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Validation of ^{131}I ecological transfer models and thyroid dose assessments using Chernobyl fallout data from the Plavsk district, Russia

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Abstract

Within the project “Environmental Modelling for Radiation Safety” (EMRAS) organized by the IAEA in 2003 experimental data of ^{131}I measurements following the Chernobyl accident in the Plavsk district of Tula region, Russia were used to validate the calculations of some radioecological transfer models. Nine models participated in the inter-comparison. Levels of ^{137}Cs soil contamination in all the settlements and $^{131}\text{I}/^{137}\text{Cs}$ isotopic ratios in the depositions in some locations were used as the main input information. 370 measurements of ^{131}I content in thyroid of townspeople and villagers, and 90 measurements of ^{131}I concentration in milk were used for validation of the model predictions.

A remarkable improvement in models performance comparing with previous inter-comparison exercise was demonstrated. Predictions of the various models were within a factor of three relative to the observations, discrepancies between the estimates of average doses to thyroid produced by most participant not exceeded a factor of ten.

Keywords

Chernobyl accident; iodine-131; environment modeling; models validation; population; thyroid dose

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1. Introduction

In 2003 the International Atomic Energy Agency (IAEA) initiated a programme of “**E**nvironmental **M**odelling for **R**adiation **S**afety” (EMRAS) to improve the predictive capabilities of environmental models used to assess the impact of radionuclide releases to any part of the environment (atmosphere, aquatic and urban environments). EMRAS continued some of the work from the previous international projects in the field of radioecological modeling designed to develop and improve capabilities for predicting the transfer of radionuclides into the environment. Those projects included VAMP (**V**alidation of **M**odel **P**redictions), BIOMOVs (**B**IOospheric **M**odel **V**alidation **S**tudy), BIOMOVs II, and BIOMASS (**B**IOsphere **M**odelling and **A**SSessment),

In the framework of the BIOMASS programme, the predictive capabilities of some radioiodine ecological models was compared using the data of the Hanford scenario that presented a description and results of ^{131}I measurements in environmental samples following an accidental release of ^{131}I to atmosphere in 1963 (IAEA-BIOMASS- 2, 2003). All the available measurements were offered to modelers as input information, but they were not ideally suited for model testing purposes. In that case, the resulting model predictions of thyroid dose in inhabitants of the tested locations due to exposure to ^{131}I varied by up to two orders of magnitude. There were only two cases of ^{131}I thyroid measurements of local residents in the scenario which could be used for the testing of model calculations.

Following a release of radioiodine into the environment estimates of internal doses are subject to a wide range of uncertainty. After the explosion at the Chernobyl NPP on April 26, 1986 the ^{131}I measurements in the human thyroid and in the environment were carried out using available devices and routine methods to attempt to acquire data for predicting the range of possible consequences. The quantity and quality of many of the measurements were not sufficient to provide accurate evaluation of the dynamics of the ^{131}I intake into the human body and the resulting thyroid doses received by the inhabitants. The large variation in inhabitants' behavior and agricultural practices also produced a considerable variation of estimated thyroid doses.

One of the six themes of the EMRAS programme was dedicated to the modeling of the transport of iodine radioisotopes in the environment. The ^{131}I Working Group's (IWG) task was to carry out an environmental modeling exercise on ^{131}I , to test and compare model predictions with environmental data available due to the Chernobyl accident, and to compare modeling approaches and model predictions among different assessors. The IWG Leader was P. Krajewski. The IWG has examined three scenarios using measurement data as described by Krajewski et.al (2008). The present paper describes the IWG's first study on model validation using the data of the Plavsk scenario.

The Plavsk district, in the Tula region of Russia, is located about 600 km north-east of the Chernobyl NPP. This area was highly contaminated with radioactive fallout after the Chernobyl accident with levels up to 600 kBq m^{-2} of ^{137}Cs . Three hundred and seventy (370) measurements of ^{131}I content in thyroid of townspeople and country residents, as well as 90 measurements of ^{131}I concentration in milk samples made in May-June 1986 were presented in the Plavsk scenario for the purpose of comparing predictions from different models. Levels of ^{137}Cs soil contamination in all settlements of the Plavsk district and the isotopic ratio of ^{131}I to ^{137}Cs in depositions at a number of locations were used as input information for model calculations. Radionuclide concentration in the air was not determined in the area. Radioactive contamination occurred due to dry and wet fallout in the Plavsk district in the period when vegetation began spring growth and local residents transferred dairy cattle to open

pasture after winter stabling. All these factors influenced variability of intakes and dose and created additional difficulties for modeling.

