Published in final edited form as:

Health Phys. 2010 July ; 99(1): 1–16. doi:10.1097/HP.0b013e3181c910dd.

RECONSTRUCTION OF RADIATION DOSES IN A CASE-CONTROL STUDY OF THYROID CANCER FOLLOWING THE CHERNOBYL ACCIDENT

Vladimir Drozdovitch^{*}, Valeri Khrouch[†], Evaldas Maceika[‡], Irina Zvonova[§], Oleg Vlasov^{**}, Angelica Bratilova[§], Yury Gavrilin[†], Guennadi Goulko^{††}, Masaharu Hoshi^{‡‡}, Ausrele Kesminiene^{§§}, Sergey Shinkarev[†], Vanessa Tenet^{§§}, Elisabeth Cardis^{***,†††,‡‡‡}, and Andre Bouville^{*}

^{*} DHHS/NIH/NCI/Division of Cancer Epidemiology and Genetics, 6120 Executive Blvd, Bethesda, MD 20892, USA

[†] Burnasyan Federal Medical Biophysical Center (formerly Institute of Biophysics), 46 Zhivopisnaya Street, 123182, Moscow, Russian Federation

[‡] Institute of Physics, 231, Savanoriu, LT-02300 Vilnius, Lithuania

[§] Institute of Radiation Hygiene, St Petersburg, Russia

^{**} Medical Radiological Research Center, Obninsk, Russia

^{††} Bundeswehr Institute of Radiobiology affiliated to the University Ulm, 80937, Munich, Germany

^{‡‡} Research Institute for Radiation Biology and Medicine, Hiroshima University, Hiroshima, Japan

^{§§} International Agency for Research on Cancer, 150, Cours Albert Thomas, 69008, Lyon, France

^{***} Centre for Research in Environmental Epidemiology (CREAL), Barcelona, Spain

^{†††} Municipal Institute of Medical Research (IMIM-Hospital del Mar), Barcelona, Spain

^{‡‡‡} CIBER Epidemiologia y Salud Pública (CIBERESP), Barcelona, Spain

Abstract

A population-based case-control study of thyroid cancer was carried out in contaminated regions of Belarus and Russia among persons who were exposed during childhood and adolescence to fallout from the Chernobyl accident. For each study subject, individual thyroid doses were reconstructed for the following pathways of exposure: (1) intake of ¹³¹I via inhalation and ingestion; (2) intake of short-lived radioiodines (¹³²I, ¹³³I, and ¹³⁵I) and radiotelluriums (^{131m}Te, ¹³²Te) via inhalation and ingestion; (3) external dose from radionuclides deposited on the ground; and (4) ingestion of ¹³⁴Cs and ¹³⁷Cs. A series of intercomparison exercises validated the models used for reconstruction of average doses to populations of specific age groups as well as of individual doses. Median thyroid doses from all factors for study subjects were estimated to be 0.37 and 0.034 Gy in Belarus and Russia, respectively. The highest individual thyroid doses among the subjects were 10.2 Gy in Belarus and 5.3 Gy in Russia. Iodine-131 intake was the main pathway for thyroid exposure.

Corresponding Author: Vladimir Drozdovitch DHHS/NIH/NCI/Division of Cancer Epidemiology and Genetics 6120 Executive blvd, EPS-7100, Bethesda, MD 20892 USA drozdovv@mail.nih.gov.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Estimated doses from short-lived radioiodines and radiotelluriums ranged up to 0.53 Gy. Reconstructed individual thyroid doses from external exposure ranged up to 0.1 Gy, while those from internal exposure due to ingested cesium did not exceed 0.05 Gy. The uncertainty of the reconstructed individual thyroid doses, characterized by the geometric standard deviation, varies from 1.7 to 4.0 with a median of 2.2.

Keywords

Chernobyl; radioiodine; dose reconstruction; thyroid

INTRODUCTION

The accident, which occurred at the Chernobyl power plant in north-western Ukraine on 26 April 1986, resulted in widespread radioactive contamination of the territories of Belarus, Russia and Ukraine. Following the accident, large amounts of radioactive materials were released to the atmosphere, including $(1.2\text{--}1.8)\times 10^{18}$ Bq of ^{131}I , $(3.5\text{--}3.7)\times 10^{18}$ Bq of ^{132}Te and ^{133}I , and $(1.3\text{--}1.4)\times 10^{17}$ Bq of long-lived ^{134}Cs and ^{137}Cs (UNSCEAR 2000). During the first month after the accident, the human thyroid gland was the main target of exposure resulting from the radioactive contamination of the environment. In Belarus, it is estimated that several thousand children received thyroid doses from ^{131}I of 2 Gy or more (UNSCEAR 2000).

The International Agency for Research on Cancer (IARC) initiated a population-based case-control study of thyroid cancer among young people who resided in the areas of Belarus and Russia that were heavily contaminated by the Chernobyl accident. Overall, 1,615 subjects, cases and controls, all aged 0-18 at the time of the accident were included in this study. A description of clinical and epidemiological aspects of the study is given elsewhere (Cardis et al. 2005).

To estimate the risk of radiation-induced thyroid cancer, the radiation absorbed dose to the thyroid gland, which resulted mainly from intake of ^{131}I , had to be evaluated for each subject in the study. In addition, three other contributions to the thyroid dose, which were quite small for the majority of individuals but relatively important for persons with no or little milk consumption, were estimated within the framework of the study: (1) Internal irradiation resulting from intake of short-lived radioiodines (^{132}I , ^{133}I , and ^{135}I) and of short-lived radiotelluriums ($^{131\text{m}}\text{Te}$ and ^{132}Te); (2) External irradiation resulting from the deposition of radionuclides on the ground; and (3) Internal irradiation resulting from intake of long-lived radionuclides such as ^{134}Cs and ^{137}Cs .

Thousands of radiation measurements were made in May-June 1986 on people living in contaminated areas of Belarus, Russia and Ukraine. These so-called "direct thyroid measurements" were obtained by placing a radiation detector against the neck. It was these exposure-rate measurements that were used as a basis to estimate ^{131}I content in the thyroid gland and to reconstruct thyroid doses to the inhabitants of the settlements (Gavrilin et al. 1999a; Zvonova and Balonov 1993; Likhtarev et al. 1993). Direct thyroid measurements can be considered as the most reliable information for dose assessment purposes, despite associated uncertainties arising from errors in the estimation of the ^{131}I thyroidal content and in the evaluation of the ^{131}I intake function (Likhtarev et al. 2003). However, these measurements covered only a fraction of the population residing in contaminated regions of Belarus and Russia, and, therefore, only a fraction of the subjects enrolled in the case-control study. For the purposes of the epidemiological study, a single uniform method for dose reconstruction was required for all individuals included in the study.

