

Public health activities for mitigation of radiation exposures and risk communication challenges after the Fukushima nuclear accident

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ABSTRACT

Herein we summarize the public health actions taken to mitigate exposure of the public to radiation after the Fukushima accident that occurred on 11 March 2011 in order to record valuable lessons learned for disaster preparedness. Evacuations from the radiation-affected areas and control of the distribution of various food products contributed to the reduction of external and internal radiation exposure resulting from the Fukushima incident. However, risk communication is also an important issue during the emergency response effort and subsequent phases of dealing with a nuclear disaster. To assist with their healing process, sound, reliable scientific information should continue to be disseminated to the radiation-affected communities via two-way communication. We will describe the essential public health actions following a nuclear disaster for the early, intermediate and late phases that will be useful for radiological preparedness planning in response to other nuclear or radiological disasters.

KEYWORDS: disaster preparation, Fukushima, nuclear disaster, public health, radiation exposure, risk communication

INTRODUCTION

During radiological emergencies, many public health actions need to be coordinated in order to best protect the health of the affected populations. As has been recently pointed out, such public health protections may need to be enforced for years to come [1]. The following presents the case of the public health actions taken after the Fukushima earthquake, tsunami, and subsequent radiological disaster of 2011.

The Great East Japan Earthquake and Tsunami of 2011, a magnitude 9.0 earthquake with a 14-m or more tsunami following, occurred on 11 March 2011. This disaster left approximately 18 000 people dead or missing. The Great East Japan Earthquake and Tsunami severely damaged the Fukushima Daiichi Nuclear Power Plant 1 (henceforth referred to as the 'damaged reactors'), owned and operated by the Tokyo Electric Power Company (TEPCO), resulting in a large release of radioactivity into the environment. Radionuclides

were released into the atmosphere by hydrogen gas explosions from the damaged reactor [2]. This serious event has been temporarily classified as Level 7 on the International Nuclear and Radiological Event Scale ('Severe Accident'), which was also applied in the case of the 1986 Chernobyl power plant accident. The Nuclear and Industrial Safety Agency of Japan (NISA) reported that 1.6×10^{17} Bq of ¹³¹Iodine (¹³¹I) and 1.5×10^{16} Bq of ¹³⁷Cesium (¹³⁷Cs) were released into the environment during the Fukushima event [3]. In comparison, 1.8×10^{18} Bq of ¹³¹I and 8.5×10^{16} Bq of ¹³⁷Cs were released into the environment in the Chernobyl accident [4, 5]. Japan declared a nuclear emergency after the failure of the cooling system at the damaged reactors. International Commission on Radiological Protection (ICRP) Publication 109 indicated that a reference levels should be set in the band of 20–100 mSv effective dose (acute or per year), so the Japanese government tried to limit additional public exposure

to radiation to under 20 mSv/year [6]. There are early, intermediate and late disaster response and recovery phases, which have distinctive public health characteristics and parameters. The early phase is dealing with the atmospheric transport of the initial radioactive plumes, which involved the radionuclides of ^{131}I and $^{134}\text{Cs}/^{137}\text{Cs}$ in the Fukushima prefecture event for at least 2 weeks after the accident. There are two main ways that radiation exposure occurs with humans: external exposure from radionuclides deposited on the ground and in the radioactive cloud, and internal exposure from inhalation and ingestion of radionuclides in the radioactive cloud and in contaminated food and water, respectively. It is important to avoid the acute doses from inhalation (^{131}I for exposure to the thyroid), and from external exposure ($^{134}\text{Cs}/^{137}\text{Cs}$, whole body) by evacuating the affected populations and administering stable iodine (KI) (blocking the radioactive ^{131}I intake). In the intermediate phase, the primary concerns are regarding sheltering, relocation, control of the radioactively contaminated environment, and foods or drinking water intake controls. In the late response and early recovery phases, long-term management and monitoring are necessary to lay the foundation for the long recovery process. Thus, the long-term health of exposed populations requires continued public health tracking.

