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Thyroid Doses due to Iondine-131 Inhalation among Chernobyl Cleanup Workers

Vladimir Drozdovitch,
Division of Cancer Epidemiology and Genetics, National Cancer Institute, NIH, DHHS, 9609 Medical Center Drive, Room 7E548 MSC 9778, Bethesda, MD 20892-9778, USA, Phone: +1-240-276-7399, Fax: +1-240-276-7840, drozdovv@mail.nih.gov

Victor Kryuchkov,
Burnasyan Federal Medical and Biophysical Centre, 46 Zhivopisnaya Street, Moscow, 123182, Russia

Ivan Golovanov,
Burnasyan Federal Medical and Biophysical Centre, 46 Zhivopisnaya Street, Moscow, 123182, Russia

Vadim Chumak,
National Research Centre for Radiation Medicine, 53 Melnikova Street, Kyiv, 04050, Ukraine

Semion Kutsen, and
Research Institute for Nuclear Problems, Belarusian State University, 11 Bobruiskaya Street, Minsk, 220050, Belarus

André Bouville
U. S. National Cancer Institute (retired)

Abstract

Several hundred thousand individuals, called 'cleanup workers' or 'liquidators', who took part in decontamination and recovery activities between 1986 and 1990 within the 30-km zone around the Chernobyl nuclear power plant in Ukraine, were mainly exposed to external irradiation. However, those who were involved in cleanup activities during the 10-day period of atmospheric releases also received doses to the thyroid gland due to internal irradiation resulting essentially from inhalation of ^{131}I. The paper presents the methodology and results of the calculation of individual thyroid doses for cleanup workers. The model that was used considers several factors, including the ground-level outdoor air concentrations of ^{131}I at the locations of residence and work of the cleanup workers, the reduction of ^{131}I activity in inhaled air associated with indoor occupancy, the time spent indoors, the breathing rate, which depends on the type of physical activity, and the possible intake of potassium iodine (KI) for iodine prophylaxis. Thyroid doses were calculated for a group of 594 cleanup workers with individual measurements of exposure rate against the neck, called 'direct thyroid measurements', that were performed from 30 April to 5 May 1986. The measured values of exposure rate were corrected to subtract the contribution of short-lived radioiodine isotopes in the thyroid to the detector response. The average thyroid dose due to ^{131}I inhalation by the cleanup workers was estimated to be 180 mGy, while the median was 110 mGy. Most of the cleanup workers (73%) received thyroid doses ranging from 50 to 500 mGy. The highest individual dose from ^{131}I inhalation among the cleanup workers with direct thyroid measurements was 4.5 Gy. To validate the model, the ^{131}I activities in the thyroids that were calculated using the model were compared with those derived from the direct thyroid measurements. The mean of the ratios of measured-to-calculated activities of ^{131}I in the thyroid was found to be 1.6 while the median of those ratios was 0.8. For 60 cleanup workers with direct thyroid measurements, a detailed description of hour-by-hour whereabouts and work history was available. For these cleanup workers the mean of the ratios of measured-to-calculated activities was found to be 1.2 and the median of those ratios was 1.0. These encouraging results suggest that the thyroid dose due to ^{131}I inhalation could be estimated for Chernobyl cleanup workers with a reasonable degree of reliability even in the absence of direct thyroid measurements. However, this conclusion assumes that detailed information on whereabouts and work history could be obtained for those cleanup workers who were not measured.

Keywords

Chernobyl; cleanup worker; thyroid; Iodine-131; radiation dose

Introduction

Between 1986 and 1990, several hundred thousand workers, called ‘cleanup workers’ or ‘liquidators’, took part in decontamination and recovery activities within the 30-km zone around the Chernobyl nuclear power plant (NPP) in Ukraine, where a major accident had occurred on 26 April 1986. Approximately 306,000 of these were cleanup workers in 1986 when the highest doses were received (UNSCEAR 2011). The main activities carried out by cleanup workers included decontamination of the reactor building, reactor site and roads, construction of the sarcophagus and settlements for reactor personnel and waste repositories, and safeguarding the 30-km zone and evacuated settlements.

Most cleanup workers were exposed to external radiation from radionuclides that had contaminated the reactor block and soil surfaces (Chumak et al. 2007; Kryuchkov et al. 2009). In addition, cleanup workers who worked during the 10-day period of releases may have received radiation doses to the thyroid gland due to inhalation of ^{131}I-contaminated air. Epidemiological studies among Chernobyl cleanup workers (Ivanov et al. 2008; Kesminiene et al. 2012; Mabuchi et al. 2013) suggest that internal exposure to ^{131}I may have caused a radiation related risk of thyroid cancer. Therefore, there is a need for a methodology to assess the thyroid dose to cleanup workers due to ^{131}I inhalation that occurred shortly after the Chernobyl accident.

Measurements of exposure rate near the thyroid, so-called ‘direct thyroid measurements’, are the best foundation to estimate thyroid doses due to ^{131}I intakes. The so-called ‘instrumental’ doses, which are based on personal measurements, are more reliable than the so-called ‘ecological’ doses, which area model-based in the absence of personal measurements. Fortunately, results of direct thyroid measurements are available for a group of cleanup workers who started their mission between 26 April and 5 May 1986. This paper presents the methodology and results of the calculation of individual thyroid doses due to ^{131}I inhalation for Chernobyl cleanup workers.

Materials and Methods

Study population

The total number of workers who were at the Chernobyl NPP site when the accident happened or before 1 May 1986 (so called ‘witnesses of the accident’) was around 2,000 (Kryuchkov et al. 2012). Direct thyroid measurements were conducted between 30 April and 5 May 1986 in a group of 617 cleanup workers at the pioneer (youth) camp ‘Skazochny’ where the operation personnel of the Chernobyl NPP were relocated from Pripyat-town. Measurements were done using two types of devices: 543 cleanup workers were measured by means of a DRG3-02 dosimeter and 131 cleanup workers were measured using a SRP-68-01 survey meter. Among them, 80 persons were measured with both types of device and seven persons were measured twice with the same device at different dates. In the analysis of the results of the measurements, 23 cleanup workers were excluded from the list of the measured individuals as their results were found to be suspect, e.g., when the record of the exposure rate measured near the thyroid was lower than the measured background radiation. The final list of reliably measured cleanup workers consisted of 594 individuals, including 523 males and 71 females. Table 1 provides the temporal distribution of the direct thyroid measurements performed among Chernobyl cleanup workers.

At the time of the direct thyroid measurement, all cleanup workers were asked to provide information on their day-by-day whereabouts, beginning on 26 April 1986, as well as on their intake of stable iodine (KI pill) to block the uptake of ^{131}I by the thyroid gland. This information is referred to, here and below, as the ‘crude route list’. In addition to the crude route list, 326 cleanup workers were asked in May-June 1986 to provide a detailed description of their activities and whereabouts during the first ten days after the Chernobyl accident, called ‘detailed route list’. The information in the ‘detailed route list’ includes an hour-by-hour description of the location and activities performed, e.g., “measuring of exposure rate in air at Chernobyl site from 8:00AM to 10:00AM on April 26”, “shopping at Pripyat-town from 2:00PM to 4:00PM on April 26”, “driving from Pripyat-town to pioneer camp “Skazochny” through village Kopachi from 6:00PM to 7:00PM on April 28”. Sixty cleanup workers were identified with detailed route list who had direct thyroid measurements. Accordingly, two groups of cleanup workers with direct thyroid measurements were considered in this study: 594 workers with crude route lists and, in that group, 60 individuals with detailed route lists.

