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THYROID DOSE ESTIMATES FOR A COHORT OF BELARUSIAN PERSONS EXPOSED *IN UTERO* AND DURING EARLY LIFE TO CHERNOBYL FALLOUT

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Abstract

Thyroid radiation doses were estimated for a cohort of 2,965 Belarusian persons who were exposed *in utero* and during early life to fallout from the Chernobyl nuclear power plant accident. Prenatal and postnatal doses to the thyroid due to intake of iodine-131 (^{131}I), external irradiation from radionuclides deposited on the ground and ingestion of cesium isotopes (^{134}Cs and ^{137}Cs) were calculated for all cohort members. Dose estimation was based on personal interviews with subjects' mothers which collected data on subjects' residential history, consumption by mothers during time of pregnancy and breastfeeding, as well as consumption by subjects after birth. Direct instrumental measurement of radioactivity in mothers and the study subjects, if available, were also used for calculation of doses. Intake of ^{131}I by mother was found to be the predominant pathway for thyroid exposure for the study subjects. The average thyroid dose due to all exposure pathways was estimated to be 137 milli-Gray (mGy) (median dose of 25 mGy, maximal dose of 14.8 Gy), including 130 mGy (median dose of 17 mGy, maximal dose of 14.8 Gy) from ^{131}I intake, 4.9 mGy (median dose of 3.0 mGy, maximal dose of 102 mGy) due to external irradiation, and 2.5 mGy (median dose of 1.7 mGy, maximal dose of 47 mGy) due to ingestion of $^{134, 137}$Cs. The dose estimates will be used to evaluate the radiation-related risk of thyroid cancer and other thyroid diseases in this unique cohort.

Keywords

Chernobyl accident; i*n utero*; radiation dose; thyroid

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INTRODUCTION

The Chernobyl accident on 26 April 1986 resulted in massive releases of radioactive materials into the atmosphere and contamination of large areas with significant levels of radioiodines (up to two months after the accident), radiocesiums and other radionuclides. To evaluate the radiation-induced risk of thyroid cancer and other thyroid diseases caused by the Chernobyl accident, a long-term epidemiological study in cohorts of about 25,000 persons in Belarus (~12,000) and Ukraine (~13,000) who were exposed in childhood and adolescence was established in the early 1990s by the Ministries of Health of Belarus and Ukraine in collaboration with the U. S. National Cancer Institute (Stezhko et al. 2004). Individual thyroid doses were reconstructed for all members of these cohorts based on measurement of exposure rate against their neck (called 'direct thyroid measurement') performed during April − June 1986 (Drozdovitch et al. 2013a; Likhtarev et al. 2014). Standardized thyroid screening examinations conducted among these cohorts have demonstrated increased risk of thyroid cancer and other thyroid diseases associated with Iodine-131 (^{131}I) received during childhood and adolescence (e.g., Tronko et al. 2006; Ostroumova et al. 2009, 2013; Brenner et al. 2011; Zablotska et al. 2011, 2015; Cahoon et al. 2017).

However, data on risk of thyroid cancer and other thyroid diseases in those exposed *in utero* are less extensive. In Ukraine, a cohort of 2,582 persons exposed in utero to Chernobyl fallout was established in 2006 (Hatch et al. 2009). The results of the thyroid screening of this cohort suggested an increase in radiogenic risk of thyroid carcinoma and nodules 20−30 years after the accident (Hatch et al. 2019).

In 2017, a comparable cohort of 2,965 Belarusian persons with *in utero* exposure and in early life to the Chernobyl fallout was established by the U. S. National Cancer Institute in collaboration with the Republican Research Center for Radiation Medicine and Human Ecology (RRCRM&HE) in Gomel, Belarus. This paper describes the methodology and the results of estimation of radiation doses to the thyroid for the subjects of this Belarusian cohort.

MATERIALS AND METHODS

Study population

The Belarusian *in utero* and early-childhood exposure cohort (referred to as the "in-utero cohort" henceforth) consists of 2,965 individuals, including 26 twins. Their 2,939 mothers were pregnant and resided between 26 April and 30 June 1986, that was the ^{131}I exposure period, in the study area: Gomel and Mogilev Oblasts as well as the city of Minsk. An Oblast is the largest administrative unit in Belarus. The typical size of an oblast is 30,000–40,000 km^2 with a population of 1.1–1.5 million persons. There are six oblasts in Belarus. Oblasts are sub-divided into raions; there are typically about 20 raions of similar size and population in one oblast. The distribution of subjects according to the raion of residence of their mothers at the time of the accident (ATA) is shown in Fig. 1. Mothers of a majority (n=2,553) of the subjects resided in Gomel Oblast; mothers of 290 subjects resided in Mogilev Oblasts. About 71% of the cohort (2,089 of 2,965) lived in raions of the Gomel and

Mogilev Oblasts that are the most contaminated from Chernobyl fallout (highlighted in grey). Mothers of 91 study individuals arrived at the study area someday after April 26 but before June 30, 1986 and that is why they are not included in the numbers shown in Fig.1.

The distribution of age ATA for the mothers of the subjects is shown in Table 1. Most (n=2,392, 89.3%) mothers were in age between 18 and 30 years, 61 (2.1%) were younger than 18 years, and 13 (0.4%) were older than 40 years. The mean and median age ATA of the mothers were 25.0 and 24.2 years, respectively.

Table 2 provides distribution of the 2,965 Belarusian *in utero* cohort members by gestation age ATA. As can be seen from the table, gestation age was distributed almost uniformly across the months of pregnancy. Conception of 12.6% of the study subjects occurred after the Chernobyl accident.

The study was reviewed and approved by the institutional review boards of the participating organizations in Belarus and the United States. All study subjects and their mothers signed informed consent.

Exposure pathways

Individual thyroid doses were reconstructed for each cohort member for the following pathways of exposure:

- Prenatally due to ^{131}I intake by mothers with inhaled air and/or consumption of foodstuffs such as cow's and/ or goat milk, milk products and leafy vegetables;
- Postnatally from ^{131}I intake by infant with breast milk or/ and other foodstuffs, if cohort member was born between 26 April and 30 June 1986;
- Prenatally and postnatally (until age of 5 years old) due to external irradiation from gamma-emitting radionuclides deposited on the ground;
- Prenatally from mother's consumption of foodstuffs contaminated with ^{134}Cs and ^{137}Cs;
- Postnatally (until age of 5 years old) from child's consumption of foodstuffs contaminated with ^{134}Cs and ^{137}Cs.

Personal interviews

Information required for estimation of individual prenatal and postnatal thyroid doses for the cohort members was collected during the personal interviews of their mothers. Personal interviews were conducted from 19 December 2012 through 22 July 2017 at two fixed centers: RRCRM&HE (Gomel) and Republican Center for Medical Rehabilitation (Minsk), and by mobile teams of the RRCRM&HE at places of residence of study subjects' mothers. Before the personal interview was conducted, each woman read and signed an informed consent statement. The study questionnaire was developed by Belarusian and the U.S. dosimetrists and epidemiologists and included questions on:

- Pregnancy and child delivery term;

- Mother's and subject's residential history; i.e., place of residence and construction material of house ATA, and, if relocated, settlements and dates of residence between 27 April and 30 June 1986 (period of exposure to ^{131}I), and between 1 July 1986 and 31 March 1992;
- Mother's consumption rates and dates of consumption of privately owned cow's and/ or goat's milk, milk from a commercial trade network, milk products (milk soup or porridge, cottage cheese, sour milk, kefir, cream, sour cream), and leafy vegetables between 26 April and 30 June 1986;
- Dates and duration of stable iodine administration by the mother between 26 April and 31 May 1986;
- Date of beginning and duration of breastfeeding;
- Mother's consumption rates and dates of consumption of privately owned cow's or goat's milk, milk from a commercial trade network, and milk products after 30 June 1986 (during pregnancy and/ or breastfeeding);
- Subject's consumption rates of privately owned cow's and/ or goat's milk, milk from a commercial trade network, and milk products at age 0−1, 1−2, and 2−5 years old.

