Appendix 1

Post - Chernobyl Thyroid Cancer in Ukraine

POST- CHERNOBYL THYROID CANCER IN UKRAINE.

REPORT 1: Estimation of thyroid doses.

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Abstract.

About 1.8 EBq of ^{131}I was released into the atmosphere during the Chernobyl accident that occurred in Ukraine on 26 April 1986. More than 10% of this activity was deposited on the territory of Ukraine. Beginning 4-5 years after the accident, an unusually high incidence of thyroid cancer among children, believed to be caused in part to exposure to ^{131}I, has been observed in the most contaminated regions of Ukraine. A detailed estimation of the thyroid doses from ^{131}I for the Ukrainian population has been carried out in the framework of large scale epidemiologic studies of childhood thyroid cancer. Individual thyroid doses have been estimated for the members of a cohort study in the most contaminated areas, while group doses, broken down according to age, gender, and location of residence at the time of the accident, have been estimated for the entire country. Results averaged over large population groups indicate that the entire territory of Ukraine can be subdivided into three zones: (1) a zone of high thyroid doses (above 35 mGy) in Zhytomyr, Kyiv, Rivne, Chernihiv, and Cherkasy oblasts; (2) a zone of moderate thyroid doses (14-35 mGy) in Volyn', Vinnytsia, Khmel'nyts'k, Chernivsi, Kirovohrad, Poltava, Sumy oblasts, Kyiv-city and the Autonomous Republic of Crimea; and (3) a zone of low thyroid doses (13 mGy and less) in the other 12 oblasts of Ukraine and the city of Sevastopol'. Data, models, and procedures required for the estimation of individual doses and of group doses are described in the paper. An analysis of the distribution with time and location of the thyroid cancer morbidity for the residents of Ukraine who were aged 1 to 18 at the time of the accident also will be submitted for publication in the near future.

Introduction

About 1.8 EBq of ^{131}I was released to the atmosphere during the Chernobyl accident that occurred in Ukraine on 26 April 1986 [*1*]. It is estimated that approximately 11% of this activity was deposited on the territory of Ukraine [*2, 3*]. The consumption of fresh milk contaminated with ^{131}I was the main source of thyroid irradiation for persons in contaminated areas. Beginning 4-5 years after the accident, an unusually high incidence of thyroid cancer among children and adolescents exposed to ^{131}I was observed in the contaminated regions of Ukraine [*4-10*], Belarus [*1,11-15*], and Russia [*16-18*].

Other radioactive isotopes of iodine (notably, ^{132}I, ^{133}I, and ^{135}I) and precursor radionuclides (^{131m}Te and ^{132}Te) were also released and could contribute to the thyroid dose. Evaluations indicate that the thyroid doses produced by these radionuclides were a relatively small fraction of the total thyroid dose for most people [*19, 20*]. This paper is therefore focused on the dose from ^{131}I.

The investigation of the high incidence of thyroid cancer among populations that were exposed to radioiodine after the Chernobyl accident consists of two components:

- Retrospective assessment of the thyroid dose for individuals and for groups of people aggregated according to age, gender, and residence from the time of the accident until the end of June 1986; and
- Assessment of the risk of thyroid cancer caused by the thyroid's exposure to radiation. This assessment can be made in the framework of three types of epidemiologic study: cohort [*21, 22*], case-control [*12*], and ecological [*4, 23*].

The present publication is devoted to a detailed estimation of the thyroid doses from ^{131}I for the Ukrainian population, and supports an associated ecological analysis of the observed thyroid cancer morbidity.

The estimation of thyroid doses resulting from the Chernobyl accident was initiated in May-June 1986 [*24*]. This estimation was based on the ^{131}I activities measured in the thyroids of people. A very simple model, which assumed a single intake of ^{131}I at the time of the accident, was used to derive the thyroid dose from the measurement of thyroidal content. Although these estimates were rather conservative, they helped to define regions with the highest thyroid doses. It was expected that populations of those regions would have the highest risk of developing radiation-induced thyroid cancers.

Since 1986, there have been many revisions of the initial dose assessments with the aim of improving their realism and reliability. Different methodologies have been developed or improved for the estimation of the thyroid doses received by people whose thyroid radioactivity content was measured in May-June 1986 as well as those received by people without such measurements [*15, 25-29*].

This research was stimulated by several large scale epidemiologic projects that surveyed childhood thyroid cancer in Ukraine [*22, 30*]. These projects were initiated circa 1996. Detailed ecological models of radioiodine transfer along food chains [*31*] and special mesoscale models of atmospheric transfer of radionuclides [*2,3*] were developed and used at that time. Results of large-scale interviewing were used to obtain information on the residential history and dietary habits of the surveyed cohort members.

In the current thyroid dosimetry system, there are three levels of dosimetry support for different types of epidemiological research. The first level (individual thyroid doses for cohort members) is used in a classical cohort study [*31*]. The second and the third levels are used in ecological studies to estimate group doses for settlements, raions[1], or oblasts, taking into account the gender and age of the inhabitants. Data, models, and procedures required for the estimation of individual doses (first level) and of group doses (second and third levels) are described in this paper. Dose estimates are presented for people who were aged ≥1 to 18 and who lived in any part of Ukraine at the time of the accident.-Infants who

[1] Raion is an administrative unit within an oblast. Usually there are 10 to 20 raions in an oblast. The raion is comparable to a county in the United Stattes, while the oblast is comparable to a state.

were less than one year old at the time of the accident are not considered in this paper. Although there were many measurements of thyroid activity performed in May-June 1986, few of these were for very young children.

An analysis of the distribution with time and location of the thyroid cancer morbidity for the residents of Ukraine who were aged 1 to 18 at the time of the accident will be.submitted for publication in the near future. The results of that analysis will consist of an assessment of the age-dependent changes in the background thyroid cancer morbidity for the Ukrainian population, and an assessment of the absolute and relative risks of the radiation-induced thyroid cancer.

Materials and methods

General equations.

The variation with time of the ^{131}I activity in the thyroid $Q_{a,s}(t)$ (Bq) for a subject of age a and gender s is defined by two main processes: (1) uptake of ^{131}I by the thyroid, which is described by a function $U_{a,s}(t)$ ($Bq \cdot d^{-1}$) and (2) excretion of ^{131}I from the thyroid, which is assumed to be exponential. It is characterized by the effective constant of elimination of ^{131}I from the thyroid, λ_a^{ef} (d^{-1}), which is the sum of the biological elimination constant, λ_a^{biol} (d^{-1}), and of the radioactive decay constant of ^{131}I, λ_I, (d^{-1}). Therefore, the function $Q_{a,s}(t)$ can be described as

$$Q_{a,s}(t) = \int_0^t U_{a,s}(t) e^{-\lambda_a^{ef}(t-\tau)} d\tau \,, \qquad (1)$$

The absorbed thyroid dose, $D_{a,s}^{th}$ (Gy), received until time T after the accident, is

$$D_{a,s}(T) = \frac{\alpha}{M_a} \int_0^T Q_{a,s} dt = \frac{\alpha}{M_a} A_{a,s}(T) \,, \qquad (2)$$

where α is energy absorbed in the thyroid due to the radioactive decay of a unit activity of ^{131}I during one day (*J/Bq·d)*; M_a is the age-dependent thyroid mass, (*kg*), averaged for boys and girls; $A_{a,s}(T)$ is the time-integrated activity of the ^{131}I content in the thyroid (during the time period from 0 to *T*) for a subject of age-gender group *a-s (Bq·d).*

Ecological model.

Variation with time of the ^{131}I activity in the thyroid, $Q_{a,s}(t)$ in eq. (1), can be estimated based on an ecological model that describes the transport of ^{131}I through the environment and in people. The model takes into account inhalation of contaminated air, the processes of ^{131}I deposition on ground and vegetation, transfer of ^{131}I into milk, consumption of contaminated foods by humans, and uptake and retention of ^{131}I in the thyroid. The output of the model is dynamics of ^{131}I activity in the thyroid during the period of exposure. Most of the ^{131}I release from the Chernobyl reactor occurred during the first few days after 26 April 1986 and radioactive decay limited the period of concern about intakes of ^{131}I in the diet to about two months.

