Comparative analysis of the countermeasures taken to mitigate exposure of the public to radioiodine following the Chernobyl and Fukushima accidents: lessons from both accidents

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ABSTRACT

In the case of a severe radiation accident at a nuclear power station, the most important radiation hazard for the public is internal exposure of the thyroid to radioiodine. The purposes of this paper were (i) to compare countermeasures conducted (following the Chernobyl and Fukushima accidents) aimed at mitigation of exposure to the thyroid for the public, (ii) to present comparative estimates of doses to the thyroid and (iii) to derive lessons from the two accidents. The scale and time of countermeasures applied in the early phase of the accidents (sheltering, evacuation, and intake of stable iodine to block the thyroid) and at a later time (control of ¹³¹I concentration in foodstuffs) have been described. After the Chernobyl accident, the estimation of the thyroid doses for the public was mainly based on direct thyroid measurements of ~400 000 residents carried out within the first 2 months. The highest estimates of thyroid doses to children reached 50 Gy. After the Fukushima accident, the estimation of thyroid doses was based on radioecological models due to a lack of direct thyroid measurements (only slightly more than 1000 residents were measured). The highest estimates of thyroid doses to children were a few hundred mGy. Following the Chernobyl accident, ingestion of ¹³¹I through cows’ milk was the dominant pathway. Following the Fukushima accident, it appears that inhalation of contaminated air was the dominant pathway. Some lessons learned following the Chernobyl and Fukushima accidents have been presented in this paper.

Keywords: Fukushima accident; Chernobyl accident; countermeasures; radioiodine; public; dose to the thyroid

INTRODUCTION

In the case of a radiation accident at a nuclear power station, with release of radionuclides into the atmosphere, the most important radiation hazard for the public is internal exposure to the thyroid from radioactive isotopes of iodine. Countermeasures are applied in order to prevent or mitigate exposure of the public to radioiodine after such an accident. Those countermeasures typically include in the early phase of the accident: (i) sheltering, (ii) evacuation, and (iii) intake of stable iodine to block the thyroid; and at a later time: control of ¹³¹I concentration in foodstuffs to prevent or mitigate ingestion intake through contaminated foods and drinking water.

The methods with which those countermeasures are implemented, and the timing of the countermeasures, have a substantial impact on the thyroid doses to members of the public from radioiodine. A comprehensive description of the radiological consequences of two severe nuclear reactor accidents at the Chernobyl and ‘Fukushima-1’ nuclear power stations (NPSs) is given in the reports prepared by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [1–3] and the International Atomic Energy Agency (IAEA) [4–6]. It is useful to make a comparative analysis of the effectiveness of the application of the countermeasures to mitigate exposure to the public following those accidents.
accidents, as well as to present estimates of the thyroid doses received by members of the public.

The purposes of this paper were (i) to compare countermeasures conducted (following the Chernobyl and Fukushima accidents) aimed at mitigation of exposure to the thyroid for the public, (ii) to present the comparative estimates of doses to the thyroid, and (iii) to derive lessons from the two accidents.

COUNTERMEASURES FOLLOWING THE CHERNOBYL ACCIDENT

Prior to the Chernobyl accident, the use of two main documents on post-accident protective actions had been established in the former USSR. The Standards of Radiation Safety [7] introduced the dose limits to workers and to members of the public, while the other document [8] was developed to provide radiological protection of the public in the event of a nuclear reactor accident. According to the criteria in those documents, two types of dose had to be considered: (i) the whole-body dose received due to external exposure and (ii) the thyroid dose from radioactive isotopes of iodine due to internal exposure (Table 1). The duration of the early phase of an accident had not formally established when the criteria were approved. With respect to internal exposure to the thyroid, both inhalation and ingestion intakes were included. The criteria presented in Table 1 were developed in order to prevent acute health effects and to reduce the probability of occurrence of stochastic health effects among the exposed population.