Thyroid doses due to ^{131}I intake

Prenatal thyroid dose—Fig. 2 shows the scheme of calculation of prenatal thyroid doses for the Belarusian *in utero* cohort members. The thyroid doses were estimated using input data specific to the mother of a cohort member (personal interview and direct thyroid measurement, when available), and ecological data (^{131}I ground deposition in the settlements). Ecological and biokinetic models were used to reconstruct the transport of ^{131}I from the ground deposition to the mother's thyroid via the radioactivity taken with contaminated air and foodstuffs. Individual behavior and consumptions data reported during the personal interview were also used in calculations. These models were used to calculate: (a) the time-integrated activity of ^{131}I in mother's thyroid, from which the 'ecological' dose was derived, and (b) the ^{131}I activity in mother's thyroid at the time of the direct thyroid measurement, called the 'ecological' ^{131}I activity in the thyroid. Estimate of 'ecological' thyroid dose for the mother was served as input to estimate 'ecological' dose to the fetus's thyroid gland using the model from ICRP Publication 88 (ICRP 2001). The model accounts for transfer of iodine between the maternal and fetal pools and retention of iodide in the placenta and predicts a continuous increase in dose with increasing gestational age such that doses are minimal early in gestation when the fetal thyroid is not yet fully active and maximal in the third trimester.

Ecological thyroid dose for a subject was calculated as:

$$D^{ecol} = \frac{13.82 \cdot E_{th}}{m_{th,\,mother}} \cdot \sum_{i=n}^{l} DF_{fetus}(t_i) \int_{t_i}^{t_{i+1}} Q_{mother}^{ecol}(t)dt, \quad (1)$$

where D^{ecol} is the ecological thyroid dose for the subject (mGy); 13.82 is a unit conversion factor (Bq kBq^{-1} g kg^{-1} J MeV^{-1} s d^{-1} mGy Gy^{-1}); $m_{th,mother}$ =15.6 g and 16.2 g is the mass of the adult female thyroid gland in Gomel or Minsk Oblasts and Mogilev Oblast, respectively (Skryabin et al. 2010); E_{th} = 0.2 is the mean energy absorbed in the thyroid per decay of ^{131}I in the thyroid (MeV decay^{-1}); $DF_{fetus}(t_i)$ is the dose factor to calculate thyroid dose to fetus of specific i-th gestation age interval due to ^{131}I intake by mother (unitless). Entire gestation period was divided into 14 gestation age intervals by 2.5 weeks; within the limits of this interval $DF_{fetus}(t_i)$ has an unchanging value. Values of dose factor derived from ICRP Publications (1993, 2001) are given in Table 3; $Q_{mother}^{ecol}(t)$ is the variation of the ecological activity of ^{131}I in the thyroid of mother (kBq); t is the time after the Chernobyl accident (d); n is the gestation age interval which is corresponding to 26 April 1986; l is the gestation age interval which is corresponding to 30 June 1986.

Approach to estimate the ecological activity of ^{131}I in the thyroid, $Q_{mother}^{ecol}(t)$ is described in detail elsewhere (Drozdovitch et al. 2013a). To calculate individual prenatal thyroid dose of the cohort member, the ecological dose was calibrated by so-called ‘scaling factor’ in the following way

$$D^{ind} = D^{ecol} \cdot SF, \qquad (2)$$

where D^{ind} is the individual prenatal thyroid dose to the cohort member due to ^{131}I intake by mother (mGy); SF is the scaling factor that is equal to the ratio of the measured a nd calculated ^{131}I activities in the thyroid at the time of the direct thyroid measurement (unitless).

Individual-based radiation measurements are the best foundation for estimation of the most reliable thyroid doses due to ^{131}I intake. About 130,000 exposure-rate measurements using detectors placed against the neck (called “direct thyroid measurements”) were made within a few weeks following the Chernobyl accident in the contaminated areas in Belarus in persons of different ages (Gavrilin et al. 1999). Radiation monitoring devices, namely, the DP-5 dose-rate meters, the SRP-68–01 survey meters and the DRG3–02 dosimeters were used in Belarus for direct thyroid measurements. These devices were not designed to measure ^{131}I activity in the human thyroids, as it could be measured by gamma spectrometer. Special efforts were made to evaluate the device-related uncertainties in direct thyroid measurements done by the SRP-68–01 (Khrutchinsky et al. 2012), similar work was also done for the DP-5 and the DRG3–02 devices. The device response due only to the ^{131}I content in the thyroid was obtained by elimination from measured exposure rate the contributions from the background radiation in the room where the measurements were done and the external surface contamination of the body and the clothes as well as the internal contamination due to presence of radiocesium isotopes (^{134}Cs, ^{136}Cs, and ^{137}Cs) in the body. Procedures of this correction, as described in detail in (Drozdovitch et al. 2013a, 2019; Kutsen et al. 2019), are not discussed in this paper.

The following three scenarios were realized among mothers of the cohort members in relation to the direct thyroid measurements (Fig. 2):

1. Direct thyroid measurement was done in mother of the study subject: To identify mothers with direct thyroid measurements, the list of mothers was linked to a database of 10,433 women of child-bearing age of 18−45 years who were measured in Belarus during April−June 1986 (Gavrilin et al. 1999). As a result of linkage, 286 mothers of 2,939 (9.7%), including three mothers with the twins, with direct thyroid measurement were found.

2. Direct thyroid measurement was not done in study subject's mother, but mother resided in the settlement or raion where such measurements were done in other women of child-bearing age: This category includes 2,088 mothers (71.1%).

3. Mothers of the cohort members resided in areas where direct thyroid measurements were not done: This category includes 565 mothers (19.2%).

The manner in which individual prenatal thyroid dose to the study subject was estimated depended on availability of direct thyroid measurements in mother, as discussed below.

Mothers with direct thyroid measurements—If mother was measured, the scaling factor was defined as:

$$SF_{mother}^{indiv} = \frac{Q_{mother}^{meas}\left(t_m\right)}{Q_{mother}^{ecol}\left(t_m\right)}, \tag{3}$$

where SF_{mother}^{indiv} is individual scaling factor derived from measured and calculated ^{131}I activity in mother's thyroid (unitless); $Q_{mother}^{meas}\left(t_m\right)$ is the activity of ^{131}I measured in mother's thyroid (kBq); $Q_{mother}^{meas}\left(t_m\right)$ is the calculated ecological activity of ^{131}I in mother's thyroid at the time of measurement, t_m (kBq).

Among 286 mothers with direct thyroid measurement, 209 mothers were measured by the DP-5 dose-rate meter and 77 by the SRP-68–01 survey meter. As was mentioned above, a value of exposure rate, which was measured near the thyroid, was corrected to obtain a value of exposure rate that is only due to the ^{131}I activity in the thyroid. The activity of ^{131}I measured in the thyroid was calculated from the corrected exposure rate, $P_{corr}(t_m)$, used the following equation:

$$Q_{mother}^{meas}\left(t_m\right) = P_{corr}\left(t_m\right) \cdot CF_{dev}, \tag{4}$$

where $Q_{mother}^{meas}\left(t_m\right)$ is the measured activity of ^{131}I in the thyroid of pregnant women (kBq); $P_{corr}(t_m)$ is the corrected exposure rate that is only due to the ^{131}I activity in the thyroid of the pregnant women (mR^{-1} h); CF_{dev} is the device-specific calibration factor that is equal to 450 and 167 (kBq mR^{-1} h) for the DP-5 and the SRP-68–01 device, respectively (Drozdovitch et al. 2013a, Khrutchinsky et al. 2012). It should be noted that the exposure dose rate measured near the thyroid gland in the following units: mR h^{-1} by the DP-5 device and μR h^{-1} by the SRP-68–01 device. For the reader's convenience, a single unit, mR h^{-1}, is used in this paper.