EVACUATIONS

Approximately 150 000 people in the Fukushima prefecture were evacuated in response to the 2011 Fukushima radiological incident. Evacuation from the 3-km zone was ordered at 21:23 on the evening of 11 March. The evacuation zone was extended to 10 km away from the damaged reactor at 5:44 on 12 March. Finally, the evacuation zone was extended to 20 km within 24 h of the initial release from the damaged reactor. Although some people in the prefectures neighboring Fukushima were voluntary evacuated, mandatory evacuation due to radiological exposure risk was ordered by the Japanese government only in regions of the Fukushima prefecture. Evacuation of hospitalized patients within 20–30 km of the damaged reactor was commenced on 15 March 2011 and completed on 18 March 2011. Some elderly hospital patients died during their transportation. This concern has been well documented by other groups [7, 8].

For predicting the atmospheric transport of radioactive materials, a System for Prediction of Environmental Emergency Dose Information (SPEEDI) was utilized [9]. Unfortunately, the data from SPEEDI had not been used when setting evacuation areas during the early phase of the Fukushima incident. Although residents had been told repeatedly that the radiation level was tolerable, on 11 April 2011 evacuation zones were suddenly extended to incorporate those areas where residents would potentially be exposed to a cumulative effective dose >20 mSv in the first year if they were not evacuated. Residents and some evacuees from the initial evacuation zone were still in this area at that early stage after the Fukushima event. Therefore, until 16 June 2011, people had been evacuated from these locations. This secondary evacuation caused confusion and mistrust among residents of the area because many were being evacuated for the second time.

IODINE PROPHYLAXIS

In Japan, people usually eat large amounts of seafood, which contains a high concentration of stable iodine [10]. Iodine deficiency is rare in Japanese people, unlike in the people around the Chernobyl Nuclear

Power Plant. As mentioned by the World Health Organization (WHO) [11], the high iodine content of the Japanese diet may reduce the uptake of radioactive iodine by the thyroid. At the time of the earthquake, stable iodine had not been pre-distributed to households in Japan. On 13 March, the Central Nuclear Emergency Response Headquarters (NERHQ) instructed evacuees less than 40 years of age to receive stable iodine for the protection of their thyroid from radioiodine as a precaution due to their potential radiation exposure of >10 000 cpm. Administration of stable iodine was not advised for people over 40 years of age because the risk of radiation-induced thyroid cancer is considered to be low in this age group. On 15 March 2011, the Nuclear Safety Commission (NSC) advised that the daily potassium iodide (KI) dose was 100 mg for children >13 years of age, 50 mg for children 3–13 years of age, 32.5 mg for infants 1 month – 3 years of age, and 16.3 mg for new-born infants under 1 month of age. Medical personnel were required to assist with the administration of stable iodine to patients with an iodine allergy or thyroid disease. However, this order for administration of stable iodine was not properly communicated to evacuees due to the confusion under the complex disaster circumstances, and KI was not administered to the general population except in a few local areas. In contrast, first responders, such as emergency workers at the Fukushima Nuclear Power Plant, were given KI. After the accident, the Nuclear Regulation Authority mandated the pre-distribution of KI by the local government in case of future accidents [12].

MORGUE MANAGEMENT

Management of dead bodies during disasters is a major public health concern. However, the many deaths in this event were all caused by the tsunamis, not by the radiation exposure. We translated the text of *Management of Dead Bodies after Disasters: a Field Manual for First Responders* published by the Pan American Health Organization into Japanese and made it electronically available to emergency managers [13]. Initially, radionuclide-contaminated dead bodies from inside the evacuation zone (within 20 km of the damaged reactor) were washed with water and then transported to outside the evacuation zone. The Ministry of Health, Labour and Welfare (MHLW) rapidly provided a manual for screening dead bodies that was followed in the evacuation zone (within 20 km of the damaged reactor) [14] because such guidelines were not available there. Decontamination was then to be carried out by clothing removal, then the body re-surveyed for radioactivity. Then the dead bodies whose dose rates were less than 10 $\mu\text{Sv}/\text{h}$ were treated, as with uncontaminated dead bodies. Decontaminated dead bodies with count values >10 $\mu\text{Sv}/\text{h}$ were washed with a wet towel and then covered with cloth and retained for identification. Initially dead bodies were buried temporarily due to a lack of crematories; however, within a few months almost all dead bodies were cremated.

FOOD AND DRINKING WATER SUPPLY PROTECTON

Before the Fukushima accident, the Japanese government prepared a safety manual for measuring the radioactivity of foods and indices for Food and Beverage intake restriction [15]. These Indices were derived from research following the earlier nuclear accident at the Chernobyl Nuclear Power Plant [15]. The MHLW adopted these Indices as provisional regulation values on 17 March 2011.