However, at the time of the Chernobyl accident, the state government had a substantial impact on the timing and scale of the implementation of emergency mitigation actions in the early phase of the accident due to (i) underestimation of the consequences of the accident, (ii) classification of the information on the radiological conditions, and (iii) prevention of local authorities from making decisions and transferring the responsibilities for making those decisions to the state government. The Government Commission on mitigation of the consequences of the Chernobyl accident was created during the first half of 26 April. This Commission, chaired by the Deputy Prime Minister of the former USSR, included various specialists (physicians, specialists in emergency situations and in radiation protection, etc.) as well as government officials. Although experts in all aspects of emergency situations were involved in the activities of the Government Commission, only government officials had the right to make decisions [9].

Analysis of the countermeasures undertaken following the Chernobyl accident occurred at 1:24 on 26 April 1986 showed the following. Recommendation for sheltering was announced by the Government Commission on the day of the accident (26 April) only for the residents of Pripyat town, located ~3 km from the reactor site, which is where most of the nuclear power station workers resided with their families. Approximately 25% of the total population of 50,000 residents of the town limited the time they spent outdoors [10]. Sheltering was not applied in the other areas.

In total, ~116,000 people (24,700 Belarusians, 91,400 Ukrainians, and 186 Russians) were evacuated during the period from 27 April to late September 1986 in the three most contaminated Republics (Belarus, Ukraine and Russian Federation) [1]. The earliest implementation of this measure occurred on 27 April from 14:30 to 17:45 (37–40 h after the accident), when evacuation of all the residents of Pripyat town was conducted because of the continuation of radioactive release from the damaged reactor, and the increase in the exposure rates in various parts of the town.

It is necessary to stress that in the first few days following the accident an extensive program of measurements of exposure rates around the Chernobyl NPS was carried out. As a result of those efforts, the first map of exposure rates in the areas around the Chernobyl NPS was completed by 1 May 1986 by the Goskomhydromet staff [9]. According to the projected dose estimates calculated on the basis of the measured exposure rates, no evacuation was required for the overwhelming majority of the public in the 30-km zone (see the criteria for the whole-body dose from external irradiation presented in Table 1). However, another factor, related to the reactor situation, was taken into account: a large increase in the temperature of the fuel that remained in the reactor core was observed on 30 April. The possibility that the core bottom would be breached, resulting in important releases of radioactive materials if the core were to interact with the pressure suppression pool beneath the reactor, could not be excluded. Because the evolution of the situation at the reactor and the meteorological conditions were unpredictable, the Government Commission made the decision to evacuate the entire population from the 30-km zone [1]. It is important to note that the decisions made to

| Parameter | Action level | A | B |
|-----------|--------------|---|---|
| Whole-body dose from external exposure, Gy | 0.25 0.75 | | |
| Absorbed dose to thyroid from intake of radioiodine, Gy | 0.25–0.30 2.5 | | |
| Time-integrated concentration of $^{131}$I in ground-level air, kBq s L$^{-1}$: | | | |
| children | 1 480 14 800 | | |
| adults | 2 590 25 900 | | |
| Total integrated intake of $^{131}$I with foodstuffs, kBq | 55.5 555 | | |
| Maximum concentration of $^{131}$I in fresh milk, kBq L$^{-1}$, or in daily diet, kBq d$^{-1}$ | 3.7 37 | | |
| Ground deposition density of $^{131}$I on pasture, kBq m$^{-2}$ | 25.9 259 | | |

If the projected dose estimates and the levels of radioiodine contamination do not exceed action level A, there is no need to introduce any countermeasure. If the projected dose estimates or the levels of radioiodine contamination reach or exceed action level B, urgent introduction of the proper countermeasures—sheltering, evacuation, and iodine prophylaxis—is recommended. If the projected dose estimates or any level of radioiodine contamination exceed action level A but do not reach action level B, the decision to apply countermeasures depends on the actual reactor situation and on local conditions.
evacuate populations during the first 10 days after the accident were solely based on the doses from external irradiation (the first criterion in Table 1). Although it was recognized that large thyroid doses due to intakes of radioactive isotopes of iodine might occur, they were not taken into consideration in the decision-making process. In other words, the second criterion in Table 1 relating to restriction of internal exposure to the thyroid from radioiodine for the public was not applied.

