Reconstruction of individual doses to the Semipalatinsk historical cohort subjects: methods and input parameters

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Abstract

A description of the methods to reconstruct the deterministic estimates of individual whole-body dose from external irradiation and dose to thyroid from internal irradiation to radioiodines (^{131}I and ^{133}I) for the subjects (more than 10,000 people) of the Semipalatinsk historical cohort, formed from the residents of ten settlements (Dolon, Kanonerka, Mostik, Cheremushki, Znamenka, Kainar, Karaul, Sarzhal, Kaskabulak and Kundyzhdy) radioactively contaminated during the atmospheric nuclear weapon testing at the Semipalatinsk Nuclear Test Site (SNTS) has been presented. Four significant nuclear tests (#1 - 29 August 1949, #2 - 24 September 1951, #4 - 12 August 1953, and #28 - 24 August 1956) that provided the major contribution to radiation doses to the cohort subjects were identified. For each above mentioned settlement the estimates of settlement-average absorbed dose to air from fallout arrival time to infinity and of radioiodine concentration in pasture grass at the fallout arrival time were calculated. In order to assess settlement-average absorbed dose to air from fallout arrival time to infinity the following sources of input data (if any) related to radiological conditions are used: (1) historical fallout patterns showing isopleths of dose in air from the fallout time of arrival until infinity, (2) historical survey meter readings (exposure rate measurements), (3) present-day thermoluminescence measurements in bricks, (4) present-day ^{137}Cs inventory, and (5) present-day ESR measurements of tooth enamel. Whole-body dose from external irradiation has been mainly determined by the radionuclides deposited on the ground following the passage of the radioactive cloud through a settlement. Dose to thyroid from internal irradiation to radioiodines has been mainly determined due to consumption of contaminated cow's (horse's) milk (koumiss) from grazing animals put on pasture. A joint U.S./Russian methodology has been applied to derive doses from external and internal irradiation. In order to derive estimates of individual whole-body dose from external irradiation and dose to thyroid from internal irradiation to radioiodines a restricted set of input personal data on the cohort subjects (date of birth, ethnicity, residence history) available in the registry created by the scientists from Kazakhstan and Japan is used. Because of lack of other personal data a life-style and dietary habits typical for a resident from specific age-group and ethnicity is used in dose reconstruction.

INTRODUCTION

The purpose of this paper is to describe (1) the methods and (2) input parameters that were used to reconstruct the deterministic estimates of individual whole-body dose from external irradiation and dose to thyroid from internal irradiation to radioiodines (^{131}I and ^{133}I) for the subjects (more than 10,000 people) of the Semipalatinsk historical cohort, formed from the residents of ten settlements (Dolon, Kanonerka, Mostik, Cheremushki, Znamenka, Kainar, Karaul, Sarzhal, Kaskabulak and Kundyzhdy) radioactively contaminated during the atmospheric nuclear weapon testing at the Semipalatinsk Nuclear Test Site (SNTS). Analysis of available data on radioactive fallout following atmospheric nuclear tests conducted at the SNTS allowed for identification of the most significant tests that provided the main contribution to the exposure to the residents from the considered settlements (Table 1). Each test presented in column 2 of Table 1 is responsible for contributing of more than 90% of total exposure to the residents of corresponding settlement during the whole period of the atmospheric nuclear testing (1949-1962). A joint U.S./Russian dose reconstruction methodology that combines the experience of scientists in Russia and the U.S. working in this area is used here [1, 2]. The U.S. scientists developed 10-term exponential functions describing exposure rate time profile for the U.S. nuclear test devices of three different designs: (1) Trinity for devices fueled with ^{239}Pu but surrounded with heavy steel and lead shielding, (2) Turbaloy, a simulated weapon fueled by ^{238}U, and (3) Tesla, for devices fueled by pure ^{239}Pu [1]. In the framework of the joint methodology each test at the SNTS was assigned with one of the three above-mentioned U.S. tests on the basis of similarity in design and fuel (see column 3 in Table 1).

Table 1. The most significant tests conducted at the SNTS that provided the main contribution to the exposure to the residents from the considered settlements.

Settlement	Main nuclear test (Semipalatinsk)	Surrogate nuclear test (Nevada)
Cheremushki	#1	Trinity (same as #1 at the SNTS)
Dolon	#1	
Kanonerka	#1	
Mostik	#1	
Kainar	#2	Tesla (typical Pu test)
Sarzhal	#4	Turbaloy (thermonuclear test)
Karaul	#4	
Kundyzhdy	#4	
Kaskabulak	#18	Tesla (typical Pu test)
Znamenka	#28	

Trajectories of radioactive clouds of the most significant tests conducted at the SNTS and location of the settlements considered in this paper are presented in Fig.1 [3]. Kundyzhdy (not shown in this map) is located below Karaul along the trajectory of test #4.