This study considered four dosimetric models that were developed during the post-accident period to evaluate thyroid doses from ^{131}I to the population of Belarus and Russia not covered by direct thyroid measurements (Gavrilin et al. 1999a; Zvonova et al. 1998; Drozdovitch et al. 1997; Vlasov and Pitkevich 1999). The dosimetry working group was set up to develop a common approach to be used to reconstruct individual thyroid doses from all exposure pathways for all study subjects. The development of the common approach included the following steps:

1. Critical review of the four dosimetry models used for dose reconstruction in Belarus and Russia.
2. Validation of four models through a first intercomparison exercise in which the four models were used to calculate average doses to populations of specific age groups from 20 settlements. The obtained results were then compared with average doses based on the direct thyroid measurements that were conducted in those settlements.
3. Modification of the two selected models that gave the best prediction in first intercomparison exercise in order to reconstruct individual doses for 42 persons taking into account the information obtained during the personal interviews.
4. Validation of the two selected models through a second intercomparison exercise in which the thyroid individual predicted doses were compared for a number of persons with individual doses calculated from direct thyroid measurements.
5. Intercomparison of the results obtained by the two models and analysis of discrepancies observed in model predictions. Selection of the best model for thyroid dose reconstruction.

This paper presents the methods and results of the reconstruction of individual thyroid doses for the subjects of the case-control study.

MATERIALS AND METHODS

Age and geographical distribution of study subjects

The study included 1,218 persons from Belarus and 397 persons from Russia, both cases and controls, all aged 0-18 y at the time of the accident in 1986. A personal interview collected information on places of residence, consumption and origin of milk, milk products and leafy green vegetables, time spent outdoors, and countermeasures (evacuation, self-relocation, stable iodine administration) in the period following the accident (Cardis et al. 2005). The distribution of the study subjects according to age at the time of the accident is given in Table 1. More than half of the study subjects were less than 5 years old at the time of the accident.

At the time of the Chernobyl accident study subjects resided in one of six heavily contaminated regions: Gomel and Mogilev oblasts in Belarus or Bryansk, Kaluga, Orel and Tula oblasts in Russia (Fig.1). The geographical distribution of the study subjects according to the oblast of residence at the time of the accident and range of mean ^{137}Cs and ^{131}I deposition in the settlements of residence is given in Table 2.

Reconstruction of thyroid doses from ^{131}I

The consumption of locally produced milk was the most important pathway of thyroid exposure to ^{131}I in the period immediately following the accident. Although leafy vegetables were not widely available in the territory of consideration at the time of deposition (early spring), their consumption was relatively important for subjects with low or no milk consumption. Internal thyroid exposure due to inhalation of ^{131}I was also important for individuals evacuated shortly after the accident and for those who stopped consuming locally produced foodstuffs. Therefore,

dose reconstruction included the following pathways of thyroid exposure from ^{131}I : (1) Internal exposure due to inhalation of ^{131}I ; (2) Internal exposure from intake of milk and milk products contaminated with ^{131}I ; and (3) Internal exposure from intake of leafy vegetables contaminated with ^{131}I .

The dosimetry working group considered four different models for reconstruction of the average thyroid dose in a settlement. These models fall into two categories. The first category involves a semi-empirical approach (Gavrilin et al. 1999a; Zvonova et al. 1998), that is based on the relation between environmental contamination (^{137}Cs or ^{131}I deposition density, ^{131}I concentration in milk) and thyroid dose estimated from direct thyroid measurements carried out in territories of Belarus and Russia with different contamination levels and in populations of all ages (infants, children, adolescents and adults). The second is a process-driven approach (Drozdovitch et al. 1997; Vlasov and Pitkevich 1999), which considers a multi-compartment process of ^{131}I activity transfer to the human thyroid either from ^{131}I deposition leading to contamination of milk and leafy vegetables or from ^{131}I concentration in ground-level air in the case of inhalation. Parameters of those models were adapted to local radioecological conditions.

To reach consensus on a single “best” method to be used in the case-control study, it was agreed that a number of further steps were needed before selecting that method: (1) Evaluation of the availability of the input information necessary for the models; (2) Comparison of doses estimated with different methods for the same settlement and scenario, and comparison of associated uncertainties; and (3) Verification that the model could take into account the information obtained with the case-control study questionnaire.

Intercomparison study for average settlement thyroid dose from ^{131}I

The dosimetry working group organized the intercomparison study to assess the adequacy of the four methods proposed. At the first stage thyroid doses from ^{131}I were evaluated by calculating the average thyroid doses to populations of specific age groups for 12 settlements in Belarus and 8 in Russia. They were randomly selected from the list of settlements where a sufficient number of direct thyroid measurements were available. The calculated doses were then compared with average thyroid doses derived from direct thyroid measurements in these settlements. The comparison assumed the same lifestyle and dietary habits as used in the calculation of doses from direct thyroid measurements.

To estimate the average thyroid dose from ^{131}I in a settlement, the following common input information for all four models was used: (1) ^{137}Cs deposition density in the settlement; (2) time-integrated ratio of ^{131}I -to- ^{137}Cs activity in deposition; (3) dates of the beginning and end of fallout in the settlement; (4) date when cows were first put out to pasture; (5) dates and types of countermeasures applied in the settlement; and (6) age dependent ICRP models that describe the kinetics of iodine, inhaled or ingested, in the human body (ICRP 1990, 1995).

Every model predicted mean thyroid doses from inhalation and ingestion and associated uncertainties for 1-, 5-, 10- and 15-year old children in the selected settlements. In order to blind the participants of the intercomparison exercise and to avoid bias in calculations, the identity of the settlements was not disclosed.

Fig. 2 compares average thyroid doses from ^{131}I assessed by four models with doses derived from direct thyroid measurements in the 20 settlements for 1-year old children. The means of the ratios of average thyroid doses from ^{131}I intake predicted by each model to those derived from thyroid measurements are 1.0 ± 0.5 (one standard deviation), 1.1 ± 1.1 , 1.3 ± 1.3 and 2.7 ± 1.2 for models #1, #2, #3 and #4, respectively; the corresponding medians of ratios were 1.0, 0.8, 0.9 and 2.6. The intercomparison exercise showed that model #1 gave the best agreement with

the “measured” doses, followed by model #2. Estimates of the ecological model #4 tended to systematically overestimate the thyroid doses in the low dose range. Model #3 is also an ecological model, but results of the estimates were normalized by introducing empirical correction coefficients previously derived from direct thyroid measurements. Nevertheless, all models were in satisfactory agreement with the “measured” doses within the range of uncertainties.