The decision to evacuate the entire population from the 30-km zone was made by the Government Commission on 2 May, and ~49 000 residents of the Ukrainian and Belarusian villages located in the 30-km zone were evacuated on 2–7 May. At a later time, from the middle of May to September 1986, ~17 000 residents from villages outside the 30-km zone were evacuated after taking into account the criteria in Table 1. It is again important to stress that, before evacuation, the residents of the 30-km zone had not been given any advice regarding changing their lifestyle or dietary habits since the accident.

It is worth noting that stable iodine (KI) pills were not immediately available for residents who lived in the areas neighboring the Chernobyl NPS, so, during 26–27 April in Prypiat town, medical officers went from door to door and to schools and kindergartens providing members of the public with KI pills. The percentage of the residents who had taken KI pills reached 62% by the afternoon of 27 April, [10] and Prypiat town was the only settlement where administration and use of stable iodine was effective. Distribution of KI pills in villages of the 30-km zone was initiated at approximately the time at which evacuation was conducted (1–7 May) [1], and was too late so had little effect. In rural areas outside the 30-km zone, stable iodine started to be used from the middle of May through August 1986, without any effect on preventing internal exposure to the thyroid from radioactive iodine for the public.

During the first few weeks after the accident, the most important radionuclide was 131I, and the concentration measured in some samples of milk was as high as 37–370 kBq L\(^{-1}\). In order to control the 131I concentration in foodstuffs, the first temporal permissible levels (TPLs) of 131I concentration in foodstuffs (3.7 kBq L\(^{-1}\) for milk and water, and 18.5–74 kBq kg\(^{-1}\) for dairy products and leafy vegetables) were adopted by the Main State Sanitary Physician of the USSR on 6 May 1986 [9]. Milk with a contamination level exceeding the TPL was processed into milk products (butter, cheese, etc.), which could be stored until the 131I had decayed to negligible levels. On 30 May 1986, the Main State Sanitary Physician of the USSR revised the TPLs and significantly decreased them, setting up the level of total beta-activity to be equal to 0.37 kBq L\(^{-1}\) for milk and water, and 0.37–18.5 kBq kg\(^{-1}\) for the other foodstuffs [9].

**COUNTERMEASURES FOLLOWING THE FUKUSHIMA ACCIDENT**

The Great East-Japan Earthquake, with a magnitude of 9.0, occurred at 14:46 on 11 March 2011 and resulted in severe damage to the ‘Fukushima-1’ NPS, which is located ~200 km north-east of Tokyo. On the evening of 11 March, evacuation of the residents living in the vicinity of the ‘Fukushima-1’ NPS was initiated. The evacuation zone gradually extended from a radius of 2 km from the NPS to 3 km. At the same time, sheltering indoors of all residents within 10 km was recommended. In the early morning of 12 March, the evacuation zone was expanded to 10 km, and in the evening of the same day to 20 km. These decisions were made in order to take precautions against possible deterioration of the radiological conditions around the ‘Fukushima-1’ NPS. Evacuation of ~78 000 residents in the 20 km zone had been completed by 15 March. On 15 March, the Government of Japan recommended the sheltering in their own homes of ~62 000 residents living between 20 and 30 km from the power station. In addition, on 16 March an instruction was issued that all people who were still remaining within 20 km of the power station should take stable iodine to prevent radioactive iodine uptake by the thyroid. This instruction was not realized because almost all people had been evacuated from the 20 km zone by that time [3].

On 16 March, according to the decisions made by the state and prefectural governments, monitoring of food and drinking water began with the purpose of precluding/restricting ingestion intake of radioactive iodine and other radionuclides by the residents. From March 2011 until the end of March 2012, the Japanese Government settled the provisional regulation levels of 131I concentration that should not be exceeded [300 Bq L\(^{-1}\) for drinking water, milk and dairy products, and 2 kBq kg\(^{-1}\) for vegetables (except for root vegetables and tubers) and fishery products]. On 25 March, the Japanese Government announced voluntary evacuation from the area between 20 and 30 km from the power station. On 22 April, ‘deliberate evacuation areas’ were established for those areas outside the 20-km zone where the effective dose for the residents might exceed 20 mSv within a year [3].