Mothers who resided in settlements and raions with direct thyroid measurements—If the mother of the subject resided in the settlement or raion where direct thyroid measurements were done in other women of child-bearing age of 18−45 years old, the scaling factor, SF^{raion}, was defined as a median of scaling factors among women who were measured at that settlement (for urban settlements) or raion (for rural settlements). These scaling factors were derived from measured and 'standard' ecological activity at the time of measurement of ^{131}I in the thyroid of women. 'Standard' ecological activity was calculated assuming 'standard' behavior, i.e. no relocation from the place of residence, except evacuated settlements, daily consumptions of cow's milk, milk products and leafy vegetables. For those raions and urban settlements where small number (<10) of direct thyroid measurements were per formed among women, the scaling factor, SF^{raion}, was calculated from measured and ecological activity of ^{131}I in the thyroid obtained for the BelAm cohort members aged 5−18 y who were not relocated before the day of measurement. Values of scaling factor used in this study are given in Table 4.

Mothers who resided in areas without direct thyroid measurements—If the mother of the subject resided in the areas where direct thyroid measurements were not done, the scaling factor, SF^{empir}, was estimated using purely empirical regression between scaling factor and 'standard' ecological thyroid dose, D_{stand}^{ecol}, in women aged 18−45 y who underwent direct thyroid measurements in Gomel and Mogilev Oblasts:

$$SF^{empir} = \alpha \cdot \left(D_{stand}^{ecol}\right)^{\beta}, \quad (5)$$

where α=3.3 and 1.9 for rural and urban settlements, respectively, and β=−0.4 are the best-fitting parameters of regression.

Postnatal thyroid dose—There were 656 subjects born between 26 April and 30 June 1986 who were potentially exposed to ^{131}I postnatally. Ecological thyroid dose of these subjects was calculated as:

$$D^{ecol} = \frac{13.82 \cdot E_{th}}{m_{th,\,child}} \cdot \int_{t=0}^{T} Q^{ecol}(t)dt, \quad (6)$$

where: $m_{th,child}$ = 1.3 g is the mass of thyroid for newborns (ICRP 2002); Q^{ecol} is the variation of the ecological activity of ^{131}I in the thyroid of a subject (kBq); t is the time after birth and t=0 corresponds to child's date of birth (d); T is the age of a child on 30 June 1986 (d).

Estimation of the variation of the ecological activity of ^{131}I in the thyroid is described in detail elsewhere (Drozdovitch et al. 2013a). There were three sources of ^{131}I intake by child:

- Mother's breast milk for breastfed study subjects;
- Locally produced foodstuffs contaminated with ^{131}I for a child who was not breastfed; and

- Both, mother's breast milk and foodstuffs.

Subjects who were breastfed—Among the 656 subjects who were born between 26 April and 30 June 1986, 579 (88.3%) were breastfed. The variation with time of the ^{131}I intake by the mother was estimated using the ecological model and the answers provided by the mother during the personal interview regarding her food consumptions during breastfeeding. Activity intake of ^{131}I by infant was estimated using a transfer coefficient of 0.37 d L^{-1} from mother's intake to breast milk (Simon et al. 2002) and breast milk consumption rate by infant of 0.8 L d^{-1}.

Subjects who were not breastfed—If a child was not breastfed, the variation with time of the ^{131}I intake by the child was estimated using the ecological model and the answers provided by the mother regarding consumptions by the child. The same approach was used for a child who consumed other foodstuffs in addition to breast milk.

The individual postnatal thyroid dose due to ^{131}I intake to the subject was scaled in the same way as the prenatal dose using the scaling factor that depended on availability of direct thyroid measurement in his or her mother (See Fig. 2).

Thyroid doses due to external irradiation and ingestion of cesium isotopes

Our approach to estimating doses from external irradiation was based on the integration of the time-dependent dose rate in air per unit deposition of the radionuclide mix in the area(s) of residence, considering the shielding properties of the residential environment and the behavior of the person in the radiation field (Minenko et al. 2006). To estimate doses to the fetus, this model was adapted considering the data provided in ICPR Publication 116 (ICRP 2010). Information on the radionuclides deposited (Drozdovitch et al. 2013b, Khrushchinskii et al. 2014) in the area(s) of residence served as the basis for calculation of doses from external irradiation.

Exposure from ingestion of caesium isotopes (^{134}Cs and ^{137}Cs) was assessed using 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 dose due to cesium ingestion derived from whole-body counter (WBC) measurements of cesium body burden. To reduce the uncertainty in the estimates of individual postnatal dose, results of 521 WBC measurements of ^{137}Cs body-burden obtained for 387 cohort members (13.1% of the total) were used. The results of individual WBC measurements for the cohort members were obtained through linkage of their information to a database of 9,605 WBC measurements carried out in 1987−1991 in Gomel and Mogilev Oblasts among children born in 1986−1987. Results of these measurements were used to calibrate model estimates of individual thyroid doses due to ingestion of Cs isotopes. By analogy with scaling factor for thyroid dose due to ^{131}I intake (equations (2) and (3)), the scaling factor for thyroid dose due to ingestion of Cs isotopes was defined as:

$$SF^{Cs-137} = \frac{Q^{WBC,\,Cs-137,\,meas}(t_m)}{Q^{WBC,\,CS-137,\,calc}(t_m)}, \quad (7)$$

where SF^{Cs-137} is individual scaling factor derived from measured and calculated ^{137}Cs body-burden in subject (unitless); $Q^{WBC,Cs-137,meas}(t_m)$ is the measured ^{137}Cs body-burden in subject (kBq); $Q^{WBC,Cs-137,calc}(t_m)$ is the calculated ^{137}Cs body-burden measured in subject at the time of WBC measurement, t_m (kBq).

RESULTS

Personal interview

The questionnaires that were completed for all 2,965 cohort members included about 321,282 answers with information required for dose calculation. Some of the mothers had difficulties answering about the foodstuff consumption or the dates of moving between locations of residence and changing of dietary habits. There were 10,287 answers (1.6% of the total) that were either devoid of information, for example, “I do not remember” or “I do not know” or fuzzy, for example, when respondents were not able to provide the exact date of relocation, stable iodine administration, or change of consumption habits. The majority of imprecise answers (n=7,465; 72.6% of 10,287) related to dates. Imputation of imprecise answers for dose calculation was done according to the rules described in (Drozdovitch et al. 2013a).

Correct residential history is important for dose calculation because ground deposition of ^{131}I in the settlement of residence is the starting point of the ecological model that describes the processes of ^{131}I transfer to and accumulation by the thyroid gland. Most mothers (1,475 from 2,939) of the study subjects changed their place of residence during the time when ^{131}I was present in the environment (26 April – 30 June 1986). About 33% (978 from 2,939) of the mothers moved once or twice during this period; the maximal number of reported relocations was 22.