Thyroid doses due to ^{131}I intake

The following information and models are typically required to calculate the absorbed doses to the thyroid due to ^{131}I intake to cleanup workers:

- Direct thyroid measurements, which are measurements of the gamma radiation emitted from the thyroid of the worker. Those direct thyroid measurements provided an estimate of the ^{131}I activity in thyroid at the time of the measurement;
- Information on the whereabouts and activities performed by the worker before and after the time of the direct thyroid measurement, as well as information on

the timing of intake of stable iodine for prophylactic reasons, when applicable; and

- Ecological and biokinetic models, which were used, in conjunction with the information included in the route lists, to reconstruct the thyroid activities before and after the time of the direct thyroid measurement.

The dose estimates obtained using those three sources of information are called ‘instrumental’ doses. Rough estimates of thyroid doses can also be obtained using only the last two sources, excluding direct thyroid measurements. Those dose estimates are called ‘ecological’ doses. The instrumental doses, which are based on personal measurements, are more reliable than the ecological doses.

The scheme of calculation of thyroid doses for cleanup workers is shown in Fig. 1. The thyroid doses were estimated using input data specific to cleanup worker (route list and direct thyroid measurement) and ecological data (^{131}I concentration in air at the locations specified in the route list). Ecological and biokinetic models were used to calculate: (a) the time-integrated activity of ^{131}I in the thyroid of the cleanup worker, from which the ‘ecological dose’ is derived, and (b) the ^{131}I activity in the thyroid of the cleanup worker at the time of the direct thyroid measurement, called the ‘ecological’ ^{131}I activity in the thyroid. To calculate the ‘instrumental’ thyroid dose, the ecological dose was calibrated by the ^{131}I activity in the thyroid derived from the direct thyroid measurement. Detailed information on the dose calculation is provided and discussed in the following sections.

Ecological thyroid dose—The ecological thyroid dose to a cleanup worker was calculated using the following equation:

$$D_{ecol} = \frac{0.58 \cdot E_{th}}{m_{th}} \cdot \left(\sum_{n=1}^{240} Q_{ecol}(n) \cdot \Delta n + Q_{ecol}(240) \cdot \int_0^{\infty} e^{-(\lambda_{th} + \lambda_r) \cdot n} dn \right) \quad (1)$$

where 0.58 is a unit conversion coefficient (Bq kBq^{-1} g kg^{-1} J MeV^{-1} s h^{-1} mGy Gy^{-1}); E_{th} = 0.2 MeV is the mean energy absorbed in the thyroid per decay of ^{131}I in the thyroid; m_{th} is the thyroid mass taken to be 20 g and 17 g for male and female workers, respectively (ICRP 2002); $Q_{ecol}(n)$ is the calculated activity of ^{131}I in the thyroid at hour n (kBq); n is the time in hours counted from 1:00 AM on 26 April (n=0); Δn=l h is the calculation step; $Q_{ecol}(240)$ is the calculated ^{131}I activity in the thyroid at hour n=240 (kBq). No ^{131}I intake via inhalation was assumed after hour n=240, i.e. after 1:00 AM on 6 May 1986, when the major release of radioactivity from the destroyed reactor came to an end (UNSCEAR 2011); λ_{th}=0.000328 h^{-1} is the biological rate of ^{131}I elimination from the thyroid of an adult (ICRP 1993); λ_r=0.003592 h^{-1} is the radioactive decay constant of ^{131}I.

Ecological activity of ^{131}I in the thyroid—The activity of ^{131}I in the thyroid at hour n after the accident was calculated as:

$$Q_{ecol}(n) = Q_{ecol}(n-1) \cdot e^{-(\lambda_{th} + \lambda_r) \cdot \Delta n} + C_{air}^{I-131}(n) \cdot V_{air}(n) \cdot F_{in}(n) \cdot CF_{KI}(n) \cdot w_{inh} \cdot w_t$$
(2)

(2)

where $Q_{ecol}(n)$ is the ecological activity of ^{131}I in the thyroid at hour n (kBq) with initial condition of $Q_{ecol}(0) = 0$; $Q_{ecol}(n-1)$ is the ecological activity of ^{131}I in the thyroid at hour n-1 (kBq); $C_{air}^{I-131}(n)$ is the time-integrated activity concentration of ^{131}I in air at hour n (kBq h m^{-3}); $V_{air}(n)$ is the breathing rate of an adult at hour n (m^3 h^{-1}), Values of $V_{air}(n)$ for different physical activities are given in Table 2 (ICRP 2002); $F_{in}(n)$ is the reduction factor of ^{131}I activity in air, relative to outdoor air, due to indoor occupancy at hour n (unitless). It was assumed that $F_{in}(n)$=0.1, 0.3 and 0.5 when the worker was indoors in Pripyat, in any building of the Chernobyl NPP, or in a rural settlement of the 30-km zone around the Chernobyl NPP, respectively, and $F_{in}(n)$=1.0 for outdoor occupancy; $CF_{KI}(n)$ is the correction factor at hour n after intake of stable iodine (potassium iodide, KI) for prophylactic reasons (unitless), when applicable. Values of $CF_{KI}(n)$ according to (Drozdovitch et al. 2013; Likhtarev et al. 2006) are given in Table 3; w_{inh}=0.66 is the fraction of inhaled iodine that is transferred to blood (unitless) (ICRP 1994); w_{th}=0.3 is the fractional iodine uptake by thyroid from blood (unitless) (ICRP 1993).

^{131}I concentration in air was calculated using the atmospheric transport model developed by Talerko (2005a, 2005b) for Ukraine. This model makes use of the available meteorological data, such as precipitation, wind speed, wind direction, and temperature, which were measured at the time of fallout across the country, and calculates activity of radionuclides in air for every 30 minutes of atmospheric transport at nodes of computational grid with spatial resolution of 10 km. Activity in air at a given location is obtained by interpolation of values calculated for grid nodes. The measured ^{137}Cs concentrations in air and ground deposition densities were used to calibrate the atmospheric transport model. First, the model calculations of ^{137}Cs deposition densities were scaled to the ^{137}Cs ground deposition densities measured in Ukrainian settlements (Talerko 2005a). Then, in a second step, a calibrated and validated model of atmospheric transport was used to calculate ^{131}I concentrations in air and ^{131}I deposition densities (Talerko 2005b). Figure 2 shows gridlines of daily average ^{131}I concentration in air in the 30-km zone around the Chernobyl NPP on 26 April and 27 April 1986.

In the implementation of the dose calculations, the time of KI intake was assumed to be noon (12:00 PM) of the day in which administration of stable iodine was reported, unless the exact time of KI intake was recorded in the detailed route list.

Instrumental thyroid dose—Instrumental thyroid dose was calculated as:

$$D_{inst} = \frac{Q_{meas}(t_m)}{Q_{ecol}(t_m)} \cdot D_{ecol} = SF \cdot D_{ecol} \quad (3)$$

where D_{inst} is the instrumental thyroid dose (mGy); $Q_{means}(t_m)$ is the activity of ^{131}I in the thyroid measured at time t_m (kBq); $Q_{ecol}(t_m)$ is the calculated ecological activity of ^{131}I in the thyroid at the time of measurement, t_m (kBq); D_{ecol} is the ecological thyroid dose (mGy); SF is the scaling factor derived from the measured and calculated ecological ^{131}I activities in the thyroid at the time of measurement (unitless).