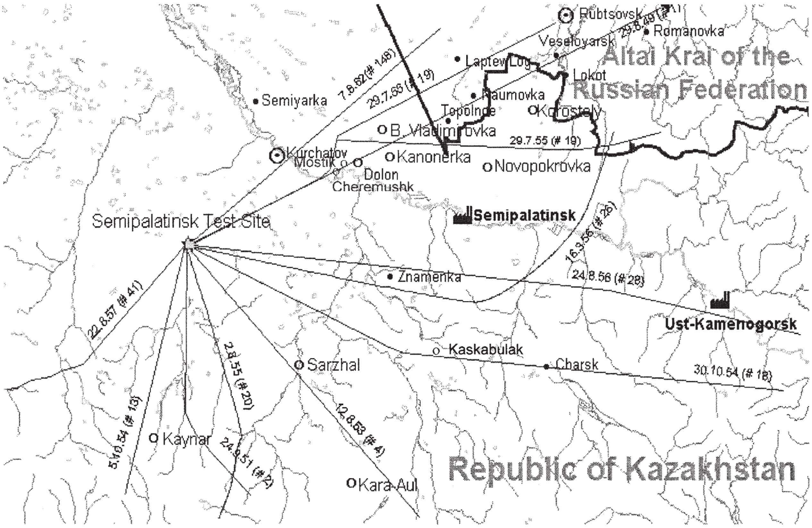

Fig. 1. Trajectories of radioactive clouds of the most significant tests conducted at the SNTS and location of the settlements considered in this paper [3].

ESTIMATION OF WHOLE-BODY DOSE FROM EXTERNAL IRRADIATION

The equation to assess a whole-body dose, D_{body}, is as follows:

$$D_{body} = D_{air} \times CF \times [t_{oudoors}+(t_{day} - t_{outdoors})/k_{shield}]/t_{day} \quad (1)$$

where D_{air} is a settlement-average dose to air from the time of fallout arrival to infinity, Gy;

CF is a conversion factor to convert absorbed dose to air to absorbed dose to the body (Gy per Gy) depending upon age (assuming 100% outdoor occupancy), dimensionless;

$t_{outdoors}$ is time spent outdoors, h;

t_{day}=24 h, hours in a day; and

k_{shield} is the shielding factor related to the ratio of the outdoor and indoor exposure rates for gamma radiation emitted from the activity deposited on the ground, dimensionless.

The age-dependent values of parameters CF and $t_{outdoors}$ are presented in Table 2. Selection of the values of parameter $t_{outdoors}$ was done accounting for the data given in publications [3, 4] according to which there is some difference in time spent outdoors between people of the same age but different ethnicity. In addition, the residents of Russian ethnicity typically lived in wooden houses, while the residents of Kazakh ethnicity lived in adobe houses. The value of shielding parameter for wooden houses regarding decrease of the exposure emitted from the activity deposited on the ground was estimated to be equal to 3, while that value for adobe houses was found to be equal to 13 [3].

Table 2. The age-dependent values of parameters CF and $t_{outdoors}$ used in assessing the estimates of whole-body dose from external irradiation.

Age	CF, conversion factor Gy per Gy [5]	Hours per day spent outdoors (h) [3, 4]	
		Kazakhs	Russians
3 mo	0.95	1	0.5
1 y	0.91	5	9
5 y	0.88	7	9
10 y	0.83	10 (5)$^{\&}$	10 (6)$^{\&}$
15 y	0.81	13 (5)$^{\&}$	11 (3)$^{\&}$
Adult	0.79	16	16

$^{\&}$ - for period starting from September 1

In order to assess settlement-average absorbed dose to air from fallout arrival time to infinity the following sources of input data (if any) related to radiological conditions were used: (1) historical fallout patterns showing isopleths of dose in air from the fallout time of arrival until infinity, (2) historical survey meter readings (exposure rate measurements), (3) present-day thermoluminescence measurements in bricks, (4) present-day ^{137}Cs inventory, and (5) present-day ESR measurements of tooth enamel. Whole-body dose from external irradiation has been mainly determined by the radionuclides deposited on the ground, while external irradiation from the radioactive cloud during its passage through a settlement contributed substantially less (a few percent) compared to the former. The most important parameter is historical record of the exposure rate measured soon following fallout in a settlement considered. However, only for five settlements of interest (Dolon, Mostik, Kainar, Sarzhal, and Karaul) such information was available for assessing dose to air D_{air}, using the method described in detail in [1]. For the other five settlements (Cheremushki, Kanonerka, Kundyzhdy, Kaskabulak, Znamenka) the other input data were used for reconstruction dose to air.