**EXPOSURE OF THE PUBLIC TO RADIOIODINE FOLLOWING THE CHERNOBYL ACCIDENT**

It is well known that the most effective way (i.e. associated with the lowest uncertainty) for estimating an individual thyroid dose is based on in vivo monitoring of the 131I thyroidal content of the person. Following the Chernobyl accident in May–June 1986, large-scale monitoring of the 131I thyroidal content of the public was conducted in the three most contaminated countries (Belarus, Ukraine and Russia). In total, direct thyroid measurements had been performed for more than 400 000 people by the end of June 1986, including more than 200 000 people in Belarus, ~150 000 in Ukraine, and ~45 000 in Russia [11–14].

Consumption of fresh milk of cows that had been put on pasture before the accident, was the main pathway of radiiodine intake for the majority of the residents after the Chernobyl accident. This resulted in large doses to the thyroids of people, and especially of children, living in rural areas in the vicinity of the damaged reactor. A high percentage of the residents with direct thyroid measurements taken (~50%) among those who lived in the most contaminated areas allowed reliable estimation of individual thyroid doses to be undertaken, which could then be compared with the action levels of the A and B criteria for applying countermeasures as presented in Table 1. For example, the distribution of individual thyroid doses derived from direct thyroid measurements for small
children up to 3 years and adults over the three dose intervals with margins corresponding to action levels of A and B from evacuated and non-evacuated villages of the three southern raions (Bragin, Khoniki and Narovlya) of Gomel Oblast of Belarus and from villages in contaminated territories of Mogilev Oblast [15].

According to the data in Table 2, a substantial proportion of the small children from evacuated and non-evacuated villages of the three southern raions of Gomel Oblast received thyroid doses >2.5 Gy (which is the maximum dose recommended before applying action level B)—about 55% and 30%, respectively. At the same time, a small fraction (~2%) of small children from villages located at farther distances in Mogilev Oblast received thyroid doses of >2.5 Gy.

Distribution of individual thyroid doses estimated on the basis of direct thyroid measurements can be satisfactorily described with a lognormal distribution. Lognormal distributions of individual thyroid doses derived from direct thyroid measurements for the Belarusian residents evacuated from the 30-km zone before 5 May 1986 were found in: (i) 688 children of up to 6 years of age from a group of evacuated villages of the three southern raions of Gomel Oblast (Fig. 1) and (ii) 226 children of up to 17 years of age from an evacuated village (Pogonnoe) of the Khoiniki raion of Gomel Oblast (Fig. 2). It is worth noting that adults received much lower thyroid doses than children in all contaminated areas. The highest estimates of thyroid doses (derived from direct thyroid measurements) to the children were found to be as high as 50 Gy [16].

Following the Chernobyl accident a typical contribution of short-lived radioiodines to the thyroid dose for the public is within a few percent of the dose to the thyroid from 131I. The leading roles among the short-lived radioiodines in terms of internal dose to the thyroid for the public belong to 133I and 132I (due to the intake of 132Te and its radioactive decay to 132I in the body) [17].

Table 2. Distribution of individual thyroid doses derived from direct thyroid measurements for small children up to 3 years and adults over the three dose intervals with margins corresponding to action levels of A and B from evacuated and non-evacuated villages of the three southern raions (Bragin, Khoniki and Narovlya) of Gomel Oblast of Belarus and from villages in contaminated territories of Mogilev Oblast [15]

| Area                                      | Age-group | Thyroid dose, Gy |
|-------------------------------------------|-----------|-----------------|
| Villages from three southern raions of Gomel Oblast evacuated before 5 May 1986 | 0–3 years | 5.6% 39.8% 54.6% |
|                                            | Adults    | 32.5% 60.0% 7.5% |
| Villages from three southern raions of Gomel Oblast non-evacuated before 5 May 1986 | 0–3 years | 14.5% 55.8% 29.8% |
|                                            | Adults    | 65.3% 33.7% 0.9% |
| Villages in contaminated territories of Mogilev Oblast | 0–3 years | 61.1% 37.1% 1.9% |
|                                            | Adults    | 94.0% 6.0% 0.02% |
EXPOSURE OF THE PUBLIC TO RADIOIODINE FOLLLOWING THE FUKUSHIMA ACCIDENT

Following the Fukushima accident, in March–April 2011, in vivo monitoring of the $^{131}$I thyroid content for the public involved only a slightly more than 1000 residents [3]. The small number of direct thyroid measurements following the Fukushima accident only enabled the testing of radioecological models of thyroid dose reconstruction.

