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Lessons from past radiation accidents: Critical review of methods addressed to individual dose assessment of potentially exposed people and integration with medical assessment

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ABSTRACT

The experiences of the Chernobyl and Fukushima nuclear accidents showed that dosimetry was the essential tool in the emergency situation for decision making processes, such as evacuation and application of protective measures. However, at the consequent post-accidental phases, it was crucial also for medical health surveillance and in further adaptation to changed conditions with regards to radiation protection of the affected populations. This review provides an analysis of the experiences related to the role of dosimetry (dose measurements, assessment and reconstruction) regarding health preventive measures in the post-accidental periods on the examples of the major past nuclear accidents such as Chernobyl and Fukushima. Recommendations derived from the review are called to improve individual dose assessment in case of a radiological accident/incident and should be considered in advance as guidelines to follow for having better information. They are given as conclusions.

1. Introduction

Measurements of the ionizing radiation doses that exposed people could have received during and after a nuclear or radiological accident are of paramount significance for decision making after such an unfavourable event. Reliable and accurate dose estimates for the affected workers and populations are needed to take decision on protective actions, and are fundamental to identify short- and long-term health

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impacts that might result following exposure to ionizing radiation due to nuclear and radiological accidents.

In particular, some kinds of decisions critically depend on information regarding the dose to a specific real person, which has been potentially affected, rather than to groups of population. Among examples of practical use of individual dosimetry are the following: decisions on needed medical treatment, removal of external or internal contamination (decontamination), estimate of the health risk resulting from the exposure, long-term health effects monitoring and communication. The methods used to evaluate individual doses are part of what is termed "occupational or population monitoring", i.e. to survey for radioactive contamination on the body (external contamination), to determine if and how much radioactive material has been taken into the body (internal contamination), to measure external radiation dose to the individual by personal dosimetry.

The general rule, observed in a nuclear or severe radiation emergencies and confirmed by both the Chernobyl and Fukushima accidents, is related to the fast changing radiation situation at the beginning (unveiled) of the release and, at the same time, limited scope of available data, which can be used for dose assessment (dose rates, air concentrations, deposition densities, individual doses and body burdens of the most relevant groups of people). When the radioactive release is completed (the source is contained), dose rates begin to drop fast, due to the radioactive decay of short-lived radionuclides in the mixture of released materials and ecological migration of deposited radionuclides. Conversely, at the initial phase of the emergency, when doses and dose rates are the highest, dosimetric and radiological information is very limited. Therefore, when considering the dosimetry of populations affected by a radiological emergency, time is essential and possibly the key-factor, which should be taken in further consideration in practice.

Focusing on the Chernobyl and Fukushima accidents, this paper summarizes the main lessons learned from the revision of the available literature and information sources on the methods used to evaluate doses to individuals, i.e. to specific real persons. The aim was to recommend improvements (Oughton et al., 2017, Ohba et al., 2020, in this issue) for better preparedness and response in the case of an accident and for long-term surveillance in existing situations. The methods used to estimate doses to a critical group of population or to representative individuals in a general population, i.e. not associated with a specific individual, will not be considered here.

2. Methods

2.1. Review methodology

A critical review of peer-reviewed papers, reports from international organizations or agencies, documents produced by governmental authorities, technical documents from companies and expert-based information was conducted by a working group under the framework of the SHAMISEN project. This essentially broadened scope of reviewed materials has a benefit of covering available sources of valuable information in different languages, not restricting analysis to well-known and easily available scientific publications. This article represents a critical evaluation of dose assessment and measurement practices implemented after the Chernobyl and Fukushima accidents. We focused on how and when the individual dosimetric assessment and measurements were performed to different categories of people, i.e. workers, evacuees and residents, including those who underwent health care or preventive actions.

2.2. Definitions

Because of the particular characteristics of the two accidents and the time elapsed between the accidents and this review, the duration of the three time phases (early, intermediate and long-term) of the accidents differs. Table 1 indicates how time phases were categorized for the two accidents. The classification of persons for whom doses should be assessed is also described in Table 1. In this paper these classifications were used when referring to the two accidents. European and International classifications were instead used for general considerations. The EU Directive 2013/59/Euratom definition of "emergency worker" is "any person having a defined role in an emergency and who might be exposed to radiation while taking action in response to the emergency" (European Council Directive 2013/59/Euratom, 2014). They may be exposed to radiation during their usual work or not. Among emergency workers, the "first responders" are the first members of an emergency service to appear at the scene of an emergency (IAEA, 2014). However, in the Chernobyl and Fukushima accidents the classification of workers was slightly different because of the specific situations. Finally, Table 2 indicates how dose assessment and individual dose evaluation are defined in this paper.

Table 1
Classification of accident time phases and categories of monitored people in the Chernobyl and Fukushima accidents.

Fukushima Daiichi	Chernobyl
Time phases:	
• Early phase was from 11th to 31 March 2011* • Intermediate phase was from 1st April* to 31 December§ • Long-term phase from 2012-	• Early phase from 26th April to 6th May 1986 • Intermediate phase: ranged from the acute period (from 6th May till the end of 1986 June corresponding to 10 half-life times of ^{13} • ^{1}I) to the stabilization period estimated as July 1986 – December 1987 • Long-term (recovery) phase. Time period: 1988 –
* The Fukushima Daiichi NPP was achieved restoring the cooling system by re-establishing electrical power on 26th March 2011 (UNSCEAR, 2013). § Conditions for cold shutdown state achieved in Unit 1–3 of the Fukushima Daiichi NPP on 16th December 2011 (IAEA, 2015).	
Categories of persons to be assessed:	
• Emergency workers (TEPCO and contractors) • First responders (e.g., police, firefighter, self-defense force (SDF), governmental officers, universities etc.) • Evacuees (mandatory and voluntary) • Other Fukushima prefecture residents • Public outside Fukushima.	• Liquidators (clean-up workers) of various affiliations and roles. This category includes first respondents, atomic workers, troops, emergency workers, support staff and all other professionals involved into clean-up activities in Chernobyl exclusion (30-km) zone from 1986 to 1990
	• Evacuees from Pripyat, the 30 km zone around the NPP; people from other resettlement zones (i.e. highly contaminated areas discovered later in time, for example, in some districts in Mogilev region in Belarus) • Population of contaminated territories.

