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ESTIMATION OF RADIATION DOSES FOR A CASE-CONTROL STUDY OF THYROID CANCER AMONG UKRAINIAN CHERNOBYL CLEANUP WORKERS

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Abstract

Thyroid doses were estimated for 607 subjects of the case-control study of thyroid cancer nested in the cohort of 150,813 male Ukrainian cleanup workers, who were exposed to radiation as a result of the 1986 Chernobyl nuclear power plant accident. Individual thyroid doses due to external irradiation, inhalation of ¹³¹I and short-lived radioiodine and radiotellurium isotopes (¹³²I, ¹³³I, ¹³⁵I, ^{131m}Te and ¹³²Te) during the cleanup mission, and intake of ¹³¹I during residence in contaminated settlements were calculated for all study subjects, along with associated uncertainty distributions. The average thyroid dose due to all exposure pathways combined was estimated to be 199 mGy (median dose of 47 mGy; range: 0.15 mGy to 9.0 Gy), with averages of 140 mGy (median of 20 mGy; range: 0.015 mGy to 3.6 Gy) from external irradiation during the cleanup mission, 44 mGy (median of 12 mGy; range: ~0 mGy to 1.7 Gy) due to ¹³¹I inhalation, 42 mGy (median of 7.3 mGy; range: 0.001 mGy to 3.4 Gy) due to ¹³¹I intake during residence, and 11 mGy (median of 1.6 mGy; range: ~0 mGy to 0.38 Gy) due to inhalation of short-lived radionuclides. Internal exposure of the thyroid gland to ¹³¹I contributed more than 50% of the total thyroid dose in 45% of the study subjects. The uncertainties of the individual stochastic doses were characterized by a mean GSD of 2.0, 1.8, 2.0 and 2.6 for external irradiation, inhalation of ¹³¹I, inhalation of short-lived radionuclides and residential exposure, respectively. The models used for dose calculations were validated against instrumental measurements done shortly after the accident. Results of the validation showed that thyroid doses could be estimated retrospectively for Chernobyl cleanup workers two-three decades after the accident with a reasonable degree of reliability.

Keywords

Chernobyl; cleanup worker; thyroid; radiation; dose

INTRODUCTION

The accident at the Chernobyl (Chornobyl) nuclear power plant (NPP) occurred on 26 April 1986 and resulted in heavy radioactive contamination of buildings and ground surface at the Chernobyl site and within the surrounding 30-km zone. Several hundred thousand workers, called ‘cleanup workers’ or ‘liquidators’, participated in decontamination and recovery activities within the 30-km zone until the end of 1990. Approximately 306,000 of these (the majority from Ukraine, Russian Federation and Belarus) worked in 1986 when the highest doses were received (UNSCEAR 2011). The main cleanup workers’ activities included decontamination of the reactor block and reactor site, construction of the sarcophagus (Object Shelter) and living quarters for the Chernobyl NPP personnel, waste repositories, safeguarding the 30-km zone and evacuated settlements.

Majority of cleanup workers were exposed to external radiation (Chumak et al. 2007; Kryuchkov et al. 2009, 2012). However, those who were involved in cleanup activities during the first 10 days after the accident may have received radiation doses to the thyroid gland resulting primarily from the inhalation of air contaminated with ^{131}I (Drozdovitch et al. 2019). Epidemiological studies of Chernobyl cleanup workers (Furukawa et al. 2012; Kesminiene et al. 2012) suggested that internal exposure of adults to ^{131}I may cause an increased risk of radiation-related thyroid cancer. Mabuchi et al. (2013) argued that there is a need for better understanding of radiation-related thyroid cancer risk following exposure in adulthood.

To fill this gap in knowledge, a case-control study of thyroid cancer nested in a cohort of Ukrainian cleanup workers was conducted in 2009–2017 by the National Research Center for Radiation Medicine (Kyiv) and the U.S. National Cancer Institute (Bethesda). In the current study, methods were developed to reconstruct individual thyroid doses to support the epidemiological study of Chernobyl cleanup workers.

MATERIALS AND METHODS

Study population

A nested case-control study of thyroid cancer was conducted in the cohort of 150,813 male adult Ukrainian liquidators who worked on the industrial site and in the most contaminated areas around the Chernobyl nuclear power plant between 26 April 1986 and 31 December 1990. The thyroid cancer cases were ascertained retrospectively through the linkage of the cohort of male Ukrainian cleanup workers with the Ukrainian Cancer Registry in five study Oblasts^{††} (Kyiv, Chernihiv, Dnepropetrovsk, Donetsk, and Kharkiv), and in Kyiv city during post-accident period until 2012. For each case ($n=149$), at least three controls were matched

^{††}An oblast is the largest administrative unit in Ukraine. The typical size of an oblast is 20,000–30,000 km² with a population of 1.1–4.3 million persons.

by year of birth (± 2 years), oblast of residence, and living at the time of diagnosis of the case.

Cleanup workers were involved in various cleanup activities, worked under different radiation monitoring and safety conditions and were ultimately exposed to different types and levels of radiation. Major categories of cleanup workers, who were the subjects of this study, included: military (236 individuals, 38.9% of the total), civilians who performed various tasks in the 30-km zone, so-called ‘sent on mission’ (137 individuals, 22.6%), early cleanup workers (64 individuals, 10.5%), and a mixed category that includes cleanup workers who were at the Chernobyl site a few times as members of different categories (152 individuals, 25.0%).

A special dosimetry questionnaire was designed to collect retrospective information to be used for dose reconstruction, including items about locations, dates and conditions of cleanup workers’ activities as well as place of residence during the cleanup mission. The questionnaire was a modified version of the instrument successfully used in the Ukrainian-American study of leukemia and related disorders (Chumak et al. 2008). Modifications included additional questions about dates of intake of potassium iodine (KI) pills for iodine prophylaxis during cleanup mission and about the subject’s residential history and diet during residence in contaminated settlements (see Section “Thyroid dose due to ^{131}I intake not related to the work as a Chernobyl liquidator (residential exposure)”). Questionnaire also contained supplementary epidemiological data needed for the consequent risk analysis (account for confounding factors) such as anthropometry, professional and/or medical contacts with ionising radiation, family history of thyroid cancer, smoking/alcohol consumption habits etc. The current questionnaire was administered in interviews with the study subjects carried out by trained personnel during the period of 15 November 2010 – 5 May 2016, some 25–30 years after the accident. In the case of deceased or incapable subjects, two proxies were interviewed: (1) a next-of-kin, usually the spouse, who provided supplementary epidemiological data and the names of persons, who worked together with the subject at Chernobyl site, and (2) identified colleague(s), who described the cleanup activities of the subject. The interviewer also collected and copied additional relevant information from the interviewee: certificates, itineraries of the cleanup worker’s transportations, etc.

Radiation dose reconstruction

Liquidators who worked at the Chernobyl NPP site and in the 30-km zone were exposed to external radiation from radionuclide-contaminated buildings and soil surface. Those who started their mission during the first 10 days after the accident may have received radiation dose to the thyroid due to inhalation of ^{131}I with contaminated air. Inhalation of short-lived radioiodines and radiotelluriums could also contribute to exposure of the thyroid gland and, therefore, this source of internal exposure was also considered in the study. In addition to the dose received as a cleanup worker, the dose received in the places of residence could also be a substantial component of thyroid exposure. Cleanup workers, who resided on the highly contaminated northern part of Ukraine, might have received thyroid doses at their places of residence due to consumption of locally produced food contaminated with ^{131}I . Table 1

summarizes characteristics of components of thyroid dose that were reconstructed for the study.

The way individual thyroid doses due to different exposure pathways were estimated to the study subjects is described in the following sections.

Thyroid doses due to external irradiation related to the cleanup worker

mission—To estimate external doses to cleanup workers, a time-and-motion method named RADRUE (Realistic Analytical Dose Reconstruction with Uncertainty Estimation) was used (Kryuchkov et al. 2009). The RADRUE technique calculates external dose as a product of the exposure rate and time of irradiation accounting for shielding properties of the local environment (location factor). The external dose absorbed in the thyroid gland during a cleanup worker mission resulted from the summation of the products of exposure rate, duration, and location factor during each time interval of exposure to radiation:

$$D_{ext} = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} C_{th} \cdot P[x(t_j), y(t_j)] \cdot \Delta t_j \cdot L_j \quad (1)$$

where D_{ext} is the thyroid dose due to external irradiation for the study subject (mGy); N_i is the number of days in cleanup mission of the study subject; N_j is the number of cleanup activities at different locations on day i considered in the calculation (usually unequal between different days of cleanup mission). Activities included time spent working, traveling, or resting during the cleanup mission; C_{th} is the conversion coefficient from ambient dose rate in air to the absorbed dose in the thyroid (mGy h⁻¹ per mGy h⁻¹); $P[x(t_j), y(t_j)]$ is the ambient dose rate in air (mGy h⁻¹) at the location $[x(t_j), y(t_j)]$ and at time t_j , where and when the study subject was present; Δt_j is the time interval of performing of complete cleanup activity j by the study subject (h); L_j is the location factor at the location of the cleanup activity j (unitless).