Provisional regulation values (PRVs) were based on protective action guides (PAGs) of a 50 mSv/year of thyroid equivalent dose for radioactive iodine and tellurium (^{131}I , ^{132}I , ^{133}I , ^{134}I , ^{135}I , ^{132}Te) and a 5 mSv/year for the effective dose for radioactive cesium and strontium (^{134}Cs , ^{137}Cs , ^{89}Sr , ^{90}Sr) during radiological emergency situations. The basic concept of PAGs and derived intervention levels (DILs) for food control in the Fukushima radiological emergency were described by Yamaguchi in a previous paper [16]. Briefly, after considering the radionuclide transfer characteristics, foods were grouped into five categories: drinking water, milk and dairy products, vegetables, grains, and others (meat, eggs, fish, nuts, etc.). We assumed that people continued to consume foods from the affected area. Derived regulatory values for the intake of each food category were calculated so that the permissible dose would not exceed 5 mSv/year. Non-contaminated food on the market diluted the concentration of contaminated radionuclides in the food supply. Thus, the average concentration of contaminated food was assumed to be half of the peak concentration for the long-lived radionuclides of cesium (physical half-life: 2 years for ^{134}Cs and 30 years for ^{137}Cs) for the induction of DILs. However, that assumption was not applied for short-lived radionuclides of ^{131}I (half-life: 8 days), where we used a dilution factor of 1. The new standard limits for radioactive cesium were established with the goal that the effective dose of radionuclides (including ^{137}Cs , ^{90}Sr , ^{106}Ru (106), plutonium (Pu) would not exceed 1 mSv/year in affected populations [16]. Standard limits were not established for radioactive iodine (which has a short half-life and is no longer detected at this time) or uranium (the uranium levels are almost the same level in the nuclear power plant site as in the natural environment). We determined that the intervention level to assign to general foods was 100 Bq/kg (500 Bq/kg in general foods for previous PRV) by taking into consideration the food intake and dose coefficient according to specific age categories. According to the MHWL estimation of effective dose from radioactive cesium based on the monitoring data of the radionuclides in foods, the median total committed effective dose was 0.043 mSv; the 90th percentile was 0.074 mSv when non-detected samples were set to be the detection limits for each measurement or 10 Bq/kg for ^{134}Cs and ^{137}Cs , respectively [17]. Natural background radiation has been estimated at 2.4 mSv/year in the world and 2.09 mSv/year in Japan [18, 19]. Compared with natural background radiation, the internal radiation exposure due to contaminated food affected by the Fukushima accident was at a low level. However, some residents outside the evacuation zone might have consumed highly contaminated local food or water before regulation values were in effect. At that time, many residents suffered from a shortage of fresh food and water because of the earthquake, and local farmers had no means of knowing whether their fields were contaminated or not. Some further consideration of the magnitude of any high-dose exposure arising via the ingestion pathway for people outside the evacuation zone might be worthwhile.

EXPOSURE ESTIMATION

Many steps were taken to monitor the radioactivity within the air after the Fukushima event. Various monitoring data from the damaged reactor area suggested that the radiological air emissions occurred from hydrogen explosions, venting and leakage throughout the month of March 2011 [20]. For the rapid assessment of dose rates, a car-borne radiological survey was performed along a motor

vehicle expressway northwest of the damaged reactor [21]. The maximum dose rate observed was 11 $\mu\text{Gy/h}$ between Fukushima City and Osaki City on 16 March 2011 [21]. In addition to monitoring the ambient radiation dose rate, additional testing was done to measure the radioactive contamination of surfaces, like skin and clothing, of 219 743 evacuees and emergency responders [22, 23].