A permanent increase of thyroid cancer morbidity among the exposed population was found in the most contaminated regions of Ukraine, Belarus and Russia starting from the fifth year after the Chernobyl accident. These findings underscore the importance of making reliable reconstructions of the population average as well as individual thyroid doses in the affected areas. Thyroid dose estimations are used to confirm the needs for special medical aid to the population and for measures of social protection, to provide information for the public and the authorities, and for ensuring reliable data for epidemiological studies. In this context a comparison of dose estimations based on radio-ecological models could be used as an additional quality control of measurement based dose estimates. At the same time multiple independent assessments are an effective means for uncovering discrepancies in expert judgments and interpretations of input data.

Ten experts presented nine models for the analysis of the Plavsk scenario data. The model prediction exercise was carried out “blind”, that is experts did not know the observed values before beginning their calculations. Some of the model predictions were tested by comparison with the observed values; others were compared to one another.

2. Plavsk scenario

2.1. Plavsk district - common description

The Plavsk district, in the Tula region of Russia, is located about 600 km north-east of the Chernobyl NPP and about 200 km South of Moscow. The area of the Plavsk district is 102,500 hectares. In 1986 the population was about 30 thousand people working mainly in agricultural production. Half of the population lived in the district centre – the town of Plavsk, the others lived in villages. The area of the Plavsk district was significantly contaminated with radionuclides on April 29–30, 1986 by the same radioactive debris cloud from the Chernobyl NPP that also contaminated the Bryansk region of Russia and Mogilev region of Belarus (Fig. 1). Soil contamination was very inhomogeneous: ^{137}Cs deposition ranged from 10 to 600 $\text{kBq}\cdot\text{m}^{-2}$, the town of Plavsk was contaminated at a level of 475 $\text{kBq}\cdot\text{m}^{-2}$. The land in the Plavsk district in 1986 was distributed among 18 collective farms, which were the main state suppliers of agricultural products.

2.2. Plavsk scenario – input information

The ^{137}Cs surface contamination levels in all the settlements and the average levels of contamination within the boundaries of 18 collective farms of the Plavsk district were used as basic information for model calculations (Roshydromet, 1993). The significant heterogeneity of the ^{137}Cs deposition within the district, but also within the areas of the collective farms lands and even within the range of a single settlement should be emphasized. For example, one collective farm could contain from 3 to 11 villages with contamination levels that differed by up to 2.5 times. The collective farms' average contamination levels were estimated using the contamination levels of villages in the farm, resulting in coefficients of variation ($\text{CV} = \text{standard deviation} / \text{mean value}$) from 0.06 to 0.48. Radioactive fallout deposition at different points of a settlement, as estimated by Roshydromet, differed from 3 to 10 times (Roshydromet, 1993). The isotopic composition of the gamma-emitting radionuclides deposited after the Chernobyl accident was estimated on the basis of soil sampling at four locations in the Tula region in May 1986 [Orlov et al., 1998]. All these locations were in areas of high surface contamination caused by wet deposition. According to these data the ^{131}I to ^{137}Cs isotopic ratio was estimated as 3.34 on May, 10, 1986.

The meteorological data for the period 27 April to 15 May 1986 also were presented as input data for the scenario. Those data were obtained from eight meteorological stations in different districts of Tula region, one of which was in the town of Plavsk. Data on wind speed and direction, precipitation, average daily air temperature, and the daily minimum and maximum soil temperature were also available. Analysis of all the meteorological information showed that the radioactive cloud passed through the Tula region from the afternoon on 29 April, until 7–10 a.m. on 30 April. During the transit of the radioactive cloud, there was rainfall of varying intensity in most parts of the Tula region. Hence, the radioactive fallout can be classified as mixed dry and wet deposition.