3. Results

3.1. Monitoring and dose assessment

3.1.1. Workers

In both accidents, workers were monitored for internal contamination by whole body counters (WBC) and thyroid counters, while the external dose was assessed by personal dosimeters. In the **Chernobyl accident** according to standing legislation, dosimetric monitoring of both staff and external workers was the responsibility of the nuclear power plant. However, due to extreme scale of the Chernobyl accident, occupational dosimetry and radiation protection was delegated to many bodies and, therefore, was fragmented. As a consequence, this resulted in a very different quality of dosimetric data. In a limited number of cases retrospective biological dosimetry was applied. The coverage of clean-up workers with such measurements differed between both

Table 2
Classification of methods of dose assessment used in this review.

Dose assessment to a critical group of population or to a representative worker	Individual or individualized dose assessment (general public or NPP or emergency worker)
Calculation of doses by: • route-of-exposure models and intake models for each important exposure pathway • activity concentrations in the environment (such as measured levels of radionuclides in the environment, in tap water and in foodstuffs, estimated amounts of radioactive material released, atmospheric dispersion and deposition patterns) • the habits of local people, e.g., the amount of locally grown food eaten, amount of time spent outdoors and in buildings, type of shielding provided by buildings, etc,	Individual measurement based assessed dose: Measurement methods for dose: • personal dosimeters (passive luminescent dosimeters, electronic/active dosimeters, pocket/pencil ion chamber) • clinical/biological dosimetry Direct measurement methods for radionuclides intake: • whole body counting • organ counting (such as thyroid or lung monitoring) Indirect measurement methods for radionuclides intake: • biological samples (e.g. excreta) • physical samples (e.g. sampling of the breathing zone with air filters) or individualized model based assessed dose: • dose assessed to the average member of population personalized to an individual by collecting the personal behaviors through surveys (the person's size and age, lifestyle, history about food intake, time spent outdoor, etc.)
These methods provide the dose to a critical group of population or to representative individuals in a general population – not associated to a specific individual	These methods provide the dose estimated for a specific real person

accidents and particular groups of workers.

The workers, classified as liquidators or clean-up workers (Table 1), were a very heterogeneous group that comprised personnel present at the moment of the accident, first responders such as firefighters, early liquidators, and military liquidators among others (Chumak, 2007; Chumak et al., 2008). For clean-up workers, received doses were mostly external from radionuclides present in the environment and at workplaces. Internal exposures due to ingestion were negligible. Same is true for doses due to inhalation, except for thyroid during early days and for some areas. In the early and intermediate phases (Table 1), professional workers from various USSR nuclear facilities performed the most challenging tasks in the construction of Object ‘Shelter’ (the structure constructed to cover the damaged reactor and restrict release of radioactive substances). In particular, the staff of the Administration of Construction (AC) No.605 (AC-605) was the best monitored group of liquidators. Internal contamination was measured using WBC for a small fraction of clean-up workers, whose external exposure doses exceeded the preset investigation level (20 Roentgens, corresponding to an effective dose of about175 mSv for exposure to external gamma radiation) (Belovodsky and Panfilov, 1997). Based on these data, internal exposure contribution to effective dose was estimated to be, on average, less than 5% of the external doses and was therefore considered negligible compared to the total dose (Chumak, 2007). Due to logistics difficulties in the intermediate phase of the Chernobyl accident, thyroid burden measurements were not organized for clean-up workers in due time, before decay of the radioiodine (the physical half-life of ^{131}I is only 8 days). Therefore, a valid range or an average dose to thyroid from short-lived radionuclides, in particular ^{131}I, cannot be given (UNSCEAR, 2011).

Analysing the external dosimetry methods used for dose assessment of clean-up workers, it is recognized that there was a great variability in the dose monitoring and assessment methods, depending on the dosimetry facility (laboratory, service or applicable ordinance in case of military), time and organization to which the clean-up workers belonged (Chumak, 2007). The methods included individual monitoring by thermoluminescent dosimeters (TLD), radio-photoluminescence glass (RPLG) dosimeters, and ionization chambers (‘pencil’ type). Initially, all personal film badge dosimeters of the professional atomic workers of Chernobyl NPP (ChNPP) got blind due to their limited dose range (up to ca. 20 mSv) and yielded no information on doses of witnesses of the accident and early liquidators. Gradually, by June 1986, adequate dosimeters were commissioned for dosimetric monitoring of professional atomic workers (main and temporarily assigned NPP personnel and workers of AC-605), these dosimeters were calibrated in rad and Roentgen and complied with the USSR regulation which was based on the ICRP 26. None of the mentioned dosimeters was able to measure anything but gamma whole body doses. No techniques for measurement of eye lens or skin doses were in place. The latter was occasionally approached by some measurements with experimental skin dosimeters by the Institute of Biophysics (Moscow), which were performed for research purposes (Osanov and Kriuchkov, 1996). Concerning military clean-up workers, the wartime dosimeters (ID-11 radio-photoluminiscence glass type dosimeter radio) used proved to be inadequate due to their low sensitivity, too high threshold, large uncertainty and inadequate energy response and allowed only for ‘group dose assessment’ (no individual dose). This group dose assessment method, when beforehand the same estimated dose value by a dosimetrist (based on measured dose rates and anticipated duration of work) was assigned to all group members, was extensively used for radiation protection and monitoring of military clean-up workers. Another, less frequently used, method of ‘group dosimetry’ was assigning to the group one dose value measured by a single dosimeter, worn by one of the group members.