A basic survey (part of the Fukushima Health Management Survey) began at the end of June 2011 to estimate levels of external radiation exposure, based on behavioral records. Individual external exposure was estimated, based on a respondent's trail, using the system for external exposure dose assessment developed by the National Institute of Radiological Sciences in Japan. Almost all people (99.9%) measured <10 mSv of committed effective dose [24]. Internal contamination can be estimated for evacuees and emergency responders by a nasal smear. However, this test was not carried out because of the many logistical challenges under the complex disaster circumstances. Therefore, such data were not available in the Fukushima incident. The local nuclear emergency response headquarters performed a simplified survey using a Sodium Iodide (NaI) scintillation survey meter for thyroid internal exposure to radioiodine, particularly ^{131}I [25]. From 28–30 March 2011 they surveyed 1149 children aged 0–15 years who were living in areas with relatively high radiation dose rates (Iwaki City, Kawamata Town and Iitate Village). Sixty-six people were unable to be measured appropriately due to a higher radiation background from radio-contaminated soil at the survey site. The thyroid radiation dose was estimated for other groups [26, 27]. The survey results for all people tested were below a thyroid equivalent dose of 100 mSv. For Fukushima residents in areas where the possibility of internal exposure might be relatively high, internal radiation levels were measured using a whole-body counter (WBC) within two years of the disaster [28, 29]. Almost all people (99.9%) measured <1 mSv of committed effective dose. Only 26 of the 90 024 total people tested measure >1 mSv. The maximum internal exposure level was 3 mSv. Fortunately, no case of acute health problems resulting exclusively from radiation exposure has yet been reported in the Fukushima event. Thus, Fukushima area residents and emergency responders were apparently not exposed to radiation doses higher than the threshold for induction of deterministic effects.

The WHO conservatively estimated that the effective doses during the first year following the Fukushima event in the most affected region of Namie town and Iitate village would have been 10–50 mSv [11] if they had not been evacuated. These values have been revised to 12–25 mSv [30]. In the rest of Fukushima prefecture, the effective dose was estimated to be within a dose band of 1–10 mSv. Effective doses for most of Japan were estimated to be within a dose band of 0.1–1 mSv, and in the rest of world, all the doses were estimated to be <0.01 mSv [11]. As described in the WHO reports, a comparison was made between the doses estimated by WHO and those estimated from direct measurements of radionuclides in Japanese residents. This gave the government health officials confidence that the estimated doses did not underestimate the actual dose in Japan [11]. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated that the evacuation of settlements within the 20-km zone averted effective doses to adults of up to ~50 mSv and absorbed doses to the thyroid of 1-year-old infants of up to about 750 mGy [31]. Although UNSCEAR estimated radiation doses to the public by assuming more realistic scenarios

than those that WHO adapted, there are still uncertainties associated with the results as a result of incomplete knowledge and information.

For example, to estimate the maximum ingestion dose among general residents in Fukushima precisely, more detailed analysis should be considered.

DECONTAMINATION AND DECOMMISSIONING

In order to mitigate public radiation exposure from contaminated soil, the Japanese government decided to carry out decontamination work. Establishing the Act on Special Measures concerning the Handling of Pollution by Radioactive Materials that was fully put into force on 1 January 2012, the Ministry of Environment committed itself to measuring and monitoring the radioactive contamination of the environment, and to processing the disposal of contaminated soil and wastes removed by decontamination activities. The Japanese government conducted the decontamination work in a special decontamination area within the former restricted zone or planned evacuation zone, whereas it was conducted by each municipality in other areas where the air dose rate was $>0.23 \mu\text{Sv/h}$ (equivalent to 1 mSv/year). The aim of decontamination is to reduce the additional exposure dose to $<1 \text{ mSv/year}$ for areas where the radiation exposure dose is $<20 \text{ mSv/year}$. In the case of a radiation exposure dose range from 20 to 50 mSv/year , the long-term aim of decontamination is to reduce the additional radiation dose to $<20 \text{ mSv/year}$ in residential and farmland areas. Decontamination should be implemented taking into consideration in future decontamination policy for extremely high-dose areas of $>50 \text{ mSv/year}$. Radiation protection should be planned for workers, including decontamination workers. This topic has been well documented in another paper [32]. We also summarized health management and radiation protection for radiation workers involved in the Fukushima accident in a previous paper [33]. In addition, the radiation safety of radiation workers engaged in decommissioning the nuclear power plant should be secured. During the fiscal year ending November 2014, radiation doses of 17 317 workers at the Fukushima Daiichi Nuclear Power Plant were monitored. Among these, although radiation doses to 468 workers were $>20 \text{ mSv}$, all workers were $<50 \text{ mSv}$ [34].

RISK COMMUNICATION

Risk communication is considered an important issue during the early emergency situation [35]. Appropriate and targeted risk communication can help to reduce the health impact of radiation emergencies and help promote food safety and food security [36]. The risk communication scientific literature has significantly contributed to our current understanding of the existing exposure situation in the Fukushima region today. WHO is trying to develop a risk communication tool that can guide policy makers, national and local governments and the medical community to establish risk consensus in public communication.