It should be noted that the computer code initially developed to implement the RADRUE method was modified for the purposes of this study to a new computer code named Rockville. Algorithms to calculate organ-specific doses due to external irradiation used in the code RADRUE were completely transferred to the code Rockville and validated by an international group of dosimetry experts. The major modifications were the following:

- Development of a special module to calculate thyroid doses due to inhalation of ¹³¹I and short-lived radioiodine and radiotellurium isotopes;
- Creation of regular grids of radiation data (exposure rate in air, ¹³¹I concentration in air, etc.) using different geostatistical interpolation techniques. Fig. 1 shows gridlines of exposure rates in air that are implemented in computer code Rockville for the 30-km zone around the Chernobyl NPP, as an example, on 26–27 April and 28–29 April 1986;
- Improvement of databases of the site and buildings of Chernobyl NPP;
- Improvement of algorithm to calculate radiation doses inside buildings of Chernobyl NPP;

- Visualization of radiation situation to facilitate questionnaire data entry for a dosimetry expert and possibility to use Google maps and Microsoft Virtual Earth with different scales.

Doses calculated using the RADRUE method were compared to the most reliable measured doses available for different groups of cleanup workers. It was shown that RADRUE doses agreed reasonably well within the uncertainty range with measured doses. Detailed descriptions of questionnaire data processing, entering and validation that are applied in the RADRUE method and of validation exercises for RADRUE method can be found elsewhere (Kryuchkov et al. 2009).

Thyroid doses due to ^{131}I inhalation during the cleanup worker mission—To calculate the individual thyroid doses for Chernobyl cleanup workers from ^{131}I inhalation the model developed by Drozdovitch et al. (2019) was used. It considers the following factors: the ground-level outdoor air concentrations of ^{131}I at the locations where liquidator worked and resided, the reduction of ^{131}I activity in inhaled air due to indoor occupancy, the time spent indoors by cleanup worker, the breathing rate during the different physical activities, and intake of potassium iodine (KI) pills for iodine prophylaxis.

As was mentioned above, a special module was designed for computer code Rockville to calculate thyroid dose due to ^{131}I inhalation. Similar to calculation of thyroid dose due to external irradiation, information on whereabouts (location, duration, indoors / outdoors) and activities performed by the study subjects was used to calculate thyroid dose due to ^{131}I inhalation using the following equation:

$$D_{inh}^{I-131} = \frac{13.82 \cdot E_{th}}{m_{th}} \cdot \sum_{i=1}^N \left[\sum_{j=1}^{N_j} I_{inh,j} \cdot w_{inh} \cdot w_{th} \cdot CF_{KI,i} \right] + Q_{thyr,inh,i-1} \cdot e^{-(\lambda_{th} + \lambda_{r,I-131})} \quad (2)$$

where D_{inh}^{I-131} is the thyroid dose due to inhalation of ^{131}I for the study subject (mGy); 13.82 is a unit conversion factor ($\text{Bq kBq}^{-1} \text{ g kg}^{-1} \text{ J MeV}^{-1} \text{ s d}^{-1} \text{ mGy Gy}^{-1}$); $E_{th}=0.2$ MeV is the mean energy absorbed in the thyroid per decay of ^{131}I in the thyroid; m_{th} is the thyroid mass for adult male (g); $N=66$ is the number of days counted since the accident until complete elimination of ^{131}I from the thyroid after inhalation; $I_{inh,j}$ is the intake function of ^{131}I with contaminated air at the location of the cleanup activity j during the day i (kBq); w_{inh} is the fraction of inhaled iodine transferred to blood (unitless); w_{th} is the fraction of iodine uptake by the thyroid (unitless); $CF_{KI,i}$ is the correction factor on day i of w_{th} that varies with time after intake of stable iodine for prophylactic reason (Table A1.4 from (Drozdovitch et al. 2013)) (unitless); $Q_{thyr,inh,i-1}$ is the activity in the thyroid of the study subject on day $i-1$ due to inhalation of ^{131}I (kBq); $\lambda_{th} = \ln(2)/T_b$ is the rate of biological elimination of iodine from the thyroid (d^{-1}), T_b is the biological half-time of iodine removal from the thyroid (d); $\lambda_{r,I-131}=0.0862 \text{ d}^{-1}$ is the radioactive decay rate of ^{131}I .

Values of dosimetry model parameters are given below in Section “Uncertainty of the thyroid doses”. The intake function of ^{131}I with contaminated air was calculated as:

$$I_{(inh, j)} = C_{(air, i, j)}^{(I-131)} \cdot B_{(m, j)} \cdot \Delta t_j \cdot F_j, \quad (3)$$

where $C_{(air, i, j)}^{(I-131)}$ is the time-integrated activity of ^{131}I in air at the location of the j -th cleanup activity during the day i (KBq d m^{-3}); $B_{(m, j)}$ is the breathing rate for adult person according to (ICRP 2002) that correspond to the physical activity m of the subject at the location of the cleanup activity j ($\text{m}^3 \text{d}^{-1}$); Δt_j is the time interval of performing cleanup activity j by the study subject (d); F_j is the reduction factor of ^{131}I activity in air that is associated with indoor occupancy at the location of the j -th cleanup activity (unitless). $F_j=0.1, 0.3$ and 0.5 if the study subject stayed indoors in Pripjat-town, buildings of Chernobyl NPP, or rural settlement in the 30-km zone around the Chernobyl NPP, respectively, and $F_j=1$ if the study subject stayed outdoors.

Values of average daily ^{131}I concentration in ground-level air were calculated for each settlement in Ukraine using the atmospheric transport model developed by Talerko (2005a, 2005b). Fig. 2 shows implemented computer code Rockville gridlines of ^{131}I concentration in air in the 30-km zone around the Chernobyl NPP, as an example, on 26 April and 27 April 1986.

Validation of model—This model was validated by a dataset of measurements of exposure rate near the neck, called ‘direct thyroid measurements’, performed from 30 April to 5 May 1986 in a group of 594 cleanup workers. Although the study subjects in this group of measured cleanup workers were not identified, the ^{131}I activities in the thyroids, which were calculated using the model, were compared with those estimated from the direct thyroid measurements done for 594 cleanup workers. The arithmetic mean $\pm$ standard deviation of the ratios of measured-to-calculated activities of ^{131}I in the thyroid was found to be 1.6 ± 2.4 (median was 0.8). Among this group of measured cleanup workers, detailed descriptions of hour-by-hour whereabouts and work history were available for 60 individuals. For these cleanup workers the mean of the ratios of measured-to-calculated activities was found to be 1.2 ± 0.7 (median was 1.0). Fig. 3 compares thyroid doses due to ^{131}I inhalation calculated by the model with those derived from direct thyroid measurements for 60 cleanup workers with detailed work history. As can be seen from the figure, the two sets of doses agree for 92.6% individuals within factor of 3 (shown by broken lines), coefficient of correlation is $r=0.75$. Detailed descriptions of the model validation could be found elsewhere (Drozdovitch et al. 2019).

Results of the model validation indicated that thyroid dose due to ^{131}I inhalation could be estimated for Chernobyl cleanup workers with a reasonable degree of reliability. However, because direct thyroid measurements were not available for the study subjects, dose estimation requires detailed information on whereabouts and work history of the cleanup worker collected in this case-control study for all subjects by means of personal interview. Unfortunately, it was not possible to evaluate the reliability of the interview responses

provided by the study subjects or proxies as there are no ‘gold’ standard data (e.g. historical questionnaire obtained shortly after the cleanup mission) for them to compare with.

Thyroid doses due to inhalation of short-lived radioiodine and radiotellurium isotopes during the cleanup worker mission—A nuclear reactor produces several short-lived radioiodine isotopes with the same behavior in the environment and the human body as ^{131}I . Also, the radiotelluriums, which are the precursor of the radioiodines, need to be taken into consideration. Because of the short half-time of these isotopes, inhalation of only ^{132}I , ^{133}I , ^{135}I , $^{131\text{m}}\text{Te}$ and ^{132}Te contributed to the thyroid exposure (Balonov et al. 2003). Thyroid dose due to inhalation of short-lived radioiodine and radiotellurium isotopes was estimated as a fraction of thyroid dose due to inhalation of ^{131}I using approach suggested by Gavrilin et al. (2004):

$$D_{inh,i}^m = D_{inh,i}^{I-131} \cdot R_{dose,m,i} \quad (4)$$

where $D_{inh,i}^m$ is the thyroid dose due to inhalation of short-lived radionuclide m for the study subject on day i (mGy); $R_{dose,m,i}$ is the ratio of thyroid doses due to inhalation of short-lived radionuclide m to that of ^{131}I on day i (unitless).