There were numerous attempts for a full-scale coordination of efforts and harmonization of dosimetric techniques between various dosimetry facilities. However, coordination and harmonization were never achieved. Additionally, there were problems with registration and retention of the results of dosimetric monitoring. For liquidators this resulted in insufficient coverage with individual dosimetric monitoring, particularly in 1986 and 1987, when the doses were the highest. Often dose records did not cover the whole period of occupational exposure; in particular, the doses related to the initial phase are missing. The keys for identification of liquidator's affiliation, which influences the quality of existing dosimetric data, are missing in the registries of Ukraine, Russia and Belarus. A special retrospective study revealed that about 95% of the official dose records available in the State Chernobyl Registry of Ukraine (SRU) were related to military liquidators (Chumak, 2007). Dose of all other categories of liquidators were not registered in the Chernobyl SRU or were not recorded in the registry at all. This indicates a scarce coordination and harmonization of dosimetry systems from facilities of different companies.

Due to extreme heterogeneity of the liquidator cohort (it officially includes anyone, who performed some activities within the exclusion zone in 1986–1990 and covers various categories from the acute radiation syndrome patients to just short-term visitors), the range of individual doses is extremely broad – from tiny fractions of mSv to several Sv. The highest doses were received by so-called ‘witnesses of the accident‘ - the persons, who were exposed immediately after the explosion. Later, when both radiation protection and dosimetric monitoring were established (since mid-May 1986), individual doses of the liquidators in most cases were in line with standing dose limits (250 mSv in 1986 with gradual reduction down to 50 mSv per year) (Chumak, 2007).

In the **Fukushima accident**, and in the intermediate phase, for the external exposure assessment, almost all alarmed electronic personal dosimeters (EPDs) were wet and inoperable due to the tsunami, and for Emergency workers EPDs were shared in groups (TEPCO, 2012). Since they maintained the emergency dose (100 mSv·person^{-1}) under a few hundred mSv·h^{-1} area to deal with the task in the nuclear accident, they used the alarmed EPDs. Thus, individual external doses by the EPDs were not available for most of the emergency workers during March in the early phase. EPDs were available from April 2011 (IAEA, 2015). For internal contamination *in vivo* whole body activity measurements with WBC (NaI(Tl) scintillation) started shortly after the accident for Emergency workers (Table 1) in Onahama located in Iwaki City (Fukushima Prefecture), and thyroid activity measurements with an HPGe detectors started by the end of April in Ibaraki Prefecture. Around June of 2011, the owner of the plant, Tokyo Electric Power Company (TEPCO) also installed new WBCs systems at the J-Village (about 30 km from the accident site). The J-Village was a football training centre and had large training fields, buildings, and accommodations for young and senior teams before the Fukushima accident. During the Fukushima accident, J-Village became the forward base for emergency workers and first responders. Because the location of J-Village was not highly contaminated, TEPCO placed WBC to measure internal contamination in emergency workers. However, in the intermediate phase, it was difficult to assess the internal contamination because the measurement spectrum on WBC was not able to actually identify short half-life radionuclides released in the accident, such as ^{131}I, ^{132}Te, ^{132}I, ^{133}I, and ^{135}I. This limitation was related to the characteristics of both the detector used and the software for identification of the radionuclides in the spectrum. These were not measured by the existing WBCs, designed for routine monitoring of radionuclides occurring under normal operation at nuclear plants, e.g., ^{60}Co, ^{54}Mn (TEPCO, 2012; Yasui, 2013b; MHLW, 2015). Even with this limitation, WBC detected high internal contamination levels for emergency workers.

In the intermediate phase, the highest estimated dose from internal contamination was 590 mSv (committed effective dose, ICRP, 2007). Successive follow-up checks revealed several causes for this value of internal contamination. Unavailability of adequate respiratory protection against volatile iodine for the emergency workers in the control room early after the onset of the accident. Iodine thyroid blocking (ITB) was not implemented, and some workers inhaled volatile radio-iodine in the control room early after the onset of the accident on 11–12 March. The stable iodine was distributed to workers after the evening of 13 March 2011 (IAEA, 2015). Respiratory protection not worn, existence of individual actions leading to inadvertent ingestion, and repeated exposure to severe working conditions in which the assigned tasks were performed (Investigation Committee on the Accident at the Fukushima Nuclear Power Stations, 2011). This situation lasted only two days (11–12 March 2011). When on-site medical team intervened in the radiation protection measures, on March 13, radiation exposure levels including internal exposure were gradually decreasing for on-site workers (IAEA, 2015). Maps of the radiological conditions at different areas of the plant were drawn, with special attention to areas where emergency activities were conducted and to routes between different working points. When countermeasure checkpoints were established, WBCs were placed in two of these checkpoints (Yasui, 2013b; MHLW, 2015). In the long-term phase, individual monitoring including the use of WBC was carried out systematically. Biological dosimetry was also used to assess the external doses of twelve emergency workers by the means of dicentric analysis from the 21st of March to the 1st of July 2011. The results indicated that the estimated absorbed whole-body dose was lower than 300 mGy, with a mean value of about 100 mGy. These results were consistent with those obtained by physical dosimetry based on personal dosimeter recording assessment (Suto et al., 2013).

For first responders, mainly police, firefighters, self-defence force (SDF), decontamination workers, governmental officers and medical staff, the Fukushima Medical University started in May 2011 internal contamination monitoring by WBC, with further assessments every half a year. Initially, unexpected, although low, levels of internal contamination (mainly ^{131}I, ^{134}Cs, and ^{137}Cs) were detected, the reason for which seems to be attributable to insufficient training in the use of respiratory protection devices (Yasui, 2013a). First responders were also provided with personal dosimeters (e.g., active personal dosimeters - APDs), starting around April 2011 for police and firefighters entering the zone. Medical staff engaged as emergency workers within 20 km from NPP were also provided with personal dosimeters.

Off-site workers, i.e. those that did not enter the nuclear plant site, were not all equipped with personal dosimeters (IAEA, 2015). Because of the low levels of external exposure, it was compulsory for offsite clean-up workers to wear personal dosimeters only if the average ambient dose rate of their working place was above 2.5 μSv·h^{-1}). For this group, the external average effective dose cumulated up to December 2011 was less than 0.2 mSv. The average yearly dose in 2012, 2013, and 2014 was 0.5, 0.5, and 0.7 mSv, respectively. No cumulative dose from 2012 to 2014 exceeded 20 mSv per year (MHLW, 2012; Yasui, 2016).