Communication difficulties between local governments, scientific experts and the local citizens were a major concern during the early radiation safety response in the Fukushima incident, and they have been recognized to be one of the difficult issues in affected areas during three years. Confusing messages in the initial phase (such as the reference level for schools), confusion about setting of deliberate evacuation areas, and difficulties in human relationships exacerbated by compensation issues associated with specific spots recommended

for evacuations and the surrounding areas caused severe difficulties in risk communication. Public health nurses have been assisting in the recovery of local communities by empowering them [37]. Public health nurses have strong communication skills. Improving nurse's health literacy skills helps in the process of effective communication. WHO reported that mental, psychological and central nervous system effects following the Chernobyl accident were due to the mental stress from fear of radiation exposure [38]. The same thing has been occurring again after the Fukushima incident [39]. There are serious concerns about mental health in relation to the Fukushima incident, including stress-related symptoms, and a potentially elevated suicide rate in Fukushima clean-up workers. The reference dose was changed from 1 mSv/year to 20 mSv/year under the existing exposure situation after the Fukushima incident, consistent with ICRP publication 60 [40]. This change was not acceptable to the public due to the lack of proper risk communication. Risk communication should be organized according to a sound strategy based on public health ethics and scientific evidence [36]. Messages to the public about the radiation risks due to the Fukushima nuclear disaster have been misunderstood because of the inappropriate manner of risk communication that has been used, without deep consideration of the situation of each person within the audience. We learned that to deal with the difficulty of risk communication we should strengthen the relationship with social scientists to find good approach. Stakeholder involvement in post-nuclear or post-radiological emergency management is a key to resolving this problem. Indeed, stakeholder involvement in preparedness planning in the UK seems to be partially adaptable to the situation in Fukushima [41–43]. For example, one of the main topics for the UK Agriculture and Food Countermeasures Working Group in this workshop was the issue of the disposal of contaminated dairy milk, which was a very real issue in Fukushima [44]. Also, in the workshop organized by the Organisation for Economic Co-operation and Development – Nuclear Energy Agency to discuss issues concerning recovery from a nuclear accident, involving relevant stakeholders in Fukushima, it was suggested that the stakeholder involvement provided a good opportunity for networking together to resolve the outstanding communication challenges.

PUBLIC HEALTH PREPAREDNESS FOR FUTURE NUCLEAR DISASTERS

Development of planning guidance is proposed for preparation in advance of a nuclear detonation [45]. The International Atomic Energy Agency (IAEA) previously published information on the importance of preparedness and emergency management plans in response to a nuclear disaster on public health [46, 47]. We have summarized public health actions after the Fukushima incident in order to provide valuable lessons for disaster preparedness (Table 1). Because this disaster was a combined severe disaster involving environmental contamination, evacuation of hospital patients and elderly persons who were not ambulatory created many challenges. Some of evacuees from Fukushima were rejected in hospitals and nursery homes basically due to confusion over radiation risk. Although the Radiation Emergency Medicine Information network (REMNET) (an informative website for radiation emergency medical information in Japan) has been established and provides many training courses, secondary or lower-level network hospitals did not sufficiently receive

Table 1. Public health actions after the Fukushima incident

| | What has been done at the Fukushima incident | Problem to be solved | Proposed guideline for nuclear disaster preparedness |
|------------------------|--|---|--|
| 1. Evacuations | <ul style="list-style-type: none"> Evacuation zone was set within 24 h after the initial release from the damaged reactor. Evacuation of hospitalized patients within 20–30 km from the damaged reactor was delayed. | <ul style="list-style-type: none"> Setting of planned evacuation areas and transition from the emergency exposure situation to the existing exposure situation. Some hospital patients with advanced disease died during transportation. | <ul style="list-style-type: none"> Radioprotection action of evacuation should be done 1 day after a nuclear incident according to the contamination level (Refer to Operational Intervention Level) and step-by-step radiation protection considering the local situation. Pay attention to evacuation of hospital patients immediately after the nuclear incident. |
| 2. Exposure estimation | Radiological assessments were utilized for dose estimation including internal dose of thyroid exposure. | <ul style="list-style-type: none"> Due to the high background radiation, the detection limit was elevated so that radiological judgement became difficult for relatively lower exposures. Individual dose calculation is challenging to estimate at present because of insufficient datasets. | <ul style="list-style-type: none"> Monitoring systems should be prepared on the assumption of insufficient materials due to the complex disaster. Biospecimens should be collected during the emergency exposure situation for later dose accuracy estimation. |
| 3. Iodine prophylaxis | NSC advised nuclear emergency response headquarters on administration of stable iodine in case surface contamination was above 10 000 cpm by using ordinary GM survey meters. However, headquarters failed to instruct local governments. | Administration of stable iodine was not conducted for the general population. | <ul style="list-style-type: none"> Stable iodine should be administered to people who are potentially exposed to a thyroid equivalent dose of >50 mSv. Local governments should provide stable iodine to the general public. |
| 4. Risk communication | Lack of proper risk communication during the emergency exposure situation. | <ul style="list-style-type: none"> Misunderstanding of messages to the public about the radiation risks. Difficulty of risk communication without a planned strategy and scientific evidence in social sciences. | <ul style="list-style-type: none"> Building capacity in risk communication and paradigm shift in communication approaches are challenging issues. |