Table 5 shows a proportion of consumers and daily consumption rate of foodstuffs that were important for intake of ^{131}I and ^{134,137}Cs among mothers during the time of pregnancy and breastfeeding according to the type of settlement (rural or urban). Consumption rates of milk during iodine period were averaged over the period 26 April – 10 May 1986 when most of the changes in milk consumption occurred and most of the ^{131}I intake from milk took place. The average daily consumptions of private cow’s milk by pregnant women were reported to be 0.58 L and 0.26 L among rural and urban residents, respectively, while among breastfeeding women – 0.33 L and 0.13 L, respectively (Table 5). The reported individual daily consumptions of milk, milk products and leafy vegetables by the mothers of the subjects in 26 April – 30 June 1986 varied widely, with about 5% of women consuming more than 1 L of milk daily (not shown).

Thyroid dose estimates

Table 6 shows the distribution of the prenatal thyroid doses from ^{131}I intake among the 2,965 Belarusian *in utero* cohort members. The arithmetic mean of prenatal thyroid doses from ^{131}I intake was estimated to be 123 mGy, while the median was 14 mGy. Fifty-three (1.8% of the total) study subjects were estimated to have received prenatal doses of greater than 1 Gy due to ^{131}I intake by mothers. Among 53 highly exposed subjects of the Belarusian *in utero* cohort, 11 individuals received thyroid doses due to ^{131}I intake of more than 4 Gy and seven individuals – more than 5 Gy. Twenty of highly exposed individuals were evacuees from the 30-km zone around the Chernobyl nuclear power plant (NPP) and 27 individuals resided in the southern part of Gomel Oblast close to the Chernobyl NPP. It should be noted that for 37 from 53 (69.8%) of the subjects, high dose estimates (> 1 Gy) were derived from the direct thyroid measurements performed in their mothers.

Characteristics of 11 study subjects with prenatal thyroid doses due to ^{131}I more than 4 Gy are shown in Table 7. Mothers of 4 subjects were evacuated from the 30-km zone. For 9 (81.8%) of the eleven subjects, dose estimates were derived from direct thyroid measurements performed in their mothers. For two subjects with mothers without direct thyroid measurements, high doses resulted, among other factors, from (1) high milk consumption by mother (4 L d^{-1}), and (2) consumption by mother of goat milk with ^{131}I concentrations 8 times greater than that in cow's milk (Ilyin et al. 1972).

Table 6 also shows the distribution of postnatal thyroid doses due to ^{131}I intake. The arithmetic mean of postnatal thyroid dose was estimated to be 6.5 mGy, while the median was zero because majority of the cohort members (2,309 from 2,965) were born after 30 June 1986 and were not exposed to ^{131}I postnatally. It should be note that, in average, postnatal thyroid dose due to ^{131}I intake among breastfed cohort members (n=579) is much higher than for those who were not breastfed (n=77) in 26 April – 30 June 1986, with mean dose of 32 *vs.* 6.4 mGy, respectively (not shown).

Table 8 shows the prenatal thyroid doses from ^{131}I intakes to the study subjects according to the place of residence ATA of their mothers, type of the settlement, and subject's sex. The highest doses (mean of 137 mGy and median of 17 mGy) were received in Gomel Oblast, the most contaminated region. Thyroid doses among boys and girls were quite similar, with mean of 126 *vs.* 120 mGy, respectively. There were no gender-specific differences in parameters of the dosimetry model in this study.

Table 9 shows the total (prenatal and postnatal) thyroid doses from external exposure and ingestion of cesium isotopes compared to the thyroid doses from ^{131}I intakes. The mean thyroid dose in the cohort was estimated to be 137 mGy, including 130 mGy from ^{131}I intake, 4.9 mGy due to external irradiation, and 2.5 mGy due to ingestion of cesium isotopes, while the median was 25 mGy (not shown). The estimated thyroid doses ranged up to: 14.8 Gy from ^{131}I intakes, and 102 mGy from external exposure, while dose from internal exposure due to cesium ingestion did not exceed 47 mGy (not shown).

DISCUSSION

This paper is the first publication on dose reconstruction done in a cohort of 2,965 Belarusian persons exposed to radiation *in utero* and during early life following the Chernobyl accident. Intake of ^{131}I by mother during pregnancy was the major pathway of exposure to the thyroid gland of the cohort members. As expected, because of use of the ICPR Publication 88 model, prenatal thyroid dose to fetus from ^{131}I intake by mother increases with gestation age: for the first, second and third trimester of pregnancy ATA doses were estimated to be 7.1, 178 and 225 mGy for mean and 0.086, 49 and 66 mGy for median, respectively.

Prenatal thyroid doses due to ^{131}I intakes in the rural areas were found to be higher than that in urban settlement, 161 mGy *vs*. 69 mGy for arithmetic mean, respectively (Table 8). It could be explained by a higher contamination of private cow's milk with ^{131}I and higher milk consumptions by pregnant women (0.58 *vs.* 0.26 L d^{-1}, respectively for mean) in rural settlements compared to urban areas.

The mean prenatal thyroid dose due to ^{131}I intakes in the Belarusian *in utero* cohort (123 mGy) was found to be higher than that of 73 mGy for the Ukrainian *in utero* cohort (Likhtarov et al. 2011). It could be expected as recruitment of the Belarusian *in utero* cohort was focused on individuals from the most contaminated regions while around 40% of the Ukrainian *in utero* cohort intentionally included individuals from low contaminated regions in Ukraine.

The mean contribution to the total thyroid dose from sources other than ^{131}I intake was estimated to be 26.4% for external exposure and 15.9% for ingestion of cesium isotopes, which is much higher than estimated for the BelAm children/adolescence cohort: 4.5% and 1.5%, respectively (Drozdovitch et al. 2013a). This is because 52.8% of the Belarusian in *utero* cohort members (1,566 from 2,965) received thyroid doses due to ^{131}I intake, both prenatal and postnatal, less than 20 mGy (mean dose = 3.7 mGy) that is compatible with the doses due to external irradiation (mean dose of 4.2 mGy) and ingestion of cesium isotopes (mean dose of 2.5 mGy).

The thyroid doses from ^{131}I intakes that were calculated in this study ranged from essentially zero (0.001 mGy) to 14.8 Gy, i.e., within seven orders of magnitude. The wide variability in doses mostly reflects the difference in ^{131}I biokinetic between different gestational ages at the time of exposure, variability in ^{131}I deposition across the study area, different consumption habits among pregnant women.

Uncertainties in dose estimates

The following sources of uncertainties in the thyroid doses were identified in this study:

1. The uncertainties attached to the iodine biokinetic model during pregnancy as ICRP Publication 88 model for fetus and pregnant women is based on rather limited human data. In addition, there are wide variabilities in the metabolic parameters between individuals. These sources of shared and unshared errors are important because the endpoint of the study is the estimation of individual doses.

2. The shared and unshared errors associated with stochastic variability and lack of knowledge about true values of parameters used in exposure assessment. There are fluctuations in the ^{131}I deposition in the location, and the concentrations of radionuclides in foodstuffs produced there as well as variability in the thyroid mass between individuals.

3. Errors in the ^{131}I activities in thyroids that were derived from direct thyroid measurements. These errors arose from device error itself, uncertainties in the estimates of the device's calibration factors, and uncertainties in correction of detector response to external and internal contamination of human body. These sources of unshared errors are important as measured activity defines the individual dose.

4. The uncertainties attached to the information collected around 30 years ago after the Chernobyl accident during personal interviews of mothers regarding relocation history and individual diet. Our previous study, which was conducted in BelAm cohort, shows that if dose-related measurements are available for study subjects, the quality of individual behavior and dietary data has, in general, a small influence on the results of the retrospective dose assessment (Drozdovitch et al. 2016). However, in this study, the direct thyroid measurements were available for only around 10% of mothers of the *in-utero* cohort members. Therefore, evaluation of quality of individual behavior and dietary data due to memory recall of mothers is important for this study. For this purpose, we are conducting a special study to interview for the second time a sample of 1,200 mothers (around 40% of the study population) using the same dosimetry questionnaire as it was used during the first interview in 2012–2017. Information collected during the second personal interview will be used to estimate thyroid doses to the study subjects and to compare these estimates with those calculated using information from the first interviews. Evaluation of reliability of questionnaire-based doses due to memory recall will be the topic of a separate paper.