The accident at the Chernobyl NPP took place in the spring at the beginning of the vegetation growth period. The average height of natural grasses in the Plavsk district was 4 cm on April, 30; 6 cm on May, 10–11 cm on May, 20. In Russia it was usual to keep the dairy cattle on pasture during the summer time, but different farms moved their cows onto pasture at different dates depending, not only on weather conditions, but also on the availability of fodder for stabled cattle. The dates at which cattle were moved onto pasture were estimated for private farms from a poll of local farmers carried out at the beginning of 1987 and for collective farms from the interviews with their heads carried out in 1995–1996. According to these polls the pasture season for private cows started between May 4 and 11; for the public herd between May 8 and 25.

The average productivity of natural grass meadows in Tula region was estimated as 0.4–0.45 kg/m² of fresh mass in summer season. During the pasture period cows may eat 40–45 kg/day of fresh grasses. Transfer of cattle to the pasture grazing regime was carried out gradually, beginning with 2 hours on pasture in first day, and then increasing over 7–10 days to full time grazing on pasture.

Data on population demography and food consumption rates were also included as input data for the scenario. The milk consumption rate for rural population was higher than for townspeople: rural adults consumed on average about 0.7 L/d, urban adults 0.25 (women) – 0.3 (men) L/d; rural children between 1 and 7 years of age – about 0.6 L/d; urban children – 0.4 L/d; rural teenagers - 0.4 (girls) and 0.6 (boys) L/d, urban teenagers - 0.22 (girls) and 0.3 (boys) L/d. Practically all rural residents consumed milk from private farms, in the town of Plavsk – only 10–15 % of population consumed milk from private farms, while all others bought milk in shops.

No protective measures to reduce intake of radioiodines were performed in the territory of the Plavsk district.

2.3. ¹³¹I measurement data for model validation

Gamma spectrometry measurements of ¹³¹I in milk samples were carried out between May 14 and June 12, 1986. Ninety samples of milk were measured in the Plavsk district. Milk samples were delivered from collective farms and the location of sampling was recorded as the name of the collective farm not the settlement. The average effective half-life for ¹³¹I in milk was determined as 4.2 days in Tula region.

Three hundred and seventy (370) people from 15 villages and from the town of Plavsk had their thyroid ¹³¹I content measured in the radiodiagnostic laboratory of the Tula regional hospital between May 13 and June 6, 1986. Counting measurements were made for the energy interval of 300–450 keV using a diagnostic spectrometer with a lead collimator.

These measurements were used later for the validation of the model predictions and they were not known to modelers before they carried out their calculations.

2.4. Task for model comparison exercises

The modeling task consisted of the reconstruction of all stages of ^{131}I transport in the environment beginning from the ground deposition using ^{137}Cs ground contamination data as a tracer, to ^{131}I accumulation in human thyroid and the final assessment of committed inhalation and ingestion doses to thyroid of different age groups of inhabitants in specified locations. Two types of comparison were carried out: model predictions of ^{131}I concentration in milk and ^{131}I contents in thyroid were compared with the observed values from the test area. In addition, a model inter-comparison was conducted in which predictions of the mean ingestion and inhalation doses to the thyroid for different age groups were compared with each other.

The end points considered in the IWG's model validation exercise were:

1. time dependent ^{131}I concentrations in milk for the period 27 April – 30 May 1986; for 18 milk farms and the town of Plavsk with different ^{131}I (^{137}Cs) deposition densities;
2. time dependent ^{131}I thyroid burdens for different age groups of rural (central villages in 18 collective farms) and urban (Plavsk town) populations. The age groups considered were: new born (less than one year old), 1–2, 3–7, 8–12 years old and adults (20 years old and older).

The end points considered for model inter-comparison:

1. ^{131}I deposition (soil concentration);
2. reconstruction of ^{131}I air concentration for 18 locations and Plavsk town
3. time dependent ^{131}I concentrations in fresh pasture (grass) for the period 27 April – 30 May 1986
4. committed doses to thyroid from ingestion, and
5. inhalation dose contribution to the total dose (optional).

Nine models from nine countries took part in the exercise. All the models estimated step by step the transport of ^{131}I from the time of the radioactive cloud's passage above the Plavsk district (when deposition on the ground took place), until the radioactive iodine accumulated in the human body. The final calculation endpoint, of course, was the thyroid dose estimations for local people. Numerical values of parameters used in models are presented in the Table 1.

Unfortunately no measurements of radionuclide concentrations in the air were performed in the area, thus the most reliable reference point for the start of the modeling was the data for surface contamination of settlements with ^{137}Cs . The lack of any relevant source information was treated individually by the experts using their own experience and knowledge.