Fundamental to the model are measurements and estimates of the radionuclide depositions in locations of interest after the accident. The total depositions of ^{137}Cs have been measured in settlements throughout Ukraine. The daily depositions of both ^{137}Cs and ^{131}I have been estimated using a mesoscale atmospheric transport model. A map of cumulative *^{131}I* deposition on the territory of Ukraine is shown on Figure 1 *[2,3]*.

Three pathways of ^{131}I intake were considered in the ecological model: inhalation, ingestion of leafy vegetables and milk. The mathematical description of the model, as well as parameter values, are given in Annex 1

Direct measurements of ^{131}I activity in the thyroid.

Direct measurements of radioactivity in the thyroids of the inhabitants of affected territories were performed between 20 and 40 days after the accident. The results of the direct measurements on the subjects (indexed by *k*) $\widetilde{Q}_{k,a,s}$ (*Bq*), were used to estimate the thyroid doses received by the individuals whose thyroid activities were measured. The methodology of thyroid measurements used in Ukraine in April-June of 1986 (groups of population, territorial distribution of the measurements, and descriptions of the measuring devices and their calibration) has been presented in detail in previous publications [*26-29*]. The results of the thyroid measurements were corrected to take into account the presence of radiocesium in the human body. Values of the correction factors for different ages and different times of measurements are described in a separate publication.

Thyroid dose estimation

Definitions and principles

The thyroid dose, $D_{a,s}(T)$ *(Gy),* estimated with help of function, $Q_{a,s}(t)$ *(Bq),* for a subject of age *a* and gender *s* who was in a settlement with a specified level of ^{131}I deposition is called *"the ecological thyroid dose".*

Thyroid dose, calculated taking into account result of thyroid activity measurement $\widetilde{Q}_{k,a,s}$ *(Bq)* is called "*the instrumentally individualized thyroid dose"* and denoted as $D_{k,a,s}(T)$ *(Gy).*

The instrumentally individualized thyroid dose based on information on the individual's diet and behavior is called "*the questionnaire-based instrumentally individualized thyroid dose".*

The questionnaire-based instrumentally individualized thyroid doses are the most reliable estimates of thyroid doses received by individuals.

Based on result of the direct thyroid activity measurement $\widetilde{Q}_{k,a,s}$ *(Bq), the individual scaling factor* for *k*-individual of age *a* and gender *s*, K_k^{scale}, can be estimated as:

$K_k^{scal} = \dfrac{\widetilde{Q}_{k,a,s}}{Q_{a,s}(t_{meas})}$, where $Q_{a,s}(t_{meas})$ is estimation of the thyroid activity at the time of measurement, t_{meas} based on ecological model. It is assumed that the dynamics of ^{131}I activity in the thyroid of individual k is linearly related to the function $Q_{a,s}(t)$. The instrumentally individualized thyroid dose $D_{k,a,s}(T)$ can therefore be calculated as:

$$D_{k,a,s}(T) = K_k^{scale} D_{a,s}(T) \quad (3)$$

Individual doses $D_{k,a,s}(T)$ are used for the estimation of the settlement-specific thyroid doses for different age-gender groups and (2) for estimation of age-gender thyroid doses aggregated over the settlement in a raion or oblast.

There are three levels of thyroid dose estimation.

First level of thyroid dose estimation

The first level of thyroid dose estimation is used for the individuals with direct thyroid measurements; it also takes into account results of the individual interviews on diet and behavior (the questionnaire-based instrumentally individualized thyroid dose) or reference diet and behavior estimated from other sources (the instrumentally-individualized thyroid dose).

For the majority of the approximately 130,000 Ukrainians whose thyroid activities were measured in 1986 instrumentally individualized thyroid doses could be estimated. Results of interviews of rural and urban inhabitants of Chernihiv oblast (9,500), Kyiv oblast (3,000) and Zhytomyr oblast (2,300) on dietary habits and food consumption rates in May-June 1986 were used for the development of reference age-gender dependent consumption rates (Table A1.2). This survey was undertaken in 1992-1994 as part of the “Thyroid Passportisation” of the affected Ukrainian population and was funded by the Ministry of Chernobyl and Emergency Situation of Ukraine [*32, 33*]. The questionnaires were developed by the Scientific Center on Radiation Medicine of Ukraine, which managed the project.

Soon after the accident the inhabitants of the settlements of the zones nearest to the Chernobyl NPP were evacuated to other settlements located in Kyiv, Chernihiv, and Zhytomyr oblasts. The thyroid doses of people who were evacuated were caused partly by the thyroid exposure at the place of evacuation and partly by the thyroid exposure at the place to which they were relocated. Thyroid activity measurements were performed for ~9,500 inhabitants of 53 evacuated settlements. The information on the settlement of evacuation and on the settlement of relocation was taken from the records of measurements, and then used in the calculation of the instrumentally individualised thyroid doses for the evacuees.

Individual interviews for more than 13,000 subjects who were less than 18 years old at the time of the accident (or of parents of the subjects who were less than 10-year old) regarding diet and post-accident relocations have been performed in the Ukraine-American cohort thyroid study [*21,22,31*]. Direct measurements of thyroid activity were performed for all subjects of the cohort.

Second level of thyroid dose estimation

The settlement-specific doses in locations where the direct thyroid measurements were performed in May-June 1986 are considered in the second level of thyroid dosimetry. The measurements were made for the inhabitants of 787 settlements of Kyiv, Chernihiv, and Zhytomyr oblasts, where contamination levels were the highest. This number includes 53 settelements from which people were evacuated. In each of these 787 settlements, there were persons whose thyroid activities were not measured, and a method for estimation of thyroid doses for those people is needed. The procedure is based on the relative time-integrated activities of ^{131}I in thyroids of different age and gender groups. The relationships for individuals whose thyroid activities were measured are used to estimate time-integrated thyroid activities for 36 age and gender groups (both males and females for yearly age intervals from 1 to 18) and then doses to the same groups in the settlements.

The largest number of thyroid activity measurements was made for children of ages 12 to 14 (Figure 2). This age interval, denoted by a_{ref}, is called the *"reference age-interval"*. There were 619 settlements where thyroid measurements were performed on children in the *reference age-interval.* In addition, measurements in the *reference age-interval* were performed in 49 settlements that were evacuated soon after the accident. The total number of measurements (ages ≥1 to 18) in these categories were ~74,000 and 8,000, respectively.

Thyroid measurements in Ukraine in 1986 were made with eight types of instruments. Results obtained using devices with gamma spectrometric capability are more reliable than those obtained from less sophisticated counting devices. For gamma spectrometric measurements, a minimum of four measurements per settlement were required for inclusion in the analysis. For non-spectrometric instruments (e.g., SRP-68-01), only settlements with ten or more measurements were included in the analysis. The number of settlements and individual measurements for which these criteria were satisfied are given in Table 1.

For every person *k* of age *a* and gender *s* with a direct measurement in settlement *j*, the instrumentally individualized time-integrated activity of ^{131}I in the thyroid is denoted as: $A_{k,a,s,j}$ (*Bq d*) and the relative time-integrated ^{131}I activity in the thyroid, $f_{k,a,s,j}$ is defined as: $f_{k,a,s,j} = \frac{A_{k,a,s,j}}{\hat{A}_{a_{ref},s,j}}$ where $\hat{A}_{a_{ref},s,j}$ is the geometric mean of the time-integrated ^{131}I activity in the thyroids of members of the same gender of the settlrment *j* in the reference age interval:

When we consider all together the settlements with direct thyroid measurements in the reference age interval, the geometric mean values $f_{a,s}$ (weighted over the number of members in the reference age-group of the settlement) for each of 36 age-gender groups were calculated using the values $f_{k,a,s,j}$. Statistical comparisons of values of $f_{a,s}$ for different subpopulations and different locations were made with the Mann-Whitney test *[16,42]*. There are statistical differences between samples of rural and urban children for the majority of age groups. There are also differences between the entire samples of boys and girls for almost all ages. In the thyroid dosimetry of the second level, six tabulated functions $f_{a,s}$ have been used for the age-gender average settlement specific thyroid dose estimations: two functions for rural areas, two functions for urban areas and two functions for the evacuated population. In each case the functions were different for males and for females. The computed geometric mean values of $f_{a,s}$ and the associated geometric standard deviations (*GSDs*) for different age and gender groups are given in Table 2. The tabulated values were used to estimate time-integrated thyroidal ^{131}I activities $\tilde{A}_{a,s,j}$ for each age-gender group in every settlement *j* where direct thyroid measurements were performed in 1986:

$$\tilde{A}_{a,s,j} = \tilde{A}_{a_{ref},s,j} \cdot f_{a,s} \tag{4}$$

where $\tilde{A}_{a_{ref},s,j}$ is the settlement-specific time-integrated thyroidal ^{131}I activity for gender *s* in the reference age interval of the settlement *j*. $\tilde{A}_{a_{ref},s,j}$ is derived from the values of $f_{a,s}$ and of the time-integrated thyroidal ^{131}I activity $A_{k,a,s,j}$ for the persons of gender *s* for which the direct measurements were performed in the settlement *j*.