According to the UNSCEAR report, the settlement-average thyroid absorbed dose estimates in the first year following the accident for evacuated residents from Fukushima Prefecture were in the ranges of 0.007–0.035 Gy for adults and 0.015–0.083 Gy for 1-year-old infants [3], while for the residents from settlements in Fukushima Prefecture and six neighbouring prefectures that were not evacuated those thyroid-absorbed dose estimates were in the ranges of 0.001–0.017 Gy for adults and 0.003–0.052 Gy for 1-year-old infants [3]. Because of a lack of direct thyroid measurements, the UNSCEAR estimates are based on the assumption that a substantial contribution of the thyroid dose was due to ingestion intake of $^{131}$I by the residents. However, analysis of direct thyroid measurements conducted on 26–30 March 2011 for 1080 children from three settlements (Iwaki city, Kawamata town and Iitate village) provided evidence that for those children inhalation intake of $^{131}$I was the dominant pathway, rather than ingestion intake [18]. According to the UNSCEAR estimates, the settlement-average thyroid absorbed doses in the first year for 1-year-old and 10-year-old children of Iwaki city were 50 mGy and 30 mGy, respectively, and of Kawamata town were 44 mGy and 23 mGy, respectively [3]. The UNSCEAR estimates include thyroid-absorbed doses due to intake of $^{131}$I and of short-lived radioiodines. According to the IAEA estimates [18], the geometric means of the distribution of individual thyroid-equivalent doses for children up to 15 years of age derived from direct thyroid measurements are as follows: 3.2 mSv for 134 children of Iwaki city and 2.2 mSv for 647 children of Kawamata town. As an example, the cumulative probability distribution of the equivalent dose to the thyroid estimated for children of Kawamata town derived from direct thyroid measurements and an assumed inhalation intake is presented in Fig. 3 [18]. With respect to internal exposure from radioactive isotopes of iodine to the thyroid, the absorbed dose is numerically equal to the equivalent dose. The IAEA estimates include thyroid doses from $^{131}$I. Kim et al. [19] analyzed direct thyroid measurements for 1080 children, and according to their assessment the 80th percentile of the distribution of individual thyroid equivalent doses from $^{131}$I was equal to 10.6 mSv for children of Iwaki city and 5.9 mSv for children of Kawamata town. The thyroid dose estimates in [19] do not contradict to those in the IAEA report [18]. Despite the fact that the settlement average thyroid-absorbed dose estimates for 1-year-old and 10-year-old children provided by UNSCEAR, and the geometric means of the distributions of individual thyroid-equivalent dose estimates for children up to 15 years of age presented by IAEA for the two abovementioned settlements cannot be compared directly, analysis of those estimates shows that the UNSCEAR estimates for the considered children derived from the radioecological model were substantially higher than the actual thyroid doses based on the direct thyroid measurements presented in the IAEA report.