3. Results and discussion

3.1. Evaluation of ^{131}I deposition

Most participants used a constant ratio 3.34 for ^{131}I to ^{137}Cs as recommended in the Scenario for 10 May 1986, with a standard error of 19% (Orlov et al., 1992). One of the participants (model 6) used the semi-empirical relationship between ^{131}I and ^{137}Cs concentration in soil suggested by (Makhonko et al., 1996; Knatko and Dorozhok, 2001):

$$\sigma_{131} = a \times (\sigma_{137})^b \quad (1)$$

where: σ_{131} , σ_{137} - deposition of ^{131}I and ^{137}Cs on 10 May 1986, kBq m^{-1} ; parameters a , b are constants, for Russian regions they are: $a = 8.85$, and $b = 0.85$.

Equation (1) reflects the different mechanisms and different velocities of dry and wet ^{131}I deposition. It should be noted that the activity ratios of ^{131}I to ^{137}Cs , evaluated either as a constant value or using power function approach, differed by less than a factor of 2 for low contamination levels ($10\text{--}50 \text{ kBq m}^{-2}$) with decreasing difference at higher ^{137}Cs soil concentrations. All the predicted values of ^{131}I deposition on soil for the different locations were very close each to one another. The differences in the uncertainty ranges evaluated by specific models resulted from different calculation methods for representing the mean of ^{137}Cs concentrations in soil for particular areas of dairy farms and as a result of personal judgment.

3.2. ^{131}I concentrations in grass

In Fig. 2 the modeling results are shown for the contamination of pasture grass with ^{137}Cs in the least and the most contaminated farms. It can be seen that at high-levels of contamination the estimates of ^{131}I concentrations on the grass using different models are quite similar and the differences lie within one order of magnitude. At a low level of contamination the calculated values differ up to 30 times. The various assumptions about interception of airborne and waterborne radionuclides by vegetation, especially since the fraction of wet and dry deposition were unknown, explains the variations of predictions. The interception factor for dry deposition in different models was in the range of $0.074\text{--}0.7$ and for wet fallout within the range of $0.03\text{--}0.7$. The values of the biological half-time of iodine on vegetation due to weathering and growth dilution assumed by different models ranged from 6 to 13 days. This parameter had a major effect on the predictions of ^{131}I concentration in milk, particularly for the second half of May.

Although, the assumption of low grass productivity resulted in a lower interception fraction, it did not significantly affect the predictions of ^{131}I concentrations in grass (no more than 10 %) compared with the assumption of fully developed grass. The fraction of deposited radioiodine calculated on the grass mass remains approximately constant.

The main differences in predictions for the first days after the deposition primarily reflect different assumptions made about the date when radioactive plume arrived in the area and the duration of the deposition. For example, in Fig. 1a, modeler 4 assumed that ^{131}I concentration in the air varied as a sigmoid function with a mean value of 02.05 at 8:00 a.m. and used an increasing grass mass in May due to seasonal vegetation growth. Other participants assumed a duration of airborne radioiodine over the Plavsk district of 12–30 hours on 29–30 of April 1986.

Expert 5 performed two types of calculation: one for contamination due to the passage of a homogeneous cloud with only dry deposition (curve 5a), and one due to the deposition arising from a homogeneous rain passing through a cloud with varying concentrations (curve 5). The actual concentrations are likely to be between those two extreme cases. At high contamination levels caused by intensive precipitation these two model variations produce almost the same results (Fig. 1b). A nonlinear relationship between ^{131}I and ^{137}Cs deposition was used in model 6.

3.3. ^{131}I concentration in milk

There are several factors that could influence the predictions of ^{131}I concentration in milk. The date at which cattle began feeding on pasture was the most important parameter affecting the predictions of ^{131}I in milk. According to the poll of the local inhabitants the pasturing period for 40 % of private farms began on 6–7 of May and for 30 % on 10–11 of May. According to

the interviews with the heads of the collective farms, the grazing of collective cattle on pasture began approximately 8 days later than private cows. Analysis of available measurements of ^{131}I in milk from collective farms however, showed that dates of beginning grazing on pasture of private cows could be more realistic than dates suggested for collective farms. According to the “agro-climate model” (Vlasov & Pitkevich, 1999) the dates of 7–10 May were the optimal for moving cattle on a pasture, since the weather in the Plavsk district was warm with a temperature of about 10–15 °C. The modelers who assumed those dates for the start of pasture grazing in dairy farms achieved better agreement with the observed data.