3.1.2. Evacuees and people living in contaminated areas

In the **Chernobyl accident** individualised doses to evacuees and residents of contaminated areas were assessed using some versions of time-and-motion method. For evacuees from Pripyat and the settlements of the 30-km zone a detailed survey of their behaviour, movements and protective measures was performed three years after the accident. This information was collected on hour-by-hour and day-by-day basis for evacuees from Pripyat and the 30-km zone, respectively (Likhtarev et al., 1994). This information was used for calculation of individual external doses and assessment of doses due to inhalation. Doses to the residents of contaminated areas in Ukraine were estimated in course of so-called ‘dosimetric passportization’, when average doses were assigned to various age groups of residents based on contamination densities (areal deposition of radionuclides, Ci·km^{-2} or Bq·m^{-2}) with respect to ecological and behavioural factors, being accounted by the models. Specific individual measurements with thyroid monitors, WBC and solid-state dosimeters were also performed and used for validation of applicable dosimetric models. However, selection criteria and approaches differed between the two accidents.

After the Chernobyl accident, people from Pripyat (the town which served as living quarters to the Chernobyl Power Plant employees), Chernobyl and 62 other Ukrainian settlements within the 30 km exclusion zone were evacuated (Ministry of Ukraine of Emergencies, 2011). Similarly, 107 contaminated settlements in Belarus underwent initial evacuation (BELTA, 2016); the evacuation was later extended to other highly contaminated places (resettlement zones) identified after a systematic radiological survey performed some weeks after the accident. WBC were not available since the beginning but efforts were made progressively to improve the situation. So, the evacuation began 34 h after the accident (Pripyat and one adjacent village) and the first wave (Chernobyl town and villages within the 30-km zone) was completed in two weeks with occasional relocations, which lasted till the end of summer 1986.

For evacuees, the pathways for internal contamination were inhalation and ingestion, except for Pripyat evacuees for whom the ingestion pathway was not relevant (as they were evacuated 36 h after the initial explosion). Practically, because of the lack of measurements of the activity concentration in air in the 30-km zone, no estimates or reconstruction of the inhalation dose of this group of population have been made. There is an isolated and highly speculative study where no individual dose reconstruction is reported (Pröhl et al., 2002). Individual external doses received by the evacuees were reconstructed (using a deterministic dosimetric model (Likhtarev et al., 1994) based on a survey of about 42,000 evacuees (from which 35,798 surveys were considered as complete and consistent), and using dose rate measurements from 31 monitoring points in Pripyat and 91 distributed in the settlements of the 30 km zone in Ukraine. In 1993–95 a revision of the received doses was conducted using more specific location factors and a stochastic model (Meckbach and Chumak, 1996). Two survey forms were used describing the behaviour of evacuees with different time and space resolution for Pripyat and for the other settlements of the 30 km zone. Although in general retrospective individual dose assessment for evacuees can be considered a success, the models were unable to assess doses for some residents with ‘non-ordinary’ behaviour who spent time in areas with high dose rates and heterogeneous contamination outside their residential areas and presumably received higher doses than other residents. It was estimated that up to 10% residents fell into this category. According to the survey data, about 5% of the population of the 30 km zone (other than Pripyat) migrated between various settlements before the evacuation, although the range of this migration was quite short (less than 10 km). This migration had a two-way effect – migration from higher contaminated settlements to less contaminated reduced doses and vice versa.

For the evacuees from Pripyat, the average individual effective dose due to external exposure, accumulated till the moment of the evacuation, was 10.1 mSv, and the maximum value of the effective dose was 75 mSv. The assessed doses for about 4% of evacuees from Pripyat, i.e. 534 out of 12,632 persons, exceeded 25 mSv, and only 18 persons received doses above 50 mSv. For the 14,084 persons evacuated from settlements in the 30 km zone excluding Pripyat, the mean effective dose was 15.9 mSv. None of evacuees received doses in excess of 250 mSv, the level A of the standing evacuation criterion of the USSR Ministry of Health in 1983. About 9% of this group exceeded 50 mSv; 0.85%, i.e. 120 persons, had effective doses higher than 100 mSv, and only one person exceeded 200 mSv (dose of 214 mSv). WBC measurements in Ukraine began in July 1986 and were not focused on evacuees (National Report of Ukraine, 2011).

The residents living in areas with ^{137} Cs contamination density above 37 kBq·m^{-2} were considered as living in contaminated territories. For Russia Belarus and Ukraine, this value was uniform over the next five years. Later, in Ukraine this definition was extended to take into account other radionuclides: ^{90}Sr and/or ^{238,239,240}Pu with contamination levels above 111 kBq·m^{-2} and 3.7 kBq·m^{-2}, respectively. Individual thyroid activity measurements of residents of contaminated territories were conducted using properly calibrated and collimated or not collimated NaI(Tl) scintillation detectors (for ^{131}I, the main radionuclide contributing to thyroid dose), and whole body internal contamination was measured by WBC (e.g. ^{134}Cs, ^{137}Cs). Several million measurements of ^{134}Cs/^{137}Cs content in the body, hundreds of analyses for ^{90}Sr and tens of analyses for Pu isotopes in autopsy samples of tissues were also been performed in Belarus, Russia and Ukraine to date. The thyroid activity measurements were plausible in May-June 1986 when radioactive iodine - which is selectively taken up by the thyroid - intake did not decay yet. In total 150,000 (including 112,000 children and teenagers) thyroid in vivo measurements were taken in Ukraine, mainly among residents of the Northern districts of Kyiv, Zhytomyr and Chernigiv regions (Likhtarev et al., 1995); 130,000 - in Belarus (Gavrilin et al., 1999); and 46,000 - in Russia (Zvonova et al., 1998). Thyroid measurements in Ukraine can be considered as exemplary: the measurements were taken in many regions of Ukraine (including places of temporal relocation of the population that resided in or was evacuated from the most contaminated northern regions); they were made with regularly calibrated energy selective ('window one-channel spectrometer') instruments of GTRM-01, HK-150, HK-350 types and some occasionally calibrated (on 26.5% occasions) non-selective NaI radiometers (68 instruments of SRP-68-01 type, 93,717 total number of measurements); and the results of measurements and calibration protocols were rigorously recorded, as were collimation and measurement geometry, and made available for analysis and a posteriori re-evaluation of calibration factors and respective uncertainty assessment. The geometric mean of the thyroid burden was 4.8 kBq and 90% of the measurements fell into the 0.58–47 kBq range. The highest individual thyroid doses (5–7 Gy) were registered in several settlements of the northern parts of Kiev, Chernihiv and Zhitomyr regions (National Report of Ukraine, 2011).