Although hour-by-hour ^{131}I activity in thyroid was calculated using Eq. (2), the exact time of n(h) when the direct thyroid measurement was done during the day was unknown. Therefore, in the implementation of the method, the calculated activity of ^{131}I in thyroid at the time of measurement, $Q_{ecol}(t_m)$, was assigned to be the arithmetic mean of the hourly ecological activities, $Q_{ecol}(n)$, calculated for the period from 9:00AM to 6:00PM of the day when the measurement was done. This time period was considered to be the range when direct thyroid measurements were conducted.

Measured activity of ^{131}I in thyroid—The activity of ^{131}I measured in the thyroid of any cleanup worker was calculated from the result of the direct thyroid measurement using the following equation:

$$Q_{meas}(t_m) = 0.001 \cdot (P_{meas}(t_m) \cdot \nu_{I-131}(t_m) - a_{bg} \cdot P_{bg}(t_m)) \cdot CF_{dev}, \quad (4)$$

where $Q_{means}(t_m$ is the activity of ^{131}I measured in the thyroid (kBq); 0.001 is a unit conversion coefficient (kBq Bq^{-1}); $P_{means}(t_m)$ is the exposure rate measured near the thyroid (μR h^{-1}); $\nu_I - 131(t_m)$ is the correction factor that is equal to the relative contribution to the detector response of the activity of ^{131}I only and is not accounted for contribution of short-lived radioiodine isotopes (^{132}I, ^{133}I and ^{135}I) (unitless); a_{bg}=0.87 is the geometric factor accounting for the measurement of background (unitless) (Bratilova et al. 2003); $P_{bg}(t_m)$ is the background exposure rate at place of measurements (μR h^{-1}); CF_{dev} is the device-specific calibration coefficient of the thyroid detector for ^{131}I (Bq per μR h^{-1}).

Calibration coefficient for the thyroid detector—As direct thyroid measurements were performed using devices that were not designed to measure radioactivity in humans, calibration coefficients for ^{131}I needed to be estimated for these devices. A Monte Carlo method of numerical simulation of radiation transport was used to calculate the device-specific calibration coefficients that were used in this study to derive the ^{131}I activities in the thyroids from the results of the direct thyroid measurements. Detailed description of the calculations for the SRP-68-01 device can be found elsewhere (Khrutchinsky et al. 2012).

Similar work was carried out for the DRG3-02 dosimeter. This device, which is equipped with an organic scintillation detector, was designed to measure the average exposure rate of X-ray and gamma radiation. The principle of its operation is based on measurement of average intensity of scintillations of air-equivalent scintillator. A photomultiplier tube (PMT), which detects the scintillations produced in the detector, converts their energy into an electrical current, and, therefore, the DRG3-02 device readout is proportional to the current registered by the PMT. In the implementation of the Monte Carlo simulations, the DRG3-02 device response was considered to be proportional to the average energy deposited in the organic scintillator. To associate the results of Monte Carlo simulations with the readout of the device a scale coefficient, *k*, is required to be known (see Khrutchinsky et al. (2012) for details). This scale coefficient is determined only by the electronic scheme of the device and does not depend on either the gamma-ray energy or the measurement geometry. For the SRP-68-01 the scale coefficient has the dimensionality of count s^{-1} per μR h^{-1} and can be determined experimentally. In contrast with the SRP-68-01 device, the scale coefficient for the DRG3-02 instrument cannot be determined only experimentally, as this type of device does not measure the average deposited energy. Therefore, both experimental research and Monte Carlo simulations were done. Measurements of exposure rates from reference point gamma radiation sources of ^{241}Am, ^{57}Co, ^{133}Ba, ^{139}Ce, ^{137}Cs, ^{228}Th, ^{152}Eu by the DRG3-02 device were carried out by the state enterprise “ATOMTEX” (Minsk, Belarus). The scale coefficient for the DRG3-02 device was estimated from the experimental measurements and the theoretical simulations to be k=960 MeV per μR s^{-1} and was used in the Monte Carlo calculations of calibration coefficients (Kutsen S., personal communication, Minsk, Belarus, 2008).

The values of the calculated calibration coefficient for ^{131}I are given in Table 4. It should be noted that the operator recorded the exposure rates measured by the various devices in different units: μR s^{-1} for the DRG3-02 device and μR h^{-1} for the SRP-68-01 device. For convenience, the results provided for the two types of devices were converted in this paper into a single unit μR h^{-1}.

Contribution of short-lived radioiodine isotopes to the result of the direct thyroid measurement—A nuclear reactor produces a number of short-lived radioiodine isotopes that have the same behavior as ^{131}I in the environment and the human body. Also, the radiotellurium isotopes, which are the precursors of the radioiodine isotopes, need to be taken into consideration. Among these, only three short-lived radioiodine isotopes (^{132}I, ^{133}I, and ^{135}I) and one short-lived radiotellurium isotope (^{132}Te) could contribute substantially to the radioactivity accumulated in the thyroid gland (Balonov et al. 2003; Gavrilin et al. 2004) and, therefore, their contribution to the response of the thyroid detector at the time of the direct thyroid measurement should be considered.

In a manner similar to what was done for ^{131}I (Eq. (2)), the activity of the k-th short-lived radioiodine isotope in the thyroid at hour n was calculated as:

$$Q_{ecol,k}(n) = Q_{ecol,k}(n-1) \cdot e^{-(\lambda_{th} + \lambda_{r,k}) \cdot \Delta n} + I_{I-131}(n) \cdot r_k \cdot e^{-\lambda_{r,k} \cdot n} \cdot w_{inh,k} \cdot w_{th} \quad (5)$$

where $Q_{ecol,k}(n)$ is the ecological activity in the thyroid of the k-th short-lived radioiodine isotope at hour n (kBq); $Q_{ecol,k}(n-1)$ is the ecological activity in the thyroid of the k-th shortlived radioiodine isotope at hour $n-1$ (kBq); $\lambda_{r,k}$ is the radioactive decay constant of the k-th short-lived radionuclide (h^{-1}); $I_{I-131}(n) = C_{air}^{I-131}(n) \cdot V_{air}(n) \cdot F_{in}(n)$ is the activity of ^{131}I inhaled at hour n (kBq); r_k is the ratio of activity of the k-th short-lived radioiodine isotope to the activity of ^{131}I in the reactor core at the time of the explosion (unitless); $w_{inh,k}$ is the fraction of inhaled k-th short-lived radionuclide that is transferred to blood (unitless) (ICRP 1994); and w_{th} is the fractional iodine uptake by the thyroid from the blood (ICRP 1993).

It should be noted that calculations for ^{132}I were done under the following considerations:

- ^{132}I is in radioactive equilibrium with its precursor ^{132}Te;
- Because of the short half-time of ^{132}I, $T_{r,I-132}$=2.3 h, only the transfer from blood to thyroid was considered for ^{132}I. Uptake of ^{132}Te by the thyroid was not considered as only 0.2% of tellurium is accumulated in the thyroid gland according to ICRP (1993).