The ratio for each day from 26 April through 6 May, when inhalation of ^{131}I and short-lived radionuclides occurred, can be expressed as:

$$R_{dose,m,i} = \frac{D_{inh,i}^m}{D_{inh,i}^{I-131}} = R_{DF,m} \cdot R_{air,m,i} \quad (5)$$

where $R_{DF,m,i}$ is the ratio of the inhalation thyroid dose coefficients of radionuclide m to that of ^{131}I on day i (ICRP 1995) (unitless); $R_{air,m,i}$ is the ratio of the intakes due to inhalation of radionuclide m to that of ^{131}I on day i that is equal to the ratio of average concentration in ground level air of radionuclide m to that of ^{131}I on day i (unitless).

Values of $R_{air,m,i}$ were calculated using the following equation:

$$R_{air,m,i} = R_{air,m,0} \cdot e^{-\lambda_{r,m} \cdot t} \quad (6)$$

where $R_{air,m,0}$ is the ratio of the activity of radionuclide m to ^{131}I in the reactor core at the time of the explosion (unitless) (Gavrilin et al. 2004); $\lambda_{r,m}$ is the radioactive decay rate of radionuclide m (d^{-1}); t is the time after the accident (d).

Values of parameters of model to calculate the ratios of thyroid dose due to inhalation of short-lived radionuclides to thyroid dose due to inhalation of ^{131}I and results of calculation are given in Table 2. As can be seen from the table, by the end of inhalation intake on 6 May 1986, the thyroid dose was almost entirely defined by ^{131}I .

Thyroid dose due to ^{131}I intake not related to the work as a Chernobyl liquidator (residential exposure)—Due to the wide-spread contamination of the

Ukrainian territory following the Chernobyl accident, cleanup workers from Ukraine additionally received radiation doses to the thyroid due to ^{131}I intake from locally produced food while residing in contaminated settlements between 26 April and 30 June 1986. Some study subjects spent some time in the south-eastern part of Belarus that was also highly contaminated with ^{131}I . The distribution of the study subjects according to the oblast of residence at the time of the accident and range of ^{137}Cs and ^{131}I deposition in the settlements of residence is given in Table 3.

Values of ^{131}I ground deposition were calculated by Talerko (2005a, 2005b) using the atmospheric transport model developed for Ukraine. Fig. 4 shows ^{131}I ground deposition in the study Oblasts that was accumulated from 26 April through 6 May 1986.

To estimate the radiation doses due to ^{131}I intakes not related to the work as a Chernobyl cleanup worker, the study dosimetry questionnaire was extended with a section designed to elicit information on the subject's residential history, consumptions of locally produced cow's milk, milk products and leafy vegetables, and administration of stable iodine to blockade intake of radioiodine. In the case of deceased or incapable subject, the spouse was interviewed to provide this information.

Direct thyroid measurements that were done shortly after the accident are the best basis to estimate reliable 'instrumental' thyroid doses due to ^{131}I intake. Unfortunately, no overlap was found in course of the linkage of the list of 607 study subjects with the database of around 50,000 direct thyroid measurements done in Ukraine among adults (Likhtarov et al. 2005). Therefore, only dose based on an 'ecological' model can be calculated for the subjects included in this study. Information obtained during the personal interviews was input into an 'ecological' model that describes transport of radioactive isotope of ^{131}I from environment to milk and dairy products and, finally, to the human's body and thyroid. Time-integrated ^{131}I activity in the thyroid, estimated via the ecological model, determined 'ecological' dose. Ecological model, which was used to calculate the thyroid dose due to ^{131}I intakes during residence, is described in detail by Drozdovitch et al. (2013) with adaption to regional-specific parameters for Ukraine (Likhtarov et al. 2014).

In brief, ecological thyroid dose due to ^{131}I intake during residence of the study subject was calculated using the following equation:

$$D_{ecol, res}^{I-131} = \frac{13.82 \cdot E_{th}}{m_{th}} \cdot \sum_{k=1}^N \left[I_{ing, k} \cdot w_{ing} \cdot w_{th} \cdot CF_{KI, k} + Q_{thyr, ing, k-1} \cdot e^{-(\lambda_{th} + \lambda_{r, I-131})} \right] \quad (7)$$

where $D_{ecol, res}^{I-131}$ is the ecological thyroid dose due to ^{131}I intake with locally produced foodstuffs during residence for the study subject (mGy); $N=66$ is the number of days counted since the accident until complete elimination of ^{131}I from the thyroid after ^{131}I intake during residence until 30 June 1986; $I_{ing, k}$ is the intake function of iodine ^{131}I with foodstuffs during the day k (kBq); $w_{ing}=1.0$ is the fraction of ingested iodine transferred to

blood (ICRP 1993) (unitless); $Q_{thy,ing,k-1}$ is activity in the thyroid of the study subject on day $k-1$ due to ingestion of ^{131}I (kBq).

The intake function of ^{131}I with foodstuffs was calculated as:

$$I_{ing,k} = \sum_n C_{n,k} \cdot e^{-\lambda_{r,I-131} \cdot \Delta t_n} \cdot RF_n \cdot V_{n,k} \quad (8)$$

where $C_{n,k}$ is the activity of ^{131}I in foodstuff n consumed by the study subject at settlement of residence on day k (kBq L $^{-1}$ (kg $^{-1}$)); t_n is the time lag between production and consumption of foodstuff n (d); RF_n is the reduction factor of ^{131}I activity in foodstuff n in comparison with raw foodstuff due to culinary processing (unitless); $V_{n,k}$ is the consumption rate of foodstuff n by the study subject on day k reported during the personal interview (L(kg) d $^{-1}$).

Consumption of the following foodstuffs was important for ^{131}I intake:

- milk from privately owned cows as is common in rural settlements;
- cow's milk from commercial trade network that is common in urban settlements;
- sour milk and/or kefir;
- sour cream and/or soft cottage cheese; and
- leafy green vegetables.

Activity concentration of ^{131}I in milk from privately owned cows produced at settlement of residence was calculated as:

$$C_{privmilk}(t) = TF_m \cdot \int_{t_1}^{t_2} A_c(\tau) \cdot \lambda_b \cdot e^{-(\lambda_b + \lambda_{r,I-131}) \cdot (t - \tau)} d\tau \quad (9)$$

where TF_m is the feed-to-cow's milk transfer factor of ^{131}I (d L $^{-1}$); $A_c(\tau)$ is the daily ^{131}I activity intake by cow (kBq d $^{-1}$); λ_b is the rate of biological elimination of ^{131}I from cow's milk (d $^{-1}$); t_1 and t_2 are time of arrival and departure from settlement of residence counted from the time of the accident (d).

The main sources of ^{131}I intake by cows were consumption of pasture grass and, because of low stage of grass development in early spring shortly after the accident, ingestion of soil on pasture. Therefore, the daily ^{131}I activity intake by cow was calculated as:

$$A_c(t) = GD_{I-131}(0) \cdot \left[\frac{f}{Y_{gr}} \cdot I_{gr} \cdot e^{-\lambda_{gr} \cdot t} + \frac{1-f}{Y_{soil}} \cdot I_{soil} \cdot e^{-\lambda_{r,I-131} \cdot t} \right] \quad (10)$$

where GD_{I-131} is the ground deposition of ^{131}I at settlement of residence at the time of deposition (kBq m $^{-2}$); f is the interception coefficient of ^{131}I by grass (unitless); I_{gr} and I_{soil} are the daily consumption of grass and soil by cow, respectively (kg d $^{-1}$); Y_{gr} is the pasture

grass yield (kg m^{-2}); λ_{gr} is the removal rate of ^{131}I from grass (d^{-1}); Y_{soil} is the mass of top layer soil on per unit of ground (kg m^{-2}); t is the time after deposition (d).

Activity of ^{131}I in leafy green vegetables was calculated as:

$$C_{LV}(t) = \frac{GD_{I-131}(0) \cdot f}{Y_{gr}} \cdot e^{-\lambda_{gr} \cdot t} \quad (11)$$

However, as was shown in persons with direct thyroid measurements, there is an area-specific bias between ^{131}I thyroidal activities calculated using the ecological model and those derived from the direct thyroid measurements (Drozdovitch et al. 2013; Likhtarov et al. 2014). Therefore, to provide more realistic and reliable estimates of thyroid doses due to ^{131}I intake during residence, the ecological thyroid doses calculated for the study subjects were adjusted in the following way:

$$D_{res}^{I-131} = \sum_{l=1}^N RA_l \cdot \frac{D_{ecol,res,l}^{I-131}}{SF_l} \quad (12)$$

where D_{res}^{I-131} is the adjusted thyroid dose due to ^{131}I intake during residence (mGy); RA_l is the type of settlement-specific relative time-integrated activity of ^{131}I in the thyroid (unitless); $D_{ecol,res,l}^{I-131}$ is the ecological thyroid dose due to ^{131}I intake during residence at settlement l (mGy); SF_l is the scaling factor used to adjust ecological thyroid dose due to ^{131}I intake during residence at settlement l (unitless).