For external exposure, tens of thousands of TLD measurements in representative age and socio-professional groups of the general population were performed in 1987–1997 in Ukraine (Chumak et al., 1999) and Russia. These measurements were used for empirical determination of behaviour factors (the ratios reflecting modification of a reference dose under standard conditions by occupational or general life behaviour of individuals) related to specific age and socio-professional groups. These behaviour factors were then used as parameters in the dosimetric models to estimate group-averaged doses. As a supplement to individual measurements, large scale measurements of gamma dose-rates, total beta-activity and determination of nuclide composition and activity of gamma emitters by the means of gamma-spectroscopy of samples of soil, milk, potatoes and other foodstuffs were organized and undertaken. The measurement network gradually expanded, with the first aerial mapping (using helicopters) completed in summer 1986. In fact, in 1987 and later, when ground measurements became available, some areas (with poor sandy soils) were identified as having anomalous soil-to-plant transfer coefficients resulting in extremely high intake of radioceasium via the food chain (and thus unproportionally high internal doses). By the end of 1986, about 20 million dose rate measurements had been taken in residential areas, 500,000 drinking water measurements, and 30 million surface contamination (vehicles, dress, residences) measurements. Gamma spectroscopy and total beta activity measurements were taken in 700,000 milk and dairy product samples, 120,000 meat and meat products, above 1 million samples of other foodstuffs (IAEA, 1989).

In the **Fukushima accident**, evacuees included both the residents living in the evacuation areas designated by the Japanese government and people who voluntarily evacuated. The designated evacuation areas were those within a 20 km radius area of the Fukushima Daiichi nuclear power station and the deliberate evacuation areas those with a predicted annual effective dose higher than 20 mSv. As a response to the accident, local governments were requested to perform a surface contamination survey of evacuees until the end of June 2011 using Geiger–Mueller (GM) survey meters. More than 244,281 people were monitored between March 12 and 21. Most measurements were very low, below 13,000 counts per minute (cpm), 901 measurements between 13,000 and 100,000 cpm, and 110 higher than 100,000 cpm. For the latter group, all measurements were below 100,000 cpm after clothing removal (Kondo et al., 2013; Ohba et al., 2014). Then, non-contaminated and decontaminated evacuees received a certification of this survey and moved to the evacuation centre as soon as possible. Considering that contamination was mainly due to the presence of radiocaesium (^{134}Cs and ^{137}Cs) the estimated skin-absorbed dose rate for the decontamination level of 100,000 cpm was 1.1 mGy·h^{-1} (Ogino et al., 2012). Cutaneous radiation injuries are observed at doses higher than 2 Gy. So, the decontamination level was of a much lower order of magnitude. However, these measurements were characterised with a high level of uncertainty because of the pressure to make them quickly, and there was no efficient system to record the results of the measurements. Queues of evacuees were long and, for each individual the monitoring was performed in few minutes (Ohba et al., 2014). Because of this, the distance between the GM meter and the body of a monitored individual was variable (1–5 cm), and the surveyors did not have time to exactly measure and record the surface contamination level.

Direct thyroid activity measurements were also performed in several groups shortly after the accident, however the total number of monitored people was limited due to lack of available equipment. An evaluation on a group of seventeen residents in Tsushima District of Namie Town, heavily contaminated with radioactive materials, and forty-five people evacuated from coastal areas (including Minami-soma City located to the north of Fukushima Daiichi Nuclear Power Plant, FDNPP) reported median thyroid equivalent doses of: 4.2 mSv for inhalation, and 4.7 mSv for ingestion in those below 20 years of age, and 3.5 mSv for inhalation, and 3.8 mSv for ingestion, for those 20 years or older (Tokonami et al., 2012). Another evaluation, on 173 subjects who lived in Fukushima prefecture at the time of the accident or in the month following, with an average length of stay of 4.8 days, reported a maximum thyroid equivalent dose of 20 mSv (Matsuda et al., 2013). This study included not only evacuees, but also business visitors and first responders. In a study of 1,080 direct thyroid measurements in children aged up to 15 years from five municipalities (Kim et al., 2019), readings were below the detection threshold in 55% of cases, and all individual thyroid equivalent doses were lower than 30 mSv excluding 5 outliers. Among them, the maximum thyroid equivalent dose was 64.6 mSv for the 1-year-old children, being the median thyroid equivalent dose for this group from 0.0 to 3.7 mSv. In the UNSCEAR (2013) Fukushima Report, settlement-averaged estimated thyroid absorbed doses received for the 1-year-old evacuated infants (who tend to accumulate higher doses from I131 than older children and adults) ranged from 0 to 59 mGy (UNSCEAR, 2013).

External and internal individualized dose assessment for **evacuees** was based on the Basic Survey, a questionnaire targeting roughly 2,050,000 residents and visitors, who stayed in Fukushima Prefecture on 11 March 2011, to Fukushima Prefecture (Fukushima Health Management Survey, 2012; Yasumura et al., 2012; Ishikawa et al., 2015). Estimated external doses for each individual were calculated using time-series ambient dose rate maps based on field measurements and predictions by System for Prediction Environmental Emergency Dose Information (SPEEDI) coupled to the individual behaviour information from the Basic Survey for the first few days. Internal doses were estimated based on responses to the questionnaires and results of the WBC and thyroid activity measurements described above (Kim et al., 2016a). Similarly, estimated external exposures for **residents** were calculated based on personal behaviour data and ambient dose monitoring data for the following four months. The results of the estimated external doses for the first four months after the accident were as follows: for 88% of residents in the Kempoku area and 93% of residents in Kenchu area the effective doses were lower than 2 mSv; for approximately 89% of residents in the Kennan area and 99% in the Aizu and Minami-Aizu areas the effective doses were lower than 1 mSv (Ishikawa et al., 2015).