The uncertainties in the doses, which were established in this study, were not evaluated in a quantitative manner because of absence of information on uncertainties in parameters' values of the iodine biokinetic model during pregnancy. However, based on extensive assessment of uncertainties in thyroid doses done for BelAm cohort (Drozdovitch et al. 2015), it was subjectively estimated that the overall uncertainties of the thyroid doses due to ^{131}I intakes in this study are characterized, in average, by geometric standard deviation (GSD) around 2.0, if direct thyroid measurements of mothers were available, and by GSD around 2.5–3.0, if direct thyroid measurements of mothers were not available.

Reliability of dose estimates

Prenatal thyroid doses due to ^{131}I intake by mother—The scaling factor, which is defined as the ratio of the 'measured' ^{131}I activity in the thyroid to the 'ecological' ^{131}I activity at the time of measurement (see eqn. (3)), integrates all steps of the thyroid dose estimation: results of direct thyroid measurement, modeling, and personal interview data.

The scaling factor is an indicator of the agreement between the dose estimated using the model and that derived from the direct thyroid measurement. Fig. 3 shows distribution of scaling factors that were derived from direct thyroid measurements done in 286 mothers of the cohort members. For 154 women (53.8%) the scaling factors' values are distributed within factor of 3 around 1.0. The agreement between the ecological and instrumental doses was found to be better in this study than that in the BelAm cohort: the arithmetic mean of the scaling factor was found to be 3.1±11 (median=0.64) *vs.* 2.9±71 (median=0.35) for *in utero* and BelAm cohorts, respectively. The possible reason for this can be the following: in this study the mothers were asked about their own dietary consumption patterns after the accident, which was the basis of prenatal doses. Memory recall can be more accurate if a woman was asked about unique events in her life, like pregnancy (Bunin et al. 2001). On the other hand, in the BelAm study, dietary information for about half of the subjects was obtained from their mothers while for the other half, questionnaire data were collected during interviews of the subject themselves, who were children and adolescents ATA.

Postnatal thyroid doses due to ingestion of Cs isotopes by subjects—Fig. 4 compares postnatal thyroid doses due to ingestion of Cs isotopes calculated by the model with those derived from WBC measurements done in 387 study subjects. Two sets of doses agree for 85.8% individuals within factor of 3 (shown by dashed lines), coefficient of correlation is r=0.65. As with ^{131}I doses, the scaling factor for dose estimates due to ingestion of Cs isotopes (see eqn. (7)) is an indicator of the agreement between the doses estimated using the model and those derived from the WBC measurement. Arithmetic mean of the scaling factors for 387 subjects with WBC measurements were found to be 1.2±1.0 (median=0.9).

CONCLUSIONS

Individual thyroid radiation doses were estimated for 2,965 Belarusian *in utero* cohort members. Thyroid doses were calculated for different pre- and postnatal exposure pathways, including intake of ^{131}I, external irradiation and ingestion of ^{134}Cs and ^{137}Cs. Individual data on residential history and consumptions that were collected for each subject through personal interviews with his or her mother were used for dose calculation. In addition, the results, if available, of dose-related measurements, i.e., direct thyroid measurements of ^{131}I in mother's thyroid and whole-body counter measurements of cesium body-burden in the subject were also used. The predominant pathway for thyroid exposure for subjects in the cohort was intake of ^{131}I by their mother. Although a point estimate of dose was provided for each study subject according to the best methodology currently available, there were uncertainties associated with reconstructed doses. The main sources of uncertainties in these thyroid dose estimates were identified but not quantified. The dose estimates are being used to evaluate the risk of thyroid cancer and other thyroid diseases in this unique cohort of individuals exposed *in utero* and during early life to Chernobyl fallout.

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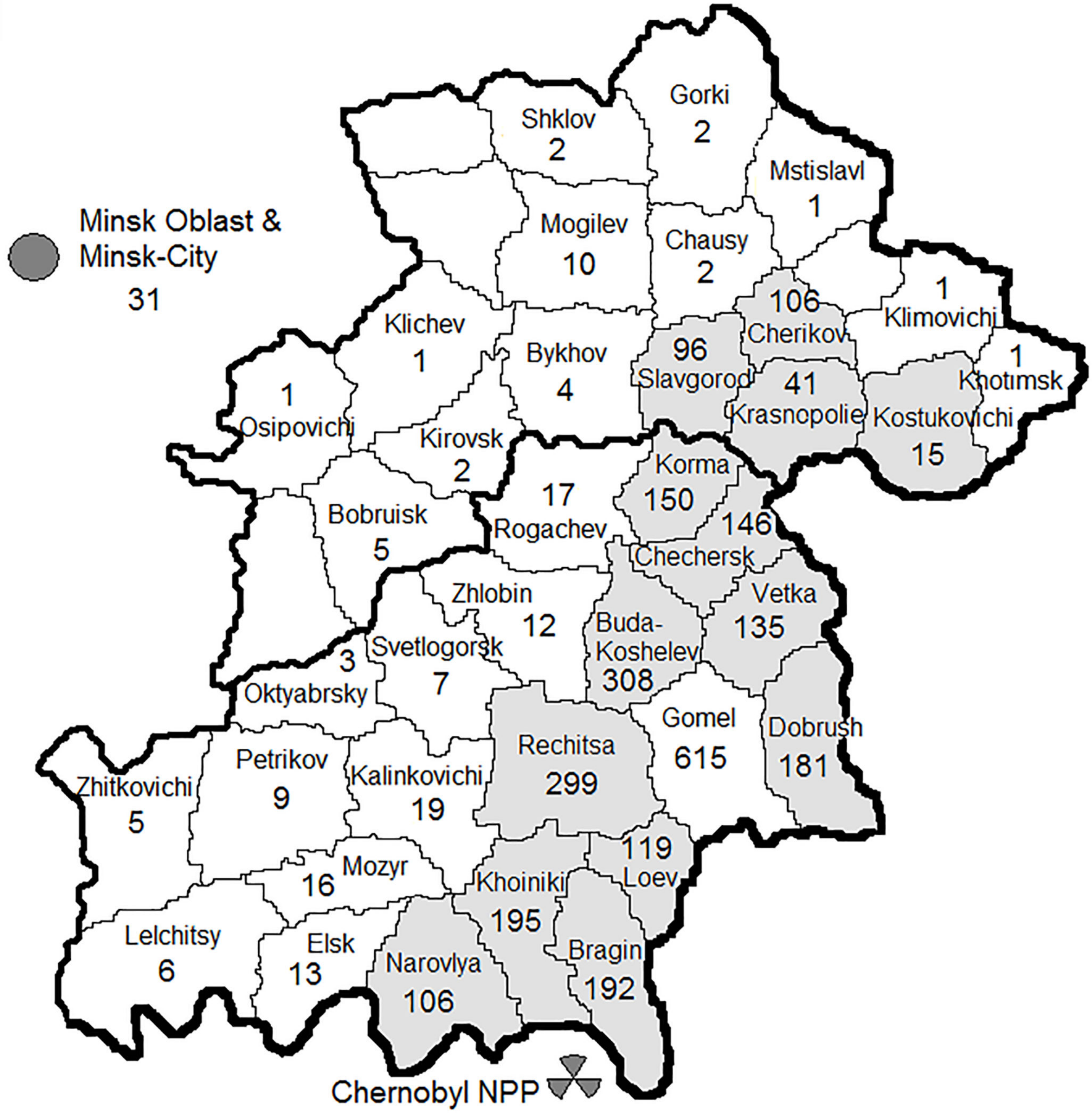

Fig. 1.