An example of ^{131}I concentration in milk predictions for one collective farm is shown in Fig. 3. It can be seen that calculations based on the date of the beginning of the grazing season for the collective farm do not correlate well with the first measurement of milk in the farm. The other calculations which took into account the date of moving privately-owned cows onto pasture produced better agreement with the observed data..

A consumption rate of fresh grass forage for cows in the range of 40–45 kg/day was suggested in the scenario description and was applied in most of models, however information on gradual transition of the cattle to grazing regime after the winter period was involved only in one model (model 6) where the daily grass consumption increased from 5 kg of fresh grass at the first day on a pasture to 45 kg/day on the fifth and following days. Different feed rations for cows in private and collective farms were used in models 2 and 6 (index “a” for collective farms at Fig. 3). Most participants used feed-to-milk transfer coefficients from the daily consumed activity within fresh grass to one litter of cow’s milk their values varied between 0,003 and 0,01 d L⁻¹. Some experts also considered ^{131}I intake to cows via inhalation by assuming breathing rates between 100 and 130 m³·d⁻¹ (for example, models 6 and 9 at Fig. 3). Models 1, 2 and 9 took into account an intake of the contaminated soil with pasture grass into cows (0.2–1.0 kg of soil per day).

On the whole a comparison of measurements and predicted ^{131}I concentrations in milk resulted in more then 50% of the predicted values lying in a range of three times the observed values to one-third the observed values. Assumptions about the time when cows were put onto pasture appear to be the most important factor affecting predictions.

3.4. ^{131}I thyroid content

This task required modelers to predict the time dependent average ^{131}I content in the thyroid for different ages groups in 15 villages situated on 14 different milk farm areas where direct thyroid measurements were conducted. Participants had to calculate 33 time series curves with 95% uncertainty ranges. There were several factors that affected model predictions of ^{131}I content in thyroids

Modelers applied the age dependent milk consumption rates reported in the scenario description. The urban population had about half the milk consumption of the rural population. The variation in milk consumption rates within different age groups contributes approximately 30% to the uncertainty in the predictions..

An Excel routine, based on the iodine metabolism model developed by Johnson (1981), was provided by P. Krajewski for those models that did not have the capability to calculate ^{131}I contents in the thyroid. Some modelers used specific formulas based on ICRP publication 56 (1989). Although metabolic parameters for particular age groups differ markedly, the ^{131}I content in thyroid is similar for different age groups and individual age does not contribute more than 20% to the uncertainty of predicted thyroid ^{131}I contents.

Measurements of thyroids in Plavsk district were performed about two weeks after the passage of the radioactive cloud, in the period of 13–30 May, though measurements were made only one day at each location. The 95% confidence interval on the mean of each age group in different settlements ranged over a factor of two. The scenario description suggested evaluating radioiodine intakes for rural inhabitants using the predictions of ^{131}I concentration in local private milk rather than milk from collective farms. For the population of Plavsk town each modeler decided which milk data were used for dose calculation.

Examples of the ^{131}I content predictions in thyroid for children of 3–7 years old living in Plavsk town are shown in Fig. 4. The predicted activities of ^{131}I in thyroids follow the previously predicted ^{131}I concentrations in consumed milk and reflect all the assumptions made about the times at which cows had been put on pasture and others assumptions made about ^{131}I deposition and precipitation onto grass. Some participants also took into account ^{131}I intake of into human body due to consumption of leaf vegetables (models 1, 2 and 4).

The predicted versus observed data for ^{131}I contents in thyroids of individuals from 15 settlements and Plavsk town are presented at Fig. 5. The models 2, 6 and 9 gave the closest to the observed data: from 60 to 74 % of model's predictions fit within a range of three times the observed values to one-third the observed values. For the remaining models the main reason for discrepancies was in the choice of the dates at which grazing on pasture began for the collective farm and private cattle. In general for most of the predicted values a range about one order of magnitude uncertainty was achieved.

