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ESTIMATION OF THE THYROID DOSES FOR UKRAINIAN CHILDREN EXPOSED *IN UTERO* AFTER THE CHORNOBYL ACCIDENT

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Abstract

This paper describes methods for estimating thyroid doses to Ukrainian children who were subjects of an epidemiological study of prenatal exposure and presents the calculated doses. Participants were 2,582 mother-child pairs in which the mother had been pregnant at the time of the Chernobyl accident on April 26, 1986 or in the two-three months following when ¹³¹I in fallout was still present. Among these, 1,494 were categorized as “exposed”; a comparison group of 1,088 was considered “relatively unexposed.” Individual *in utero* thyroid dose estimates were found to range from less than 1 mGy to 3,200 mGy, with an arithmetic mean of 72 mGy. Thyroid doses varied primarily according to stage of pregnancy at the time of exposure and level of radioactive contamination at the location of residence. There was a marked difference between the dose distributions of the exposed and comparison groups, although nine children in the latter group had calculated doses in the range 100–200 mGy. For those children who were born after the accident and prior to the end of June 1986, postnatal thyroid doses were also estimated. About 7.7% (200) of the subjects received thyroid doses after birth that were at least 10% of their cumulative doses.

Keywords

in utero; dose; Chernobyl; dose estimation; thyroid; exposed; pregnancy

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INTRODUCTION

As a result of the Chornobyl accident, which occurred in Ukraine on 26 April 1986, very large amounts of radioactive materials, including about 2 EBq of ^{131}I , were released into the atmosphere (UNSCEAR 2000). Vast territories of Belarus, Russia, and Ukraine were contaminated by ^{131}I , resulting in turn in the contamination of such important food products (especially for rural populations) as cows' milk and leafy vegetables. Thus, it is expected that many pregnant women who either did not know about the danger of contaminated food products, or knowingly continued, at least for some time, to consume them, exposed their unborn children to ^{131}I .

Within the framework of the cooperation between the Scientific Center for Radiation Medicine (SCRM) of Ukraine and the National Cancer Institute (NCI) of the United States, Hatch et al. (2009) conducted a screening study of thyroid cancer and other thyroid diseases among individuals exposed *in utero* to ^{131}I fallout from the Chornobyl accident.

The study subjects were divided into two sub-cohorts: “exposed” and “relatively unexposed” children. Children in the exposed sub-cohort, which is referred to as the “contaminated” group in the screening study (Hatch et al. 2009), were born between April 26, 1986 and March 31, 1987, meaning that their mothers were pregnant prior to or during the two-month period following the accident when the environmental concentrations of ^{131}I were substantial. At the time of the accident (ATA) their mothers lived in some of the most contaminated territories** of Ukraine (parts of Chernihiv, Kyiv, Vinnytsia, and Zhytomyr oblasts). One group of 720 exposed children (denominated as L1-C) were born to mothers who in May or June, were subjected to a direct thyroid activity measurement. This group was expanded by adding children born during the same period whose mothers lived in contaminated settlements where there were women whose thyroid activities were measured, but who themselves did not have a direct thyroid measurement (group L2-C; 774 children).

The “relatively unexposed” group (L1-NC; 1088 children), referred to as the “comparison” group in the screening study (Hatch et al. 2009), were children, born in the same time interval, but whose mothers resided ATA in areas that were classified as “non-contaminated”. Neither those mothers nor other women in their villages were subjected to direct thyroid measurements.

Altogether, 1,494 mother-child pairs were included into the exposed sub-cohort and 1,088 were in the relatively unexposed sub-cohort, yielding a total of 2,582 subjects and 2554 mothers (including 28 pairs of siblings). The residential locations of the mother-child pairs ATA are shown in Figure 1.

The purpose of this paper is to describe how individual thyroid doses were estimated for all subjects and to present the results that were obtained. Most subjects were exposed only *in utero*; however, those born before July 1986 also received thyroid doses as infants. Only thyroid doses received from intakes of ^{131}I have been taken into account. Other pathways such as external or internal irradiation from radionuclides other than ^{131}I have not been included in the dose calculation: it is estimated that their contributions to the thyroid dose would be a few percent of the dose from ^{131}I intakes (UNSCEAR, 2000).

**The contaminated territories in Ukraine were defined for administrative purposes as areas with ^{137}Cs deposition densities greater than 37 kBq m^{-2} , that is, $>1 \text{ Ci km}^{-2}$ in units used at the time. Other parts of the country have been called “non-contaminated” in that context.