The scaling factor used to adjust ecological thyroid dose due to ^{131}I intake for given individual was derived from comparison of ^{131}I activities in the thyroid estimated from direct thyroid measurement and calculated using ecological model for the time of measurement. As was mentioned above, direct thyroid measurements did not occur for the subjects included in this study. To adjust ecological dose, the following approach developed by Likhtarov et al. (2005) for two groups of individuals without direct thyroid measurements was used:

1. The study subjects resided in areas (raions) where direct thyroid measurements were done in May-June of 1986. For these subjects, raion-specific scaling factor derived from direct thyroid measurements of other male individuals was used to adjust ecological thyroid dose (see Table 4).
2. The study subjects resided in raions where no direct thyroid measurements were done. For these subjects, a scaling factor was calculated for settlement of residence using the following pure-empirical equation:

$$SF_l = B \cdot (GD_{Cs-137,l})^\beta \quad (13)$$

where $GD_{Cs-137,l}$ is the ^{137}Cs ground deposition in the settlement l (kBq m^{-2}); B and β are parameter of fitting function.

Values of dosimetry model parameters are given below in Section “Uncertainty in the thyroid doses”. It should be noted that thyroid dose due to inhalation of ^{131}I during the residence was calculated using the same approach as for cleanup mission using eqns (2) and (3).

Uncertainties of thyroid doses

A procedure of Monte-Carlo simulation was used to estimate the uncertainties in thyroid doses received by the study subjects. A set of multiple (typically 1,000 or 10,000) individual stochastic doses (trials) was calculated for each study subject, if only unshared errors were considered, or for the entire study population, if shared and unshared errors were considered.

Thyroid doses calculated using RADRUE method: external irradiation and inhalation of ^{131}I and short-lived radionuclides during the cleanup mission—

The RADRUE method allows us to estimate the dose and the uncertainties in the dose estimates associated with uncertainties of the input parameters. The same information on location of cleanup mission, its duration, staying indoors / outdoors and activities performed by the study subjects are used in computer code Rockville for calculation of thyroid dose due to external irradiation and inhalation of ^{131}I and short-lived radionuclides. Therefore, these three exposure pathways are considered here together.

Parameters of the RADRUE model and their distributions used to calculate individual stochastic thyroid doses are given in Table 5. All parameters were considered to be sources of unshared errors. A separate study was conducted to evaluate significance of accounting for the sources of the shared and unshared errors in the estimation of uncertainties of the RADRUE doses. Kryuchkov et al. (2009) evaluated probability that two or more cleanup workers, from 434 who were on mission in 1986, were at the same location at the same time and, therefore, their doses were defined by the exposure rate (or ^{131}I concentration in air) shared at that location. The result of the study shows that the ‘shared’ dose caused by the situation when individuals sharing the same location at the same time represents less than 1% of the total dose.

Thyroid dose due to ^{131}I intake during residence—An approach similar to that used in the studies of thyroid cancer and other thyroid diseases in Belarusian-American (BelAm) and Ukrainian-American (UkrAm) cohorts (Drozdovitch et al. 2015; Likhtarov et al. 2014) was used here to estimate uncertainties for the thyroid dose due to ^{131}I intake during residence. According to this approach, 1,000 sets of the study population thyroid doses, considering sources of shared and unshared errors, were calculated. For a specific dose realization some of the model parameter values were considered to be shared (common) among the study subjects represented entire study population or specific subgroups. These subject-independent, or shared, parameters included parameters of the ecological model describing variation with time of ^{131}I contamination in the ground and foodstuff (Table 6). Other sources of errors were considered to be subject-dependent, or unshared. This group of errors included errors in assigning of thyroid-mass value to the study subject, parameters of biokinetic models of iodine in human body (Tables 5 and 7), and the uncertainties associated

with the imprecise answers on relocation history and individual consumptions reported during personal interview (Table 8 and Table 9).

For the implementation of this approach, values for shared parameters were assigned before the calculation of each dose set for the entire study population. The same value for each shared parameter was used to calculate one dose set for all study subjects for whom this parameter was assigned to be shared. During the calculation of dose set, values of unshared parameters were sampled from their distributions for each study subject and one dose set was calculated for entire study population. The thousand realizations of dose for given study subject represent the individual stochastic thyroid doses assigned for this person.

RESULTS

Individual thyroid doses

Table 10 provides a summary of thyroid doses reconstructed for study subjects from different exposure pathways. The arithmetic mean of thyroid doses among the study subjects was estimated to be 199 mGy, including 140 mGy from external irradiation during the cleanup mission, 44 mGy due to ^{131}I inhalation, 11 mGy due to inhalation of short-lived radionuclides, and 42 mGy due to ^{131}I intake during residence. It should be noted that arithmetic means of thyroid doses are given only for the study subjects who were exposed to the given exposure pathway. Therefore, arithmetic mean of total dose is not equal to the sum of arithmetic means of components of the dose. The median thyroid dose from all exposure pathways was estimated to be 47 mGy. The individual thyroid doses from external exposure ranged up to 3,630 mGy, from ^{131}I inhalation – up to 1,680 mGy, from inhalation of short-lived radionuclides – up to 377 mGy, and those from exposure to ^{131}I during residence – up to 3,430 mGy. The maximal individual thyroid dose from all exposure pathways was found to be 9,020 mGy.

Thyroid doses by category of cleanup workers are presented in Table 11. For one study subject who was staff member of the Kurchatov Institute thyroid dose was estimated to be 1010 mGy. The highest exposure categories of cleanup workers included liquidators who worked at the Chernobyl site several times as members of different categories, ‘mixed’ in Table 11 (mean total dose = 471 mGy), staff of AC-605 (206 mGy), and military cleanup workers (138 mGy). Representatives of these three categories (early cleanup workers, military cleanup workers and mixed) received thyroid doses from inhalation of ^{131}I and short-lived radionuclides as they started cleanup mission during period between 26 April and 6 May 1986.

Table 12 provides the distribution of thyroid dose due to different exposure pathways for the study subjects. Most subjects (390, 64.3% of the total) received low doses to the thyroid, less than 100 mGy from all exposure pathways combined; median contribution of internal irradiation to the total thyroid dose in this group was about 60%. Twenty study subjects (3.3% of the total) received thyroid dose of 1000 mGy or higher, mainly due to external irradiation (Fig. 5). For the subject with maximal thyroid dose in the study (9,020 mGy), exposure to ^{131}I was estimated to be 5,110 mGy (57% of the total dose), including 1,680 mGy due to inhalation during the cleanup mission and 3,430 mGy during residence (Fig. 5).

Uncertainties in thyroid doses

Sets of multiple individual stochastic doses were calculated for each study subject: 10,000 doses due to external irradiation, 10,000 doses due to inhalation of ^{131}I , 10,000 doses due to inhalation of short-lived radionuclides, and 1,000 doses due to ^{131}I intake during residence. Fig. 6 shows, as example, normal probability plot of individual stochastic doses (logarithm of values) due to different exposure pathways calculated for one of the study subjects. Distribution of individual stochastic doses was found to be lognormal and the geometric standard deviation (GSD) characterizes the uncertainty of the doses.

Table 13 shows distributions of the GSDs attached to the individual stochastic thyroid doses calculated in this study. The GSDs in the individual stochastic doses due to external irradiation varied from 1.2 to 6.9 with a mean equal to 2.0. For almost half of the study subjects the GSDs of the individual stochastic doses due to external irradiation vary between 1.5 and 2.0. The largest GSDs (> 3.0) were associated with the highest doses and were due to uncertainties in exposure rate grids in highly contaminated locations at the Chernobyl site and in exact duration and location of performance of cleanup mission task as reported by the study subject. The GSDs in the individual stochastic doses due to ^{131}I inhalation varied from 1.3 to 5.4 with a mean equal to 1.8. For majority of the study subjects (80%) the GSDs varied between 1.5 and 2.0. The GSDs in the individual stochastic doses due to inhalation of short-lived radioiodines and radiotelluriums varied from 1.4 to 14.7 with a mean equal to 2.0. The GSDs in the individual stochastic doses due to ^{131}I intake during residence varied from 1.8 to 4.8 with a mean of 2.6.

DISCUSSION

Individual thyroid doses from different exposure pathways were estimated in this study for 607 subjects of a case-control study of thyroid cancer among Chernobyl cleanup workers. Internal exposure of the thyroid from ^{131}I , both during the cleanup mission and during residence, was found to be an important exposure pathway for the Ukrainian cleanup workers, as it contributed more than 50% to the total thyroid dose for 265 from 592 study subjects (15 from 607 study subjects were not exposed either to ^{131}I or short-lived radionuclides). Kesminiene et al. (2012) found that ^{131}I intake was the major contributor to the thyroid dose for Belarusian liquidators because they were residents of contaminated settlements and were returning home every evening or after weekly shift-work.

The thyroid doses from external and internal (inhalation of ^{131}I and short-lived radionuclides during the cleanup mission and intake of ^{131}I during residence) irradiation are not correlated with each other ($r=0.13$). Fig. 7 compares thyroid doses due to internal irradiation with doses due to external irradiation during cleanup mission for 592 study subjects who were exposed to both pathways.