3.5. Dose assessment – ingestion dose

The final goal of the scenario exercise was to predict mean values of the thyroid dose (committed equivalent dose to thyroid) from ingestion and inhalation for five different age groups - new born, age 1–2, 3–7, 8–12 and adults for particular dairy farm areas and Plavsk town. Ingestion and inhalation dose conversion factors were provided in scenario from publications ICRP (ICRP. Publ. 67, 1993; ICRP 71, 1995)

Predicted doses from ingestion are shown in Fig.5. Small symbols present modeler's estimates for all farms. Large dark squares with bars represent the geometric mean of all dose predictions with 95% confidence interval for each farm. Large light rhombuses with bars represent dose estimates of the scenario providers (Balonov and Zvonova, 2002). The range of predicted ingestion doses is about one order of magnitude at each location, which reflects mainly the differences in the predicted ^{131}I concentrations in milk made by particular participants.

When estimating the dose, the authors of the scenario assumed the intake of radioactive iodine into the human body via inhalation and consumption of milk and other foods (Zvonova, et al., 2000). The parameters ratios in the intake function and their numerical values were assessed on the basis of the monitoring data collected in May 1986 and the results of the ^{131}I content measurements in the human thyroid. The dependencies of the age group average thyroid doses for the urban and rural populations were calculated, using the results of all the direct measurements in the Tula, Bryansk and Oryol regions. These dependencies were used for dose estimations for the age groups that were not measured in May-June 1986.

In the cases, where no direct ^{131}I measurements of the settlement's inhabitants were performed, the empirical correlations were used of the dose standardized by age and the date of cattle being moved onto pasture (cattle's pasture started before the radioactive fallouts) with the ^{131}I concentration in milk, and milk concentration with the surface contamination of the area with ^{137}Cs . With this calculation scheme, the critical parameter for the estimation of doses is also the date at which the cows began grazing on pasture..

The dose estimates of the scenario providers were within the range of model predictions. The mean values of model predictions for most locations were higher than the dose estimates made from direct measurements on average in two times but their confidence intervals were overlapping almost in all cases. About 50 % of model's dose predictions for different locations and age groups differ from the scenario providers dose estimates by less than $\pm 50\%$ of the dose value calculated from direct measurements. Only in one location the difference was up to 5–6 times. This level of agreement between dose estimations based on direct measurements and on ecological model calculations can be considered as quite acceptable in view of wide range of used model parameters and imperfect input data.

The range of differences we observed are typical when dose estimates made using ecological models are compared with estimates based on measurements. The same situation was observed after the Chernobyl accident, internal dose estimates in people from cesium isotopes calculated using modeling of contaminated food consumption were about two-three times higher than the doses calculated from whole body measurements of inhabitants (Balonov and Travnikova, 1993).

It is interesting to consider dose estimates normalized per 1 kBq m^{-2} of ^{137}Cs soil contamination. These ratios based on the geometric means of the model calculations and the scenario provider's estimates are shown in Fig. 7. It can be seen that the normalized thyroid dose decreases from 2.5–3.0 mSv per 1 kBq m^{-2} at soil contamination levels below 30 kBq m^{-2} to a constant level of about 0.3 mSv per 1 kBq m^{-2} , according to the scenario provider's estimates, or to the level 0.7–0.9 mSv per 1 kBq m^{-2} , according to the average of the modeler's estimates at soil contamination levels above 100 kBq m^{-2} . The reason for some single settlements having outlier values was the particular conditions of the cows pasturing and the variation in behaviors of the inhabitants.

It should be noted that these estimates were made for the area where the cows commenced grazing on pasture after the radioactive fallout, about May 7–10, so they can not be applied to other locations where grazing on pasture started at different times or with other climatic conditions. For the territories where the cows had started grazing on pasture before the beginning of the radioactive fallout, the thyroid dose in children of 3–7 years old normalized to 1 kBq m^2 of ^{137}Cs depositions should be about 2–3 times higher than the estimations based on the direct measurements in this study.

3.6. Dose assessment – inhalation dose

The inhalation doses calculated for the same locations reflect differences in predictions of ^{131}I concentrations in air. Different assumptions based on experience of different modelers were made regarding the portioning of airborne radioiodine (aerosol, elemental, organic), the contribution of dry and wet deposition to the total deposition, dry deposition velocity, and washout ratio. They are summarized in Table 1 for particular models.