In April 2011, a six-expert team from the Federal Medical Biological Agency of the Russian Federation was sent to the Russian Embassy in Tokyo with the aim of assessing the external and internal exposure doses to the Russian citizens. During this trip (8–20 April 2011), the team measured the exposure rates outdoors and indoors, the level of contamination within the territory of the Embassy and within cars, and (most importantly) they provided radiation monitoring of the Embassy staff, members of their families, and other Russian citizens (in total 268 people, including a few children) with respect to determination of the content of $^{131}$I in the thyroid and $^{134}$Cs+$^{137}$Cs in the body. Direct thyroid measurements were conducted with the use of a mobile scintillation spectrometer (InSpector 1000). The duration of the thyroid measurement was 2 min, and the minimum detectable activity was equal to 100 Bq of $^{131}$I in an adult thyroid. Of all the measured people, only 3 adults exceeded the minimum detectable activity and reached up to 130 Bq of $^{131}$I in the thyroid. Each individual thyroid measurement was accompanied by a personal interview (according to a questionnaire developed in advance) in order to identify the residence history and dietary habits of the person from the day of the accident until the day of thyroid measurement, and also to determine a realistic estimate of the intake of radionuclides for that person. It was revealed that all measured people were staying in the city of Tokyo and consumed food and drinking water from stores after the accident. Taking into account the fact that the main radioactive fallout in the Tokyo area occurred on 15 March 2011 [3], and assuming that the inhalation intake was taken place that day for every measured person, the three persons with identified $^{131}$I thyroidal content have received absorbed doses to the thyroid of ~2 mGy. This
thyroid dose estimate is believed to be the highest one for all adults measured. The results of analysis of the distributions of the individual thyroid dose estimates of the residents from one settlement and the same age-group following the Chernobyl accident showed that the ratio between the highest thyroid dose estimate and the average one in such a distribution is typically equal to ~10 [11, 17]. Application of such a ratio to the distribution of the thyroid dose estimates for the Russian people measured in the Embassy allowed for estimation of an average thyroid dose equal to ~0.2 mGy for adults. Assuming that inhalation intake that occurred on 15 March 2011 was the main pathway for radioiodine intake both for adults and for children staying in Tokyo, the estimates of the highest and average absorbed dose to the thyroid for a child of 1 year of age are equal to 4 mGy and 0.4 mGy, respectively. It is reasonable to assume that the group of almost three hundred Russian people, who had only inhalation intake during their time in Tokyo after the accident, can be considered as representative of all Tokyo residents who stayed in the city and did not consume contaminated food and drinking water (with respect to distribution of individual thyroid doses). It is important to stress that the abovementioned group of people is the only one with direct thyroid measurements of those who were living in Tokyo at that time. Murakami and Oki [20] assessed the average thyroid-equivalent doses to the citizens of Tokyo after the Fukushima accident with an assumed ingestion intake of $^{131}$I due to consumption of contaminated drinking water and foods. According to their estimates (based on model assumptions regarding levels of contamination), the average thyroid-equivalent doses for adults and infants without countermeasures were equal to 0.42 mSv and 2.08 mSv, respectively, while those with countermeasures were equal to 0.28 mSv and 1.14 mSv, respectively. The authors of paper [20] did not assess the thyroid doses due to inhalation intake of $^{131}$I, and they did not confirm their model calculations with actual measurements of the $^{131}$I thyroidal content of the Tokyo citizens. However, analysis of the available set of direct thyroid measurements of people who lived in Tokyo after the accident, and the results of model calculations of thyroid doses assuming ingestion intake of $^{131}$I, show that the average absorbed thyroid doses for the citizens of Tokyo were very low, only about a few tenths of a milligray.

A typical contribution of short-lived radioiodines to the thyroid dose for residents who lived in areas where the main fallout occurred on 15 March 2011, and who did not consume contaminated drinking water and foods, is estimated to be within 15% of the dose to the thyroid from $^{131}$I. The contribution to the thyroid dose for residents who lived in areas where the main fallout occurred on 12 March 2011 might be as great as 30–40%. The main contributors to the thyroid dose among the short-lived radioiodines are $^{133}$I and $^{132}$I (through intake of $^{132}$Te and its radioactive decay to $^{132}$I in the body) [21].

**DISCUSSION**

The experience of the Chernobyl and Fukushima accidents clearly shows the importance of having a justified national strategy on introduction, implementation, and withdrawal of countermeasures to protect the public from ionizing radiation in the case of a large nuclear accident. In addition, such a strategy should be enacted in a thorough and responsible manner if a nuclear accident occurs. Late notification of the public about the actual scale and level of radioactive fallout following the Chernobyl accident, and delay in application of urgent countermeasures did not allow the residents to preclude ingestion intake of radioactive iodine through consumption of contaminated foods locally produced immediately after the accident had occurred. Consumption of cows’ milk contaminated with $^{131}$I, for which prompt countermeasures were lacking, was the dominant pathway for radiiodine intake for the public following the Chernobyl accident. This resulted in high thyroid doses (up to 50 Gy [16]), which exceeded the levels at which countermeasures had to be obligatorily applied, for many residents, especially for children in rural areas. It is worth noting that for the residents who consumed fresh cows’ milk contaminated with $^{131}$I after the accident, the ratio of the thyroid dose from the milk to that from inhalation of contaminated air was a factor of ~100. So, the thyroid dose from inhalation intake for those residents was negligible compared with that from ingestion intake with cows’ milk.