The time-dependent relative contribution to the detector response of the activity of each radioiodine isotope k in the thyroid, $\nu_k(n)$, was calculated as:

$$\nu_k(n) = \frac{P_k(n)}{\sum_k P_k(n)}, \quad (6)$$

where $P_k(n)$ is the device response to the fractional activity of radionuclide k in the thyroid (μR h^{-1} per Bq) that was calculated using the following equation:

$$P_k(n) = \frac{Q_{ecol,\,k}(n)}{\sum_k Q_{ecol,\,k}(n)} \,/\, CF_{dev,\,k}, \quad (7)$$

where $CF_{dev,k}$ is the device-specific calibration coefficient of the thyroid detector for radionuclide k (Bq per μR h^{-1}).

The parameter values of the model used to estimate the contribution of the short-lived radioiodine isotopes in the thyroid to the detector response are given in Table 4. As was mentioned above, the exact time when the direct thyroid measurement was done during the day is unknown. Therefore, the calculated relative contribution to the detector response, $\nu_k(t_m)$, was assigned to be the arithmetic mean of contributions at hours, $\nu_k(n)$, from 9:00 AM to 6:00 PM of the day when measurement was done.

Figure 3 shows the estimated variation with time of the relative contribution of ^{131}I and the short-lived radioiodine isotopes in the thyroid to the response of the DRG3-02 device. As can be seen from the figure, by the end of the measurement campaign in pioneer camp “Skazochny” on May 5, the response of the DRG3-02 device was almost entirely defined by ^{131}I. A similar variation with time was obtained for the relative contributions of the radioiodine isotopes in the thyroid to the response of the SRP-68-01 device (not shown).

Results

Table 5 shows the distribution of the thyroid doses due to inhalation of ^{131}I that were calculated for 594 Chernobyl cleanup workers with direct thyroid measurements. The average thyroid dose was estimated to be 180 mGy, while the median was 110 mGy. Most cleanup workers (73% of the total) received thyroid doses in the range from 50 to 500 mGy. For six cleanup workers with direct thyroid measurements (1% of the total) the thyroid doses were estimated to be greater than 1 Gy with the highest individual thyroid dose of 4.5 Gy.

Table 6 shows the thyroid doses from inhalation of ^{131}I according to gender, date of the beginning of iodine prophylaxis and residence at rural settlement during 26 April – 4 May 1986. Thyroid doses were higher for male cleanup workers than for females, 190 vs 130 mGy for the mean doses and 120 vs 89 mGy for the median doses (p<0.005). There were no gender-specific differences in the parameter values of the dosimetry model used in this study, except for the thyroid mass. However, such difference was expected as the proportion of cleanup workers who worked at the Chernobyl NPP site was much higher for male than for female cleanup workers as compared to other less contaminated sites (Chumak et al. 2018).

Stable iodine administration led to a reduction in the thyroid dose from ^{131}I intake. A majority of cleanup workers took stable iodine shortly after the accident when blockade of radioactive iodine uptake was the most effective method to prevent thyroid exposure: 307 (52% of the total) cleanup workers on 26 April 1986 (with subsequent administration later for some cleanup workers) and 106 (18%) on 27 April 1986 (Table 6). However, 62 (10% of the total) cleanup workers did not take stable iodine during the period from 26 April to 5 May 1986.

Assuming identical exposure scenarios on each day for all cleanup workers included in the study, a reduction in thyroid doses due to stable iodine administration should be expected with maximal effect following earlier administration (see Table 3). However, it is difficult to reach definite conclusions about the protective effect of stable iodine administration on the basis of the thyroid doses given in Table 6 because of the high degree of heterogeneity of exposure scenarios: the workers started their cleanup activities at different dates, the durations of their clean-up activities were variable, they stayed at locations with different ^{131}I concentrations in air, etc. This is in contrast with the clearly visible reduction in thyroid dose due to stable iodine administration that was observed for the general population exposed under identical scenarios (Drozdovitch et al. 2013).

According to the route lists, 36 cleanup workers stayed a day or two in neighboring villages or accompanied their families to the location of evacuation from Pripyat and, therefore, in addition to inhalation intake of ^{131}I, they might have consumed foodstuffs contaminated with ^{131}I, e.g. milk from privately owned cow, or leafy vegetables, before their direct thyroid measurement. Indeed, thyroid doses are higher among those cleanup workers, who stayed some time in rural settlements during the period from 26 April to 4 May than among the others: 210 mGy vs 180 mGy for arithmetic mean and 160 mGy vs 110 mGy for median, respectively (p<0.005) (see Table 6). Unfortunately, this assumption cannot be validated as cleanup workers were not asked, upon their return to the pioneer camp “Skazochny”, to provide information on their consumption of locally produced foodstuffs at locations outside of the 30-km zone.

Discussions and Conclusions

The thyroid doses from inhalation of ^{131}I that were calculated in this study for 594 Chernobyl cleanup workers with direct thyroid measurements range from 1.1 mGy to 4.5 Gy, i.e., over three orders of magnitude. The wide variability in dose reflects the variability in ^{131}I concentration in air across the 30-km zone and outside, different locations of work and activities among cleanup workers, different dates and durations of stable iodine administration by individuals, and other factors.

Uncertainties in dose estimates

Correct accounting for uncertainty in dose estimates is a well-recognized concern in radiation epidemiology studies. The following sources of uncertainty in the thyroid doses were estimated in this study:

1. The shared and unshared errors associated with stochastic variability and lack of knowledge about true values of the parameters used in the exposure assessment. For example, ^{131}I concentration in air was calculated using an atmospheric transport model, but was not validated by measurements of ^{131}I in air as these are not available for locations in the 30-km zone.

2. Errors in the ^{131}I activities in thyroids that were derived from direct thyroid measurements. These errors arose from device’s measurement error, assumptions made to estimate the contribution of short-lived radioiodine isotopes in the thyroid to the detector response, uncertainties in the estimates of the device’s calibration coefficients and improper geometry of measurements, e.g. use of lead collimator with the SRP-68-01 device that might influence the device’s calibration coefficients. These sources of shared and unshared errors are important because measured activity defines the individual instrumental dose.

3. The uncertainties attached to the iodine biokinetic model for inhalation and thyroid mass. Obviously, there are wide variabilities in the metabolic parameters between individuals. These sources of unshared errors are important because the endpoint of the radiation epidemiology study is the estimation of individual doses.

The uncertainties in the thyroid dose estimates obtained in this study were not evaluated in a quantitative manner. Based on extensive assessments of uncertainties in thyroid doses from ^{131}I intakes carried out for more than 25,000 individuals included in Belarusian-American (Drozdovitch et al. 2015) and Ukrainian-American (Likhtarev et al. 2014) cohorts, it is subjectively estimated that the overall uncertainties of the thyroid doses due to ^{131}I inhalation in this study are characterized, on average, by geometric standard deviations (GSDs) of about 1.8.