The median thyroid doses $\tilde{D}_{a,s,j}$ for each of 36 age-gender groups in settlement *j* (where direct measurements of children were performed) are calculated as:

$$\tilde{D}_{a,s,j} = \frac{\alpha}{M_a} \tilde{A}_{a_{ref},s,j} \cdot f_{a,s} \quad (5)$$

Statistical properties of the first and second levels of thyroid dose estimations

Analysis of distributions of the measured thyroid activities, $(\tilde{Q}_{k,a,s,j})_t$ and of the instrumentally-individualized time-integrated thyroid activities, $A_{k,a,s,j}$, for different age-gender groups in the same settlement, showed that according to Lilliieforts test [*43*], (70-100% for different age-gender groups) these distributions are lognormal for most settlements.

Comparison of arithmetic and geometric means for the samples of measured thyroid activities, $(\tilde{Q}_{k,a,s,j})_t$, made on the same day *t* for children of the same age and gender in the same settlement *j* showed that this ratio is rather stable for all samples. It ranges from *1.35* to *1.53*. Ratios between arithmetic and geometric means for instrumentally-individualized time-integrated thyroid activities $A_{k,a,s,j}$ for people of the same gender, age, and settlement *j* averaged over all settlements ranged from *1.28* to *1.61* for all age-gender groups.

Comparison of results obtained in the first and second levels of thyroid dose estimation shows that for all age-gender groups geometric means of the instrumentally-individualized time-integrated thyroid activities $A_{k,a,s,j}$ are very close to the calculated values of $\tilde{A}_{a,s,j}$: the ratios averaged over all age groups are *1.06* and *1.08* for boys and girlrs with standard deviation of about *0.05*. The ratios of the arithmetic means of $A_{k,a,s,j}$ to $\tilde{A}_{a,s,j}$ in the same sets are substantially greater, with values averaged over all age groups of *1.5- 1.4* with standard deviation of *0.15-0.14*.

Therefore, group assessments of the thyroid doses of the second level, $\tilde{D}_{a,s,j}$, obtained for age-gender group *a-s* of any settlement *j*, are close to the geometric means of the instrumentally-individualized doses obtained for the same age gender group from the same settlement. Assuming that distributions of the estimated thyroid doses of the second level are lognormal, the corresponding arithmetic means of those distributions can easily be derived from the geometric means and geometric standard deviations [*44*].

The third level of thyroid dose estimation

The third level of thyroid dose estimation provides oblast-specific thyroid dose estimates for the 36 age-gender groups. The procedure of the oblast-level thyroid dose aggregation includes dose estimates for settlements with and without direct thyroid measurements. The first subsection deals with the three oblasts where thyroid measurements were made in some settlements. Then the procedure of dose estimation for oblasts without thyroid activity measurements is presented.

Direct measurements of thyroid activity were performed on children, adolescents (aged ≤ 18 y) and adults in the 787 settlements of Kyiv, Zhytomyr and Chernihiv oblasts (including Kyiv, Zhytomyr and Chernihiv cities). The thyroid doses for 36 age-gender groups in 748 of these 787 settlements were estimated using the second level of thyroid dose estimation. Although many direct thyroid measurements were performed in Kyiv, Zhytomyr and Chernihiv oblasts, there are raions in these oblasts where no measurements were made The settlements in these oblasts (and in general in the whole territory of Ukraine) can be subdivided into three groups:

- Group 1 includes settlements where direct measurements were performed in 1986; the second level of thyroid dose estimation was used for the inhabitants of these settlements. Index *j* was used for the identification of the settlements of group 1.
- Group 2 includes settlements where no direct thyroid measurements were made, but that are located in raions where measurements were made in other

settlements. Index j^* will be used for the identification of the settlements of group 2.

- Group 3 includes settlements that are located in raions, or oblasts, where no direct thyroid measurements were made. Index j^{**} will be used for the identification of the settlements of group 3.

Most of the settlements in Ukraine fall into Group 3.

Thyroid dose estimation for the settlements of Group 2. The estimation of the average time-integrated thyroidal ^{131}I activities $A_{a,s,j*}$ (Bq d) for settlements of Group 2 are based on dose estimates derived from direct thyroid measurements in settlements in the same raion as the settlement of interest. This was done using a raion scaling factor $K^{scal}_{s,\,raion}$ which is the average value of the scaling factors for the settlements j of Group 1 $K^{scal}_{s,\,j}$. Scaling factor $K^{scal}_{s,\,j}$ were defined as ratio of the time-integrated thyroidal ^{131}I activity estimated using the ecological model $A^{ecol}_{a_{ref},s,j}$, (Bq d), to the time-integrated thyroidal ^{131}I activity $\tilde{A}_{a_{ref},s,j}$ estimated based on results of direct thyroid measurements using the function $f_{a,s}$. Values of $K^{scal}_{s,\,raion}$ estimated for each gender in 14 different raions of Kyiv, Zhytomyr, and Chernihiv oblasts are given in Table 3. Total number of settlements in each raion and number of settlements that were used for the development of the scaling factors $K^{scal}_{s,\,raion}$ also are given in Table 3.

The thyroid doses for the 36 age-gender groups in the settlements j^* of Group 2, where direct thyroid measurements were not performed in 1986, D_{a,s,j^*},are estimated as:

$$D_{a,s,j^*} = \frac{\alpha}{M_a} \cdot \frac{A^{ecol}_{a_{ref},s,j^*}}{K^{scal}_{s,\,raion}} \cdot f_{a,s} \qquad (6)$$

Thyroid dose estimation for the settlements of Group 3. Direct thyroid measurements were not performed in 21 oblasts of Ukraine and the Republic of Crimea. These areas include 25,803 settlements with about 12 million people aged 1-18 years old. All these settlements as well as the settlements of Kyiv, Zhytomyr, and Chernihiv oblasts located in the raions where there were no direct measurements belong to the settlements of Group 3.

Table 3 shows that there are rather substantial differences between the time-integrated thyroid ^{131}I activities for the reference age interval calculated with the ecological model ($A^{ecol}_{a_{ref},s,j}$) and those based upon thyroid measurements ($\tilde{A}_{a_{ref},s,j}$). A number of reasons may cause such differences, including inaccuracies in the estimates of ^{131}I deposition densities, in the parameters of the ecological model and overestimation of consumption rates of milk and leafy vegetable due to personal or parental restriction. It is assumed that personal or parental restriction of dietary intake was correlated with the level of local deposition of radioactivity. Information on ^{137}Cs deposition was used in this analysis as these data are easily available. The time-integrated thyroidal ^{131}I activities $A_{a,s,j^{**}}$ for the settlements j^{**} were calculated using the scaling factor $K^{scal}_{s,j^{**}}$ determined as: $K^{scal}_{s,j^{**}} = B \cdot \sigma^{\beta}_{Cs,j^{**}}$. For the estimation of the parameters B and β the correlation between values of scaling factors $K^{scal}_{s,j}$ for all settlements j of Group 1 in Kyiv, Chernihiv and Zhytomyr oblasts**,** and the measured cumulative density of ^{137}Cs deposition $\sigma_{Cs,j}$ ($kBq \cdot m^{-2}$) for these settlements was analyzed. Parameters B and β used $K^{scal}_{s,j^{**}}$ estimated, by fitting, for rural and urban boys and girls, are given in Table 4. For the settlements with low levels of ^{137}Cs deposition, $\sigma^{\beta}_{Cs,j^{**}}$, the calculated value $K^{scal}_{s,j**}$ was found to be lower than 1 and, a value $K^{scal}_{s,j**}$ =1 for these settlements was assumed. Thus the thyroid doses for each of 36 age-gender groups in the settlements of Group 3 , $D_{a,s,j^{**}}$, is:

$$D_{a,s,j^{**}} = \frac{\alpha}{M_a} \cdot \frac{A^{ecol}_{a_{ref},s,j^*}}{K^{scal}_{s,j**}} \cdot f_{a,s} \qquad (7)$$

Oblast-specific thyroid doses for different age-gender groups of Kyiv, Zhytomyr and Chernihiv oblasts were estimated as sum of population weighed doses averaged over the settlements of Group 1 ($\tilde{D}_{a,s,j}$), Group 2 (D_{a,s,j^*}) and group 3 ($D_{a,s,j^{**}}$)[2]. In the oblasts with no direct thyroid measurements in 1986 all settlements belong to Group 3. Therefor the oblast-specific thyroid doses for every age gender group in these oblasts were estimated as the population weighted doses $D_{a,s,j^{**}}$ averaged over all settlements of the oblasts.