MATERIALS AND METHODS

The estimations of the *in utero* and neonatal thyroid doses are based on:

- an ecological model of thyroid dose calculation that can be applied to all Ukrainian subjects, whether children or adults, and that takes into account the level of information available for the individual (Likhtarev et al. 2005; Likhtarev et al. 2006);
- a model for calculation of the thyroid dose received *in utero* (Berkovski 2004);
- responses provided during personal interviews of the 2,554 mothers of the subjects: the information collected concerns the whereabouts of the mothers between the times of conception and of birth, the intakes of milk and leafy vegetables, and, if that was the case, intake of stable iodine to block their thyroids;
- results of direct thyroid measurements for the mothers of subjects or for women who lived in the same village

The methods used to estimate thyroid doses prior to and, when appropriate, after birth, are presented in the following sections.

Estimation of the thyroid doses during gestation

The general scheme of calculation of *in utero* doses for the members of groups L1-C, L2-C, and L1-NC is illustrated in Figure 2. The figure indicates similarities in the calculation procedure, but also shows that there are differences in the dose calculations for the three groups. The procedures are discussed below.

Thyroid exposure of fetus

The estimation of the thyroid dose for the cohort subject k due to *in utero* exposure has been carried out in two steps. In a first step, the ecological-questionnaire thyroid dose, $D_{k,F}^{ecol-quest}$, has been calculated for all subjects, using the estimated ^{131}I activity intakes by the mothers of the subjects and values of fetal (F) thyroid dose coefficients provided by ICRP (2001) for acute maternal intake at conception and at specific times after conception. In a second step, the ecological-questionnaire thyroid doses have been calibrated using scaling factors that take into account the results of the direct thyroid measurements performed in the areas of residence of the mothers of the subjects; the results of the calibration process are the individual fetal thyroid doses, $D_{k,F}^{ind}$. There are no differences in the calculation of questionnaire individualized ecological doses, $D_{k,F}^{ecol-quest}$, based upon the responses of the mothers of the subjects in the L1-C, L2-C and L1-NC groups. The principal difference in the estimation of the individual fetal thyroid doses, $D_{k,F}^{ind}$, for the three groups is in the scaling process.

Estimation of the ecological-questionnaire thyroid dose, $D_{k,F}^{ecol-quest}$ —For an ^{131}I intake by the mother of subject k occurring on day n after the beginning of fallout, $q_{k,mother}^{ecol-quest,n}$, the partial ecological-questionnaire thyroid dose, $d_{k,F}^{ecol-quest,n}$, has been calculated as the product of $q_{k,mother}^{ecol-quest,n}$ and of the fetal thyroid dose per unit intake of ^{131}I by the mother, $h_T(\tau)$, where τ , in weeks, is the stage of pregnancy of the mother on day n after the beginning of fallout, taken to be 26 April 1986 for all Ukrainian locations. The entire ecological-questionnaire thyroid dose, $D_{k,F}^{ecol-quest}$, has been calculated as the sum of the

partial ecological-questionnaire thyroid doses, $D_{k,F}^{ecol-quest,n}$, over all days n of ^{131}I intake. The maximum value for n , denoted as N , is 66, corresponding to the number of days between 26 April and 30 June 1986. By the latter date, much less than 1% of the ^{131}I fallout was still present in the environment and, therefore, in milk or leafy vegetables. However, for the estimation of the thyroid dose during gestation, daily intakes are only considered until the date of birth of the child. Therefore, $N = 66$ if the date of birth occurs after 30 June 1986 and $N < 66$ if the date of birth occurs earlier.

The calculation process can be mathematically expressed as follows:

$$D_{k,F}^{ecol-quest} = \sum_{n=1}^N d_{k,F}^{ecol-quest,n} \quad (1)$$

with

$$d_{k,F}^{ecol-quest,n} = h_T(\tau) \times q_{k,mother}^{ecol-quest,n}. \quad (2)$$

Daily intakes of ^{131}I by the mother—The ^{131}I activity intake by the mother of cohort's subject k results primarily from the consumption of milk and leafy vegetables, with a generally small contribution from inhalation of contaminated air. Daily intakes have been calculated for each day n after the beginning of fallout. The daily intakes by ingestion are the products of (1) the concentrations of ^{131}I in milk and leafy vegetables (Bq L^{-1} and Bq kg^{-1} , respectively) in the mother's diet on day n , and (2) the corresponding consumption rates (L d^{-1} and kg d^{-1}). The daily intakes by inhalation depend on the air concentration on day n (Bq m^{-3}) and on the breathing rates ($\text{m}^3 \text{d}^{-1}$). The concentrations of ^{131}I in milk, leafy vegetables, and air are based on the ^{131}I ground deposition at the settlement of residence and are calculated using the ecological model and parameters described in Likhtarov et al. (2005) and in Likhtarev et al. (2006). The consumption rates of milk and leafy vegetables are obtained from the responses provided by the mother during her personal interview, while the breathing rate for female adults was taken to be $21.6 \text{ m}^3 \text{d}^{-1}$ (NRSU 2003; ICRP 1994). The partial daily intakes of ^{131}I from consumption of milk, consumption of leafy vegetables, and inhalation are summed for each day n after the beginning of fallout to obtain the total daily intakes, denoted as $q_{k,mother}^{ecol-quest,n}$.