Intercomparison study for individual thyroid dose from ^{131}I

Originally, the models calculate age-dependent average thyroid doses under the assumption of standard behaviour of the population, i.e., countermeasures like self-evacuation, interruption of milk consumption, iodine blockade were not taken into account. To use these models for estimating individual thyroid doses for subjects with individual behaviour, a number of modifications were made. Specifically, models had to take into account the information obtained from personal interview including consumption rates and origin of foodstuffs, behaviour, residence history, and administration of stable iodine.

The second intercomparison exercise validated the adequacy of the two best models for individual dose reconstruction. This was carried out by comparing predicted individual doses with doses calculated from direct thyroid measurements for a number of individuals for whom information on lifestyle and diet was obtained using the study questionnaire. Forty-two individuals aged 0-16 years were randomly selected for the exercise among children for whom direct thyroid measurements were available in four oblasts where the case-control study was conducted: Gomel and Mogilev oblasts in Belarus, and Bryansk and Kaluga oblasts in Russia. They were traced and interviewed using the dosimetry questionnaire, which was used in this case-control study. Information from the interview was provided for model dose calculations together with the input data for the settlements of residence (except the name of the settlement).

Fig.3 shows the comparison of the individual thyroid doses from ^{131}I assessed by the two models with doses derived from direct thyroid activity measurements for the 42 individuals. The dispersion (Fig.3) of the ratios of individual thyroid doses estimated using the model and those based on direct thyroid measurements could be due to relatively large uncertainties associated with the model calculation and uncertainties of doses derived from measurements. However, it should be noted that there was no systematic difference between calculated and “measured” doses. The means of the ratios of individual thyroid doses from ^{131}I intake predicted by the model to that from thyroid measurement were 1.6 ± 1.6 and 1.7 ± 1.9 while the medians of the ratios were 1.0 and 0.8 for models #1 and #2, respectively. Therefore, the intercomparison exercise showed that model #1 gave better agreement with the individual “measured” thyroid doses than did model #2.

Test calculation of individual thyroid doses from ^{131}I

The two models that gave the best predictions were then compared. Individual thyroid doses from ^{131}I were calculated for the subjects included in the case-control study using data from the dosimetry questionnaires. The comparison of the individual thyroid dose estimated using models #1 and #2 for study subjects from Belarus and Russia is shown in Fig.4. As can be seen from Fig.4, the variability of the ratios of the two sets of dose estimates is within a range of one order of magnitude. Nevertheless, the thyroid doses reconstructed by both models are in reasonably good agreement within, in general, the range of uncertainties for the majority of individuals. The distribution of the ratios of the thyroid doses estimated by model #2 to that estimated by model #1 in the whole dose range is characterized by an arithmetic mean of 1.0 ± 0.9 and a median of 0.8.

As a result of the validation study, model #1 (Gavrilin et al. 1999a) was selected to estimate the individual thyroid doses from ^{131}I intake for the subjects of the case-control study. A brief description of this semi-empirical model is given in the Appendix.

Reconstruction of thyroid doses from short-lived radioiodines (^{132}I , ^{133}I , ^{135}I), and short-lived radiotelluriums ($^{131\text{m}}\text{Te}$ and ^{132}Te)

A nuclear reactor produces a number of short-lived radioiodines with half-lives of the order of one hour to one day. Their behaviour in the environment and the human body is the same as ^{131}I . Also, the radiotelluriums, which are the parents of the radioiodines, need to be taken into consideration. Among these, only five short-lived radioiodines and radiotelluriums (^{132}I , ^{133}I , ^{135}I , $^{131\text{m}}\text{Te}$, and ^{132}Te) could contribute substantially to the thyroid doses of population.

Pripyat-town located near the Chernobyl nuclear power plant was the only settlement where short-lived radionuclides were measured *in vivo* among the exposed population (Balonov et al. 2003). As exposure was due to inhalation only and occurred within 1.5 days after the reactor explosion and before evacuation, the contribution of short-lived radionuclides to the thyroid doses was expected to be highest in that population. According to the *in vivo* measurements, the mean contribution of ^{133}I , ^{132}I , and ^{132}Te to total thyroid doses was 30% in residents evacuated from Pripyat who did not take potassium iodide to block radioiodine uptake by the thyroid gland during the first 1.5 days after the accident (Balonov et al. 2003). By analogy with Pripyat, a similar contribution of short-lived radionuclides to the total thyroid dose would be expected for people who were exposed via inhalation only and evacuated shortly after the accident from the 30-km zone around the Chernobyl nuclear power plant. The contribution of short-lived radionuclides to the thyroid dose for residents of Russian settlements is estimated to be small. Based on evidence from Belarusian settlements with similar radiation conditions, it was estimated to have amounted to 10% at most for people whose intake was only via inhalation (Gavrilin et al. 2004). Although the contribution of short-lived radioiodines and radiotelluriums to the total dose was small, it is very important to estimate it, because of the suspicion that the impact of the short-lived radionuclides on thyroid cancer induction could be greater than that from ^{131}I (NCRP 1985).

The distance of the settlement of residence from the Chernobyl Nuclear Power Plant and the pattern of the radioactive clouds in the first day(s) after the accident were used for the evaluating the thyroid doses from short-lived radioiodines and radiotelluriums. To group the regions with similar kinetics of radioiodine fallout, Gavrilin et al. (2004) used measured ^{131}I daily fallout (Makhonko et al. 1996), ^{137}Cs ground deposition density, and information about precipitation. A classification of the territory of Russia by probable level of dose from short-lived radionuclides was based on the same approach.

For each exposure pathway (i.e. inhalation, milk and leafy vegetable consumption) the age-dependent and region specific ratios of internal thyroid dose due to intake of short-lived radionuclides to internal thyroid dose due to ^{131}I intake were estimated. Table 3 gives those ratios for subjects who did not change their behaviour during the first two weeks after the accident. For the subjects who changed residence, diet, or took stable iodine shortly after the accident, information from personal interview was taken into account in thyroid dose reconstruction.