Uncertainties in thyroid doses

A similar pattern of uncertainties for doses due to external irradiation were found in other case-control studies among Chernobyl cleanup workers that used the RADRUE method for dose calculations: in the Ukrainian-American study of leukaemia and related disorders the

mean GSD among 1,000 subjects was found to be 2.0 (Chumak et al. 2015) and the mean GSD was found to be 1.9 among 357 and 530 subjects of the IARC-coordinated studies of haematological malignancies (Kesminiene et al. 2008) and of thyroid cancer (Kesminiene et al. 2012), respectively.

It should be noted that the RADRUE methodology takes into account only the so-called 'intrinsic' uncertainty, e.g., uncertainty in the dose-rate data due to interpolation and extrapolation and uncertainty of the expert-dosimetrist's decisions while converting the questionnaire data into personal histories with RADRUE data format. So-called 'questionnaire-based' or 'human factors' uncertainty that associated with uncertainty of recollection and reporting of the events related to the cleanup activities of the study subject by himself or by proxies is not quantified by RADRUE methodology (Kryuchkov et al. 2009). Estimation of the human factor uncertainty is the subject of a separate study.

In addition, all parameters of dosimetry models in the RADRUE methodology were considered to be sources of unshared errors. Although, as was mentioned above, a fraction of 'shared' dose caused by the situation when the study subjects sharing the same location at the same time was estimated to be small (<1%), there are other possible sources of shared errors that were not considered, for example, errors associated with extrapolation in time and space of exposure rate measurements to create grids of ambient exposure rate in computer code Rockville. The same comment applies to ^{131}I concentration in air.

Larger uncertainty in doses due to ^{131}I intake during residence was observed in our study in comparison with the IARC-coordinated study of thyroid cancer amount Chernobyl cleanup workers. In the IARC study, GSDs for residential doses due to ^{131}I intake varied from 1.9 to 2.5 with a mean of 2.2 (Kesminiene et al. 2012). This can be expected as individual doses were estimated in this study based on personal interview data on consumption of milk, milk products and leafy vegetables. In the study of Kesminiene et al. (2012) individual thyroid doses represented settlement-average doses at the subject's residence as no information was collected for the study subjects on individual consumption around the time of the accident.

Validation of thyroid doses due to ^{131}I intake during residence

There are no subjects with direct thyroid measurement in this study. However, 70 study subjects resided in 26 April – 30 June 1986 in 33 Ukrainian settlements and 1 Belarusian settlement where direct thyroid measurements were performed in other individuals. Estimated in this study individual residential thyroid doses due to ^{131}I intake for 70 subjects were compared with mean thyroid doses in settlements of residence derived from direct thyroid measurements conducted among adults and young adolescents (Fig. 8). As can be seen from the figure, the two sets of doses agree for 94.3% individuals within a factor of 3 (shown by broken lines), the coefficient of correlation is $r=0.87$. The mean of the ratios of thyroid dose estimated using the model to the settlement-average thyroid doses derived from direct thyroid measurements was 1.1 ± 0.8 and the median of ratios was 0.9. It should be noted, that the study subjects who reported they did not consume any locally produced food were excluded from validation exercise as settlement-average thyroid doses derived from direct thyroid measurements reflect typical behaviour of the measured population, including

consumption of local cow's milk, milk products and/or leafy vegetables, not only inhalation intake of ^{131}I .

CONCLUSIONS

Individual thyroid doses were estimated for 607 subjects in a case-control study of thyroid cancer among Ukrainian cleanup workers of the Chernobyl accident. Thyroid doses were calculated for different exposure pathways, including external irradiation and inhalation of ^{131}I and short-lived ^{132}I , ^{133}I , ^{135}I , $^{131\text{m}}\text{Te}$ and ^{132}Te during cleanup mission at the Chernobyl site as well as intake of ^{131}I during residence in contaminated settlements. It should be noted that internal exposure of the thyroid from ^{131}I was found to be an important exposure pathway for the Ukrainian Chernobyl cleanup workers, as it contributed more than half to the total thyroid dose in 45% of the study subjects. Also, it was found there is no correlation between thyroid dose due to inhalation and due to external irradiation, which dictates the need for separate estimation of those components of thyroid dose. The models used in this study to calculate doses were validated against instrumental measurements done after the accident. Implementation of dose calculations was based on detailed data on location and timing of different activities during cleanup worker mission as well as information on residential history and consumption of locally produced food during residence, all of which was collected by personal interviews. Results of the models' development and validation led us to conclude that thyroid doses could be estimated with a reasonable degree of reliability some 30 years after the accident for use in an epidemiological study of thyroid cancer among Chernobyl cleanup workers.

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REFERENCES

- Arefieva ZS, Badyin VI, Gavrilin YuI. et al. Guidance on estimation of human thyroid dose from radioiodine. Moscow: Energoatomizdat; 1988.
- Balonov M, Kaidanovsky G, Zvonova I, Kovtun A, Bouville A, Luckyanov N, Voillequé P. Contribution of short-lived radioiodines to thyroid doses received by evacuees from the Chernobyl area estimated using early in vivo activity measurements. *Radiat Prot Dosim* 105:593–599; 2003.
- Carrroll RJ, Ruppert D, Stefanski LA, Crainiceanu CM. *Measurement Error in Nonlinear Models: A Modern Perspective*, 2nd ed. Chapman & Hall/CRC, Boca Raton; 2006.
- Chumak VV. Physical dosimetry of Chernobyl cleanup workers. *Health Phys* 93:452–461; 2007. [PubMed: 18049221]
- Chumak VV, Romanenko AY, Voillequé PG, Bakhanova EV, Gudzenko N, Hatch M, Zablotska LB, Golovanov IA, Luckyanov NK, Sholom SV, Kryuchkov VP, Bouville A. The Ukrainian-American

- study of leukemia and related disorders among Chernobyl cleanup workers from Ukraine: II. Estimation of bone marrow doses. *Radiat Res* 170:698–710; 2008. [PubMed: 19138037]
- Chumak V, Drozdovitch V, Kryuchkov V, Bakhanova E, Golovanov I, Hatch M, Zablotska L, Babkina N, Luckyanov N, Voillequé P, Bouville A. Results of dosimetric support of the Ukrainian-American case-control study of leukemia and related disorders among Chernobyl cleanup workers. *Health Phys* 109(4): 296–301; 2015. [PubMed: 26313587]
- Drozdovitch V, Minenko V, Khrouch V, Leshcheva S, Gavrillin Yu, Khrutchinsky A, Kukhta T, Kutsen S, Luckyanov N, Shinkarev S, Tretyakevich S, Trofimik S, Voillequé P, Bouville A. Thyroid dose estimates for a cohort of Belarusian children exposed to radiation from the Chernobyl accident. *Radiat Res* 179:597–609; 2013. [PubMed: 23560632]
- Drozdovitch V, Minenko V, Golovanov I, Khrutchinsky A, Kukhta T, Kutsen S, Luckyanov N, Ostroumova E, Trofimik S, Voillequé P, Simon SL, Bouville A. Thyroid dose estimates for a cohort of Belarusian children exposed to ^{131}I from the Chernobyl accident: assessment of uncertainties. *Radiat Res* 184:203–218; 2015. [PubMed: 26207684]
- Drozdovitch V, Kryuchkov V, Chumak V, Kutsen S, Golovanov I, Bouville A. Thyroid doses due to Iodine-131 inhalation among Chernobyl cleanup workers. *Radiat Environ Biophys*; 2019 10.1007/s00411-019-00781-6
- Furukawa K, Preston D, Funamoto S, Yonehara S, Ito M, Tokuoka S, Sugiyama H, Soda M, Ozasa K, Mabuchi K. Long-term trend of thyroid cancer risk among Japanese atomic-bomb survivors: 60 years after exposure. *Int J Cancer*. 132:1222–1226; 2012. [PubMed: 22847218]
- Gavrillin Y, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemiakina E, Ulanovsky A, Bouville A, Anspaugh L, Voilleque P, Luckyanov N. Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus-part I: ^{131}I , short-lived radioiodines (^{132}I , ^{133}I , ^{135}I), and short-lived radiotelluriums ($^{131\text{m}}\text{Te}$ and ^{132}Te). *Health Phys* 86: 565–585; 2004. [PubMed: 15167120]
- Goosens LHJ, Harrison JD, Kraan DCP, Cooke RM, Harper FT, Hora SC. Probabilistic accident consequence analysis – uncertainty assessment for internal dosimetry. Appendix C. Report NUREG/CR-6571 and EUR 16773 US Nuclear Regulatory Commission, Washington DC, USA and Commission of European Communities, Brussels, Belgium; 1998.
- ICRP (International Commission of Radiological Protection). Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 2. Ingestion Dose Coefficients ICRP Publication 67. Oxford: Pergamon Press; 1993.
- ICRP (International Commission on Radiological Protection). Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 4. Inhalation Dose Coefficients: ICRP Publication 71. Ann. ICRP 25(3/4); 1995.
- ICRP (International Commission on Radiological Protection). Basic anatomical and physiological data for use in radiological protection: Reference values. ICRP Publication 89. Ann. ICRP 32(3/4); 2002.
- Kesminiene A, Evrard AS, Ivanov VK, Malakhova IV, Kurtinaitis J, Stengrevics A, Tekkel M, Anspaugh L, Bouville A, Chekin S, Chumak VV, Drozdovitch V, Gapanovich V, Hubert P, Illichev SV, Khayt MS, Krjuchkov VP, Maceika E, Maksyoutov M, Mirhaidarov AK, Polyakov S, Shchukina N, Tenet V, Tierekhovich T, Tsykalo A, Tukov A, Cardis E. Risk of hematological malignancies among Chernobyl liquidators. *Radiat Res* 170:721–735; 2008. [PubMed: 19138033]
- Kesminiene A, Evrard AS, Ivanov VK, Malakhova IV, Kurtinaitis J, Stengrevics A, Tekkel M, Chekin S, Drozdovitch V, Gavrillin Y, Golovanov I, Kryuchkov VP, Maceika E, Mirkhaidarov AK, Polyakov S, Tenet V, Tukov AR, Byrnes G, Cardis E. Risk of thyroid cancer among Chernobyl cleanup workers. *Radiat Res* 178:425–436; 2012. [PubMed: 22998226]
- Korobova E, Anoshko Y, Kesminiene A, Kouvyline A, Romanov S, Tenet V, Suonio E, Cardis E. Evaluation of stable iodine status of the areas affected by the Chernobyl accident in an epidemiological study in Belarus and the Russian Federation. *Journal of Geochemical Exploration* 107(2):124–135; 2010.
- Kryuchkov V, Chumak V, Maceika E, Anspaugh LR, Cardis E, Bakhanova E, Golovanov I, Drozdovitch V, Luckyanov N, Kesminiene A, Voillequé P, Bouville A. RADRUE method for reconstruction of gamma external doses to Chernobyl cleanup workers in epidemiological studies. *Health Phys* 97:275–298; 2009. [PubMed: 19741357]