Reliability of dose estimates

Scaling factor—The scaling factor, which is defined as the ratio of the 'measured' ^{131}I activity in the thyroid to the 'ecological' ^{131}I activity at the time of measurement (Eq. (3)), integrates all steps of the thyroid dose estimation: results of direct thyroid measurements, modeling, and route list data. The scaling factor is an indicator of the agreement between the dose estimated using the model and the individual behavior data, and the dose derived from the direct thyroid measurement. Figure 4 shows the distribution of individual scaling factors that were derived from the direct thyroid measurements performed on cleanup workers using the detailed and the crude route lists. It was found that the agreement between the ecological and instrumental doses is substantially better for the cleanup workers with detailed route lists in comparison with those with crude route lists: arithmetic mean ± standard deviation (SD) of the scaling factor was found to be 1.2 ± 0.7 (median=1.0) vs 1.6 ± 2.4 (median=0.8), respectively, for the detailed and crude route lists. For 82% of cleanup workers with detailed route list the values of the scaling factors are distributed within a factor of 2 around 1.0, while the same range was obtained for only 41% of the cleanup workers with crude route list. Also, the range of scaling factors is much narrower for cleanup workers with detailed route list in comparison with those with crude route list, 0.3–3.9 vs 0.01–30, respectively.

Influence of quality of individual behavior data on dose estimates derived from direct thyroid measurements—To evaluate how the quality of individual behavior data influences the dose estimates derived from direct thyroid measurements, instrumental thyroid doses for 60 cleanup workers were compared that were calculated using their detailed and crude route lists (see Fig. 5a). As can be seen from the figure, a reasonable agreement is observed between the two sets of doses (correlation coefficients for natural numbers $r = 0.99$). Distribution of ratios of instrumental thyroid doses based on detailed route list to that based on crude route list is characterized by arithmetic mean of 1.05 ± 0.12 and median of 1.00. This confirms previous findings that, in general, uncertainties in instrumental thyroid doses are not driven by questionnaire data (Drozdovitch et al. 2015) and that, if human-based radiation measurements (in this case, direct thyroid measurements) are available for the study subjects, the quality of individual behavior data has, in general, a small influence on the quality of the retrospective dose assessment (Drozdovitch et al. 2016).

Ecological thyroid doses for 60 cleanup workers that were calculated using their detailed and crude route lists were also compared (see Fig. 5b). As can be seen from the figure, the agreement between the two sets of doses is poorer than that for the instrumental doses ($r =$ 0.67). The distribution of the ratios of ecological thyroid doses based on detailed route lists and on crude route lists is characterized by an arithmetic mean of 0.94 ± 0.66 and a median of 0.83, which is much wider than what is obtained for the instrumental doses.

Comparison of thyroid doses due to external and internal irradiation—For the 29 cleanup workers with detailed route list the thyroid doses from external irradiation were calculated using the RADRUE method (Kryuchkov et al. 2009). These doses were compared with the thyroid doses due to inhalation of ^{131}I that were calculated in the present study. The results, presented in Fig. 6, show that there is no correlation between the thyroid doses due to external and internal irradiation (r=0.10). This lack of correlation could be expected because (1) the external doses were not defined by the ^{131}I concentration in air and deposition on the ground and building surfaces but by other short-lived radionuclides, such as ^{132}Te+^{132}I, ^{140}Ba+^{140}La, and ^{133}I, while ^{131}I contributed only a few per cent to the dose rate in air at locations within the 30-km zone during the time period from 26 April to 5 May 1986 (UNSCEAR 2000); and (2) a detailed map of exposure rates was used in RADRUE to calculate the doses due to external irradiation whereas the information on the ^{131}I concentrations in air was more space-averaged.

It should be noted that Khrouch et al. (1988) reported thyroid dose estimates due to ^{131}I inhalation for a group of 650 adult residents of Pripyat-town, mainly personnel of Chernobyl NPP, with direct thyroid measurements. It is not clear if this group of measured individuals and the group of cleanup workers included in the present study are the same or if they overlap to some degree. The reported mean thyroid dose among the 650 measured adults measured by Khrouch et al. (1988) is 210 mGy, which is close to the value of 180 mGy estimated in the present study.

In summary, thyroid doses from ^{131}I inhalation were calculated for 594 Chernobyl cleanup workers with direct thyroid measurements. The main sources of uncertainty in these thyroid dose estimates were identified but not quantified by calculations of individual stochastic doses. It has been assumed in this study that the thyroid doses were only due to intakes of ^{131}I by inhalation. It is possible, however, that some cleanup workers, in addition to inhalation intake of ^{131}I, consumed foodstuffs contaminated with ^{131}I, e.g. milk from privately owned cows or leafy vegetables.

The agreement between ecological and instrumental dose estimates was found to be reasonable if information on detailed individual hour-by-hour cleanup worker's activities was available for the dose calculations. These encouraging results suggest that internal thyroid doses could be estimated with a reasonable degree of reliability, even in the absence of direct thyroid measurements. However, this conclusion assumes that detailed route lists could be obtained during the personal interviews for cleanup workers who were not measured for ^{131}I activity in the thyroid.