Reconstruction of thyroid doses from long-lived sources of exposure: external exposure and ingestion of cesium

External exposure of the population after the Chernobyl accident resulted from the ground deposits of gamma-emitted radionuclides, such

as ^{95}Zr , ^{95}Nb , ^{99}Mo , ^{103}Ru , ^{106}Ru , ^{132}Te , ^{131}I , ^{132}I , ^{133}I , ^{134}Cs , ^{136}Cs , ^{137}Cs , ^{140}Ba , ^{140}La , ^{141}Ce , and ^{144}Ce . The contribution to the external exposure due to submersion in the radioactive cloud during its passage was negligible. Internal exposure of the population from long-lived radionuclides was mainly due to the ingestion of foodstuffs contaminated with radiocesiums (^{134}Cs and ^{137}Cs).

The dosimetry working group considered two models developed in Belarus and Russia for the estimation of the average whole body dose from long-lived sources of exposure: external exposure and ingestion of ^{134}Cs and ^{137}Cs . Models for external dose reconstruction (Drozdovitch et al. 2002; Pitkevich et al. 1996) in both countries used similar approaches based on the integration of the time-dependent dose rate in air per unit deposition, taking into account the shielding properties of the residential environment and the behaviour of the person. Only the model parameter values are slightly different. Models considered to estimate ingestion doses were, however, different in their approaches. One was a semi-empirical approach (Minenko et al. 2006) based on the relation between environmental contamination (^{137}Cs deposition density and ^{137}Cs soil-to-milk transfer) and internal dose derived from direct whole body measurements of radiocesium body burden, carried out in regions of Belarus with different contamination levels and in populations of different ages. The second was a process-driven approach (Vlasov and Pitkevich 1999), which considered a multi-compartment process of cesium activity transfer from deposition to human diet.

Intercomparison study for whole body doses from long-lived sources of exposure

An intercomparison study was set-up to assess the adequacy of the two available models (model #5 and model #6). Two dosimetry teams received the input data (^{137}Cs deposition density, radionuclide composition in deposition, dates of the fallout in the settlement, date when cows were first put on pasture, and soil-to-milk transfer of ^{137}Cs) for 10 settlements (where the case-control study subjects resided) selected within each of the four study oblasts in Russia. Similar to the previous exercise, the identity of the settlements was not disclosed to the participants.

Average whole body doses from external exposure and radiocesium ingestion for adults were reconstructed using models for the first year and cumulatively for the 10 years after the Chernobyl accident. The calculated doses were compared with those reported in the Russian Catalogue of doses (Balonov et al 1999) – considered as the “gold” standard.

The agreement between the external doses calculated by each of the two methods and the “gold” standard was satisfactory. The distribution of the ratios of the model estimates and of the “gold” standard for external dose during the first year after the accident is characterized by an arithmetic mean of 1.0 ± 0.1 and a median of 1.0 for both models. Predictions of external dose during the first 10 years after the accident were also very close for both models: a mean 1.1 ± 0.1 and a median of 1.0 were estimated for this distribution of ratios.

However, for internal dose from ingestion of radiocesium, the difference between models and the “gold” standard was more marked. The means of the ratios of predicted internal dose during the first year after the accident to the “gold” standard were 1.7 ± 1.3 for model #5 and 2.4 ± 3.2 for model #6; the median of the ratio was 1.3 for both models. Similar differences were observed for the cumulative doses predicted over the first 10 years after the accident. The means of these ratios were 1.7 ± 1.6 and 3.0 ± 4.6 , and the medians were 1.2 and 1.5 for the same models. In general, model #5 showed a better agreement with the “gold” standard than did model #6.

Estimation of individual thyroid doses from long-lived sources of exposure

In order to apply the dose reconstruction models to estimate individual thyroid doses from long-lived sources of exposure within the case-control study, a number of modifications were

made to the models to allow estimation of individual doses to the thyroid instead of the whole body. In addition, modifications took into account the information on the consumption and origin of foodstuffs, behavior patterns and residential history obtained from the personal interview.

The individual thyroid doses from external exposure and $^{134,137}\text{Cs}$ ingestion for the study subjects were calculated with the two models using data from the questionnaires. The comparison showed that thyroid doses reconstructed by both models are in good agreement for the majority of subjects. The distribution of the ratios of the thyroid doses estimated by model #6 to that estimated by model #5 is characterized by an arithmetic mean of 1.0 ± 0.3 and a median of 1.0 for external exposure and characterized by an arithmetic mean of 1.4 ± 1.7 and a median of 1.1 for internal exposure.

Following the results of the intercomparison exercise, the dosimetry working group selected model #5 (Drozdovitch et al. 2002; Minenko et al. 2006) for the reconstruction of individual thyroid doses from long-lived sources of exposure for the subjects of the case-control study.

Reconstruction of individual doses for subjects who were in Ukraine during the first two months following the accident

According to the definition of the study population, all subjects resided in Belarus or Russia at the time of the accident; however, after analysis of the residential history from study questionnaires it appeared that several study subjects spent some time in contaminated Ukrainian settlements during the first two months after the accident. Internal thyroid doses from ^{131}I were also estimated for them based on the results of dose reconstruction carried out in Ukraine (Likhtarev et al. 1993). Although the thyroid dose reconstruction model used in Ukraine was not included in the intercomparison studies discussed above, the method was based on results of wide-scale direct thyroid measurements performed in Ukraine in May-June 1986, and the information provided in questionnaires was incorporated in the same way as in Belarus and Russia.

Uncertainties in thyroid doses

Although the process of dose reconstruction provides a point estimate of each subject's dose, it is obvious that there is uncertainty associated with these dose calculations. The uncertainty analysis was performed using a Monte-Carlo simulation method. According to this method, dose realizations were simulated for each person taking into account the distributions of the model parameters, the available radiation data, and the answers to the questionnaire. This procedure was repeated 10,000 times with changed parameter values; therefore, 10,000 values of thyroid dose were obtained for each subject.

To run the Monte Carlo simulations, the probability density functions for all uncertain model parameters were assigned. It is important to note that for a single dose realization, some of the model parameter values were considered to be common, "shared" by certain groups of subjects, implying that any error made on this parameter was shared by all subjects to whom it applies. For example, the date of the fallout in the settlement is uncertain, but the same simulated value was used for all individuals of the settlement, while calculating each estimate of dose. Therefore, besides setting up proper probability density functions for the parameters, the inter-individual correlations were defined in order to take into account shared errors.

Other uncertainties were considered to be independent among subjects, for example, information from personal interviews regarding milk consumption and residence history. It is important to note that different degrees of uncertainty were associated with those unshared errors depending on the reliability of the answers obtained during personal interviews, i.e. the

interviewer's evaluation at the end of interview on how reliable were the subject's answers was taken into account.