Distribution of the cohort members by raion of residence of their mothers at the time of the Chernobyl accident. The most contaminated raions are highlighted in grey.

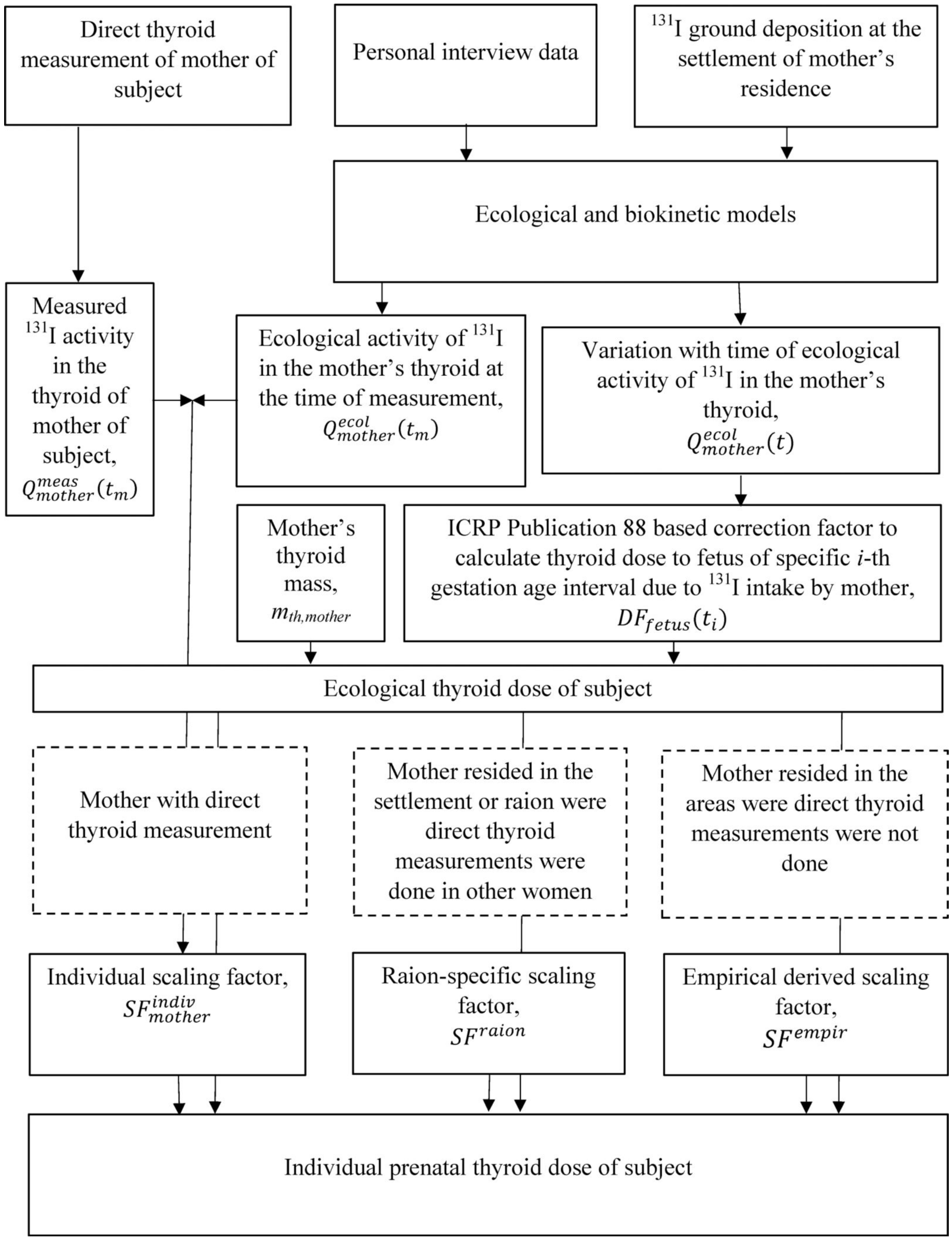

Fig. 2.

The scheme of thyroid dose calculation for the subjects of the Belarusian *in utero* cohort.

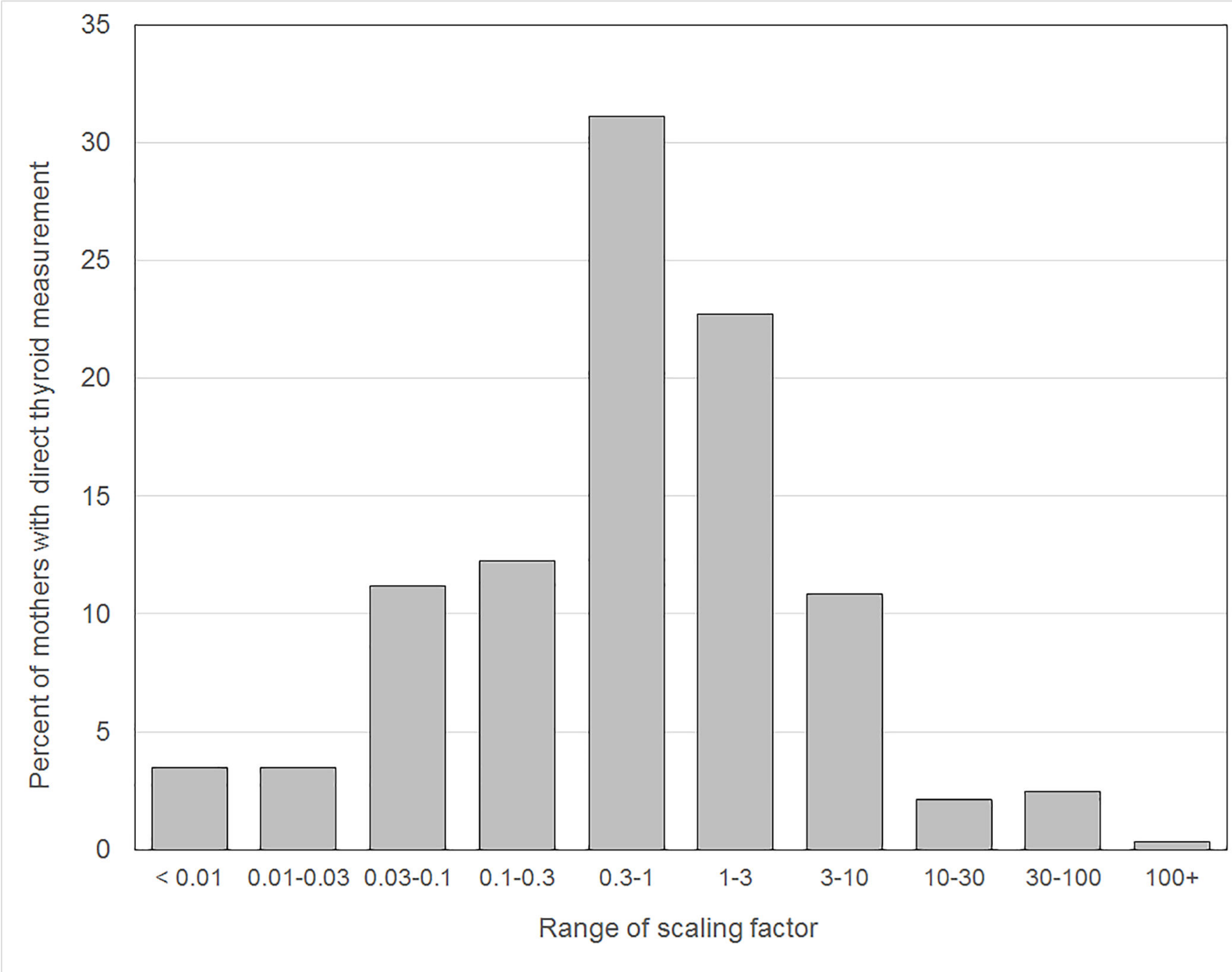

Fig. 3.