Estimation of the fetal thyroid dose per unit intake of ^{131}I by the mother, $h_T(\tau)$ —The values of the fetal thyroid dose per unit intake of ^{131}I by the mother, $h_T(\tau)$, have been derived from ICRP (2001). In that report, thyroid dose coefficients, expressed in Sv Bq^{-1} , are calculated using a multi-compartment model of iodine metabolism and are given for gestational ages, τ , of 5, 10, 15, 25 and 35 weeks at the time of intake. Because the radiation-weighting factor for radiations emitted by ^{131}I is equal to 1 (ICRP 2007), the fetal thyroid doses per unit intake, expressed in Gy Bq^{-1} , are numerically equivalent to the thyroid dose coefficients. For the purposes of this article, values of the fetal thyroid dose per unit intake of ^{131}I for gestational ages different from those given above have been calculated using the same multi-compartment model of iodine metabolism which is presented in Figure 3 (Berkovski 1999a, 1999b; ICRP 2001). Results are provided in Table 1 for ingestion intakes. Dose coefficients for I_2 are estimated to be about 10% lower than those for ingestion. Estimated values for inhalation intakes of CH_3I and particles are lower. The actual airborne iodine species mixture is not known. In our calculations, the dose coefficients for ingestion are used to calculate doses from inhalation as well. Because the intakes of ^{131}I by

inhalation are much smaller than those by ingestion, this approximation results in a very small overestimation of the thyroid doses.

Estimation of the individual fetal thyroid doses, $D_{k,F}^{ind}$ —The estimate of the individual dose received by the fetus, $D_{k,F}^{ind}$, is derived from the ecological dose, $D_{k,F}^{ecol-quest}$, using a scaling factor $K_{k,mother}^{scal}$ based on the measurements that are as much as possible representative of the dose, so that:

$$D_{k,F}^{ind} = K_{k,mother}^{scal} \cdot D_{k,F}^{ecol-quest} \quad (3)$$

The values of the scaling factor, $K_{k,mother}^{scal}$, are obtained differently according to the group of subjects that is considered:

$$K_{k,mother}^{scal} = \begin{cases} K_{k,mother}^{scal,measur} & \text{for group L1-C} \\ K_{j,women}^{scal} & \text{for group L2-C} \\ K_{j,Cs} & \text{for group L1-NC} \end{cases} \quad (4)$$

Estimation of the scaling factor for members of group L1-C—The scaling factor for a member of group L1-C ($K_{k,mother}^{scal,measur}$) is an individual scaling factor for the mother of subject k who had a direct thyroid measurement in May–June of 1986. The scaling factor $K_{k,mother}^{scal,measur}$ is the ratio

$$K_{k,mother}^{scal,measur} = \frac{Q_{k,mother}^{measur}}{Q_{k,mother}^{ecol-quest}(t=t_{measur})}, \quad (5)$$

where $Q_{k,mother}^{measur}$ is the ^{131}I thyroid activity directly measured in the mother's thyroid and $Q_{k,mother}^{ecol-quest}(t=t_{measur})$ is the calculated thyroid activity on the day of measurement $t = t_{measur}$ due to intakes of ^{131}I by the mother via all pathways. Time t (d) is counted from April 26, 1986.

According to the one-compartment biokinetic model for iodine metabolism of ICRP Publication 30 (ICRP 1988), the value of $Q_{k,mother}^{ecol-quest}(t=t_{measur})$ can be written as:

$$Q_{k,mother}^{ecol-quest}(t=t_{measur}) = K_{mother}^{uptake} \times \sum_{n=1}^{n=t_{measur}} q_{k,mother}^{ecol-quest,n} \cdot e^{-\lambda_{mother}^{eff} \cdot (t_{measur}-n)}, \quad (6)$$

where $\lambda_{mother}^{eff} = 0.095 \text{ d}^{-1}$ is the effective rate constant for the elimination of ^{131}I from the mother's thyroid; K_{mother}^{uptake} is the fractional uptake of ^{131}I by the thyroid of the mother.

According to ICRP Publications 30 and 67 (ICRP 1988, 1993), $K_{mother}^{uptake} = 0.3$, that is, 30% of the ^{131}I intake is immediately transferred from blood to the thyroid irrespectively of age and gender.