Therefore, the following errors in reconstructed thyroid doses were considered in the uncertainty analysis: (1) shared and unshared errors associated with parameters of the dosimetry models; (2) unshared errors that are associated with the information from the personal interview when answers from the study subjects are available; and (3) unshared errors that are associated with missing data values from the personal interview or associated with answers that could be considered as unreliable. A detailed description of the uncertainty analysis can be found elsewhere (Drozdovitch et al. 2007).

RESULTS AND DISCUSSION

Individual thyroid doses

Validated models were used to estimate individual thyroid doses for the 1,615 subjects of the case-control study. Reconstruction of doses was carried out blindly in regard to the case/control status of study subjects. For all study subjects, estimates of individual thyroid dose included:

1. Internal exposure from intakes of ^{131}I due to
 - a. Inhalation of radionuclide during the passage of radioactive clouds resulting from the accident,
 - b. Consumption of contaminated milk and milk products during the time period from the accident (26 April) until 20 June 1986 when ^{131}I can be considered as decayed, and (c) Consumption of leafy vegetables during time period from 26 April until 20 June 1986;
2. Internal exposure due to intake of short-lived radioiodines and radiotelluriums via inhalation and ingestion during the first day(s) after the accident;
3. External exposure from radionuclides deposited on the ground during the time period from the accident until the date of diagnosis of the case and the same date for his/her controls within the same match; and
4. Internal exposure resulting from the ingestion of ^{134}Cs and ^{137}Cs during the time period from the accident until the date of diagnosis of the case and the same date for his/her controls within the same match.

The assessment of individual thyroid doses took into account: (1) the knowledge of the whereabouts and dietary habits of the subjects, which was obtained by means of personal interviews and (2) information on radiation contamination available for each settlement where the subject resided during the post-accidental period.

Table 4 gives thyroid doses reconstructed for study subjects from different exposure pathways. A large difference in thyroid doses between Belarusian and Russian subjects was found. The median dose in Belarus was over 10 times higher than the median dose in Russia: 0.37 and 0.034 Gy, respectively. In Russia, 96% of the doses were below 0.37 Gy, a value that was the median estimated dose in Belarus. The highest reconstructed thyroid doses were about 10.2 Gy in the group of Belarusian subjects and 5.3 Gy in Russian subjects. Intake of ^{131}I with milk was the main pathway for thyroid exposure. However, for some of the subjects from Belarus, intake of leafy vegetables resulted in up to 4.9 Gy to the thyroid gland. The estimated doses from short-lived iodine and tellurium isotopes ranged up to 0.53 Gy; the median dose in Belarus was almost 10 times higher than the median dose in Russia: 1.7 mGy and 0.14 mGy, respectively. The estimated individual thyroid doses from external exposure ranged up to 0.1

Gy, while those from internal exposure due to cesium ingestion did not exceed 0.05 Gy. Doses from long-lived sources of exposure in Belarus were twice those in Russia.

Table 5 shows the contribution of different exposure pathways to the total thyroid dose. As can be seen from Table 5, ^{131}I intake with milk was the main pathway for thyroid exposure; the median contributions to total thyroid dose are 90% and 74% in Belarus and Russia, respectively. The lower contribution observed in Russia could be explained by lower milk consumption rates in Russia compared to Belarus (370 vs 470 mL d⁻¹, respectively for median) and a higher consumption rate of leafy vegetables reported by study subjects in Russia than in Belarus (20 vs 0 g d⁻¹, respectively for median). Different milk consumption rates are related to the fact that about 70% of Belarusian subjects were under 5 years at the time of the accident, therefore, milk and milk products were a dominant part of their diet. In comparison, only 30% of Russian subjects were less than 5 years at the time of the accident. In addition, animals were put out to pasture later in Russia. Among all study subjects, the median contributions to total thyroid dose from exposure sources other than ^{131}I intake was estimated to be 0.5% for intake of short-lived radioiodine and tellurium isotopes, 1.1% for external exposure, and 0.5% for ingestion of cesium isotopes.

It should be noted that for a small fraction of the study subjects, the contribution of long-lived sources of exposure to the thyroid dose was found to be higher than 50%. Five subjects of this study were relocated from contaminated villages shortly after the accident and before the date of main deposition, and, therefore, these individuals received relatively small doses from ^{131}I due to inhalation and/or consumption of locally produced foodstuffs. In addition, 14 study subjects indicated that they did not consume local foodstuffs and that they resided permanently in villages that were highly contaminated with radioactive materials as a result of fallout associated with precipitations, and, therefore they received relatively low doses from ^{131}I inhalation. For these 19 individuals, long-lived sources of exposure during the years following the accident were the predominant components of the thyroid dose.

Table 6 compares thyroid doses in Belarus and Russia in terms of age at the time of the accident. The thyroid dose decreased with increasing age: the median doses were 0.38, 0.37, 0.13, 0.041 and 0.015 Gy, respectively in the <2, 2-4, 5-9, 10-14 and 15-18 year age groups. The dose to young children is higher than that to adolescents because (1) the thyroid mass in children is smaller, and even for the same ^{131}I intake, a child's thyroid receives a higher radiation dose because the same amount of energy is deposited in a smaller thyroid mass; and (2) dairy products, as the main route of ^{131}I intake, were reported to be consumed in higher quantities during childhood: the fractions of consumers of milk and milk products were found to be 70%, 91%, 85%, 84%, and 87% in the <2, 2-4, 5-9, 10-14 and 15-18 year age groups, respectively, while the daily consumptions were reported to be 500, 520, 470, 460, and 440 g in the same age groups.

Table 7 shows gender-specific distributions of thyroid doses estimated for the study subjects of different ages. As can be seen from Table 7, at all ages (except age group 2-5 y in Russia) thyroid doses for boys were found to be higher than that for girls. It should be noted that there were no any gender-specific differences in parameters of dosimetry models used in this study; and, moreover, doses were calculated blindly to the study subject's gender. Higher doses among boys were due to the larger fraction of milk consumers and higher consumption of dairy products among boys than that among girls. In Belarus, fraction of milk consumers among boys and girls of all ages was 82% and 78%; daily consumption of milk and milk products among consumers was 560 g and 470 g for boys and girls, respectively. Although the same fractions of consumers of dairy products among boys and girls were found in Russia (87%), higher daily consumption was reported by boys in comparison with girls, 520 g and 430 g, respectively.

Uncertainty of reconstructed thyroid doses

An uncertainty analysis was performed on the estimates of thyroid dose from ^{131}I intake as this was the dominant pathway for thyroid exposure for the majority of study subjects. For each study subject, a set of 10,000 values of thyroid dose from ^{131}I was calculated. Distributions of those 10,000 doses were found to be approximately lognormal. Distributions of the geometric standard deviation of the individual thyroid dose from ^{131}I among persons included in the study are shown in Fig. 5. The geometric standard deviation of the thyroid dose varies from 1.7 to 4.0 with median values of 2.3 and 2.1 for Belarusian and Russian subjects, respectively.