- Kryuchkov VP, Kochetkov OA, Tsovijanov AG. Mitigation of accident consequences at Chernobyl NPP: Radiation and dosimetry issues. Asmolov VG and Kochetkov OA, Edts. Moscow: IzdAT; 2012.
- Likhtarov I, Kovgan L, Vavilov S, Chepurny M, Bouville A, Luckyanov N, Jacob P, Voilleque P, Voigt G. Post-Chornobyl thyroid cancers in Ukraine. Report 1: Estimation of thyroid doses. Radiat Res 163:125–136; 2005. [PubMed: 15658887]
- Likhtarov I, Kovgan L, Masiuk S, Chepurny M, Ivanova O, Gerasymenko V, Boyko Z, Voillequé P, Antipkin Y, Lutsenko S, Oleynik V, Kravchenko V, Tronko M. Estimating thyroid masses for children, infants, and fetuses in Ukraine exposed to (131)I from the Chernobyl accident. Health Phys. 104(1):78–86; 2013. [PubMed: 23192090]
- Likhtarov I, Kovgan L, Masiuk S, Talerko M, Chepurny M, Ivanova O, Gerasymenko V, Boyko Z, Voilleque P, Drozdovitch V, Bouville A. Thyroid cancer study among Ukrainian children exposed to radiation after the Chornobyl accident: improved estimates of the thyroid doses to the cohort members. Health Phys 106(3):370–396; 2014. [PubMed: 25208014]
- Mabuchi K, Hatch M, Little MP, Linet MS, Simon SL. Risk of thyroid cancer after adult radiation exposure: Time to re-assess? Radiat Res 179 254–256; 2013. [PubMed: 23252377]
- Müller H, Pröhl G. ECOSYS-87: A dynamic model for assessing radiological consequences of nuclear accidents. Health Phys 64:232–252; 1993. [PubMed: 8432643]
- Prister BS. Problems of agricultural radioecology and radiobiology during contamination of environment by young mixture of fission products. Chernobyl: Institute of NPP Safety; 2008 (in Russian).
- Pröhl G, Olyslaegers G, Kanyar B, Pinedo P, Bergstrom U, Mobbs S, Eged K, Katona T, Simón I, Hallberg UB, Chen Q, Kowe R, Zeevaert T. Development and comparison of five sitespecific biosphere models for safety assessment of radioactive waste disposal. J Radiol Prot 25:343–373; 2005. [PubMed: 16352869]
- Talerko N Mesoscale modelling of radioactive contamination formation in Ukraine caused by the Chernobyl accident. J Environ Radioact 78:311–329; 2005a. [PubMed: 15511565]
- Talerko N Reconstruction of (131)I radioactive contamination in Ukraine caused by the Chernobyl accident using atmospheric transport modeling. J Environ Radioact 84:343–362; 2005b. [PubMed: 16024139]
- UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). Sources and Effects of Ionizing Radiation, UNSCEAR 2008 Report Annex D: Health effects due to radiation from the Chernobyl accident. Sales No. E.11.IX.3. New York: United Nations Scientific Committee on the Effects of Atomic Radiation; United Nations; 2011.

Fig. 1. Grids of ambient dose rate in air in the 30-km zone around the Chernobyl NPP: a) on 26–27 April and b) 28–29 April 1986. Point with coordinates (0, 0) is 4-th Unit of Chernobyl NPP.

Fig. 2. Daily ^{131}I concentration in air in the 30-km zone around the Chernobyl NPP a) on 26 April and b) on 27 April 1986. Point with coordinates (0, 0) is 4-th Unit of Chernobyl NPP.

Fig. 3. Comparison of the thyroid doses due to ^{131}I inhalation calculated by the model with those derived from direct thyroid measurements. Broken lines show factor of 3 difference between two sets of doses.

Fig. 4.
 ^{131}I ground deposition in the study Oblasts that was accumulated from 26 April through 6 May 1986.

Fig. 5.
Contribution of different exposure pathways to thyroid dose of 20 study subjects who received dose of 1000 mGy or higher.

Fig. 6. Normal probability plot of individual stochastic doses (logarithms) due to different exposure pathways calculated for the study subject.

Fig. 7.
Comparison of thyroid doses for 592 study subjects: internal irradiation vs external irradiation.

Fig. 8.

Comparison of residential thyroid dose from ^{131}I intake: calculated in this study for 70 study subjects and mean thyroid doses in settlements of residence derived from direct thyroid measurements. Broken lines show factor of 3 difference between two sets of doses.

Table 1.

Characteristics of components of thyroid doses that were reconstructed for the study subjects.

Component	Pathway of exposure	Time frame of exposure	Exposure occurred at
External	Gamma-emitted radionuclides	Cleanup mission between 26 April 1986 and 31 December 1990	Chernobyl NPP and within the 30-km zone
Internal	Inhalation of ^{131}I	Cleanup mission between 26 April 1986 and 6 May 1986	Chernobyl NPP and within the 30-km zone
Internal	Inhalation of ^{132}I , ^{133}I , ^{135}I , $^{131\text{m}}\text{Te}$ and ^{132}Te	Cleanup mission between 26 April 1986 and 6 May 1986	Chernobyl NPP and within the 30-km zone
Internal	Intake of ^{131}I via inhalation and with locally produced food	Residence between 26 April and 30 June 1986	Settlement of residence

Table 2.

Parameters of model and results of calculation of the ratios of thyroid dose due to inhalation of short-lived radionuclides to thyroid dose due to ^{131}I inhalation.

	$^{131\text{m}}\text{Te}$	^{132}Te	$^{132}\text{I}^a$	^{133}I	^{135}I	Total
$R_{DF,m}$	0.082	0.17	0.009	0.19	0.038	–
$R_{air,m,0}$	0.18	1.30	1.33	1.48	0.91	–
$\lambda_{r,m} (\text{d}^{-1})$	0.555	0.213	7.23	0.8	2.52	–
$R_{dose,m,i}$						$R_{dose,i}$
26 April	0.012	0.208	0.012	0.202	0.013	0.447
27 April	0.007	0.183	0.010	0.099	0.001	0.300
28 April	0.005	0.161	0.009	0.048	–	0.223
29 April	0.003	0.142	0.008	0.024	–	0.177
30 April	0.002	0.125	0.007	0.012	–	0.146
1 May	0.001	0.110	0.006	0.006	–	0.123
2 May	0.001	0.097	0.005	0.003	–	0.106
3 May	–	0.085	0.005	0.001	–	0.091
4 May	–	0.075	0.004	0.001	–	0.080
5 May	–	0.066	0.004	–	–	0.070
6 May	–	0.058	0.003	–	–	0.061

^aResult of calculation is given for radioactive equilibrium with precursor ^{132}Te .

Table 3.

Distribution of the study subjects according to the place of residence at the time of the accident and range of ^{137}Cs and ^{131}I deposition in locations of residence.