Main results and discussion

First level of thyroid dosimetry: instrumentally individualized thyroid doses

About 130,000 instrumentally individualized thyroid doses were reconstructed for Ukrainian people whose thyroid activities were measured in 1986. These measurements were made in Kyiv, Zhytomyr, and Chernihiv oblasts, which were the most contaminated after the Chernobyl accident. The estimated instrumentally individualized doses for different age and gender groups in Kyiv, Zhytomyr, and Chernihiv oblasts are given in Table 5. The doses are given separately for rural and urban populations, as well as for

[2] This is an approximation as the sum of medians is not equal to the median of the sum, if the distributions are lognormal. This approximation is considered to be adequate for the purposes of the present analysis

large cities Kyiv, Zhytomyr, and Chernihiv. At the end of the table are dose distributions for the evacuees. Age distributions for individuals with unknown gender are given separately, as records of many measurements do not include that information.

Second level of thyroid dosimetry: settlement- specific thyroid doses

Age and gender settlement-specific thyroid doses were estimated for 748 settlements of Kyiv, Zhytomyr, and Chernihiv oblast where thyroid activity measurements were performed in May-June 1986. For every settlement 36 thyroid doses (18 ages for two genders) were estimated using values of $f_{a,s}$ (Table 2) and results of the thyroid measurements made in the settlement. The distributions of the number of settlements according to the thyroid dose for the reference age interval ($\tilde{D}_{a_{ref,j}}$) are shown on Table 6.

Third level of thyroid dosimetry: oblast specific thyroid doses

Oblast-specific thyroid dose estimates for 36 age- and gender groups are shown in Table 7 for 24 oblasts, Kyiv-city, the Crimean Republic, and the city of Sevastopol'. The estimated thyroid doses for different Ukrainian oblasts are between *3 mGy* (Zakarpattya oblast) and *84 mGy* (Zhytomyr oblast). The thyroid doses for particular age and gender groups in Zhytomyr oblast are in the range *29-176 mGy,* for Kyiv oblast the range is *28-172 mGy*; for Chernihiv oblast the range *is 20-121 mGy*. Two other oblasts with upper range doses in excess of 100 mGy are Rivne oblast (*23-149 mGy*), and Cherkasy oblast (*18-117 mGy*). In all cases, the highest doses are estimated for children who are 1or 2 years old.

Future work

The approaches used for three levels of thyroid dose estimation summarize the current status of retrospective thyroid dosimetry achieved in Ukraine up to the year 2003. In the framework of the Ukrainian-American cohort thyroid study [*21,22,31*] the questionnaire-based instrumentally individualized approach is used to estimate the individual thyroid doses. The other approaches are employed in the ecological epidemiologic analyses of thyroid cancer incidence after the Chernobyl accident.

At this point, it is also appropriate to identify a number of areas of dosimetric research needed for reducing the uncertainty associated with thyroid dose estimations. There are:

- Modification of some parameters of iodine metabolism depending on the level of stable iodine in the diet. This is most important for the condition of iodine deficiency, which was prevalent in northern Ukraine at the time of Chernobyl accident;
- Clarification of the age-dependent thyroid mass for the children and adolescents of Ukraine at the time of Chernobyl accident, as influenced by the level of dietary iodine..
- More precise description of reference diets, especially for young children at the time of the accident. This is because restrictions of milk and leafy vegetable consumption most likely were applied by parents to this subgroup of children.
- Evaluation of the uncertainties of the ^{131}I deposition estimates and of the parameter values s used in the ecological model .
- Evaluation of the doses received by children aged less than 1 year at the time of the accident.
- Evaluation of the uncertainties in the models used for the three levels of thyroid dose estimation.

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List of footnotes.

Page 4. [1] Raion is an administrative unit within an oblast. Usually there are 10 to 20 raions in an oblast. The raion is comparable to a county in the United Stattes, while the oblast is comparable to a state.

Page 15. [2] This is an approximation as the sum of medians is not equal to the median of the sum, if the distributions are lognormal. This approximation is considered to be adequate for the purposes of the present analysis

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Figure 1. Estimated cumulative ^{131}I deposition on the territory of Ukraine [*2, 3*].

Figure 2. Distribution of the numbers of direct thyroid measurements made in Ukraine in 1986 for children and adolescents.

Table 1. Number of Ukrainian settlements where direct thyroid measurements were made in 1986 and number of the measurements. *M* is male, *F* is female, and *Unknown* corresponds to "gender is not given in record", *Evacuees, Non-evacuees* refer to measurements of persons from settlements which were or were not evacuated (resettled) in May 1986, respectively.

Type of population	Number of settlements	Number of thyroid measurements			
		F	M	Unknown	Total
1. Total amount of measurements performed at the settlements					
1. All measurements	787	59,628	52,,001	18,625	130,254
1.1 Evacuees	53	4,911	4,277	362	9,550
1.2 Non-evacuees	734	54,717	47,724	18,263	120,704
2. Settlements where ≥ 10 thyroid measurements were made by SRP and/or ≥ 4 measurements were made by other devices [a]					
2.1. Evacuees	51	4,079	4,069	-	8,148
2.2 Non-evacuees: Rural&Urban	697	37,788	37,559	-	75,347
2.2.1 Rural	661	20,453	20,153	-	40,606
2.2.2 Urban	36	17,335	17,406	-	34,741
3. Settlements with thyroid measurements in the reference age-interval of 12-14 years old [a]					
3.1.Evacuees	49	4,069	4,049	-	8,118
3.2.Non-evacuees: Rural&Urban	619	36,899	36,807	-	73,706
3.2.1 Rural	584	19,566	19,401	-	38,967
3.2.2 Urban	35	17,333	17,406	-	34,739

[a] Persons whose gender was unknown are not included to the analysis

Table 2. Values of the relative age and gender time-integrated thyroidal ^{131}I activity, $f_{a,s}$, estimated for the urban and rural population and evacuees of Kyiv, Chernihiv and Zhytomyr oblasts. The reference age group is 12–14 y. *M* is male, *F* is female, *GM* is geometric mean; *GSD* is geometric standard deviation.