Sources of error were ranked according to their contribution to the uncertainty of model prediction. For individuals with standard behavior (average diet, no evacuation, no iodine blockade) the model is most sensitive to the following parameters: thyroid dose coefficient (that is mainly due to variability in thyroid mass) for ingestion and coefficient B and C_{comb} of the semi-empirical model for combined dry-wet fallout (eqn. (A.1) of Appendix).

Comparison of individual thyroid dose estimates with thyroid dose derived from direct measurements

There were 81 individuals (63 from Belarus and 18 from Russia) for whom direct measurements of ^{131}I activities in the thyroid were performed in May or in the beginning of June 1986. "Measured" thyroid doses were recalculated for those subjects taking into account individual data obtained from the case-control study questionnaire. Fig. 6 compares individual thyroid doses from ^{131}I assessed by the model with those derived from direct thyroid measurements.

A rather wide range of ratios between those two sets of doses can be seen in Fig. 6. This effect is due to the relatively large uncertainties of the model calculations caused by errors in the parameter values of the dosimetry models and by the low reliability of individual information obtained more than 10 years after the accident. The mean of ratios of thyroid dose estimated using the model to that estimated from direct thyroid measurements is 2.0 ± 2.2 and the median of ratios is 1.2.

CONCLUSION

The design of the epidemiological study required that the same procedure for dose calculation be used for all cases and controls to avoid possible biases. Within this study a common dosimetry approach was developed and validated to reconstruct thyroid dose using the same input data for all persons included in the study for Belarus and Russia. A series of intercomparison exercises validated four models for reconstruction of thyroid doses from ^{131}I intake and two models for reconstruction of doses from external exposure and ingestion of cesium isotopes. All tested models were in satisfactory agreement within the range of uncertainties with both, average to population of specific age group and individual "measured" doses. Following the results of the validation studies, the models that showed the best agreement were selected to estimate the individual thyroid doses for 1,615 subjects of the case-control study.

For each study subject, individual thyroid doses were reconstructed for the following pathways of exposure: (1) intake of ^{131}I via inhalation and ingestion; (2) intake of short-lived radioiodines (^{132}I , ^{133}I , and ^{135}I) and radiotelluriums ($^{131\text{m}}\text{Te}$, ^{132}Te) via inhalation and ingestion; (3) external dose from radionuclides deposited on the ground; and (4) ingestion of ^{134}Cs and ^{137}Cs . Results of this study show that internal exposure from intake of ^{131}I was the main pathway for thyroid exposure for the majority of persons living in contaminated areas following

the Chernobyl accident. In general, the fraction of the thyroid dose due to exposure from short-lived iodine and tellurium isotopes, external exposure, or radiocesium ingestion was about 1 % for each pathway. Similar results were obtained for the thyroid dose estimates for subjects of the case-control study of childhood thyroid cancer conducted in Belarus in 1992-1994 (Minenko et al. 2006). However, for individuals who did not consume locally produced foodstuffs, inhalation of ^{131}I was estimated to be primary exposure pathway followed by external exposure. There is also a group of 19 study subjects who (1) were relocated from contaminated areas shortly after the accident before the date of main deposition, or (2) did not consume local foodstuffs shortly after the accident and resided permanently in villages that were highly contaminated with ^{137}Cs due to wet deposition. For these individuals, who received relatively small doses from ^{131}I intake, long-lived sources of exposure during the years following the accident were the predominant components of the thyroid dose.

For a number of individuals included in the study, direct measurements of ^{131}I activities in the thyroid were available, and thyroid doses for them were reconstructed based on those measurements. A comparison of the “measured” and estimated thyroid doses from ^{131}I showed a rather wide range of ratios between them across both low and high doses. The mean ratio of thyroid dose estimated using the model to that estimated from direct thyroid measurements was found to be 2.0 ± 2.2 and the median ratio was found to be 1.2. This large dispersion of the ratios shows the relatively large uncertainties of the model calculations caused by errors in the parameters of the dosimetry models and reliability of individual information obtained more than 10 years after the accident.

A point estimate of dose was provided for each subject in the study. Also, for each subject of the study a set of 10,000 values of thyroid dose from ^{131}I was generated by Monte Carlo simulations to estimate uncertainties of reconstructed doses. Shared and unshared errors associated with parameters of the dosimetry models as well as with the available and missed information from the personal interview were considered in the calculation of stochastic doses. The geometric standard deviation of the thyroid dose varies from 1.7 to 4.0 with a median of 2.2. These sets of equally possible dose estimates are used to average the likelihood of the radiation risk parameters from which risk estimates are derived with confidence intervals taking into account the errors in doses.

Acknowledgments

Funding for this study was provided by contracts FI4C-CT96-0014 and ERBIC15-CT96-0308 from the European Union (Nuclear Fission Safety and INCO-Copernicus Programmes) and a contract from the Sasakawa Memorial Health Foundation (Chernobyl Sasakawa Health and Medical Cooperation Project). The authors are grateful to all of the study subjects who agreed to participate in the study. Special thanks are due to the staff that conducted the dosimetry interviews. The authors also gratefully acknowledge the contribution of Prof. Mikhail Balonov (Institute of Radiation Hygiene, St Petersburg, Russia) to the development and testing of the dose reconstruction methods and for his fruitful discussion of the results; and to Ms Lesley Richardson (Montreal, Canada) for useful discussions about the presentation of results.

REFERENCES

- Balonov MI, Golikov VY, Bruk GY, Shutov VN, Bazukin AB, Zvonova IZ, Travnikova IG, Zhesko TV, Vlasov AY, Gordeev AV. Mean effective cumulated in 1986-1995 whole body doses for inhabitants of settlements of Brynsk, Kaluga, Orel, Tula, Ryazan, and Lipetsk oblasts of Russian Federation radioactive contaminated following the accident on the Chernobyl NPP in 1986. *Radiat Risk*. 1999; (Special Issue) (in Russian).
- 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* 2003;105:593–599.