Place of residence	N	Deposition density (kBq m ⁻²)	
		^{137}Cs	^{131}I
Kyiv Oblast	222	6.3 – 4,640	115 – 536,600
Kyiv-city	136	26	470
Chernihiv Oblast	37	2.1 – 64	33 – 1,055
Dnipropetrovsk Oblast	95	1.1 – 15	7.0 – 95
Donets'k Oblast	54	3.3 – 38	15 – 205
Kharkiv Oblast	21	5.8 – 15	32 – 83
Zhytomir Oblast	8	4.4 – 375	67 – 6,335
Other oblasts of Ukraine	16	1.6 – 18	14 – 250
Outside Ukraine	18	0 – 18,530	0 – 507,400
Entire study	607	0 – 18,530	0 – 536,600

Table 4.

Raion-specific values of scaling factor (Liktharov et al. 2005).

Oblast	Raion	Raion-specific values of scaling factor, SF_l			
		AM	SD	GM	GSD
Zhytomir	Korosten	6.2	3.4	5.4	1.7
Zhytomir	Narodychi	2.8	2.3	2.2	2.1
Zhytomir	Ovruch	3.9	2.6	3.2	1.8
Kyiv	Borodianka	6.9	4.8	5.7	1.9
Kyiv	Vyshhorod	4.8	2.3	4.3	1.6
Kyiv	Ivankiv	6.0	4.3	4.9	1.9
Kyiv	Makariv	2.1	1.1	1.9	1.6
Kyiv	Poliske	10.5	17.7	5.4	3.2
Chernihiv	Kozelets	2.5	1.9	2.0	2.0
Chernihiv	Ripky	2.3	4.4	1.1	3.5
Chernihiv	Chernihiv	1.3	1.8	0.8	2.8

Table 5.

Parameters of RADRUE model and their distributions used to calculate individual stochastic thyroid doses due to external irradiation and inhalation of ^{131}I and short-lived radionuclides which were considered to be shared (subject related).

Description	Parameter	Symbol	Unit	Central value (arithmetic mean (AM))	Distribution	Reference
Duration of performance of cleanup mission task		t_j	d	AM and CV^a from database	$U((1-CV)\times AM, (1+CV)\times AM)^b$ or $U(0.9\times AM, 1.1\times AM)$	(Kryuchkov et al. 2009)
<i>External irradiation</i>						
Exposure rate in air		$P(x(t_j), y(t_j))$	mGy h^{-1}	AM and GSD from database	$TLN(GM^c, GSD, GSD^{-2}\times GM, GSD^2\times GM)^d$	(Kryuchkov et al. 2009)
Conversion coefficient from exposure rate in air to the thyroid dose		C_{th}	mGy h^{-1} per mGy h^{-1}	0.739	$TN(AM, 0.1\times AM, AM-2\times SD, AM+2\times SD)^e$	Expert judgement
Shielding factor		L_j	unitless	Table 2 from (Kryuchkov et al. 2009)	$TN(AM, 0.25\times AM, AM-2\times SD, AM+2\times SD)$	(Kryuchkov et al. 2009)
<i>Inhalation of ^{131}I and short-lived radionuclides</i>						
^{131}I concentration in air		C_{air}^{I-131}	kBq m^{-3}	AM and GSD from database	$TLN(GM^c, GSD, GSD^{-2}\times GM, GSD^2\times GM)^d$	(Talerko 2005b)
Ventilation rate		Bm	$\text{m}^3 \text{d}^{-1}$	(ICRP 2002)	$TLN(0.94\times AM, 1.4, 0.5\times GM, 2\times GM)$	(Goossens et al. 1998)
Thyroid mass		m_{th}	g	20	$TLN(0.94\times AM, 1.4, 0.5\times GM, 2\times GM)$	(Likhartov et al. 2013)
Fraction of inhaled iodine transferred to blood		w_{inh}	unitless	0.66	$TR(0.5, 0.66, 0.82)^f$	(ICRP 1995)
Fraction of iodine uptake by thyroid		w_{th}	unitless	0.3	$TR(0.2, 0.3, 0.4)$	(ICRP 1993)
Biological half-time of iodine removal from the thyroid		T_b	d	89	$TR(76, 89, 102)$	(ICRP 1993)

^aCoefficient of variation, $CV = AM/SD$.

^b $U(\text{min, max})$: uniform distribution with the following parameters: minimal value (min), maximal value (max).

^c $GM = AM \cdot \left[\sqrt{\frac{\ln(GSD)^2}{e}} \right]^{-1}$ (derived from (Carroll et al. 2006); GM: geometric mean; AM: arithmetic mean; GSD: geometric standard deviation).

^d $TLN(GM, GSD, \text{min, max})$: truncated lognormal distribution with the following parameters: geometric mean (GM), geometric standard deviation (GSD), minimal value (min), maximal value (max).

^e $TN(AM, SD, \text{min, max})$: truncated normal distribution with the following parameters: arithmetic mean (AM), standard deviation (SD), minimal value (min), maximal value (max).

$f_{TR}(\text{min}, \text{mode}, \text{max})$; triangular distribution with the following parameters: minimal value (min), mode of distribution (mode), maximal value (max).

Table 6.

Selected parameters of dosimetry model to calculate thyroid dose due to ^{131}I intake during residence which were considered to be shared (subject independent).

Description	Parameter	Symbol	Unit	Central value (arithmetic mean (AM))	Distribution	Shared among subjects	Reference
Daily deposition of ^{131}I ^a		GD_{T-131}	kBq m^{-2}	database	$\text{TLN}(0.9 \times \text{AM}, 1.6, 0.4 \times \text{GM}, 2.6 \times \text{GM})$ ^a	living in the same settlement	(Talerko 2005b)
Coefficient of ^{131}I interception by grass		f	unitless	0.19	$\text{TLN}(0.94 \times \text{AM}, 1.4, 0.5 \times \text{GM}, 2 \times \text{GM})$	living in the same settlement	(Prister 2008)
Removal rate of ^{131}I from grass		λ_{gr}	d^{-1}	0.15	$\text{TR}(0.13, 0.15, 0.17)$ ^b	all	(Arefieva et al. 1988)
Pasture grass yield		Y_{gr}	kg m^{-2}	0.75	$\text{TR}(0.5, 0.75, 1.0)$	all	(Likhtarov et al. 2014)
Soil per unit of ground		λ_{soil}	kg m^{-2}	1.0	$\text{TR}(0.3, 1.0, 1.5)$	all	(Korobova et al. 2010)
Consumption of grass by cow		I_{gr}	kg d^{-1}	45	$\text{TR}(30, 45, 60)$	all	(Likhtarov et al. 2014)
Consumption of soil by cow		I_{soil}	kg d^{-1}	0.55	$\text{TR}(0.4, 0.55, 0.7)$	all	(Pröhl et al. 2005)
Rate of biological elimination of ^{131}I from cow's milk		λ_b	d^{-1}	1.0	$\text{TR}(0.5, 1.0, 1.74)$	all	(Müller and Pröhl 1993)
Feed-to-cow's milk transfer factor of ^{131}I		TF_m	d L^{-1}	0.01	$\text{TLN}(0.0065, 2.5, 0.001, 0.04)$	all	(Likhtarov et al. 2014)
Raion-specific scaling factor		SF_I	unitless	Table 3	$\text{TLN}(\text{GM}, \text{GSD}, \text{GSD}^{-1} \times \text{GM}, \text{GSD} \times \text{GM})$,	living in the same raion	(Likhtarov et al. 2005)
Parameters of fitting function (eqn (13)):							
Rural settlement		B	unitless	0.59 (GM)	$\text{TLN}(0.59, 1.1, 0.54, 0.65)$	living in the same settlement	(Likhtarov et al. 2005)
		β	unitless	0.36	$\text{TN}(0.36, 0.1, 0.26, 0.46)$ ^c	living in the same settlement	(Likhtarov et al. 2005)
Urban settlement		B	unitless	0.36 (GM)	$\text{TLN}(0.36, 1.5, 0.24, 0.54)$	living in the same settlement	(Likhtarov et al. 2005)
		β	unitless	0.61	$\text{TN}(0.61, 0.11, 0.50, 0.72)$	living in the same settlement	(Likhtarov et al. 2005)

^a $\text{TLN}(\text{GM}, \text{GSD}, \text{min}, \text{max})$: truncated lognormal distribution with the following parameters: geometric mean (GM), geometric standard deviation (GSD), minimal value (min), maximal value (max).

^b $\text{TR}(\text{min}, \text{mode}, \text{max})$: triangular distribution with the following parameters: minimal value (min), mode of distribution (mode), maximal value (max).

^c $\text{TN}(\text{AM}, \text{SD}, \text{min}, \text{max})$: truncated normal distribution with the following parameters: arithmetic mean (AM), standard deviation (SD), minimal value (min), maximal value (max).

Table 7.

Selected parameters of dosimetry model to calculate thyroid dose due to ¹³¹I intake during residence which were considered to be unshared (subject related).