The value of Q_{mother}^{uptake} that is used in the multi-compartment model of ICRP (2001) is not given explicitly, but it can be derived from the fact that the calculated time-integrated ^{131}I activities in the thyroid must be the same, whether the model in ICRP (2001) or in ICRP Publication 30 is used, for a given intake of ^{131}I . For a unit acute intake of ^{131}I , this is expressed as:

$$\int_0^\infty Q_{mother}^{ICRP}(t) dt = \tilde{K}_{mother}^{uptake} \cdot \int_0^\infty e^{-\lambda_{mother}^{eff} t} dt, \quad (7)$$

which results in:

$$\tilde{K}_{k,mother}^{uptake} = \lambda_{mother}^{eff} \times \int_0^\infty Q_{mother}^{ICRP}(t) dt \quad (8)$$

In equations (7) and (8), $Q_{mother}^{ICRP}(t)$ is the ^{131}I thyroid activity calculated according to the multi-compartment biokinetic model for iodine metabolism in the mother's body (ICRP 2001), and $\tilde{K}_{mother}^{uptake}$ is the value implicitly used in that model for the fractional uptake of ^{131}I by the thyroid of the mother. According to equation (8), the value of $\tilde{K}_{mother}^{uptake}$ is equal to 0.39*, if λ_{mother}^{eff} for ^{131}I is taken to be 0.095 d^{-1} . This value of 0.39 has been used for the calculation of individual scaling factors $K_{k,mother}^{scal-quest}$ in equations (4) and (5) as well as for the calculation of group average scaling factors $K_{j,woman}^{scal}$ and $K_{j,Cs}^{scal}$.

Estimation of the scaling factor for members of group L2-C—The scaling factor

$\left(K_{j,woman}^{scal}\right)$ for a member of group L2-C, whose mother resided in settlement j ATA, is the arithmetic mean of individual scaling factors estimated for the adult women with direct thyroid measurements in the settlement j . Default assumptions about the residential histories and dietary habits of the adult women with direct thyroid measurement were used in the assessment of their instrumental thyroid doses (Likhtarov et al. 2005).

Estimation of the scaling factor for members of group L1-NC—The scaling factor

$\left(K_{j,Cs}^{scal}\right)$ for a member of group L1-NC, whose mother resided in settlement j ATA, reflects the local average ^{137}Cs deposition density ($\sigma_{j,Cs}$, kBq m^{-2}) measured for settlement j . Likhtarov et al. (2005) assumed that personal decisions about dietary intakes were related to information about local contamination levels, which at that time were expressed in terms of the local ^{137}Cs deposition density. Likhtarov et al. (2005) analyzed the relationship between measured thyroid activities and ^{137}Cs deposition density and estimated a scaling factor as a function of two best-fit parameters, B and β . In the context of this report, that scaling factor is expressed as

$$K_{j,Cs}^{scal} = B \sigma_{j,Cs}^\beta \quad (9)$$

*The differences in the values of the fractional uptake of ^{131}I by the thyroid of the mother relate to different levels of stable iodine in the diet used in the two ICRP models: the uptake by the thyroid is higher when the intake with diet is lower. In ICRP Publication 88 (ICRP 2001) the iodine intake with diet is $150 \mu\text{g d}^{-1}$ whereas in ICRP Publication 30 (ICRP 1988) the stable iodine intake with diet is $200 \mu\text{g d}^{-1}$.

The parameters B and β were estimated separately for rural and urban settlements. Best-fit values of B for females in urban areas were 0.34 with a geometric standard deviation of 1.5; for females in rural villages, the corresponding values were 0.47 (geometric mean) and 1.1 (geometric standard deviation). Best-fit values of β for females in urban and rural areas were 0.58 ± 0.11 (mean $\pm$ standard deviation) and 0.36 ± 0.10 , respectively (Likhtarov et al. 2005).

Estimation of the thyroid doses received after birth

Because the thyroid uptake of ^{131}I from breast feeding is higher than the uptake of the fetus at the end of the *in utero* period, the ratio of the thyroid doses received by the child and the mother keeps increasing after birth (Zvonova and Balonov 1993). It is therefore important to also estimate the thyroid doses received after birth. The calculation included several successive steps. The first task was to estimate the variation with time of the ^{131}I intake by the mother $q_{k,mother}^{ecol-quest,n}$ using both the ecological model described by Likhtarov et al. (2005) and the responses provided by the mother regarding her consumption of milk and leafy vegetables and her relocation history. In a second step, the concentration of ^{131}I in the mother's breast milk was estimated. Simon et al. (2002) recommended a transfer coefficient $K_{mother-baby}$ of 0.37 d L^{-1} , which was used to make these estimates.