Most participants assumed an inhomogeneous spatial concentration of ^{131}I in air that reflected the inhomogeneous spatial pattern of ^{131}I deposition relative to the ^{137}Cs deposition. In such assumptions inhalation dose estimates were proportional to ^{137}Cs deposition as seen in Fig.8.

One model assumed a uniform ^{131}I concentration in the near-surface air everywhere in the Plavsk district (model 5a). Equal inhalation dose for people in different locations resulted from that particular approach. It is interesting that the ^{131}I concentration in the air reconstructed in model 6 increased with increased ^{137}Cs deposition at locations but the ratio of the integrated ^{131}I concentration to the level of ^{137}Cs contamination decreased. In total, these assumptions resulted in the estimations of inhalation doses to be approximately the same in all villages of the district. Some differences were introduced by different assumptions about time

spent outdoors (from 5 to 24 hours) and house filtration factors (0.5–0.7 or this factor was not taken into account).

Different starting conditions did not significantly influence the dose estimates in highly contaminated areas but differences of dose predictions in locations with low contamination were up to 30–50 times in different age groups. Unfortunately these calculations could not be compared with any experimental data

On average the estimates of inhalation dose formed less than 10% of the total dose to the thyroid in children under 3 years old, 8–15 % in children of 3–7 years and about 20% in older children and adults. The ratio of inhalation and ingestion doses depended strongly on the date of transfer the cattle to grazing on pasture. An inhalation dose could be equal or higher than the estimated ingestion dose in locations when late dates of beginning the grazing season were used for model dose estimations.

Conclusions

Nine models were involved in IWG exercises of the EMRAS programme. The main results of the work on the Plavsk Scenario (Russian area heavily contaminated following the Chernobyl accident) were the following:

- ^{131}I deposition can be reconstructed with acceptable uncertainty using ^{137}Cs deposition data. A constant ratio for ^{131}I to ^{137}Cs deposition can be used for highly contaminated areas (where wet deposition occurred) but can underestimate the ^{131}I deposition in low contaminated locations. Then, an empirically established nonlinear relationship between ^{131}I and ^{137}Cs depositions in the areas with mixed radioactive fallout (dry and wet) has to be used.
- When modeling the grass interception fraction its dependence on precipitation should be taken into account, for example using the experimental data.
- The time when cows were brought onto pasture seems to be the most important factor affecting model predictions.
- Maintaining dairy cattle indoors on a diet of stored food without any supplementation of fresh grass, and a late seasonal move them to grazing on pastures seems to be very effective measures for minimizing the public's intake of ^{131}I through consuming contaminated dairy products.
- Most model predictions of ^{131}I concentration in milk and ^{131}I thyroid burden in local people were within a factor of three of corresponding observed values.
- ^{131}I doses assessed by ecological models and dose estimations based on direct measurements shows acceptable level of agreement not exceeding a factor of ten.

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Fig. 1.
Location of the Plavsk district in Tula region on the map of the ^{137}Cs contamination of Belarus, Russia and Ukraine.

Fig. 2. Examples for predictions of ^{131}I concentrations in grass for the two milk farms with the lowest (top panel) and highest radionuclide soil contamination levels (lower panel).

Fig. 3.

An example of ^{131}I concentration in milk predictions for the collective farm Ol'hi where dates of private cows moving to a pasture were 7 of May and for collective cattle - 13 of May (according to interviews); large circles represent measured values.

Fig. 4.
Predictions of ^{131}I content in thyroid for children 3–7 years old from Plavsk town; large light circles the mean values of measurements with 95 % confidence intervals

Fig. 5.
Selected predictions of ^{131}I thyroid content against observed data for the Plavsk Scenario. The red and blue dotted lines indicate the range of 1/3 to 3 times the observation interval

Fig. 6. Comparison of predictions of thyroid doses from ingestion in Plavsk district for children 3–7 years old; settlements ordered according deposition of ^{137}Cs at locations. Small symbols present model's predictions; large dark squares with bars represent geometric mean of all dose predictions; large light rhombuses with bars represent the dose estimates of the scenario providers, bars – 95 % confidence interval.

Fig. 7.

Thyroid dose due to ¹³¹I ingestion in children of 3–7 years old normalized to 1 kBq m⁻² of ¹³⁷Cs deposition depending on ¹³⁷Cs soil contamination in Plavsk district.

