted in individuals belonging to Group 2 (see Table XI). However, the groups selected for the purposes of this comparison were not large enough and hence it is impossible to conclude definitely that there is any appreciable difference between the magnitudes observed.

In the overall picture of neoplastic disorders observed, the most important place is occupied — over the entire period of interest — by cancer of the digestive tract, and in particular by cancer of the oesophagus (see Table XII). We see a tendency towards increased cancer of the oesophagus in Group 1, which was the group subjected to the highest doses, but even so these higher figures are not statistically significant.

Attention is also drawn to fatal cases of lymphatic neoplasms and neoplasms in haematopoietic tissue. The mortality coefficient in Group 1 was 13.2×10^{-5} as compared with 4.7×10^{-5} in the other groups. Although these differences are not statistically reliable because they are based on only three fatalities, we should note that the effective dose equivalent in this group amounted to 52 cSv, which is close to the critical dose for leukaemia induction.

The level of mortality due to neoplastic disorders, broken down by decades, is shown in Table XIII for the zone directly affected by the deposition track and compared with intensive indices for the neighbouring regions Chelyabinsk (1) and Sverdlovsk (2). The figures show that lethality regularly increases from the first decade to the next. Overall, in the zone affected by the track and by the operations of nuclear facilities, it rose from 145.8 to 160.7 ± 25 per 100 000 of population, and in regions one and two, from 167.6 ± 3.2 and 159.4 ± 6.6 per 100 000. In the nearest settlement the figure was only 105 ± 12.7, although the radiation dose here was higher. This lower figure is due entirely to the younger average age of the population in this settlement.

Analysis of the cause of morbidity due to malignant neoplasms following the irradiation accident suggests a frequency grouping for the initially diagnosed

TABLE XIV. PERCENTAGE OF INDIVIDUALS WHO MARRIED AND HAD CHILDREN

Group	Age at time of accident	Number of individuals	% married	% with children
Infants	Under 1 year	56	91 (82–97)	84 (73–92)[a]
Children	1–9 years	295	93 (89–96)[a]	90 (86–93)[a]
Juveniles	10–19 years	203	93 (89–96)[a]	93 (89–96)
Adults	20–29 years	201	95 (92–98)[a]	91 (87–94)
Adults	30–59 years	308	98 (96–99)[a]	98 (96–99)[a]
Controls (USSR as a whole)			81.9–82.6	94.6

[a] Significant differences from control.

tumours as a function of certain external factors. It was noted, for example, from the morbidity data in Chelyabinsk, that there was no connection between enhanced morbidity and dose rate. On the other hand, a clear and complete correlation was found between morbidity and releases of SO_2 to the atmosphere. Although SO_2 is not itself a carcinogen, it is extremely useful as a gauge of general chemical contamination. Actual data show that when there are no SO_2 releases morbidity amounts to 225 cases per 100 000 individuals per year, whereas in situations where SO_2 is released in amounts of 50 000, 100 000 and 150 000 t per year the morbidity figures rise to 250, 275 and 300 cases per 100 000, respectively. Accordingly, on the Chelyabinsk map the cancer mortality figures correlate not with the radioactive contamination track but with the location of metallurgical and chemical plants.

A great deal of attention has been given to the reproductive state of individuals irradiated at different ages. The figures in Table XIV indicate no systematic deviations from the norm — as far as this extremely important demographic indicator is concerned — among the individuals who received the largest doses. It will be seen from Table XIV that those who were newborn infants at the time of the accident and who married by the time they were 27 years of age have, as yet, comparatively few children. Among those who were older at the time, on the other hand, marriage frequency has been higher than among the controls, and the number of children has been either no different or slightly less than among the controls (this applies to individuals who were up to nine years old at the time of the accident). At the same time, the birth rate coefficients per 1000 inhabitants, as can be seen from Table XV, are higher among the population in the affected region than in the district as a whole.

TABLE XV. DYNAMICS OF BITH RATE COEFFICIENTS AMONG THE EVACUATED POPULATION (PER 1000)

Time after accident (a)	1	5	10	15	20	25	30	1-30
Number of children	51	271	491	717	960	1242	1586	1616
Birth rate coefficient	37.4	42.2	30.2	27.5	26.4	27.8	30.0	31.8
Standardized coefficients	40.4	48.7	31.8	26.9	24.8	26.2	26.6	31.8
Birth rate coefficients for Chelyabinsk province	24.1	20.8	14.8	16.0	16.7	19.8	16.7	18.4

One gets the impression that living conditions and social factors among the population evacuated at the time of the accident are somewhat more favourable than among the rest of the agricultural population in the region. There may also be some other factors, such as special national characteristics, involved.

In conclusion, we may note that observations on health, morbidity and mortality among the population subjected to the accidental release of radiation — with whole body exposure doses from 1–52 cSv and irradiation of individual organs up to 150 cSv — have revealed no significant variations from the comparable values found among healthy unexposed individuals.