	$f_{a,s}$ – values											
age, years	Non-evacuated population								Evacuated population			
	Urban				Rural				Urban & Rural			
	F		M		F		M		F		M	
	GM	GSD	GM	GSD	GM	GSD	GM	GSD	GM	GSD	GM	GSD
1	0.81	3.26	0.61	3.03	0.58	3.06	0.47	3.23	0.75	2.69	0.82	3.56
2	0.81	2.84	0.62	3.02	0.64	2.83	0.55	2.82	0.84	2.79	0.95	3.23
3	0.77	2.48	0.61	2.82	0.64	2.74	0.54	2.60	0.81	3.61	0.68	5.13
4	0.86	2.35	0.67	2.51	0.70	2.59	0.56	2.88	0.77	4.05	0.74	2.27
5	0.97	2.52	0.86	2.54	0.70	2.63	0.59	2.59	0.80	2.86	0.88	2.88
6	1.03	2.30	0.86	2.27	0.77	2.49	0.66	2.62	0.88	2.83	0.85	3.08
7	1.00	2.13	0.85	2.31	0.75	2.24	0.70	2.35	0.92	3.39	0.76	2.63
8	0.88	2.39	0.79	2.37	0.76	2.36	0.72	2.46	0.71	2.82	0.80	2.28
9	0.91	2.18	0.81	2.15	0.80	2.39	0.79	2.36	0.81	3.08	0.66	2.80
10	0.92	2.17	0.81	2.17	0.81	2.38	0.84	2.19	0.87	2.58	1.10	2.46
11	0.97	2.11	0.91	2.09	0.89	2.20	0.85	2.32	0.80	2.97	0.86	2.44
12	0.95	2.08	0.94	2.14	0.95	2.09	0.90	2.24	0.94	2.84	0.92	2.32
13	1.00	2.11	0.96	2.16	1.01	2.07	1.00	2.24	0.97	2.02	0.95	2.23
14	1.06	2.12	1.11	2.22	1.04	2.12	1.11	2.24	1.06	2.25	1.13	2.44
15	1.11	2.21	1.14	2.28	1.03	2.32	1.21	2.36	1.06	2.39	1.27	3.27
16	1.16	2.37	1.14	2.50	1.04	2.38	1.28	2.51	0.84	3.38	1.10	3.00
17	1.19	2.53	1.12	2.33	1.03	2.35	1.12	2.43	0.76	1.94	1.03	2.98
18	1.12	2.81	1.01	2.96	0.95	2.66	1.07	2.14	0.86	2.31	2.42	1.96

Table 3. Raion-specific scale factor $K^{scal}_{s,raion}$ for raions in Kyiv, Zhytomyr and Chernihiv oblasts. *M* is male, *F* is female, *STD* is standard deviation.

Oblast	Raion	Gender	Number of settlements		$K^{scal}_{s,raion}$	
			Total number in raion	Number of settlements with direct measurements	Mean	STD
Zhytomyr	Korosten'	F	112	53	5.2	3.1
		M		54	6.2	3.4
	Luhyny	F	49	3	4.7	4.1
		M		2	8.4	7.9
	Narodychi	F	84	67	2.5	2.1
		M		64	2.8	2.3
	Ovruch	F	157	116	3.2	2.3
		M		122	3.9	2.6
	Olevs'k	F	61	10	4.7	2.1
		M		7	5.4	3.3
Kyiv	Borodianka	F	47	29	5.1	3.7
		M		29	6.9	4.8
	Vyshhorod	F	59	40	3.5	1.7
		M		40	4.8	2.3
	Ivankiv	F	73	49	4.8	3.6
		M		49	6.0	4.3
	Kyievo-Sviatoshyn	F	51	3	3.6	1.8
		M		3	5.9	1.6
	Makariv	F	68	42	1.6	0.7
		M		42	2.1	1.1
	Polis'ke	F	61	43	5.5	8.2
		M		44	10.5	17.7
Chernihiv	Kozelet's	F	111	82	2.1	1.4
		M		81	2.5	1.9
	Ripky	F	120	59	2.1	3.3
		M		58	2.3	4.4
	Chernihiv	F	128	85	0.9	1.0
		M		85	1.3	1.8

Table 4. Values of parameters of function approximating *scaling factors for the settlements of group 3,* $K_{s,j**}^{scal}$ estimated for the different subpopulations in the settlements without direct thyroid measurements; $K_{s,j**}^{scal} = B \cdot \sigma_{Cs}^{\beta}$,. *M* is male, *F* is female, *B* and *β* are the parameters of the function.

Subpopulation		*B*		*β*	
		GM	GSD	Mean	STD
Rural	M	0.59	1.1	0.36	0.103
	F	0.47	1.1	0.36	0.103
Urban	M	0.36	1.5	0.61	0.110
	F	0.34	1.5	0.58	0.110

Table 5. Distribution of the instrumentally-individualized thyroid doses due to the Chernobyl accident in Chernihiv, Zhytomyr and Kyiv oblasts over the age-sex groups.

Age group (years)	Male			Female			Unknown gender			All		
	Number of measurem	Dose		Number of measureme	Dose		Number of measurem	Dose		Number of measurem	Dose	
		GM	GSD		GM	GSD		GM	GSD		GM	GSD
Chernihiv oblast, rural settlements												
1-4	1827	166	3.4	1907	156	3.3	2305	153	3.3	6039	158	3.4
5-9	2323	111	3.2	2495	96	3.2	2710	92	2.9	7528	99	3.1
10-14	2600	79	3.6	2866	67	3.5	2869	69	3.0	8335	72	3.3
15-18	725	65	4.3	922	41	4.4	1049	43	3.5	2696	47	4.1
19+	1546	30	3.1	3572	32	3.4	2903	28	2.9	8021	30	3.2
All	9021	84	3.8	11762	64	3.9	11836	66	3.6	32619	70	3.8
Chernihiv oblast, towns												
1-4	140	60	2.6	134	67	2.7	87	61	3.0	361	63	2.7
5-9	142	35	2.6	206	33	2.5	127	46	2.3	475	37	2.5
10-14	192	34	2.2	192	24	2.4	73	31	2.2	457	29	2.3
15-18	49	25	2.6	87	16	2.8	63	28	2.7	199	21	2.8
19+	46	24	2.3	132	17	2.6	141	18	2.6	319	18	2.6
All	569	37	2.6	751	28	2.9	491	33	2.8	1811	32	2.8
Chernihiv-city												
1-4	696	140	2.8	733	135	2.6	324	106	3.0	1753	131	2.7
5-9	1035	98	2.2	1059	88	2.3	427	80	2.6	2521	91	2.3
10-14	886	51	2.3	989	44	2.4	714	49	2.4	2589	48	2.4
15-18	120	52	2.5	218	43	2.2	152	52	2.6	490	48	2.4
19+	118	29	3.1	463	29	2.8	364	24	2.5	945	27	2.7
All	2855	81	2.7	3462	65	2.8	1981	55	2.9	8298	67	2.8
Zhytomyr oblast, rural settlements												
1-4	1933	552	4.0	1985	550	3.9	192	1536	3.6	4110	578	4.0
5-9	2666	293	3.6	2551	281	3.5	271	513	3.5	5488	296	3.6
10-14	3318	228	3.4	3298	191	3.3	332	289	3.2	6948	212	3.4
15-18	1574	232	3.3	1537	154	3.3	99	214	3.8	3210	190	3.4
19+	8013	284	2.9	11778	274	3.1	170	189	3.1	19961	277	3.0
All	17504	289	3.3	21149	266	3.4	1064	411	4.1	39717	279	3.4
Zhytomyr oblast, towns												
1-4	236	430	2.3	267	413	2.2	-	-	-	503	421	2.3
5-9	865	130	2.8	791	116	3.0	188	79	2.3	1844	117	2.9
10-14	1952	77	2.7	1743	66	2.6	639	44	2.8	4334	67	2.7
15-18	79	68	2.6	90	45	2.5	15	36	2.7	184	53	2.6
19+	97	113	3.1	59	91	3.4	2	35	3.3	158	103	3.2
All	3229	101	3.0	2950	90	3.1	844	50	2.8	7023	89	3.1