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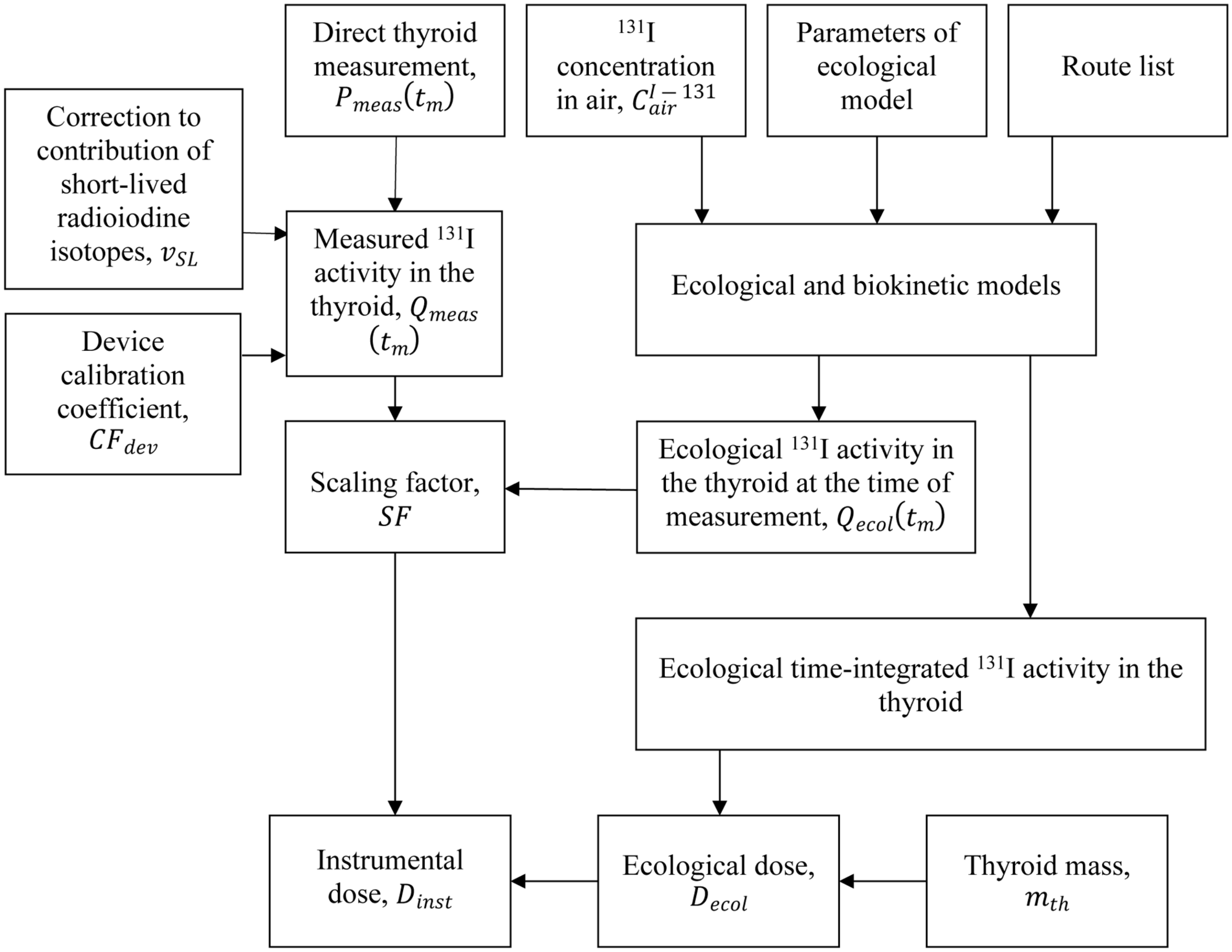
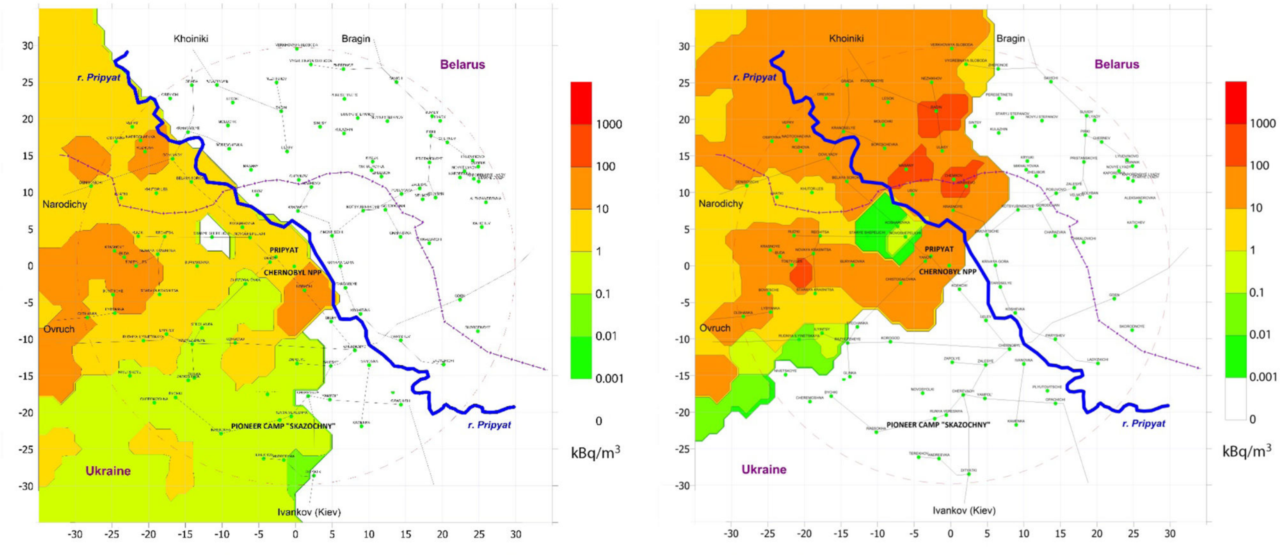


Fig. 1.
Scheme of thyroid dose calculation for Chernobyl cleanup workers with direct thyroid measurements.



April 26, 1986 April 27, 1986

Fig. 2.

Daily ^{131}I concentration in air (kBq m^{-3}) in the 30-km zone around the Chernobyl NPP on 26 April and 27 April 1986. Point with coordinates (0, 0) is 4-th Unit of Chernobyl Nuclear Power Plant (NPP).

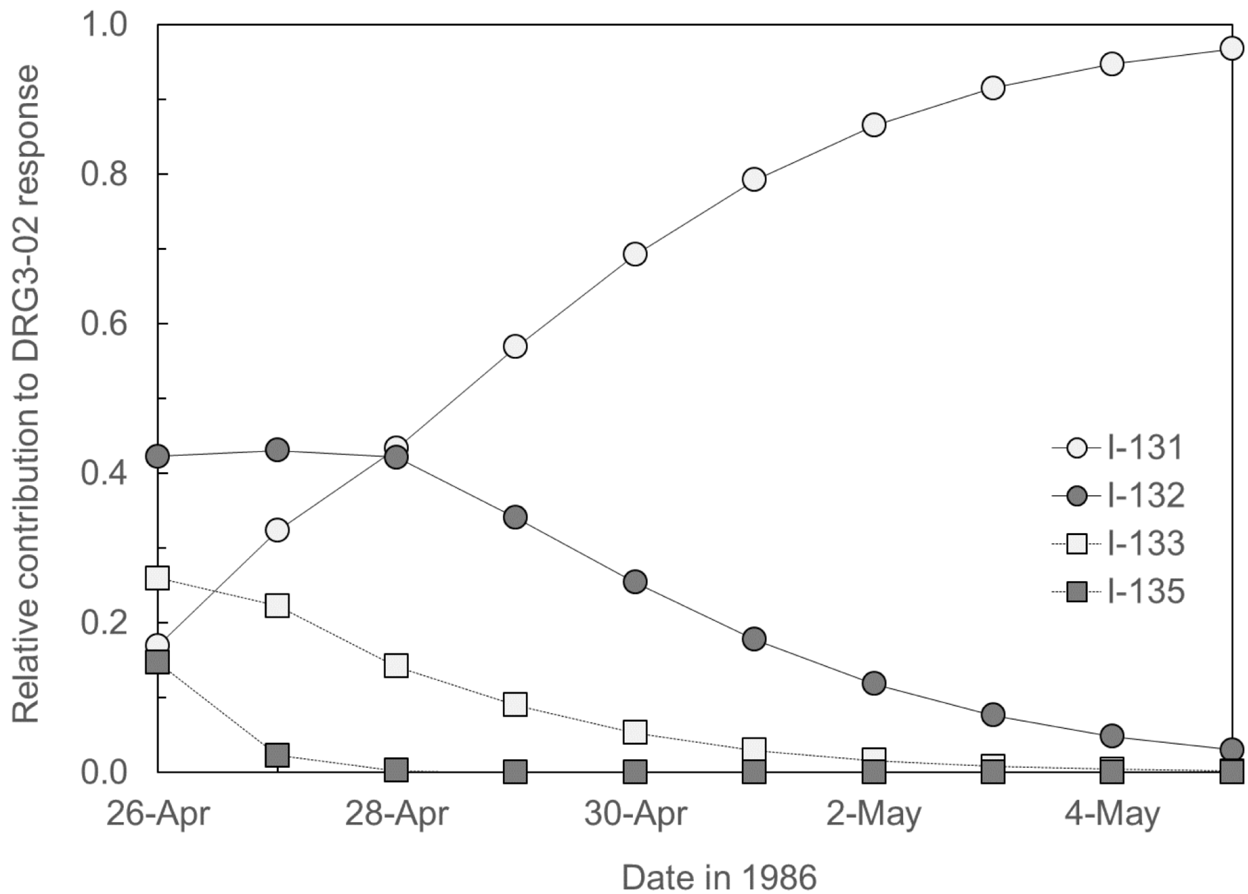


Fig. 3.
Relative contribution of ^{131}I and short-lived radioiodine isotopes in the thyroid to the response of the DRG3-02 device.