ESTIMATION OF DOSE TO THYROID FROM INTERNAL IRRADIATION TO RADIOIODINES

It is important to stress that the main pathway of radioiodines intake for the residents of the settlements around the SNTS is ingestion with milk of cows and mares. Inhalation intake of radioiodines during the passage of the radioactive cloud is negligible compared to ingestion intake. Leafy vegetables were not included in typical diet in 1949-1962. So, the equation to assess internal dose to thyroid from ingestion of i-th isotope of radioiodine for age (k) will be as follows:

$$D_{i,k} = DF_{i,k} \times V_{m,k} \times \int_{0}^{t_2} C_{m,i}(t)dt / p_{m,i,k} \qquad (2)$$

where $DF_{i,k}$ is age-dependent thyroid dose factor from ingestion of radioiodine i, Gy Bq^{-1};

$V_{m,k}$ is age-dependent milk consumption rate, L d^{-1};

$C_{m,i}(t)$ is concentration of radioiodine i in milk, Bq L^{-1};

$p_{m,i,k}$ is age-dependent fraction of intake of radioiodine i with milk in the entire intake, dimensionless.

Only two isotopes of radioiodine (^{131}I and ^{133}I) are important to assess dose to thyroid. Age-dependent dose factors for ingestion intake $DF_{i,k}$ are taken from [6]. One of the main differences between Russians and Kazakhs is that Russians drank only cow's milk, while Kazakhs drank both cow's and horse's (koumiss) milk. The values of parameter $V_{m,k}$ derived from [3, 4] are given in Table 3. Accounting for that ingestion of radioiodines with milk is the dominant pathway a constant value of $p_{m,i,k}$ equal to 0.9 was chosen for the residents of all ages.

Table 3. The age-dependent values of milk consumption rate $V_{m,k}$ used in assessing the estimates of dose to thyroid.

Age	Kazakhs (cow's milk)	Russians (cow's milk)	Kazakhs (koumiss)
3 mo	0.18[&]	0.4[&]	-
1 y	0.25	0.55	0.1
5 y	0.4	0.7	0.25
10 y	0.4	0.55	0.25
15 y	0.4	0.8	0.45
Adult	0.4	0.8	0.45

[&] - for non breast feeding

Concentration of radioiodine i in milk at time t is estimated as:

$$C_{m,i}(t) = \beta_i \times TF_{m,i} \times \int_0^t C_{gr,i}(\tau) \times Q_f \times \lambda_{c,i} \times e^{-(\lambda_{c,i}+\lambda_i)\times(t-\tau)} d\tau \qquad (3)$$

where $C_{gr,i}(t)$ is concentration of radioiodine i in pasture grass at time t, Bq kg^{-1};

β_i is solubility of radioiodine i in biologically active fraction of fallout [7];

$TF_{m,i}$ is feed-to-milk of cow (mare) transfer factor for radioiodine i, d L^{-1} [8];

Q_f is daily intake rate of pasture grass by cow (mare), kg d^{-1} wet [8];

$\lambda_{c,i}$ is biological removal rate of radioiodine i from cow (mare) to milk, d^{-1} [8];

λ_i is radioactive decay constant for radioiodine i, d^{-1}.

Concentration of radioiodine i in grass at time t is estimated as:

$$C_{gr,i}(t) = C_{gr,i}(0) \times \exp(-(\lambda_{gr,i} + \lambda_i)\times t) \qquad (4)$$

where $C_{gr,i}(0)$ is concentration of radioiodine i in pasture grass at time-of-arrival (TOA), Bq kg^{-1};

$\lambda_{gr,i}$ is weathering removal rate of radioiodine i from pasture grass, d^{-1} [8];

t is time counted from TOA, d.

Concentration of radioiodine i in grass at TOA is estimated as:

$$C_{gr,i}(0) = C_{gr,i}(TOA) = C_{gr,i}(H+12h) \times \exp(-(\lambda_{gr,i} + \lambda_i) \times (TOA/24-0.5)) \qquad (5)$$

where $C_{gr,i}(H+12h)$ is concentration of radioiodine i in pasture grass at 12 h after detonation, Bq kg^{-1};

TOA is fallout arrival time expressed in h.