Distribution of individual scaling factor, SF_{mother}^{indiv}, for 286 mothers with direct thyroid measurements.

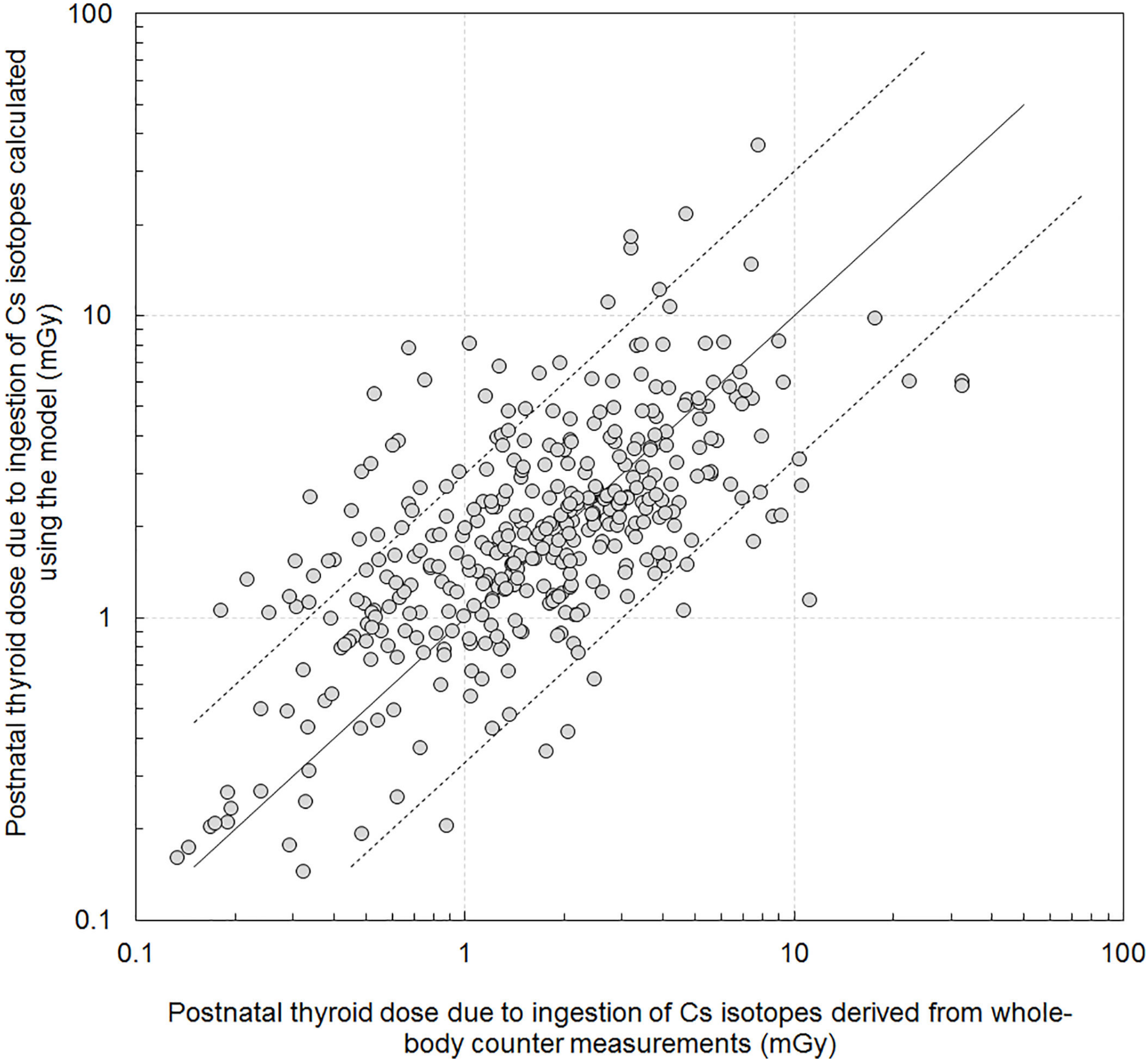

Fig. 4.

Comparison of postnatal thyroid doses due to ingestion of Cs isotopes calculated by the model with those derived from whole-body counter measurements for 387 Belarusian *in utero* cohort members. Dashed lines show factor of 3 difference between two sets of doses.

Table 1.

The distribution of age at the time of the accident (ATA) for the mothers of the cohort members.

Age ATA (y)	N	Percentage
<17	22	0.7
17–17.9	39	1.3
18–18.9	122	4.2
19–19.9	218	7.4
20–20.9	246	8.4
21–21.9	257	8.7
22–22.9	271	9.2
23–23.9	259	8.8
24–24.9	223	7.6
25–25.9	223	7.6
26–26.9	167	5.7
27–27.9	163	5.5
28–28.9	124	4.2
29–29.9	119	4.0
30–30.9	104	3.5
31–31.9	89	3.0
32–32.9	65	2.2
33–33.9	59	2.0
34–34.9	48	1.6
35–35.9	36	1.2
36–36.9	32	1.1
37–37.9	21	0.7
38–38.9	12	0.4
39–39.9	7	0.3
40–40.9	4	0.2
41–41.9	2	0.1
42–42.9	2	0.1
43–43.9	2	0.1
44–44.9	2	0.1
45+	1	0.03
Entire cohort	2,939	100.0

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Table 2.

Distribution of the 2,965 Belarusian *in utero* cohort members by gestation age at the time of the Chernobyl accident (ATA).

Gestation age ATA (d)	N	Percentage
<=0	375	12.6
1–30.9	202	6.8
31–60.9	313	10.6
61–90.9	297	10.0
91–120.9	286	9.7
121–150.9	303	10.2
151–180.9	327	11.0
181–210.9	320	10.8
211–240.9	296	10.0
241+	246	8.3
Entire cohort	2,965	100.0

Table 3.

Values of dose factor to calculate thyroid dose to fetus of specific gestation age interval due to ^{131}I intake by mother, $DF_{fetus}(t_i)$, ICRP (1993, 2001).

Gestation age interval at the time of ^{131}I intake in		$DF_{fetus}(t_i)$
weeks	days	
<5	<35	0
5	35	0.0006
7.5	53	0.002
10	70	0.01
12.5	88	0.09
15	105	0.56
17.5	123	0.81
20	140	1.07
22.5	158	1.33
25	175	1.58
27.5	193	1.83
30	210	2.07
32.5	228	2.31
35	245	2.56

Table 4.

Raion and settlement-specific scaling factors, SF^{raion}.