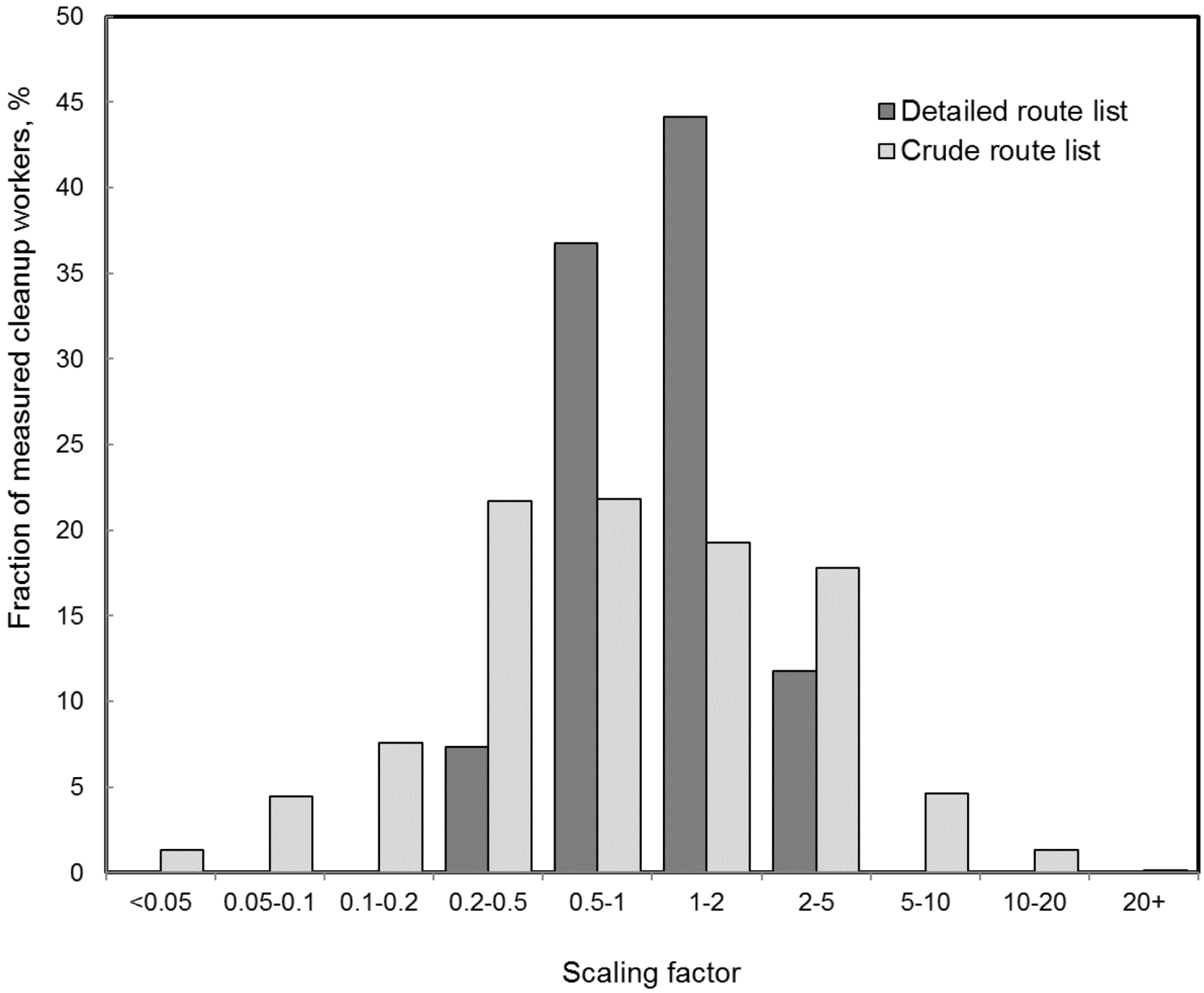
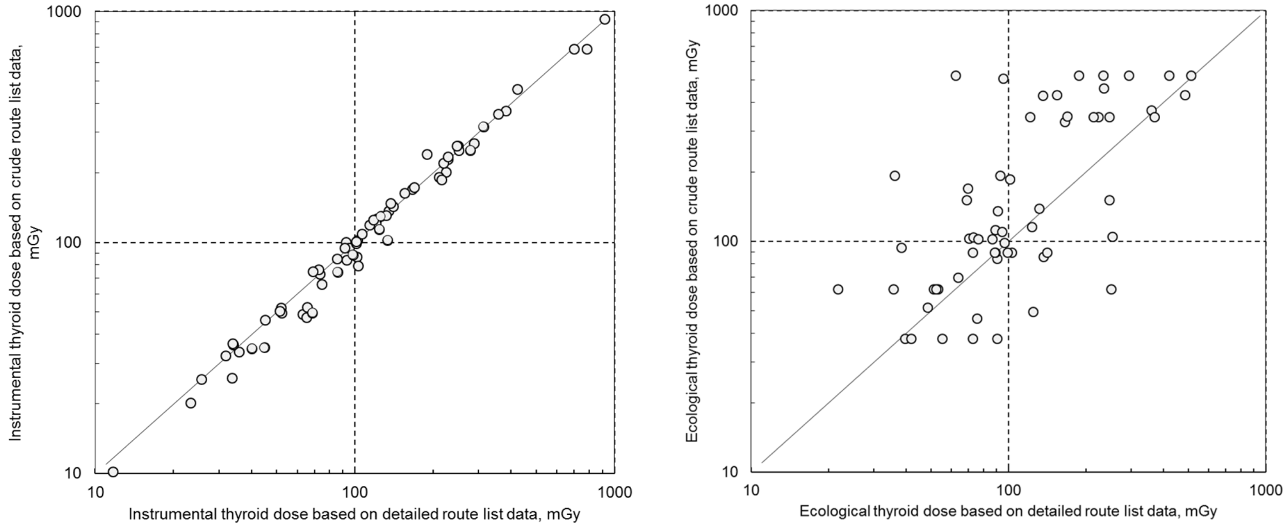


Fig. 4.

Distribution of scaling factor (measured–to–calculated ^{131}I activity in the thyroid) for cleanup workers with direct thyroid measurements.



(a) (b)

Fig. 5.
Comparison of thyroid doses due to ^{131}I inhalation estimated for 60 cleanup workers using detailed and crude individual data: (a) instrumental dose and (b) ecological dose.