Concentration of radioiodine i in grass at t = H+12h is estimated as:

$$C_{gr,i}(t) = P(t) \times (q_i/P)(t) \times N_{50} \times alpha \quad (6)$$

where $P(t)$ is the exposure rate at time T=H+12h, mR/h;

$(q_i/P)(t)$ is the ratio of ground deposition density of radioiodine i to the exposure rate at H+12h, (kBq/m2)/(mR/h);

N_{50} is fraction of the activity in fallout assigned to the biologically active particles with diameter d≤50 μm [7];

alpha is mass interception factor, m^2 kg^{-1} [7].

Parameters $P(t)$, q_i, β_i, N_{50}, TOA are derived from available input data related to: (1) a nuclear explosion, (2) meteorological conditions along the radioactive trace, and (3) radiological conditions for a settlement.

RESULTS AND DISCUSSION

Estimates of settlement-average dose to air are presented in Table 4 (third column) with indication of what input information (fourth column) was used for dose reconstruction. In addition, the estimates of ground deposition densities of the most important radionuclides (q_{137} for ^{137}Cs, q_{131} for ^{131}I, and q_{133} for ^{133}I) in the settlements are given in columns 5 through 7 in Table 4. Estimates of the values of parameters q_{137}, q_{131}, and q_{133} were done assuming various degree of fractionation between refractory and volatile elements in the settlements considered. No fractionation was assumed between volatile elements of iodine and cesium.

Table 4. Estimates of settlement-average dose and of ground deposition densities of the most important radionuclides (q_{137} for ^{137}Cs, q_{131} for ^{131}I, and q_{133} for ^{133}I) in the settlements of interest.

Settlement	TOA, h	Dose to air, mGy	Major parameters	q_{137}, kBq/m^2	q_{131}, MBq/m^2	q_{133}, MBq/m^2
Cheremushki	1.9	260	map, ^{137}Cs, ESR	2.7	2.1	28
Dolon	2.4	430	$P(t_m)$	4.7	3.8	49
Kanonerka	3.0	220	TL, map	2.6	2.1	27
Mostik	2.0	140	$P(t_m)$	1.5	1.2	16
Kainar	5.2	120	$P(t_m)$	2.9	2.7	32
Sarzhal	1.7	890	$P(t_m)$	8.4	5.3	75
Karaul	2.9	740	$P(t_m)$	8.4	6.3	81
Kundyzhdy	3.8	10	Map	0.12	0.095	1.2
Kaskabulak	5.4	5	Map	0.40	0.36	4.3
Znamenka	1.8	70	Map	0.85	0.61	8.4

It is worth noting that calculations done according to [7] showed that the major activity of radioiodines deposited on the ground in the settlements considered is attached to the fallout particles with diameter higher than 50 μm, which cannot be retained by vegetation and dropped on the ground. For example, only 3.2% of total deposited activity was thought to have been retained by pasture grass in Dolon, 2.6% - in Cheremushki, 0.7% - in Znamenka. In addition, due to low solubility only small amount of radioiodines (about 20 %) ingested with pasture grass is thought to have been absorbed from the gut to cow's (horse's) body fluids. Thus, discriminating factor of about 100-1000 resulted in much less estimates of dose to thyroid for the residents leaving in the areas neighboring to the SNTS compared to that for the residents leaving around the Chernobyl NPP in case of contamination of residential settlements with the same level of deposition density of radioiodines.

The estimates of individual whole-body dose from external irradiation and dose to thyroid from internal irradiation to radioiodines for the subjects of the Semipalatinsk historical cohort depending upon residential settlement, age, and ethnicity are presented in companion paper [9].

CONCLUSIONS

To reconstruct settlement-average dose to air the historical exposure rate measurements were used only for five settlements (Dolon, Mostik, Kainar, Sarzhal, and Karaul), while other input information (fallout patterns, TL-, ESR-measurements, ^{137}Cs deposition density) was used for five settlements (Cheremushki, Kanonerka, Kundyzhdy, Kaskabulak, Znamenka).

To reconstruct individual whole body dose from external exposure and thyroid dose to radioiodines from internal exposure available personal input data on (a) residential settlement, (b) age and (c) ethnicity were used.

Due to low fraction of total activity related to fallout particles with AMAD less than 50 μm and low solubility of them the estimates of dose to thyroid from radioiodines for the residents leaving near the SNTS are much less (by a factor of 100-1000) than the estimates of thyroid dose for the residents leaving around the Chernobyl NPP in case of contamination of residential settlements with the same level of deposition density of radioiodines.

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