In the third and final step, the thyroid dose to the infant was estimated. Among the 329 cohort members who were born between 26 April and 30 June 1986, 291 of them were breastfed. The breast milk consumption rate w_{baby} was taken to be 0.8 L d^{-1} and it was assumed that there was no other source of ^{131}I intake for the child. Therefore the thyroid dose received by a breastfed child born between 26 April and 30 June 1986 is:

$$d_{k,baby}^{ecol-quest,n} = \frac{\alpha}{M_{baby}^{th} \cdot \lambda_{baby}^{eff}} \times q_{k,mother}^{ecol-quest,n} \times K_{mother-baby} \times w_{baby} \times K_{uptake}^{th,baby} \quad (10)$$

where M_{baby}^{th} is the assumed thyroid mass for breast-fed infants ($M_{baby}^{th} = 1.5 \text{ g}$); α is the energy absorbed in the thyroid following the radioactive decay of ^{131}I ($\alpha = 3.20 \cdot 10^{-14} \text{ J Bq}^{-1}$); $\lambda_{baby}^{eff} = 0.132 \text{ d}^{-1}$ - is the effective rate constant for the elimination of ^{131}I from the newborn's thyroid (ICRP 56; 1989) and $\tilde{K}_{uptake}^{th,baby} = 0.30$ - is the fractional uptake of ^{131}I by the thyroid of the newborn (ICRP 67; 1993).

The total questionnaire-individualized ecological dose estimate for the baby is the summation of the daily doses received by consumption of mother's milk:

$$D_{k,baby}^{ecol-quest} = \sum_{n_b=1}^{N_b} d_{k,baby}^{ecol-quest,n_b} \quad (11)$$

where n_b is equal to 1 for the day of birth and equal to N_b on 30 June 1986. The individual dose to the baby subject k is scaled in the same manner as the fetal dose [equation (3)], using scaling factors that depend upon the group to which subject k belongs [equation (4)].

RESULTS AND DISCUSSION

Responses to the personal interviews

Personal interviews were conducted with the 2,554 mothers of all subjects to obtain information on their pregnancy, as well as on their residence history and dietary habits

during the two months following the Chernobyl accident. The following paragraphs summarize the information gathered from the 2,554 mothers for the 2,582 subjects (there were 28 pairs of siblings).

The places of residence of exposed and relatively unexposed subjects at the time of the accident are shown in Figure 1. There is a clear geographical separation between the places of residence of the exposed and relatively unexposed children. The distributions of subjects in each group according to type of settlement (urban or rural) are given in Table 2. About 76% of the subjects resided in rural areas ATA.

The age distributions of the mothers of the cohort members ATA, broken down for each group and for all subjects together, are shown in Table 3. Most (89.3%) of the mothers were in the age range from 18 to 33 years; 52 were 16–17 years of age, and 12 were older than 40. The age distributions for the two groups are similar.

The distributions of the subjects according to stage of pregnancy of the mothers ATA are shown in Table 4. The numbers per month, which are relatively low for the early stages of pregnancy, reach a plateau after the third month. It is worth noting that almost 10% of the subjects were conceived during the two months following the accident.

Information about the numbers of relocations reported by the mothers of subjects in each of the two groups is presented in Table 5. Most subjects (81% among the exposed and 83% among the unexposed) did not change their place of residence during the time period when ^{131}I was present in the environment (April–June of 1986). About 16% of the subjects moved 1–2 times during this period and about 2% moved more than 2 times.

The reported individual daily consumptions of milk and leafy vegetables by the mothers of the subjects in April–June of 1986 vary in a rather wide interval, with 18% of women consuming more than 1 liter of milk daily, while about 12% of women answered that they did not consume milk at all (Table 6). According to personal interview 35 mothers did not consume milk or leafy vegetables. For those mothers, the thyroid doses were only due to inhalation.

The average daily consumptions, broken down according to type of settlement (urban or rural), are presented in Table 6. In rural settlements, the average daily consumptions of milk and leafy vegetables were 0.45 L and 28 g respectively. In urban areas, the average daily consumption of milk was 0.29 L and the average daily consumption of leafy vegetables was 24 g. These results are close to the reference daily consumption of milk and leafy vegetables used for the adult inhabitants of rural and urban settlements in the “ecological” modeling of thyroidal ^{131}I activity: 0.35 L of milk and 25 g of leafy vegetables for the rural settlements and 0.22 L of milk and 19 g of leafy vegetables for the urban settlements.