Zhytomyr-city

1-4	6	12	2.7	6	26	8.6	-	-	-	12	18	5.2
5-9	64	23	2.1	59	21	2.1	-	-	-	123	22	2.1
10-14	65	19	3.5	70	10	2.1	-	-	-	135	13	2.9
15-18	1	9	-	4	6	2.7	-	-	-	5	7	2.4
All	136	20	2.8	141	13	2.7	-	-	-	277	16	2.8
Kyiv oblast, rural settlements												
1-4	567	288	3.6	567	345	3.7	39	209	3.5	1173	311	3.7
5-9	2569	87	3.0	2369	78	2.9	285	59	2.7	5223	81	3.0
10-14	5769	68	2.9	5648	54	2.8	641	46	2.6	12058	60	2.8
15-18	2191	68	3.0	2202	52	2.8	347	58	2.4	4740	59	2.9
19+	20	56	3.7	550	77	3.2	20	92	3.4	590	77	3.3
All	11116	78	3.1	11336	65	3.1	1332	54	2.7	23784	70	3.1
Kyiv oblast, towns												
1-4	59	86	1.9	64	94	2.0	13	110	1.7	136	91	1.9
5-9	238	49	2.1	217	47	2.2	22	55	2.1	477	48	2.2
10-14	528	40	1.7	484	34	1.8	168	32	1.9	1180	36	1.8
15-18	238	33	1.8	218	27	1.9	43	26	1.7	499	30	1.9
19+	2	16	0.0	5	13	4.5	1	18	0.0	8	14	3.4
All	1065	42	1.9	988	37	2.1	247	35	2.0	2300	39	2.0
Kyiv-city												
1-4	75	75	4.1	67	97	4.7	37	226	3.1	179	104	4.3
5-9	552	27	2.2	543	25	2.0	107	31	2.3	1202	27	2.1
10-14	1484	20	1.9	1413	18	1.7	245	20	1.8	3142	19	1.8
15-18	76	25	2.4	58	20	2.2	11	29	2.1	145	23	2.3
19+	42	43	3.5	97	24	4.8	68	36	2.7	207	31	3.9
All	2229	23	2.2	2178	21	2.2	468	29	2.8	4875	23	2.2
Chernihiv, Zhytomyr and Kyiv oblasts, all settlements												
1-4	5539	259	4.0	5730	259	4.0	2997	168	3.8	14266	237	4.0
5-9	10454	119	3.6	10290	107	3.6	4137	93	3.2	24881	109	3.5
10-14	16794	77	3.5	16703	64	3.4	5681	60	3.1	39178	69	3.4
15-18	5053	93	3.8	5336	64	3.7	1779	49	3.4	12168	72	3.7
19+	9884	188	4.0	16658	149	4.5	3669	30	3.1	30211	132	4.6
All	47724	120	4.0	54717	106	4.2	18263	67	3.7	120704	104	4.1
Evacuated inhabiatnces												
1-4	696	419	4.3	719	389	3.9	60	498	4.0	1475	407	4.1
5-9	1182	169	3.6	1163	174	3.8	87	206	3.5	2432	173	3.7
10-14	1700	102	3.5	1595	94	3.4	101	120	4.4	3396	98	3.5
15-18	582	104	3.7	667	82	3.5	87	130	3.7	1336	93	3.6
19+	117	309	3.8	767	108	3.6	27	180	3.5	911	126	3.8
All	4277	152	4.1	4911	134	4.0	362	182	4.2	9550	144	4.0

Table 6. Distribution of settlements where direct thyroid measurements were performed in 1986 according to average thyroid dose among children aged 12 to 14 (reference age interval).

Oblasts [a]	No of settle-ments	No of children aged 1 to 18 in 1986	Number of settlements with thyroid doses to the reference age-interval in the indicated dose-interval							
			<20 mGy	20-50 mGy	50-100 mGy	100-200 mGy	200-500 mGy	500-1000 mGy	1000-2000 mGy	>2000 mGy
Kyiv	255	97.200	-	38	103	68	37	4	5	-
Zhytomyr	261	74.400	1	9	42	62	87	37	18	5
Chernihiv	229	36.800	16	71	56	49	31	5	1	

[a] These results do not include estimates for the reference age-group in the largest cities of the oblasts. Thyroid doses to the reference age-interval in Kyiv-city, Chernihiv city, and Zhytomyr city are estimated to be *18.6 mGy*, *48.6 mGy,* and 12.2 *mGy*, respectively.

Table 7. Oblast-specific thyroid doses (*mGy*) for different age and gender groups in Ukraine.

Oblast	Population	Sex	Average		Age in 1986: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
					Dose, mGy																	
Kyiv	241100	F	76	81	170	148	127	123	103	93	76	63	58	53	53	51	48	42	38	36	33	28
	247190	M	85		162	149	128	118	110	95	83	71	68	65	62	61	61	59	64	61	48	38
Chernihiv	159070	F	54	58	120	104	89	84	74	64	52	42	39	37	37	33	33	32	28	26	24	20
	162630	M	62		121	109	93	88	82	71	60	52	47	45	44	42	40	39	44	41	34	28
Zhytomyr	195730	F	80	87	169	165	128	129	109	98	81	69	62	57	57	50	48	46	38	33	34	29
	205410	M	94		170	177	143	132	122	10	95	83	78	74	71	65	64	66	69	63	55	47
Kyiv – city	319030	F	32	32	77	64	52	51	47	41	33	25	23	21	20	18	17	17	16	15	14	12
	329510	M	32		68	57	48	46	48	40	33	26	24	21	21	21	19	20	19	17	15	12
Cherkasy	177240	F	49	55	112	99	84	82	70	63	52	44	40	34	34	29	27	26	25	22	21	18
	186710	M	61		117	109	92	86	79	70	62	54	51	48	45	43	43	44	45	40	33	28
Rivne	173910	F	64	71	143	128	109	105	89	79	65	56	52	43	43	42	40	38	35	30	28	23
	177460	M	77		149	140	128	109	98	88	77	68	65	59	55	54	54	55	56	50	42	35
Kherson	168680	F	12	14	27	24	20	19	17	15	12	10	9	8	8	7	7	6	6	5	5	4
	167930	M	16		32	29	24	23	21	19	16	14	13	12	11	11	10	11	10	9	8	7

Oblast	Population	Sex	Average		Age in 1986																	
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			Dose, mGy																			
Kirovohrad	147060	F	31	35	73	62	53	51	45	40	32	27	24	21	21	18	18	17	16	14	14	11
	156800	M	38		77	70	59	55	52	45	39	34	32	29	27	26	25	26	25	22	19	16
Vinnytsia	223970	F	13	14	29	26	22	21	18	16	13	11	10	9	9	7	7	7	7	6	6	5
	254830	M	16		32	29	25	23	21	19	16	14	13	12	11	11	11	11	11	10	8	7
Sumy	166960	F	25	28	59	51	42	42	37	32	27	22	20	18	17	15	14	14	13	12	11	9
	175580	M	31		62	56	48	44	42	36	32	27	25	24	22	22	21	22	22	19	16	13
Poltava	197750	F	19	21	45	39	33	31	27	24	19	16	15	13	13	12	11	11	10	9	9	7
	218520	M	23		48	44	37	34	32	28	24	21	19	17	17	16	16	16	16	15	13	11
Dnipropetrovs'k	483400	F	5	6	12	10	9	8	7	7	5	4	4	3	3	3	3	3	3	2	2	2
	496010	M	6		13	11	9	9	9	7	6	5	5	4	4	4	4	4	4	3	3	3
Khmel'nytsk	178920	F	14	16	31	28	23	23	19	17	14	12	11	10	9	8	8	8	7	7	6	5
	203950	M	18		35	32	28	26	24	21	18	16	15	14	13	13	13	13	13	12	10	8
Donets'k	630920	F	8	9	20	17	14	14	13	11	9	7	6	6	5	5	5	4	4	4	4	3
	707700	M	10		21	18	15	14	14	12	10	8	7	7	7	6	6	6	6	6	5	4

Oblast	Population	Sex	Average		Age in 1986																	
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			Dose, mGy																			
Chernivsi	129210	F	14	15	32	28	24	23	20	17	14	12	11	9	9	8	8	8	7	6	6	5
	133090	M	16		33	31	26	24	21	19	17	15	14	12	12	11	10	11	11	9	8	7
Volyn'	148440	F	32	35	70	62	53	51	44	39	32	27	25	22	21	21	20	19	17	15	14	12
	154330	M	39		76	70	59	55	50	44	39	34	33	31	29	28	28	29	29	26	22	18
Ivano-Frankivs'k	188550	F	7	8	15	13	11	11	9	8	7	6	5	5	5	4	4	4	4	3	3	2
	204540	M	8		16	15	13	12	10	9	8	7	7	6	6	5	5	6	6	5	4	4
Mykolaiv	170940	F	8	8	17	15	13	12	11	10	8	6	6	5	5	5	4	4	4	4	3	3
	171260	M	9		19	17	14	13	13	11	9	8	7	7	6	6	6	6	6	6	5	4
Odesa	338050	F	6	6	13	11	9	9	8	7	6	5	4	4	4	3	3	3	3	3	2	2
	354290	M	6		14	12	10	10	9	8	7	6	5	5	5	4	4	4	4	3	3	3
L'viv	364170	F	5	6	12	11	9	9	7	7	5	4	4	4	3	3	3	3	3	2	2	2
	383440	M	6		13	12	10	10	9	8	7	6	5	5	5	4	4	4	4	4	3	3
Kharkiv	389410	F	9	9	22	18	15	15	13	12	9	8	7	6	6	5	5	5	5	4	4	3
	404420	M	10		22	19	16	15	15	13	11	9	8	7	7	7	7	7	7	6	5	4