Fig. 8.
Predictions of the inhalation thyroid dose for children of 3–7 years old in the Plavsk district.

Table 1

Summary of parameters used by participants

Parameters	1. LIETDOS	2. CLIMRAD	3. SPADEV.6	4. UniYes	5. ECOSYS	6. CLRP	7. ASTRAL	8. Plavsk Dose	9. OSCAR
The date, time when first radioactive cloud arrived the Plavsk district	30.04 (8:00)	29.04 (12:00)	29.04 (18:00)	Sigmoid variation with the mean value 2.05 (8:00)	29.04 (13:00)	29.04 (12:00)	29.04 (13:30)	29.04	29.04 (12:00)
The date, time when radioactive fallout finished at the Plavsk district	1.05 (8:00)	30.04 (12:00)	30.04 (6:00)		30.04 (19:00)	30.04 (9:00)	30.04 (11:30)	29.04	30.04 (10:00)
Used date of transfer cows at pasture in collective farms	YES	Own agro-climate model		Sigmoid function with mean at date of collective farms	YES	-	YES	YES	-
in private farms	-		YES		-	YES	YES	-	YES
Grass yield (kg·m ⁻² fresh weight)	0.45	0.2	0.425	0.55	0.16	0.08	0.4	Dry: below 0.05	0.15
Grass interception fraction for dry deposition	0.36	Own evaluation	0.7	0.7	-	0.13	0.056 (if 5mm)	0.21	0.074
for wet deposition	0.36		0.7	0.7	≈ 0.03	0.05	0.028 (if 10mm)	0.21	0.074
formula used: $f = 1 - \exp(-\mu Y)^{1/2}$, $\mu =$	4.0	1.75	2.8	-	1	7	0.019 (if 15mm)	-	2.8
Biological ¹³¹ I half-life on grass [d] (weathering + dilution due to growth of grass mass)	8.7	8.8	13.2	10	10.5	≈ 6	11.6	≈ 11	10
¹³¹ I transfer coefficient from daily forage to 1 L of cow milk [dL ⁻¹]	0.003	0.01	not explicitly used	0.007	0.003	0.008	0.003	0.004	0.0044
¹³¹ I iodine speciation in the air (%): particulate reactive gas (I ₂) organic	40 30 30	70 15 15	NC ²⁾	100	100	29/30Apr. 25%/28% 40%/55% 35%/17%	intermediate	NC	23 26 51
Dry deposition velocity (m·s ⁻¹) particulate reactive gas (I ₂) organic	1.6×10 ⁻³ 9.5×10 ⁻³ 7.0×10 ⁻⁵	1.0×10 ⁻² 1.0×10 ⁻³ 1.0×10 ⁻⁴	NC	1.8×10 ⁻³	3.4×10 ⁻³	1.2×10 ⁻³ 1.1×10 ⁻² 1.1×10 ⁻⁴	1×10 ⁻³	NC	2.0×10 ⁻³ 1.0×10 ⁻² 1.0×10 ⁻⁴
Washout factor w _r ³⁾ particulate reactive gas (I ₂) organic	2.5×10 ⁶ 5.0×10 ⁶ 8.0×10 ³	2.×10 ⁵ 1.0×10 ⁵ 1.0×10 ⁴	NC	2.0×10 ⁵	1.3×10 ⁵	2.0×10 ⁴ 2.0×10 ⁵ 2.0×10 ⁵	(5±2)×10 ⁵	NC	3.0×10 ⁵ 2.0×10 ⁵ 2×10 ³

¹⁾ Chamberlain formula: $f =$ part of falling radionuclides initially retained by the vegetation; μ – mass interception factor, m²/kg; Y – dry weight of ground vegetation biomass from the unit of square, kg/m².

²⁾ NC – Not considered

³⁾ Dimensionless, defined as the ratio of the concentration of radionuclide in surface-level precipitation to the concentration in surface level air during the period of rainfall: $W_{wet} = \mathbf{w}_T \times \mathbf{R}$, where: W_{wet} – wet deposition ($Bq \cdot m^{-2}$), C – concentration in air ($Bq \cdot m^{-3}$), R – rainfall (m)

⁴⁾ Ingestion and inhalation dose conversion factors were provided in scenario from publications ICRP [ICRP. Publ. 68, 1995; ICRP 71, 1995]