For internal dose estimation, WBC measurements started at the end of June 2011 for residents living near the FDNPP and those living in areas where the ambient dose rate was high (Tsubokura et al., 2012; Hayano et al., 2014). Results of the measurements in the early phase showed that their Committed Effective Dose was below 0.1 mSv for most people by radio-caesium (^{134}Cs and ^{137}Cs) (Kim et al., 2016a, 2016b). After that, a WBC survey was independently implemented for residents in some municipalities. This survey included 57 WBCs (including, 11 mobile). Estimated effective doses for the period June 2011-August 2016 were lower than 1 mSv for 297,160 residents including evacuees, and above1 mSv for only 26 of them (Fukushima Prefecture, 2016; Kamiya et al., 2016). No data were available concerning doses in the first months (March-May 2011). Dose assessment based on radioactivity measurements in food started in each municipality in September 2011. These assessments were performed to reassure residents, and were provided to food producers to improve their production or demonstrate compliance with the permissible levels of contamination in food (Kamiya et al., 2016). Finally, for public outside Fukushima area, Nagasaki and Hiroshima Universities started WBC for those persons who demanded.

For external exposures, local governments distributed personal dosimeters to 36,767 residents in Fukushima City, 24,115 in Koriyama City, 8,725 in Nihonmatsu and 4,559 in Tamura, in each three months since Autumn 2011. Personal dosimeters (optically stimulated luminescence (OSL) or radioluminescence glass (RLG) dosimeters) were distributed to infants, elementary, junior high school students, and pregnant women, except in Date City where dosimeters were distributed to 9,443 people of all ages. In 22 municipalities of Fukushima prefecture, the estimated median annual external effective dose for residents was less than 1 mSv for children and adults (Kamiya et al., 2016). Use of personal dosimeters also took place in citizen science projects. The main experiences were done with D-Shuttle (Tsubokura et al., 2018; Adachi et al., 2016) and Safecast (Brown et al., 2016). These experiences implemented participatory, open-source, citizen-science-centered radiation mapping solutions providing information for experts, decision makers and citizens. Although, the analysis of these experiences is beyond the purpose of the present paper, it is worth to mention that citizen participation provided useful information for both citizens and authorities and should be encouraged. The information provided has proven useful to experts, to policy makers, and to the public (Brown et al., 2016).

3.2. *Dose assessment on individuals undergoing health care or preventive actions*

Furthermore, this section provides a review on individual dose assessment of people undergoing health care or medicalization in the first phases after the accident. Due to the difficult situation of the early phase, dose reduction countermeasures and prophylaxis were recommended in both accidents, rather than individual dose measurements, so part of this section will be dedicated to the analysis of how these countermeasures were carried out. Similarly, to the previous sections, this one will be divided between clean-up workers from Chernobyl accident and emergency workers and first responders from Fukushima accident, and between evacuees and people living in contaminated areas in Chernobyl and Fukushima.

3.2.1. *Chernobyl clean-up workers and Fukushima emergency workers and first responders*

In the early phase of the **Chernobyl accident**, sorting of victims started in the first hours of the accident at the medical post of the plant. Some triage started also at the local Medical Sanitary Department no 126 in the town of Pripyat. During the first 12 h, 132 persons were hospitalized, 350 people were examined and treated for injuries, and 499 people were suspected to have Acute Radiation Syndrome (ARS). Eventually, 237 initially diagnosed with ARS were hospitalized. A medical team of the Institute of Biophysics arrived from Moscow twelve hours after the accident and performed a radiological triage taking into account time and onset of vomiting and nausea, blood counts and skin erythema. Patients were transported to Hospitals in Moscow and Kiev where the patients were controlled for external contamination and then decontaminated. Potassium iodine was administered to these victims from the first day. ARS diagnosis was confirmed during the first days in hospital in 134 of the initial 237 patients (Gusev et al., 2001). For patients hospitalised in Moscow the severity of the ARS was supported by biological dosimetry (cytogenetics) and clinical dosimetry during the first two weeks. Estimated doses for victims of Chernobyl accident varied from 0.2 to 9.8 Gy (Nugis, 2016). Clinical studies in the post-Chernobyl period confirmed that biological dosimetry based on blood parameters is a valuable tool mainly for people exposed to high doses and presenting acute radiation syndrome, and not for doses below 0.1 Gy because of the high inter-individual variability of these indices in the absence of radiation exposure (Becker et al., 1984; Gruzdev and Chistopol’skiĭ, 1992).

In the **Fukushima accident**, during the early phase, medical treatment for conventional injuries was difficult for emergency workers because several hospitals had been closed due to evacuation or sheltering, and some were not prepared to treat patients potentially contaminated with radioactive material. In the very first days after the accident, about 30 emergency workers went to hospitals for treatment of trauma and/or other illnesses not related to radiation exposure (METI, 2011, Tominaga et al., 2012, 2014). From 16th March an emergency radiation medicine unit was set up at Fukushima Medical University (FMU) by cooperation between the emergency radiation medicine support room in Fukushima Prefecture, Japan’s Self-Defense Forces (SDF) and the Japanese Atomic Energy Agency (JAEA). On March 24 two workers received high doses to their feet from the contaminated water in the basement of the Unit 3 reactor building. They were initially evaluated and decontaminated at the seismically isolated building, which was the place that still had electricity energy supply. Therefore, initially this decontamination was done in a non-medicalized area facility. After that workers were sent to FMU Hospital. FMU medical staff took care of these patients and a medical doctor from the National Institute of Radiological Sciences (NIRS) and radiation emergency medicine specialists from Nagasaki University supported the treatment and the decontamination. The assessment of dose estimation, integrated by measurement data and simulation process made by NIRS, were as follows: equivalent dose to the skin of 466 mSv for each worker, and committed effective dose of 39 mSv and 35 mSv respectively (TEPCO, 2012). No skin burns were observed and because internal dose assessment showed low levels of Cs contamination, no further counter measure was taken.