Estimates of the thyroid dose received by the thyroid of the fetus

The results of the thyroid dose estimation are shown in Tables 7 and 8. Table 7 shows the distributions of doses received by the subjects in the exposed and relatively unexposed categories. The distributions differ markedly, with more than 97% of the relatively unexposed group having estimated doses lower than 50 mGy, while only about 57% of estimated doses to members of the exposed group were that low. The mean dose to subjects in the exposed group was about 120 mGy. The mean thyroid dose for all subjects was 72 mGy, the values for exposed and for relatively unexposed group being 120 and 10 mGy respectively. Individual thyroid dose estimates range from less than 1 mGy to 3,200 mGy.

As expected, most of the doses of individuals in the relatively unexposed or “comparison” group are small (<100 mGy), but dose estimates for nine subjects are in the 100–200 mGy range. One reason for such high doses is that, according to their questionnaires, some of the mothers spent some time in April–June in settlements with relatively high contamination. In the low-contaminated areas there are several locations with relatively substantial levels of deposition (for example, the settlements Bakhmach and Baturin of Chernihiv oblast where the ^{137}Cs deposition densities are 14 and 44 kBq m^{-2} , respectively). The residence of mothers in these settlements during the late stage of pregnancy (or after birth in late April or May), as well as high consumption rates of milk and/or leafy vegetables, resulted in elevated thyroid doses to those children of the “comparison” group.

The breakdown of the thyroid doses as a function of the stage of pregnancy (Table 8) shows, for the 2 groups of subjects, that the dose increases substantially with the stage of pregnancy. The difference between the first and second trimester reflects the development of the organ, which does not become active until 9 – 12 weeks after conception.

Estimation of the thyroid doses received after birth

The thyroid doses received after birth (D_{pn}) were calculated for all cohort members and compared with the doses received while *in utero* (D_f). Results of the comparison are presented in Table 9. For 91% of the subjects, either the fetal or the postnatal thyroid doses were very small. For the remainder of the cohort, i.e., 352 subjects, the ratio of the doses received after birth to the total dose ($D_f + D_{pn}$) ranged from 0.01 to 1. Among these subjects with non-negligible in-utero or postnatal exposures the dose received after birth was found to be less than 10% of the total dose for 152 subjects and greater than the fetal dose for 102 subjects. When the subjects with negligible in-utero exposure are included, it is estimated that 219 subjects (8.5%) received thyroid doses after birth that were at least 10% of their cumulative doses.

Comparison of the thyroid doses received by the mother and by the child

In Table 10 the ratios of thyroid doses received by children and thyroid doses received by their mothers are shown. As is clear from the table the child's thyroid doses are less than 1% of mothers' doses if the stage of pregnancy at the time of the accident was less than 60 days. This ratio increases rapidly as the stage of pregnancy ATA increases. The thyroid doses of subjects who were exposed *in utero* during the last trimester of pregnancy are significantly greater than the thyroid doses of their mothers.

Uncertainties

The uncertainties attached to the thyroid dose estimates are admittedly large, but very difficult to quantify. The main sources of uncertainty are expected to be related to:

- the transfer coefficient $h_T(\tau)$ from ^{131}I intakes by the mother to the thyroid dose received by the child. This uncertainty is important for all subjects, but is larger for those whose *in utero* exposure occurred during the early stages of fetal thyroid development (Berkovski 2004).
- the determination of the gestational age τ at the time of the accident; it varies from one subject to another according to the knowledge of the mother about the beginning of her pregnancy.

Additional sources of uncertainty are related to the application of estimated scaling factors for adjustment of thyroid activities calculated for mothers of subjects in groups L2-C and L1-NC. These uncertainties concern:

- whether the village mean scaling factors employed for mothers in contaminated areas but without direct thyroid measurements (group L2-C) are representative for subjects in that group. This uncertainty is shared, at least at the village level and perhaps by all members of group L2-C.
- the estimation of the scaling factors for the “non-contaminated areas” that apply to subjects in group L1-NC. The scaling factors are more uncertain in locales that are characterized by smaller numbers of radiation measurements.

The estimation of the uncertainties related to the *in utero* thyroid dose estimates will be the topic of a separate paper.

CONCLUSIONS

Doses were estimated for 2,582 Ukrainian children who were exposed *in utero* to ^{131}I following the accident at the Chernobyl power station in 1986. There were two groups of “exposed” children (1,494 in all) and one group of 1,088 “relatively unexposed” children. Thyroid dose estimates for all children were made using an ecological model that relied on information (residence locations, gestational age, food consumption patterns, iodine prophylaxis, etc) provided by their mothers during personal interviews.