- Cardis E, Kesminiene A, Ivanov V, Malakhova I, Shibata Y, Khrouch V, Drozdovitch V, Maceika E, Zvonova I, Vlasov O, Bouville A, Goulko G, Hoshi M, Abrosimov A, Anoshko J, Astakhova LN, Chekin S, Demidchik E, Galanti R, Ito M, Korobova E, Lushnikov E, Maksimov M, Masyakin V, Nerovnia A, Parshin V, Parshkov E, Pilipitsch N, Pinchera A, Polyakov S, Shabeka N, Suonio E, Tenet V, Tsyb A, Yamashita S, Williams D. Risk of thyroid cancer after exposure to ^{131}I in childhood. *J. Natl. Cancer Inst* 2005;97:724–732. [PubMed: 15900042]
- Drozdovitch VV, Goulko GM, Minenko VF, Paretzke HG, Voigt G, Kenigsberg YI. Thyroid dose reconstruction for the population of Belarus after the Chernobyl accident. *Radiat Environ Biophys* 1997;36:17–23. [PubMed: 9128894]
- Drozdovitch, VV.; Shevchuk, VF.; Mirkhaidarov, AK. Uncertainty analysis of external doses used to assess radiological consequences of the NPPs accident, Minsk, Belarus, IPEP-70. 2002. (in Russian)
- Drozdovitch V, Maceika E, Khrouch V, Zvonova I, Vlasov O, Bouville A, Cardis E. Uncertainties in individual doses in a case-control study of thyroid cancer after the Chernobyl accident. *Radiat Prot Dosim* 2007;127:540–543.
- Gavrilin YI, Khrouch VT, Shinkarev SM, Krysenko NA, Skryabin AM, Bouville A, Anspaugh L, Straume T. Chernobyl accident: reconstruction of thyroid dose for inhabitants of the Republic of Belarus. *Health Phys* 1999a;76:105–119. [PubMed: 9929121]
- Gavrilin YI, Khrouch VT, Shinkarev SM. Validation of semi-empirical models of the thyroid gland internal irradiation dose formation and selection of areas (x) at estimating thyroid doses for adults of rural regions. *Bulletin of Public Information Centre on Atomic Energy* 1999b;11:33–41. 54. (in Russian).
- Gavrilin Y, Khrouch V, Shinkarev S, Drozdovitch V, Minenko V, Shemiakina E, Ulanovsky A, Bouville A, Anspaugh L, 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* 2004;86:565–585. [PubMed: 15167120]
- Ilyin, LA.; Arkhangelskaya, GV.; Likhtarev, IA. Collection of rules and standards on radiation safety in atomic energy. Vol. 2. Ministry of Health; Moscow: 1989. Instruction to provide an iodine prophylaxis in the case of nuclear reactor accident (1967).; p. 105-108.(in Russian)
- Ilyin, LA.; Arkhangelskaya, GV.; Konstantinov, YO.; Likhtarev, IA. Radioactive iodine in the problem of radiation safety. Atomizdat; Moscow: 1972.
- International Commission on Radiological Protection. Age-dependent doses to members of the public from intakes of radionuclides: Part 1. Ingestion dose coefficients. *Ann ICRP* 1990;20(2) ICRP Publication 56.
- International Commission on Radiological Protection. Age-dependent doses to members of the public from intake of radionuclides: Part 4: Inhalation dose coefficients. *Ann ICRP* 1995;25(3/4) Publication 71.
- Likhtarev IA, Shandala NK, Goulko GM, Kairo IA. Exposure doses to thyroid of the Ukrainian population after the Chernobyl accident. *Health Phys* 1993;64:594–599. [PubMed: 8491614]
- Likhtarev I, Minenko V, Khrouch V, Bouville A. Uncertainties in thyroid dose reconstruction after Chernobyl. *Radiat Prot Dosim* 2003;105:601–608.
- Makhonko KP, Kozlova EG, Volokitin AA. Dynamics of radioiodine accumulation on soil and reconstruction of doses from iodine exposure on the territory contaminated after the Chernobyl accident. *Radiat Risk* 1996;7:90–112.
- Matsunaga T, Kobayashi K. Sensitivity analysis on the effectiveness of iodine prophylaxis to reduce thyroid gland exposure in nuclear emergency. *Proc. of IRPA-10* 2000:11–307.
- Minenko V, Ulanovsky A, Drozdovitch V, Shemiakina E, Gavrilin Y, Khrouch V, Shinkarev S, Bouville A, Anspaugh L, Voillequé P. Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus - Part II: Contribution from long-lived radionuclides and external radiation. *Health Phys* 2006;90:312–327. [PubMed: 16538137]
- National Council on Radiation and Measurements. Induction of thyroid cancer by ionizing radiation. Bethesda, MD: 1985. NCRP Report No. 80
- Pitkevich VA, Guba VV, Ivanov VK, Chekin SY, Tsyb AF, Vakulovsky SM, Shershakov VM, Makhonko KP, Golubenkov AV, Kosykh VS. Reconstruction of the composition of the Chernobyl radionuclide

fallout and external radiation absorbed doses to the population in areas of Russia. *Radiat Prot Dosim* 1996;64:69–92.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. United Nations; New York: 2000. 2000 Report; Sales No. E.00.IX.4

Vlasov OK, Pitkevich VA. Agro-climate model for estimation of radionuclides transport on food chain and for formation of internal exposure to population. *Radiat Risk* 1999;11:65–85. (in Russian).

Zvonova, IA.; Balonov, MI. Radioiodine dosimetry and prediction of consequences of thyroid exposure of the Russian population following the Chernobyl accident.. In: Mervin, SE.; Balonov, MI., editors. The Chernobyl papers. Vol.1. Doses to the Soviet population and the early health effects studies. Research Enterprises, Inc.; Richland, WA: 1993. p. 71-125.

Zvonova IA, Balonov MI, Bratilova AA. Thyroid dose reconstruction for population of Russia suffered after the Chernobyl accident. *Radiat Prot Dosim* 1998;79:175–178.

Fig. 1.
Oblasts of Belarus and Russia contaminated following the Chernobyl accident where the case-control study was conducted.

Fig. 2. Comparison of the average thyroid dose estimates from ^{131}I that were calculated by four models for 1-year old children in 20 settlements with the doses derived from direct measurements. The error bars represent 95% confidence intervals.

Fig. 3. Comparison of the individual thyroid dose estimates from ^{131}I that were calculated by two models for 42 individuals with the doses derived from direct measurements. The error bars represent 95% confidence intervals.

Fig. 4. Comparison of the individual thyroid dose estimates from ^{131}I calculated by two models for the subjects of the case-control study. The error bars represent 95% confidence intervals.

Fig. 5.
Distributions of the geometric standard deviation (GSD) of the individual thyroid dose from ^{131}I for the subjects of the case-control study.

Fig. 6. Comparison of individual thyroid dose estimates from ^{131}I for 81 study subjects calculated using the model with the doses derived from direct thyroid measurements. The error bars represent 95% confidence intervals.