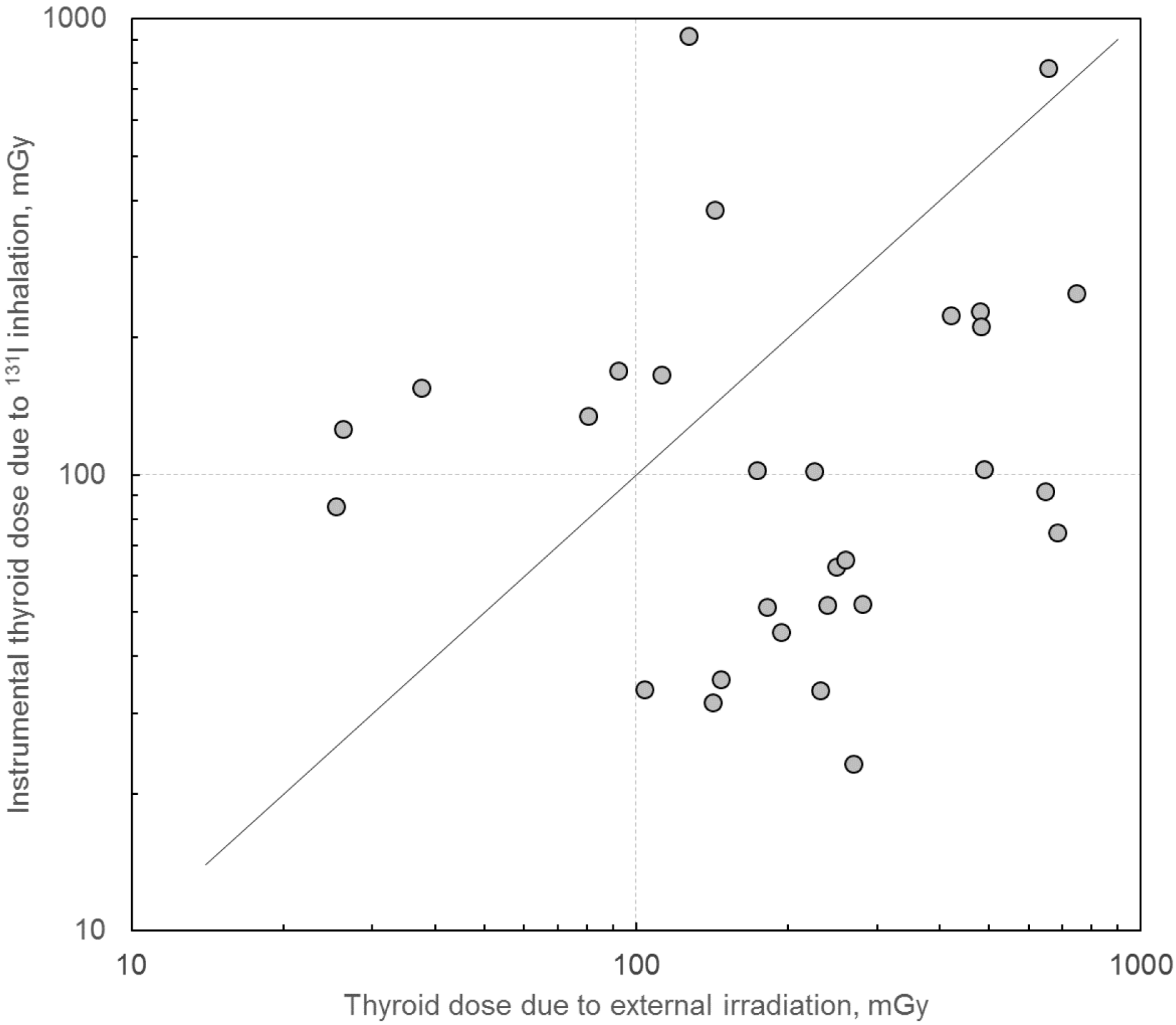


Fig. 6.

Comparison of thyroid doses for 29 cleanup workers with detailed route list: doses due to ^{131}I inhalation vs doses due to external irradiation.

Table 1

Temporal distribution of the direct thyroid measurements done among 594 Chernobyl cleanup workers.

Parameters	**Date of measurement in 1986**						**Total**
	30 April	**1 May**	**2 May**	**3 May**	**4 May**	**5 May**	
Device[a]							
DRG3-02	126	102	106	29	128	52	543
SRP-68-01	94	37	–	-	-	-	131
Gender							
Male	125	119	96	22	114	47	523
Female	16	19	10	7	14	5	71
Entire study population	141	138	106	29	128	52	594

[a]Number of measurements, including those to 80 cleanup workers who were measured by both devices on 30 April (79) and 1 May 1986 (1).

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Table 2

Breathing rate for adult person, V_{air}, for different physical activities (ICRP 2002).

Activity	Breathing rate (m^3 h^{-1})	
	Male	Female
Sleep	0.45	0.32
Sitting	0.54	0.39
Light exercise	1.5	1.3
Heavy exercise	3	2.7
Daily average	0.93	0.76

Table 3

Correction factor, CF_{KI}, of the uptake of ^{131}I by the thyroid after intake of stable iodine.

Time relative to the intake of KI-pill (d)	Values of correction factor, CF_{KI}, of the uptake of ^{131}I by the thyroid	
	Single intake	Multiple intakes[a]
−1	1	1
0	0.2	0.2
1	0.23	0.07
2	0.48	0.07
3	0.64	0.07
4	0.76	0.07
5	0.84	0.07
6	0.89	0.07
7	0.92	0.07
8	0.95	0.07
9	1	0.07

[a] At the end of the multiple intakes, the values for single intake are used (0.23 for the first day after the cessation of the intake, etc.).

Table 4

Parameters of model to estimate contribution of short-lived radioiodine isotopes in the thyroid to the detector response.

Parameter	^{131}I	^{132}Te	^{132}I	^{133}I	^{135}I
Ratio of radionuclide activity to activity of ^{131}I in the reactor core at the time of the explosion, r_k (Gavrilin et al. 2004)	1.0	1.30	1.33	1.48	0.91
Radioactive decay constant (h^{-1})	$3.28 \cdot 10^{-4}$	$8.88 \cdot 10^{-3}$	0.301	0.033	0.105
Fraction of inhaled radionuclide transferred to blood, $w_{inh,k}$ (ICRP 1994)	0.66	0.10	0.66	0.66	0.66
Fractional iodine uptake by thyroid from blood, w_{th} (ICRP 1993)	0.3	-	0.3	0.3	0.3
Calibration coefficient for the DRG3-02 device (Bq μR^{-1} h), $CF_{DRG3-02,k}$	233	-	40	147	63
Calibration coefficient for the SRP-68-01 device (Bq μR^{-1} h), $CF_{SRP-68-01,k}$ (Khrutchinsky et al. 2012)	167	-	86	220	223

Table 5

Distribution of the thyroid doses from inhalation of ^{131}I for the 594 Chernobyl cleanup workers with direct thyroid measurements.

Dose interval (mGy)	N	%	Mean dose in interval (mGy)
<19.9	34	5.7	14
20–49.9	89	15.0	36
50–99.9	150	25.2	76
100–199.9	156	26.3	140
200–499.9	129	21.7	310
500–999.9	30	5.1	680
≥1,000	6	1.0	1,800
Entire study population	594	100.0	180

Table 6

Thyroid doses from ^{131}I inhalation for 594 Chernobyl cleanup workers with direct thyroid measurements broken down according to various subgroups.

Parameter	N	Thyroid doses (mGy)	
		Mean	Median
Gender			
Male	523	190	120
Female	71	130	89
Iodine prophylaxis started on			
26 April	307	150	100
27 April	106	230	140
28 April	64	210	140
29 April	27	160	99
30 April	11	91	45
1–5 May	17	220	76
No	62	230	110
Stay at rural settlement sometime during 26 April – 4 May 1986[a]			
Yes	36	210	160
No	558	180	110
Entire study population	594	180	110

[a]Potential intake of ^{131}I with locally produced cow's milk, dairy products and / or leafy vegetables; direct thyroid measurement was done after visiting rural settlement.