At the time of the accident, mothers of the first two groups of children resided in areas with substantial amounts of contamination, while mothers of children in the relatively unexposed category resided in areas with little post-accident radionuclide deposition. Distributions of estimated doses generally reflected that difference; mean doses to the exposed infants were ~120 mGy, more than ten times higher than the mean dose (~10 mGy) for relatively unexposed. More than 97% of the latter group received thyroid doses less than 50 mGy; only about 57% of the exposed group received doses in that range. Nine subjects in the relatively unexposed group (0.8%) had thyroid dose estimates between 100 and 200 mGy; these higher doses were due to reported periods of residence in more contaminated areas after the accident. On the other hand, estimated thyroid doses for 28.3% of the exposed group exceeded 100 mGy. The overall range of doses was from less than 1 mGy to 3.2 Gy. The lowest thyroid doses were estimated for subjects whose estimated fetal ages were less than 90 d at the time of the accident. Thyroid dose estimates generally increased with the stage of development, but also depended upon individual circumstances reported by the mothers.

The main sources of uncertainty in these thyroid dose estimates have been identified but have not been quantified. Included are the estimates of fetal age at the time of the accident and the related issue of thyroidal uptake of ^{131}I , particularly in the early stages of fetal thyroid development. The uncertainty in the applied dose scaling factors also remains to be quantified.

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Figure 1. Places of residence ATA of the mothers of the exposed and relatively unexposed children. Levels of the estimated ^{131}I contamination levels are also indicated.

Figure 2.
Structure of the *in utero* dose calculation for the three groups of subjects

Figure 3.
Model of iodine biokinetics during pregnancy (ICRP 2001, Berkovski 1999a)

Table 1

Fetal thyroid dose (Gy) per 1 Bq of ^{131}I ingestion intake by mother as a function of the gestational age

Stage of pregnancy (weeks) at the time of ^{131}I intake	$h_T(\tau)$, Gy Bq $^{-1}$	
	Values used for the dose calculation	ICRP (2001)
5	$2.2 \cdot 10^{-10}$	$2.2 \cdot 10^{-10}$
10	$3.2 \cdot 10^{-9}$	$3.2 \cdot 10^{-9}$
12	$9.8 \cdot 10^{-8}$	
15	$2.4 \cdot 10^{-7}$	$2.4 \cdot 10^{-7}$
18	$3.6 \cdot 10^{-7}$	
21	$4.4 \cdot 10^{-7}$	
25	$6.8 \cdot 10^{-7}$	$6.8 \cdot 10^{-7}$
27	$7.2 \cdot 10^{-7}$	
30	$8.7 \cdot 10^{-7}$	
35	$1.1 \cdot 10^{-6}$	$1.1 \cdot 10^{-6}$

Table 2

Distribution of the subjects at the time of the accident according to type of settlement

Settlement	Number of subjects		
	Exposed	Relatively unexposed	Total
Rural areas	1205	768	1973
Urban areas	289	320	609
All locations	1494	1,088	2,582

Table 3

Distribution of exposed and relatively unexposed subjects according to the age of their mothers at the time of the accident (ATA)

Mother's age (y) ATA	Number of subjects		
	Exposed	Relatively unexposed	Total
16	6	6	12
17	22	18	40
18	57	53	110
19	89	80	169
20	128	89	217
21	122	85	207
22	104	91	195
23	105	77	182
24	102	71	173
25	101	71	172
26	102	68	170
27	83	61	144
28	88	49	137
29	76	53	129
30	60	39	99
31	53	33	86
32	37	34	71
33	23	22	45
34	30	17	47
35	28	22	50
36	17	11	28
37	13	8	21
38	14	7	21
39	9	7	16
40	7	3	10
41	2	4	6
42	1	1	2
43	0	1	1
44	1	1	2
45	0	1	1
Unknown	14	5	19
Total	1494	1,088	2,582

Table 4

Distribution of the number of subjects according to the stage of pregnancy of their mothers at the time of the accident (ATA)

Stage of pregnancy, (days) ATA	Number of subjects		
	Exposed	Relatively unexposed	Total
<=0	96	137	233
1–30	88	72	160
31–60	108	74	182
61–90	125	83	208
91–120	181	111	292
121–150	211	85	296
151–180	227	107	334
181–210	188	131	319
211–240	174	141	315
>240	96	147	243

Table 5

Number of relocations in May–June of 1986 reported by the mothers of the subjects.

Number of relocations	Number of subjects		
	Exposed	Relatively unexposed	Total
0	1204	906	2110
1	167	62	229
2	85	106	191
3	21	7	28
4	11	4	15
5	2	1	3
6	1	1	2
7	1	-	1
8	1	1	2
9	-	-	-
10	1	-	1
Totals	1494	1,088	2582

Table 6

Daily consumption of milk and leafy vegetables reported by the mothers of the subjects in the three groups.