Description	Parameter		Unit	Central value (Geometric mean (GM))	Distribution	Reference
	Symbol					
Relative time-integrated activity of ^{131}I in the thyroid:						
Rural settlement		RA_r	unitless	1.07	$\text{TLN}(1.07, 2.1, 0.51, 2.2)^a$	(Likhitarov et al. 2005)
Urban settlements		RA_u	unitless	1.1	$\text{TLN}(1.1, 3.0, 0.37, 3.3)$	(Likhitarov et al. 2005)

^aTLN(GM, GSD, min, max): truncated lognormal distribution with the following parameters: geometric mean (GM), geometric standard deviation (GSD), minimal value (min), maximal value (max).

Table 8.

Sources of unshared errors of dosimetry model to calculate thyroid dose due to ^{131}I intake during residence that associated with the information from the personal interview.

Description	Parameter	Symbol	Unit	Central value	Distribution
<i>Imprecise date of relocation, change of consumption habits or administration of stable iodine</i>					
Answer: "End of April"		–	–	28 April	DU(27, 28, 29, 30 April) ^a
Answer: "Beginning of May"		–	–	5 May	DU(1, 2, 3, 4, 5, 6, 7, 8, 9, 10 May)
Answer: "Middle of May"		–	–	15 May	DU(11, 12, 13, 14, 15, 16, 17, 18, 19, 20 May)
Answer: "End of May"		–	–	25 May	DU(21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31 May)
Answer: "June"		–	–	15 June	DU(1 – 30 June by 1 day)
Date of stable iodine administration		–	–	Questionnaire	B(0.5) ^b
<i>Consumption rate</i>					
Consumption rate of cow milk, milk from shop, milk products (milk in soup, sour milk, sour cream, soft cottage cheese, kefir), and leafy vegetables reported during personal interview		$V_{n,k}$	L d ⁻¹ kg d ⁻¹	Questionnaire	TR(0.75×AM, AM, 1.25×AM) ^c
<i>Imprecise consumption rate</i>					
Response: "I did consume (<i>foodstuff</i>), but I do not remember how much (<i>foodstuff</i>) I consumed"		$V_{n,k}$	L d ⁻¹ kg d ⁻¹	Table 9	TLN(GM, GSD, GSD ⁻² ×GM, GSD ² ×GM) ^d
Response: "I do not remember if I consumed (<i>foodstuff</i>)"		$V_{n,k}$	L d ⁻¹ kg d ⁻¹	P _{cons} ×AM (Table 9)	TLN(GM, GSD, GSD ⁻² ×GM, GSD ² ×GM) with probability of B(P _{cons})

^aDU($a_1, a_2, \dots, a_n$): discrete uniform distribution that returns $a_1, a_2, \dots, a_n$ with equal probability of n^{-1} .

^bB(p): Bernoulli distribution that returns "1" with probability (P_{cons}) and returns "0" with probability (1-P_{cons}).

^cTR(min, mode, max): triangular distribution with the following parameters: minimal value (min), mode of distribution (mode), maximal value (max).

^dTLN(GM, GSD, min, max): truncated lognormal distribution with the following parameters: geometric mean (GM), geometric standard deviation (GSD), minimal value (min), maximal value (max).

Table 9.

Fraction of consumers (P_{cons}), arithmetic mean (AM), geometric mean (GM) and geometric standard deviation (GSD) of consumption rates of foodstuff used for imputation of imprecise responses provided during the personal interviews.

Food	P_{cons}	Consumption rate L d ⁻¹ (kg d ⁻¹)		GSD
		AM	GM	
<i>Rural settlements</i>				
Private cow's milk	0.629	560	400	2.4
Shop milk	–	–	–	–
Sour milk, kefir	0.443	190	130	2.5
Sour cream, soft cheese	0.676	75	65	2.1
Leafy vegetables	0.792	445	30	2.4
<i>Mixed rural - urban type of settlements</i>				
Private cow's milk	0.439	385	200	3.2
Shop milk	0.298	160	110	2.3
Sour milk, kefir	0.407	175	85	3.8
Sour cream, soft cheese	0.721	65	60	2.1
Leafy vegetables	0.866	50	25	2.4
<i>Urban settlements</i>				
Private cow's milk	–	–	–	–
Shop milk	0.468	220	200	2.0
Sour milk, kefir	0.476	125	90	1.9
Sour cream, soft cheese	0.668	70	65	1.8
Leafy vegetables	0.777	30	20	2.5

Table 10.

Thyroid doses from different exposure pathways reconstructed for study subjects of case-control study.

Parameter	Thyroid dose ^a (mGy) due to				Total
	External irradiation	Inhalation of ¹³¹ I during the mission	Inhalation of short-lived radionuclides during the mission	Intake of ¹³¹ I during residence	
N	607	200	198	587	607
Arithmetic mean	140	44	11	42	199
Median	20	12	1.6	7.3	47
Range	0.015 – 3,630	~0 – 1,680	~0 – 377	0.001 – 3,430	0.15 – 9,020

^a Arithmetic mean, median and range of thyroid doses are given for *N* study subjects who were exposed to the given exposure pathway. Therefore, arithmetic mean of total dose does not equal to the sum of arithmetic means of components of the dose.

Table 11.

Thyroid doses due to all exposure pathways by category of cleanup workers included in the case-control study.

Category of cleanup workers	Number of subjects	External irradiation			Inhalation of ^{131}I during the mission			Thyroid dose (mGy) due to Inhalation of short-lived radionuclides during the mission			Intake of ^{131}I during residence			Total	
		Mean	Range		Mean	Range		Mean	Range		Mean	Range		Mean	Range
Early cleanup workers	64	68	0.24–867		20	~0–194		5.0	~0–59		17	0.22–109		100	~0–891
Chemobyl NPP personnel	1	68	–		–	–		–	–		5.9	–		74	–
Sent to assist the Chemobyl NPP staff	4	108	0.32–375		–	–		–	–		12	5.1–29		120	20–385
Staff of AC-605	6	200	3.9–788		–	–		–	–		6.7	1.7–24		206	6.7–790
Staff of Kurchatov Institute	1	1,010	–		–	–		–	–		3.0	–		1,010	–
Military	236	121	0.14–1,670		32	~0–277		6.5	~0–78		8.5	0.04–102		138	0.53–1,670
Sent on mission	137	24	0.01–755		2.3 ^a	–		0.21	–		24	0.24–808		47	0.7–820
Staff of “Combinat”	6	36	0.15–187		–	–		–	–		40	8.9–122		70	0.15–196
Mixed ^b	152	299	0.28–3,630		57	~0–1,680		15	~0–377		122	0.001–3,430		471	1.5–9,020
Entire study	607	140	0.015–3,630		44	~0–1,680		11	~0–377		42	0.001–3,430		199	0.15–9,020

^aOne study subject was exposed to inhalation of ^{131}I and short-lived radionuclides.

^bMixed refers to a set of liquidators who worked at the Chernobyl site several times as members of different categories.

Table 12.

Distribution of thyroid dose due to different exposure pathways for the study subjects.

Interval of thyroid dose (mGy)	External irradiation		Inhalation of ^{131}I during the mission		Inhalation of short-lived radionuclides during the mission		Intake of ^{131}I during residence		Total	
	N	%	N	%	N	%	N	%	N	%
< 0.1	10	1.6	13	6.5	45	22.7	6	1.0	—	—
0.1 – 0.99	92	15.2	30	15.0	46	23.2	33	5.6	6	1.0
1.0 – 9.99	156	25.7	55	27.5	52	26.3	322	54.9	105	17.3
10 – 99.99	179	29.5	82	41.0	54	27.3	195	33.2	279	46.0
100 – 999.99	156	25.7	19	9.5	1	0.5	28	4.8	197	32.4
1,000	14	2.3	1	0.5	—	—	3	0.5	20	3.3
Entire study	607	100.0	200	100.0	198	100.0	587	100.0	607	100.0

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Table 13.

Distributions of the geometric standard deviations (GSD) attached to the individual stochastic thyroid doses.

GSD interval	External irradiation during the mission			Inhalation of ^{131}I during the mission			Inhalation of short-lived radionuclides during the mission			Intake of ^{131}I during residence		
	N	%	Mean dose (mGy)	N	%	Mean dose (mGy)	N	%	Mean dose (mGy)	N	%	Mean dose (mGy)
< 1.5	96	15.8	183	12	6.0	47	7	3.5	7.2	-	-	-
1.5 – 1.99	291	47.9	105	160	80.0	38	156	78.9	11	8	1.4	5.3
2 – 2.49	125	20.6	129	22	11.0	91	24	12.1	20	290	49.4	33
2.5 – 2.99	49	8.1	158	4	2.0	10	4	2.0	0.2	231	39.4	42
3 – 3.49	18	3.0	361	1	0.5	1.2	1	0.5	14	55	9.4	92
3.5	28	4.6	244	1	0.5	0.01	6	3.0	$1.2 \cdot 10^{-4}$	3	0.5	4.2
Entire study	607	100.0	140	200	100.0	44	198	100.0	11	587	100.0	42