		Rural settlement			Urban settlement		
Oblast	Raion	N	Scaling factor[a]		N	Scaling factor[a]	
			Median	GSD		Median	GSD
Gomel	Bragin (Evac)	879	0.20	2.9	–	–	–
Gomel	Bragin (Non-evac)	1,495	0.23	2.8	310	0.13	2.8
Gomel	Buda-Koshelev	71	0.09	1.5	119	0.08	1.2
Gomel	Vetka	214	0.20	2.6	336	0.09	2.4
Gomel	Gomel	11	0.29[b]	1.7	721	0.20	2.9
Gomel	Korma	33	0.043	2.0	38	0.03	1.5
Gomel	Loev	303	0.21	3.3	241	0.09	3.0
Gomel	Narovlya (Evac)	305	0.12	2.6	–	–	–
Gomel	Narovlya (Non-evac)	430	0.16	2.7	624	0.11	3.1
Gomel	Rechitsa	560	0.36[b]	3.2	209	0.49[b]	3.4
Gomel	Khoiniki (Evac)	420	0.27	2.5	–	–	–
Gomel	Khoiniki (Non-evac)	1,436	0.29	2.6	1,066	0.14	2.8
Mogilev	Klimovichi	116	0.035	2.7	–	–	–
Mogilev	Kostyukovichi	260	0.08	2.3	25	0.14	1.8
Mogilev	Krasnopolie	348	0.27	2.0	–	–	–
Mogilev	Slavgorod	106	0.05	2.5	239	0.03	3.1
Mogilev	Cherikov	295	0.05	2.5	–	–	–
Minsk	Minsk	–	–	–	432	1.1[b]	2.8

[a]Based on direct thyroid measurements for women aged 18–45 y unless otherwise indicated.

[b]Based on direct thyroid measurements for the subjects of BelAm cohort aged 5–18 y who did not move from the place of residence ATA before direct thyroid measurement.

Table 5.

Proportion of consumers (P_{cons}), arithmetic mean (AM), geometric mean (GM) and geometric standard deviation (GSD) of consumption rates of foodstuff by mothers as reported during the personal interviews.

Foodstuff	Rural settlements				Urban settlements			
	P_{cons}	Consumption rate L d^{-1} (kg d^{-1})		GSD	P_{cons}	Consumption rate L d^{-1} (kg d^{-1})		GSD
		AM	GM			AM	GM	
Pregnant women during ^{131}I period (26 April – 30 June 1986):								
Private cow milk	0.612	0.58	0.38	2.7	0.283	0.26	0.16	2.9
Milk from shop	0.242	0.26	0.16	2.9	0.564	0.27	0.18	2.6
Milk products	0.947	0.19	0.14	2.4	0.923	0.14	0.10	2.6
Leafy vegetables	0.833	0.040	0.025	3.1	0.746	0.040	0.024	3.4
Breastfeeding women during ^{131}I period (26 April – 30 June 1986):								
Private cow milk	0.286	0.33	0.15	4.5	0.194	0.13	0.10	2.2
Milk from shop	0.357	0.26	0.19	2.5	0.516	0.20	0.14	2.5
Milk products	0.978	0.17	0.13	2.2	0.864	0.13	0.10	2.4
Leafy vegetables	0.667	0.037	0.023	3.1	0.591	0.036	0.021	3.4
Pregnant women after 30 June 1986:								
Private cow milk	0.610	0.61	0.40	2.7	0.302	0.37	0.23	2.9
Milk from shop	0.367	0.31	0.20	2.6	0.666	0.29	0.19	2.6
Milk products	0.951	0.19	0.14	2.3	0.954	0.15	0.10	2.8
Breastfeeding women after 30 June 1986:								
Private cow milk	0.699	0.67	0.46	2.5	0.305	0.40	0.25	3.0
Milk from shop	0.347	0.32	0.22	2.6	0.617	0.33	0.23	2.5
Milk products	0.957	0.20	0.15	2.2	0.954	0.15	0.11	2.5

Table 6.

Distribution of prenatal, postnatal and total thyroid doses due to ^{131}I intake for the Belarusian *in utero* cohort members.

Dose interval (mGy)	Prenatal exposure to ^{131}I			Postnatal exposure to ^{131}I			Total dose from ^{131}I		
	N	%	Mean dose (mGy)	N	%	Mean dose (mGy)	N	%	Mean dose (mGy)
0	367	12.4	0	2,557	86.2	0	338	11.4	0
0.001–19.9	1,244	42.0	4.7	319	10.8	3.3	1,218	41.1	4.8
20–49.9	384	13.0	33	33	1.1	31	392	13.2	33
50–99.9	287	9.6	72	14	0.5	79	292	9.8	73
100–199.9	259	8.7	143	18	0.6	147	272	9.2	142
200–499.9	272	9.2	305	15	0.5	317	290	9.8	304
500–999.9	99	3.3	674	7	0.2	663	108	3.6	682
≥1000	53	1.8	2,630	2	0.1	2030	55	1.9	2,620
Entire cohort	2,965	100.0	123	2,965	100.0	6.5	2,965	100.0	130

Table 7.

Characteristics of 11 cohort members with prenatal thyroid doses due to ^{131}I intake more than 4 Gy.

Subject	Gestation age ATA (wks)	Raion of residence ATA	^{131}I deposition (MBq m^{-2})	Milk consumption by mother[a] (L d^{-1})	Date of first relocation in 1986	Date of mother's thyroid measurement in 1986	^{131}I activity measured in mother's thyroid, kBq	Prenatal thyroid dose due to ^{131}I, Gy	Scaling factor, SF^{indiv}_{mother}
A	29	Khoiniki[b]	30	0.5	6 May	26 May	468	14.8	3.0
B	31	Bragin	3.7	0.5	2 May	15 May	535	8.1	8.7
C	22	Khoiniki	2.7	1.0	8 May	23 May	385	6.5	3.4
D	24	Khoiniki	5.0	4.0	–[c]	–	–	5.8	–
E	25	Rechitsa	0.66	1.0[d]	–[c]	–	–	5.6	–
F	21	Khoiniki[b]	85	0.5[e]	4 May	18 May	391	5.4	2.9
G	31	Rechitsa	0.85	0.5	13 June	9 May	554	5.2	2.6
H	30	Gomel	0.38	1.5	23 June	9 May	534	4.9	2.4
I	34	Bragin[b]	254	0.025[f]	1 May	29 May	68.4	4.2	0.5
J	30	Gomel	0.74	1.0[e]	11 May	11 May	425	4.2	1.4
K	35	Bragin[b]	9.7	0.25	10 May	12 May	439	4.0	4.2

[a]Consumption of private cow's milk unless otherwise indicated.

[b]Settlement was evacuated from the 30-km zone around the Chernobyl nuclear power plant.

[c]There was no relocation from the place of residence ATA during Iodine period of 26 April – 30 June 1986.

[d]Goat milk.

[e]Milk from commercial trade network.

[f]Milk products.

Table 8.

Prenatal thyroid doses from ^{131}I intakes by selected groupings of the Belarusian *in utero* cohort members.

Parameter	N	^{131}I thyroid dose (mGy)	
		Mean	Median
Place of residence ATA			
- Gomel Oblast	2,553	137	17
- Mogilev Oblast	290	44	7.4
- Minsk City and Minsk Oblast	31	20	1.3
- Others	91	18	0.01
Type of settlement of residence			
- Rural	1,741	161	20
- Urban	1,224	69	8.8
Gender			
- Male	1,490	126	14
- Female	1,475	120	14
Entire cohort	2,965	123	14

Table 9.

Thyroid doses from different exposure pathways estimated for the Belarusian *in utero* cohort members.

Range of thyroid dose from ^{131}I intake[a] (mGy)	N	Mean thyroid dose[a] (mGy) in the range due to			Mean total thyroid dose in the range (mGy)
		Intakes of ^{131}I	External exposure	^{134,137}Cs ingestion	
0	338	0	4.0	2.3	6.3
0.001–19.9	1,218	4.8	4.3	2.5	12
20–49.9	392	33	4.5	2.2	39
50–99.9	292	73	4.4	2.1	79
100–199.9	272	142	4.6	2.2	149
200–499.9	290	304	6.4	2.8	313
500–999.9	108	682	9.5	3.6	695
≥1000	55	2,620	12	2.7	2,640
Entire cohort	2,965	130	4.9	2.5	137

[a]Sum of prenatal and postnatal doses