Early notification of the public and urgent application of countermeasures following the Fukushima accident, in contrast to what occurred after the Chernobyl accident, allowed for exclusion of ingestion intake of $^{131}$I with contaminated drinking water and foods for the majority of the residents. So, the dominant pathway for those residents was inhalation intake of $^{131}$I with contaminated air (during the passage of a radioactive cloud through the residential places). This circumstance resulted in much smaller thyroid doses (up to a few hundred mGy [3]) compared with that for the residents after the Chernobyl accident.

The large-scale monitoring of the $^{131}$I thyroidal content of the public following the Chernobyl accident formed a solid basis for the reliable estimate of individual thyroid doses for several hundred thousand measured people, and for developing realistic radioecological models for assessing thyroid doses to unmeasured people who lived in the same areas as the measured people. It is important to stress that the estimates of individual thyroid dose based on direct thyroid measurements are associated with the lowest uncertainties compared with any other method of thyroid dose assessment. Unfortunately, the delayed start of the direct thyroid measurements after the Chernobyl accident did not allow their use in decision-making. Those numerous direct thyroid measurements were widely used at a later time to provide individual thyroid dose reconstruction in several epidemiological cohort and case-control studies of thyroid cancer and other thyroid diseases in the exposed public.

The small number of direct thyroid measurements following the Fukushima accident allowed their use only for testing a radioecological model of thyroid dose reconstruction. Those measurements were also not used in a decision-making process. In addition, in the framework of the Fukushima Health Management Survey encompassing ~370 000 children, the thyroid dose reconstruction was conducted on the basis of developed radioecological models [6] (which are associated with large uncertainties), rather than on direct thyroid measurements as it was in the epidemiological studies following the Chernobyl accident.

The available experience clearly shows that after a severe nuclear accident, public exposure to radioactive isotopes of iodine is a very important problem. It would appear reasonable to introduce a large-scale monitoring of the $^{131}$I thyroidal content of members of the
public in the early stage of emergency management, in order to enable application of the most appropriate scale and type of countermeasures.

Alexakhin et al. compared the effectiveness of the countermeasures in terms of cost per unit of averted dose following the Chernobyl accident and found that timely use of stable iodine (pills of KI) in Prypiat town on 26–27 April 1986 was a factor of ~1 000 000 times more effective than the restriction of consumption of contaminated food implemented in 1989 in Bryansk Oblast in the Russian Federation [22].

LESSONS FROM THE CHERNOBYL AND FUKUSHIMA ACCIDENTS

(i) Strategy for the introduction, implementation and withdrawal of countermeasures should be driven by relevant national radiological criteria taking into account global experience in mitigation of the consequences of radiation accidents.

(ii) Early notification of people that might be affected by a radiation accident at a nuclear power station, and immediate introduction of emergency plans for radiological protection of the personnel (if any) and the public, are extremely important in preventing deterministic health effects and reducing the risk of stochastic health effects.

(iii) Timely implementation of urgent countermeasures in the early phase of a nuclear accident is the most effective way to avert radiation doses to people. In the early phase, the cost per unit of averted dose to the public is less than that in the intermediate and late phases.

(iv) Large-scale monitoring of thyroidal iodine content among the public is a solid basis for reliable estimates of individual thyroid doses for measured people, as well as for developing realistic radioecological models for assessing thyroid doses for unmeasured people who live in the same areas as measured people (as was possible after the Chernobyl accident). A small number of direct thyroid measurements (as occurred after the Fukushima accident) only enables the testing of radioecological models of thyroid dose reconstruction. Early commencement of direct thyroid measurements would allow their use for adjusting the time and scale of countermeasures.

(v) Prevention of ingestion intake of radioactive isotopes of iodine by the public (as was widely applied in the Fukushima accident) is a strong and effective countermeasure for mitigation of exposure to the thyroid that could otherwise be several orders higher (as occurred in the Chernobyl accident).

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CONFLICT OF INTEREST

The authors state that there are no conflicts of interest.

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