Oblast	Population	Sex	Average		Age in 1986																	
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			Dose, mGy																			
Luhans'k	337507	F	4	4	10	8	7	7	6	5	4	3	3	3	3	2	2	2	2	2	2	1
	373885	M	5		9	8	7	6	6	5	5	4	3	3	3	3	3	3	3	3	2	2
Zaporizhzhia	256625	F	10	11	23	20	17	16	14	12	10	8	8	7	7	6	5	5	5	4	4	4
	262238	M	12		26	23	20	18	17	15	13	11	10	9	9	7	7	7	7	6	6	5
Ternopil'	144017	F	6	7	15	13	11	10	9	8	6	5	5	4	4	4	3	3	3	3	3	2
	156910	M	8		16	15	13	12	10	9	8	7	7	6	6	5	5	5	5	5	4	4
Zakarpattia	186357	F	3	3	6	6	5	5	4	3	3	2	2	2	2	2	2	2	2	1	1	1
	192349	M	4		7	7	6	5	5	4	4	3	3	3	3	3	3	3	3	2	2	2
Crimea	258945	F	13	14	29	25	21	21	18	16	13	10	10	9	8	8	7	7	7	6	6	5
	268493	M	16		33	29	25	23	22	19	16	14	13	12	11	11	10	10	10	9	8	7
Sevastopol' city	47164	F	20	20	49	41	33	33	30	26	21	16	15	13	13	12	11	11	10	9	9	8
	53812	M	19		43	37	31	30	31	25	21	17	16	14	14	13	13	13	12	11	10	8

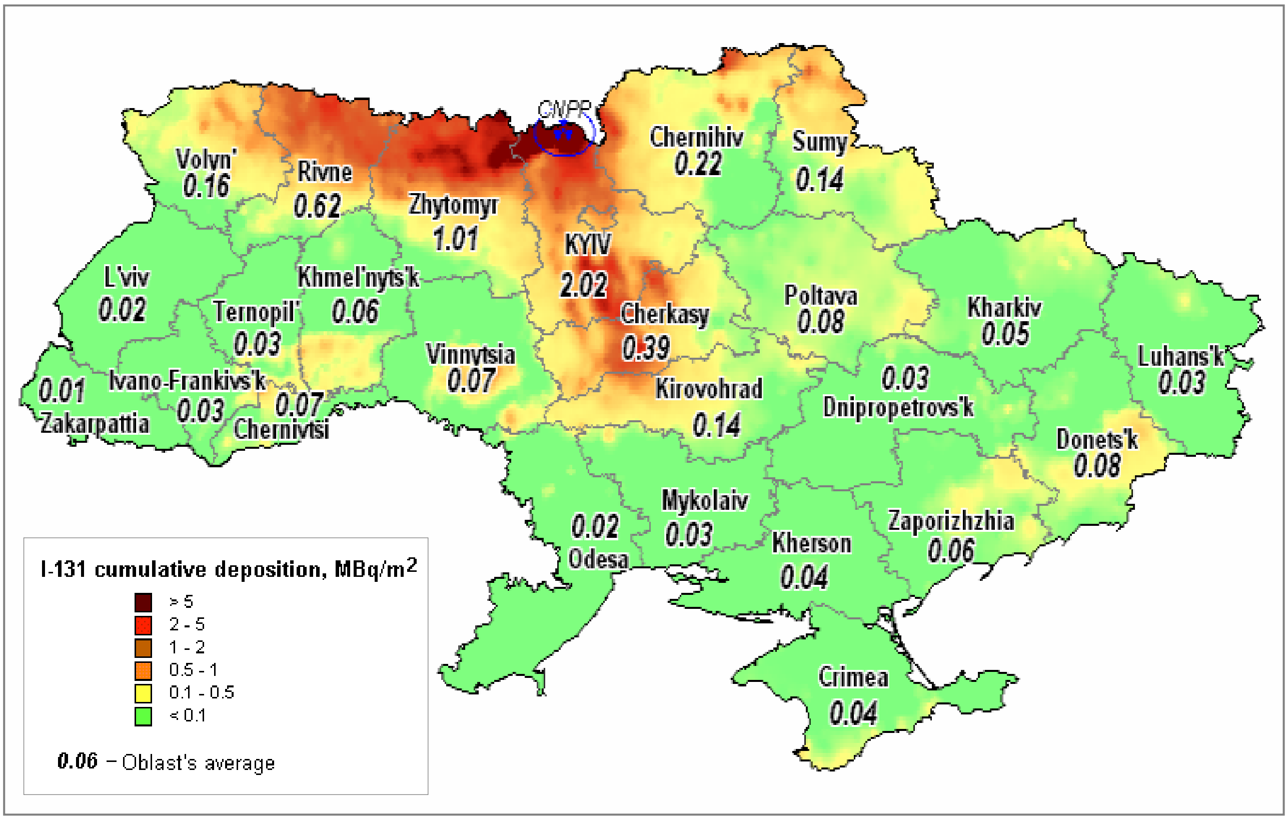

Figure.1. Estimated cumulative ^{131}I deposition on the territory of Ukraine [*2, 3*].

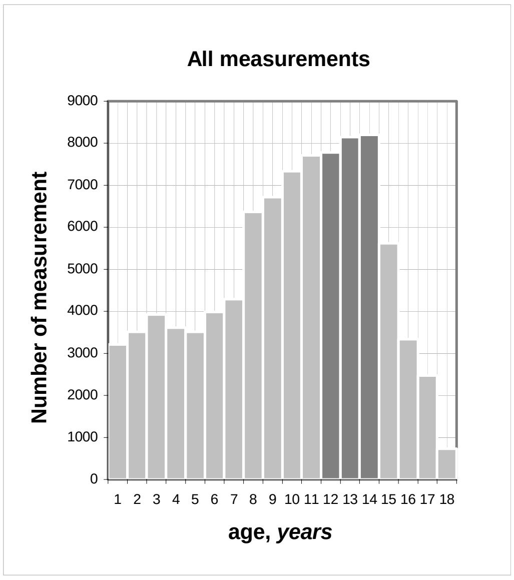

Figure 2. Distribution of the numbers of direct thyroid measurements made in Ukraine in 1986 on children and adolescents.

Annex 1 – ECOLOGICAL MODEL USED FOR THE FIRST LEVEL OF THYROID DOSE ESTIMATION: EQUATIONS AND PARAMETERS

The description of the ecological model is given below for the simple case of a single ground deposition σ_r $(Bq \cdot m^{-2})$ of radionuclide *r* on the territory of the settlement. The following notations will be used to specify the considered nuclides: ^{131}I ($r=1$), ^{137}Cs($r=2$), ^{134}Cs($r=3$), ^{136}Cs($r=4$). In the actual dose calculations, the estimates of daily depositions of radionuclides between 26 April and 5 May are taken into account.

The radionuclide concentration in the thyroid due to the inhalation pathway $Q_{a,s}^{I,inhal}(t)$ was considered only for ^{131}I and calculated as follows:

$$Q_{a,s}^{I,inhal}(t) = \frac{\sigma_1}{v_I} \cdot w_a^{inhal} \cdot K_{inhal\cdot}^{I} \cdot K_{uptake}^{1}\, e^{-\lambda_a^{I,ef} \cdot t} \qquad \text{(A1.1)}$$

here: w_a^{inhal} is the breathing rate for persons of age *a*, $(m^3 \cdot d^{-1})$,

v_r is the dry deposition velocity,($m\ d^{-1}$) for nuclide r,

K_{inhall}^{I} is the fraction of ^{131}I inhalation intake transferred to blood via lung;

K_{uptake}^{r} is the uptake of radionuclide *r* from blood to the thyroid (body),

$\lambda_a^{r,ef}$ is the effective elimination rate constant for radionuclide r.