Due to the effects of the tsunami, stable iodine tablets were not initially available at the main reactor control rooms, and iodine thyroid blocking (ITB) was implemented as a protective measure on March 13. For emergency workers under 40 years old, and for those over 40 years who wished it, ITB was provided when emergency work could result in a projected thyroid equivalent dose of 100 mSv or more. From August 3 to 21 November 2011, ITB was implemented only for emergency workers carrying out emergency work in designated buildings where there was a risk of ^{131}I exposure. During the entire period of on-site implementation of ITB, approximately 17,500 tablets were administered to 2,000 emergency workers. In total, 178 emergency workers were estimated to have incurred thyroid equivalent doses of over 100 mSv based on direct measurements using NaI(Tl) scintillation detector. Twenty-five emergency workers under the age of 40 were found not to have taken stable iodine tablets (TEPCO, 2012). For SDF members, firefighters and persons from medical emergency teams ITB was implemented in advance of their operations at the site to prevent internal exposure.

Firefighters, who worked in the restricted area around the Fukushima Daiichi NPP, were checked for internal contamination at FMU from May 2011 until 2013. Health consultation depended on the results of internal/external dose assessments provided by FMU and Nagasaki University doctors. Since 2013, these firefighters have been following regular checks in the Hirata central hospital, every four months, where internal exposure monitoring and systematic health check-ups are done.

3.2.2. Evacuees and residents of contaminated areas

In the case of the **Chernobyl accident,** due to lack of information from authorities, radiation protection measures were taken only by a small fraction of the affected population, mainly on their own initiative (Likhtarev et al., 1994). Only 25% of interviewed Pripyat residents restricted their stay outdoors. Another 20% applied wet cleaning as self-introduced countermeasures. 55% of residents applied no countermeasures at all. In the official announcement about the evacuation, the public was informed that it would be a short-term relocation, so residents were instructed to take along only documents, valuables and three-day supply of foodstuffs. The reverse side of this was the absence of panic during the evacuation, which resulted in the absence of casualties during evacuation. With respect to reducing thyroid dose, evacuation was implemented later for the 30 km zone (apart from Pripyat) and other heavily contaminated area. About 62% (Likhtarev et al., 1994) of Pripyat residents were administered stable iodine pills (45% on the first day of the release, April 26th, 1986). However, for most of the public outside restriction zone the iodine prophylaxis was not applied systematically due to the complex fallout pattern and late response of the authorities. In addition, although the recommendation of the USSR Ministry of Health published five years before the accident mandated ITB administration to children and adults with an expected thyroid dose of 0.3 Gy or higher, there was no initial consensus on the dosage of iodine and it was only on the 7th of May that a recommended dosage of stable iodine was decided (Serdiuk et al., 2011), though it is known that consumption of stable iodine can reduce the total dose of thyroid by 95% if done before the entry of radioactive iodine in the body; by 50% if prophylaxis is done within 6 h after radioactive iodine intake; and is practically useless if given after 24 h or more (Pietrzak-Flis et al., 2003). Thus, administration of stable iodine was timely and effective in reducing thyroid dose for the residents of Pripyat but not for the rest of population (Shinkarev, 2016).

The USSR Ministry of Health recommendation also indicated that intake of radioactive iodine with contaminated foodstuffs (mainly milk) may be the most important contribution to thyroid dose. Although it was not possible to control consumption of individually produced milk (from local cows), in the collective farm (industrial) dairy production, milk from geographically separated rayons (counties) was mixed, thus reducing extremes in milk contamination. Contaminated milk was used for production of matured dairy (cheese, dry milk etc.) in order to allow radioactive decay of ^{131}I. Since May 6, 1986 incoming milk began to be monitored at milk processing facilities and milk contaminated in excess of 3700 $\mathrm{Bq{\cdot}l^{-1}}$ was rejected (IAEA, 1989).

Thus, effective countermeasures were identified as the prohibition of locally produced milk consumption, and the provision of clean fodder for dairy animals. However, the recommendation was labelled as "of restricted circulation" and was not available to medical institution at the time of the accident (Ilyin and Gubanov, 2004). Further, timely determination and evaluation of the radiation-ecological situation was impeded due to the following circumstances: a) the release of radioactive material lasted for a long time (up to one month) resulting in a complicated and patchy geographical distribution of the contamination; and, b) the radiation contamination covered large areas that were not only directly adjacent to the accident, but situated hundreds kilometres from the plant in areas inhabited by millions of people. This heterogeneity and complex time course of monitoring efforts and identification of contaminated spots influenced the timeliness of medical and preventive countermeasures (Serdiuk et al., 2011).

Among the **Fukushima residents and evacuees**, ITB was administered to a very limited number of individuals. In addition, the countermeasures were not implemented uniformly, due to inadequate pre-planned arrangements. On the 14th of March, the Fukushima Prefecture decided to distribute, outside the 20 km radius and within an approximate radius of 50 km, liquid potassium iodine for children under 3 years old, one tablet of 50 mg potassium iodine for those under 13 years old, and two tablets for those over 13 years old; on 16th March, the National government's HeadQuarters in Fukushima issued an order indicating that stable iodine should be administered to those being evacuated (20 km radius). However, this was not possible since all people were already evacuated. By the 20th of March approximately 1,000,000 stable iodine tablets had been distributed. Some local governments distributed stable iodine tablets but did not advise taking them, while others distributed the tablets and advised the public to take them, and still others awaited instructions from the national Government (IAEA, 2015). It is worth to mention that the optimal period of ITB administration is less than 24 h prior to, and up to two hours after the expected onset of exposure. However, it seems still reasonable to administer ITB up to eight hours after the estimated onset of exposure. Commencing ITB later than 24 h following the exposure may do more harm than benefit (by prolonging the biological half-life of radioactive iodine that has already accumulated in the thyroid). In case of prolonged (beyond 24 h) or repeated exposure, unavoidable ingestion of contaminated food and drinking water, and where evacuation is not feasible, repeated administration of stable iodine may be necessary). Neonates, pregnant and breastfeeding women and older adults (over 60 years), should not receive repeated ITB (WHO, 2017). Restrictions of consumptions and distributions of food and drink items were ordered, based on the predicted internal dose for Fukushima residents but also for people living outside Fukushima, where a significant level of contamination was detected. Based on the results of the internal dose assessment, the decision of administering Prussian Blue was taken, to speed up the excretion of radioactive caesium.