Table 1

Distribution of the study subjects according to age at the time of the accident.

Age, years	Belarus		Russia			Total
	Gomel	Mogilev	Bryansk	Kaluga	Orel	Tula
<2	463	60	25	4	7	15
2-4	302	47	18	11	22	22
5-9	204	17	10	20	32	37
10-14	74	51	7	14	44	24
15-18	-	-	4	1	55	25
Total	1,043	175	64	50	160	123
						1,615

Table 2

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 settlements of residence.

Country	Oblast	Number of subjects	^{137}Cs deposition density ^a (kBq m ⁻²)	Time-integrated ^{131}I deposition density (MBq m ⁻²)
Belarus	Gomel	1,043	6 – 18,529	0.15 – 284
	Mogilev	175	2 – 2,754	0.03 – 21.3
Russia	Bryansk	64	4 – 3,500	0.06 – 23.6
	Kaluga	50	3 – 178	0.02 – 1.11
	Orel	160	3 – 209	0.04 – 1.33
	Tula	123	3 – 468	0.05 – 2.96

^a According to Belarusian Hydrometeorological Committee (for Belarusian settlements) and Hydrometeorological Committee of Russia (for Russian settlements). Deposition density corrected to May 1986.

Table 3

Range of ratios of internal thyroid dose estimates due to short-lived radionuclides to that due to ^{131}I for different exposure pathways.

Country	Region	Ratio according to exposure pathway ^a		
		Inhalation	Private milk consumption	Leafy vegetables consumption
Belarus	30-km zone	0.38–0.55	0.021–0.032	0.07–0.14
	Southern part of Gomel oblast	0.19–0.27	0.009–0.014	0.04–0.07
	Mogilev-Bryansk cesium spot	0.14–0.20	0.008–0.015	0.09–0.20
	Gomel city	0.07–0.10	0.004–0.006	0.01–0.02
	Mogilev-city	0.06–0.08	0.001–0.002	0.01–0.02
	Rest of Gomel and of Mogilev oblast	0.06–0.08	0.002–0.003	0.01–0.03
Russia	Mogilev-Bryansk cesium spot	0.06–0.09	0.010–0.019	0.08–0.19
	Rest of Bryansk oblast and Kaluga, Orel, and Tula oblasts	0.05–0.08	0.001–0.002	0.01–0.02

^aRange reflects age-dependence of ratio. The lowest value corresponds to the adolescents, the highest value to infants.

Table 4

Thyroid dose estimates for the study subjects.

Pathway and radionuclides of exposure	Thyroid dose ^a (Gy)		
	Belarus	Russia	Both countries
Inhalation of ¹³¹ I	0.009 (0–0.17)	0.0017 (0.0002–0.028)	0.007 (0–0.17)
¹³¹ I intake with milk	0.27 (0–7.6)	0.020 (0–5.2)	0.15 (0–7.6)
¹³¹ I intake with leafy vegetables	0 ^b (0 – 4.9)	0.002 (0–0.51)	0 ^b (0–4.9)
Short-lived radionuclides ^c	0.0017 (0–0.53)	0.00014 (9×10 ^{−6} –0.026)	0.0012 (0–0.53)
External exposure	0.0024 (0.0001–0.098)	0.001 (2×10 ^{−5} –0.031)	0.0022 (2×10 ^{−5} –0.098)
^{134,137} Cs ingestion	0.0012 (2×10 ^{−5} –0.042)	0.0005 (1×10 ^{−5} –0.012)	0.001 (1×10 ^{−5} –0.042)
All exposure pathways	0.37 (0.001–10.2)	0.034 (0.0003–5.3)	0.21 (0.0003–10.2)

^aMedian (range).^bMore than half of subjects reported that they did not consume leafy vegetables.^cShort-lived radioiodines ¹³²I, ¹³³I, ¹³⁵I, and short-lived radiotelluriums ^{131m}Te, ¹³²Te.

Table 5

Contribution of different exposure pathways to the total thyroid dose.

Pathway and radionuclides of exposure	Contribution ^a of exposure pathways to the total thyroid dose (%)		
	Belarus	Russia	Both countries
Inhalation of ¹³¹ I	2.3 (0–89)	5.3 (0.2–87)	2.9 (0–89)
¹³¹ I intake with milk	90 (0–99.9)	74 (0–99.2)	84 (0–99.9)
¹³¹ I intake with leafy vegetables	0 ^b (0–96)	4.8 (0–94)	0 ^b (0–96)
Short-lived radionuclides ^c	0.6 (0–18)	0.5 (0.06–7.3)	0.5 (0–18)
External exposure	0.8 (0.01–68)	2.7 (0.07–76)	1.1 (0.01–76)
^{134,137} Cs ingestion	0.4 (0.02–32)	1.5 (0.08–19)	0.5 (0.02–32)

^a Median (range).^b More than half of subjects reported that they did not consume leafy vegetables.^c Short-lived radioiodines ¹³²I, ¹³³I, ¹³⁵I, and short-lived radiotelluriums ^{131m}Te, ¹³²Te.

Table 6

Distribution of thyroid dose estimates of the study subjects according to their age at the time of the accident and country of residence.

Age at time of the accident	Thyroid dose ^a (Gy)		
	Belarus	Russia	Both countries
<2	0.44 (0.001–8.4)	0.12 (0.003–5.3)	0.38 (0.001–8.4)
2-5	0.45 (0.002–6.3)	0.075 (0.005–3.5)	0.37 (0.002–6.3)
5-10	0.29 (0.002–10.2)	0.030 (0.0003–0.42)	0.13 (0.0003–10.2)
10-15	0.12 (0.001–3.0)	0.020 (0.001–0.13)	0.041 (0.001–3.0)
15-18	-	0.015 (0.001–0.31)	0.015 (0.001–0.31)

^aMedian (range).

Table 7

Distributions of median thyroid dose estimates between boys and girls at different ages and country of residence

Age at time of the accident	Belarus				Russia			
	Males		Females		Males		Females	
	N	Dose (Gy)	N	Dose (Gy)	N	Dose (Gy)	N	Dose (Gy)
<2	210	0.49	313	0.39	35	0.16	16	0.10
2-5	115	0.55	234	0.42	38	0.062	35	0.094
5-10	84	0.36	137	0.25	32	0.033	67	0.029
10-15	29	0.22	96	0.091	10	0.043	79	0.019
15-18	-	-	-	-	30	0.019	55	0.014
All ages	438	0.46	780	0.32	145	0.045	252	0.03