The component of radionuclide activity in the thyroid/body that is due to the consumption of leafy vegetables $Q_{a,s}^{r,veg}(t)$ is:

$$Q_{a,s}^{r,veg}(t) = K_{uptake}^{r} \cdot K_{ing}^{r} \frac{k_w^r}{M_{biom}} \cdot \sigma_r \cdot w_{a,s}^{veg} \cdot \Bigg[\frac{a_r}{L_I^r - \lambda_a^{r,biol}} \left(e^{-\lambda_a^{r,ef} \cdot t} - e^{-L_I^{r,ef} \cdot t} \right) +$$

$$+\frac{1-a_r}{L_2^r-\lambda_a^{r,biol}}\cdot\left(e^{-\lambda_a^{r,ef}\cdot t}-e^{-L_2^{r,ef}\cdot t}\right)\Bigg], \qquad \text{(A1.2)}$$

here: K_{ing}^r is the resorption factor from gastrointestinal to blood for the radionuclide r; $K_{ing}^r = 1$

[34] for cesium and iodine radionuclides,

k_w^r is the interception factor by pasture grass for radionuclide r;

M_{biom} is the yield of pasture grass ($kg\ m^{-2}$);

$w_{a,s}^{veg}$ is the daily consumption of leafy vegetables by a representative of the *a-s* age-gender group ($kg{\cdot}d^{-1}$),

L_1^r, L_2^r are rate constants of removal of radionuclide r from the grass surfaces by weathering (d^{-1}); $L_1^{r,ef} = L_1^r + \lambda^r$ and $L_2^{r,ef} = L_2^r + \lambda^r$;

a_r is the fraction of the contamination that is removed with the coefficient L_1^r;

λ_r is the radioactive decay rate constant of radionuclide r (d^{-1}).

The milk component of the radionuclide activity in the thyroid/body $Q_{a,s}^{r,m}(t)$ can be calculated as:

$$Q_{a,s}^{r,m}(t)=K_{uptake}^r\cdot K_{ing}^r\,\frac{k_w^r}{M_{biom}}\cdot\sigma_r\cdot w_{a,s}^{veg}\cdot\cdot\,TF_r\cdot w_{grass}^{cow}\cdot\sum_{n=1}^{2}\,Q_{cow,n}^r\cdot\lambda_{cow,n}^r\times$$

$$\times\Bigg[\frac{a_r}{\lambda_{cow,n}^r-L_1^r}\left(\frac{e^{-\lambda_a^{r,ef}\cdot t}-e^{-L_1^{r,ef}\cdot t}}{L_1^r-\lambda_a^{r,biol}}-\frac{e^{-\lambda_a^{r,ef}\cdot t}-e^{-\lambda_{cow,n}^{r,ef}\cdot t}}{\lambda_{cow,n}^r-\lambda_a^{r,biol}}\right)+ \qquad \text{(A1.3)}$$

$$+\frac{1-a_r}{\lambda_{cow,n}^r-L_2^r}\left(\frac{e^{-\lambda_a^{r,ef}\cdot t}-e^{-L_2^{r,ef}\cdot t}}{L_2^r-\lambda_a^{r,biol}}-\frac{e^{-\lambda_a^{r,ef}\cdot t}-e^{-\lambda_{cow,n}^{r,ef}\cdot t}}{\lambda_{cow,n}^r-\lambda_a^{r,biol}}\right)\Bigg].$$

here: $\lambda_{cow,n}^{r,ef}$ is the effective elimination rate constant for radionuclide r (d^{-1});

$\lambda^{r,ef}_{cow,1} = \lambda^{r}_{cow,1} + \lambda^{r}$ and $\lambda^{r,ef}_{cow,2} = \lambda^{r}_{cow,2} + \lambda^{r}$;

w^{cow}_{grass} is the daily consumption of pasture grass by the cow ($kg \cdot d^{-1}$);

TF_r is the transfer factor for radionuclide r from daily cow's intake to concentration in cow's milk ($d\ L^{-1}$).

The values of the parameters used in the ecological model described above are given in Table A1.1. The age and gender dependent daily consumption rates of milk, $w^{m}_{a,s}$, and leafy vegetables, $w^{veg}_{a,s}$, that were used in the model are shown in Table A1.2.

Table A1.1 Values of parameters used in the ecology-dosimetric model related to the cow, grass and human for radionuclides of iodine and cesium [*35, 36*].

Groups of parameters	Parameter	Units	Symbol	Radionuclide	
				Iodine	Cesium
				Default values	
Grass a) and leafy vegetables	Half-time of elimination - 1	d	T^{r}_{1}	**11**	**3**
	Half-time of elimination - 2	d	T^{r}_{2}	**50**	**50**
	Fraction of component – 1	-	a_r	**1**	**0.7**
	Fraction of component – 2	-	$1- a_r$	**-**	**0.3**
	Interception factor	-	k^{r}_{w}	**0.5**	**0.2**
	Culinary factor for leafy vegetables	-	K_{cul}	**0.8**	**0.5**
	Velocity of deposition	$m \cdot s^{-1}$	v_r	**600**	**-**
Cow b)	Half-time of elimination - 1	d	$T^{r}_{cow,1}$	**0.75**	**1**
	Half-time of elimination - 2	d	$T^{r}_{cow,2}$	**-**	**30**
	Fraction of compartment - 1	-	Q^{r}_{cow1}	**1**	**0.2**
	Fraction of compartment - 2	-	Q^{r}_{cow2}	**-**	**0.8**
	Transfer factor (cow's intake - milk)	$d\ L^{-1}$.	TF_r	**0.004**	**0.01**
Human	Uptake to blood from lung	-	K^{I}_{inhall}	**0.66**	**-**
	Resorption factor from gastrointestinal to blood for the radionuclide		K^{r}_{ing}	**1**	**1**
	Uptake of radionuclide from blood to the thyroid (I) or body (Cs)	-	K^{r}_{uptake}	**0.3**	**1**

- a) Yield of pasture grass (M_{biom}) is taken to be 0.7 $kg \cdot m^{-2}$

b) Cow's grass consumption rate (w^{cow}_{grass}) is taken to be 40 $kg \cdot d^{-1}$

Table A1.2. Daily milk consumption rates ($w^{m}_{a,s}$, *L per day*) and leafy vegetable consumption rates ($w^{veg}_{a,s}$, *kg per day*) for different age-gender groups used for the ecological thyroid doses estimations

age (*years*)	Rural inhabitants		Urban inhabitants		Rural inhabitants		Urban inhabitants	
	Male	Female	Male	Female	Male	Female	Male	Female
	Milk, *L per day*				Leafy vegetables, kg per day			
1	0.67	0.59	0.39	0.37	0.007	0.006	0.005	0.004
2	0.68	0.58	0.41	0.35	0.016	0.015	0.013	0.010
3	0.70	0.56	0.42	0.34	0.021	0.020	0.017	0.014
4	0.70	0.52	0.35	0.27	0.023	0.021	0.018	0.015
5	0.72	0.50	0.35	0.27	0.025	0.022	0.020	0.016
6	0.74	0.48	0.35	0.27	0.027	0.023	0.021	0.017
7	0.76	0.46	0.35	0.27	0.029	0.024	0.022	0.019
8	0.75	0.45	0.37	0.27	0.029	0.024	0.022	0.019
9	0.75	0.45	0.37	0.27	0.030	0.024	0.023	0.019
10	0.75	0.45	0.37	0.27	0.030	0.024	0.023	0.019
11	0.76	0.44	0.37	0.27	0.031	0.025	0.023	0.019
12	0.82	0.48	0.35	0.25	0.031	0.025	0.023	0.019
13	0.83	0.47	0.35	0.25	0.032	0.025	0.023	0.019
14	0.83	0.47	0.35	0.25	0.033	0.025	0.024	0.019
15	0.83	0.47	0.35	0.25	0.033	0.025	0.024	0.019
16	0.84	0.48	0.38	0.26	0.034	0.025	0.024	0.019
17	0.85	0.47	0.38	0.26	0.035	0.025	0.024	0.019
18	0.85	0.47	0.38	0.26	0.035	0.025	0.025	0.019