In the long-term phase, detailed surveys were carried out for evacuees and for other Fukushima residents (Fukushima Health Management Survey 2012). These surveys were: an *ultrasound examination of thyroid disorders* that covers roughly 360,000 residents aged 0 to 18 years at the time of the nuclear accident; and a *comprehensive health check*, that included 210,000 former residents of evacuation zones whose lifestyle changed drastically after the accident. The aim of this health check was an early detection and treatment of diseases as well as prevention of lifestyle-related diseases, and included a *mental health and lifestyle survey* that aimed at providing adequate care mainly for evacuees who were at a higher risk of developing mental health problems such as post-traumatic stress disorder (PTSD), anxiety and stress; and a *pregnancy and birth survey* that aided in providing appropriate medical care and support to mothers who were given a Maternal and Child Health Handbook between 1st August 2010 and 31st July 2011 and to their children. Surveys outcomes were reported from 2011 to 2019 from Fukushima Prefecture in 2020 (Fukushima health management survey, 2019).

4. Discussion and recommendations

The analysis carried out in this work showed that both countries had a preparedness and response plan for radiation protection and dose assessment in the event of a NPP accident. However, there are always unexpected events in an accident, which diminish the efficacy of the pre-planned actions and, therefore, every plan needs to be adapted according to the evolution of the accident, and should be improved from the lessons learned.

From the analysis of the two accidents, the lessons learned related to individual or individualized dose assessment are mostly related to the intermediate phase. For nuclear staff and external workers, both accidents showed several problems in performing monitoring and in the data interpretation. The scales and specific circumstances of both accidents, and *in primis* the tsunami in Japan, went far beyond the original capacity of dosimetric monitoring facilities in place. Even in the later phase there was scarce coordination and harmonization of dosimetry systems from different facilities/companies. For instance, due to the different calibration and collimation to measure ambient dose, measurement data had to be corrected by conversion factors with an instrument type and facilities/companies in each measurement in the Chernobyl accident.

In Chernobyl during the intermediate phase (until mid-June 1986) the results of individual dose measurements were lost. In Fukushima, the surface contamination measurements made on hundreds of thousands of evacuees were also lost. For both accidents, and for the assessment of external exposures, personal dosimeters in place went off-scale, out of work or were inadequate or inoperable. The use of WBC on site of the NPP was difficult due to high background levels and/or possible contamination. In addition, existing WBC were prepared for routine monitoring, not to detect radionuclides released due to a nuclear accident. Hence, in the preparedness phase shielded WBC should be prepared to detect the presence of short half-life radionuclides in a scenario with a background radiation level much higher than the natural one. In the Chernobyl accident, at the stage of triage and identification of cases with ARS, the dose assessment was mostly based on clinical symptoms. Retrospective dosimetry by means of cytogenetic analysis was only done for those individuals more severely exposed, techniques used were time consuming and no harmonized techniques among laboratories existed. Nowadays automatization and regional networks of laboratories with harmonized protocols allow to analyse a large number of individuals (Kulka et al., 2017).

For public, evacuees and people living in contaminated territories, there was confusion in registration and record keeping. In addition, many data were not recorded because considered not relevant. Due to the priority given to decontamination, surface contamination monitoring data were not systematically recorded despite that this might have been used somehow for the dose assessment.

An important lesson learned from both accidents is the lack of a pre-planned registration system of the populations monitored, which is a critical impediment for health surveillance and epidemiology after the accident. Attention should be put, therefore, in the preparedness phase, in developing a core questionnaire and protocol for registering of information on affected persons, including some demographic data, results of monitoring and, if they agree, permission to keep their data for future dose and health monitoring. It is essential to note that dosimetric concerns in the early and intermediate phases are different from those in the following phase. Individual monitoring at the initial and early stage focused on triage (screening) of large populations rather than the dose assessment. The associated uncertainty of such monitoring was not estimated in advance, and pre-selection of those groups of people for which a more accurate monitoring was necessary did not exist. It was shown by both accidents that timely individual thyroid contamination measurements are a crucial element, though equipment and pre-planned measurement protocols were lacking. Thus, it is important to examine internal thyroid exposure due to intake of short-lived radioiodine, in particular for children. A practical monitoring procedure for potentially contaminated subjects was not designed in advance. During the present review it was clearly stated that for evacuees and people living in contaminated territories, WBC on site were logistically difficult and expensive and no sharing capabilities among nearby countries was planned. Although this aspect was not considered in this review, future emergencies response plans will have to consider the consequences (benefits and drawbacks) of the use of informal sensors and citizen involvement. First experience from the Fukushima accident can be very instructive (Brown et al., 2016). To empower people to take an active role in their own radiation protection measurements can help them to better apprehend and manage the situation, and increase the radiation protection culture, as demonstrated by the ICRP Dialogue Meetings building close interaction and fluid communication between experts/authorities and local affected populations (ICRP, 2009; Kulka et al., 2017; Lochard et al., 2019). The International Commission on Radiological Protection is now incorporating a similar message (ICRP 201X).

When integration of dose information with initial medical assessment/management was considered, the review pointed out that hospitals were not prepared or not willing to receive possibly contaminated people. There was an inhomogeneity in the management of the health countermeasures, iodine administration, for workers and for residents.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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