A. Consumption of milk

Daily milk consumption (L)	Percentage of subjects		
	Urban areas	Rural areas	All areas
No consumption	12.0	13.3	12.3
< 0.5	45.4	59.6	48.7
0.5–1	17.7	14.0	16.9
1–1.5	17.3	7.1	14.9
1.5–2	1.3	0.7	1.1
2–2.5	1.3	0.7	1.2
2.5–3	0.2	0.0	0.1
≥ 3	0.7	0.2	0.6
No definite amount	4.1	4.6	4.2
Total	100.0	100.0	100.0
Mean values			
Mean for all (L)	0.3	0.5	0.4
Mean for milk consumers (L)	0.3	0.5	0.5

B. Consumption of leafy vegetables

Daily consumption of leafy vegetables (g)	Percentage of subjects		
	Urban areas	Rural areas	All areas
No consumption	10.0	13.6	10.9
< 10	23.7	31.5	25.5
10–20	17.9	11.3	16.4
20–30	11.0	8.7	10.5
30–40	13.8	12.0	13.4
40–50	11.4	12.6	11.7
50–100	10.2	7.1	9.5
≥ 100	0.7	0.8	0.7
No definite amount	1.2	2.3	1.4
Total	100.0	100.0	100.0
Mean values			
Mean for all (g)	24	28	27
Mean for consumers of leafy vegetables (g)	27	31	30

Table 7

Distributions of thyroid doses (mGy) for the exposed and relatively unexposed cohort members.

Thyroid dose, range (mGy)	Exposed subjects		Relatively unexposed subjects		Total	
	Number	Percent of total	Number	Percent of total	Number	Percent of total
0–20	565	37.8	932	85.7	1497	61.75
20–50	285	19.1	126	11.6	411	15.35
50–100	221	14.8	21	1.9	242	8.35
100–200	188	12.6	9	0.8	197	6.70
200–500	160	10.7	-	-	160	5.35
500–1000	50	3.3	-	-	50	1.65
>1000	25	1.7	-	-	25	0.85
Total	1,494	100	1,088	100	2582	100

Table 8

Distribution of the mean thyroid doses of the subjects according to stage of pregnancy

Stage of pregnancy (d) ATA	<u>Mean dose (mGy) for group members</u>	
	Exposed	Relatively unexposed
<=0 – 30	0	0
31–60	1	0
61–90	14	1
91–120	67	5
121–150	100	8
151–180	155	9
181–210	176	14
211–240	252	14
>240	308	29

Table 9

Distribution of postnatal thyroid doses according to the relative magnitude of thyroid doses received while *in utero* (D_f) and *postpartum* (D_{pm})

	Exposed subjects			Relatively unexposed subjects		
	Number of subjects	Postnatal dose interval, mGy		Number of subjects	Postnatal dose interval, mGy	
		min	max		min	max
Negligible <i>in-utero</i> exposure ($D_f \approx 0$; $D_{pm} > 0$; birth soon after the accident)	11	24	997	8	7	68
Negligible <i>in-utero</i> and <i>postnatal</i> exposures ($D_f \approx 0$; $D_{pm} \approx 0$; conception time after March 1986)	142	<1	<1	195	<1	<1
Negligible <i>postnatal</i> exposure (contribution in total exposure < 1%; birth after May 1986)	1209	<1	9	665	<1	2
Substantial <i>in-utero</i> and <i>postnatal</i> exposure (contribution in total exposure 1% – 100%)	132	<1	1600	220	<1	148
Including cases of contribution in total exposure:						
1% – 10%	73	<1	137	79	<1	14
10% – 25%	20	3	231	35	<1	12
25% – 50%	11	7	221	32	<1	22
50% – 75%	17	15	685	25	1	33
75% – 100%	11	5	1600	49	2	148
Total	1494	<1	1600	1088	<1	148

Table 10

Ratios of thyroid doses received by the children *in utero* (D_f) and *in utero* and after birth ($D_f + D_{pn}$) to the thyroid doses received by mothers (D_{moth})

Stage of pregnancy ATA (days)	Exposed group		Relatively unexposed group	
	D_f/D_{moth}	$(D_f + D_{pn})/D_{moth}$	D_f/D_{moth}	$(D_f + D_{pn})/D_{moth}$
31–60	<0.01	<0.01	<0.01	<0.01
61–90	0.11	0.11	0.13	0.13
91–120	0.39	0.39	0.44	0.44
121–150	0.67	0.67	0.69	0.69
151–180	0.80	0.80	0.87	0.87
181–210	1.26	1.29	1.34	1.35
211–240	1.54	1.57	1.53	1.71
>240	1.40	2.24	1.03	2.65