such training. Because it is very common for each hospital to treat radioactive patients outside a nuclear medicine department, the general principle should be preparedness for radiation protection in the entire hospital. Furthermore, although REMNET has provided educational courses that have dealt with internal radiation exposure, training for external measurement using a WBC was insufficient for almost all hospitals equipped with WBCs, and the use of bioassay samples, such as nasal swabs, were very limited. In addition, the

public health rationale for exposure screening using a survey meter was not well communicated in Fukushima. The main role of such screening should be for iodine prophylaxis decision-making. Excessive attention to decontamination and the lack of sufficient decontamination resources due to the massive contamination in Fukushima caused the change in the screening level to rise from 13 000 cpm to 100 000 cpm. This level corresponds to a dose rate of 1 μ Sv/h at a distance of 10 cm as the screening level of first responders, according

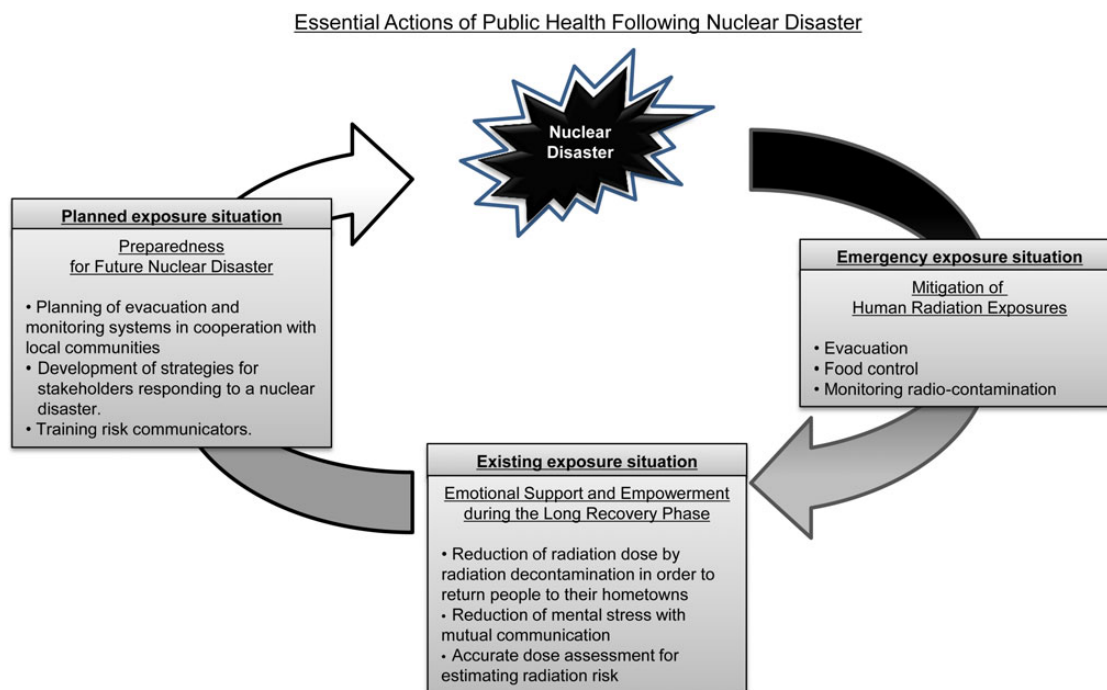


Fig. 1. Public Health Actions in response to nuclear disaster. Essential public health actions under emergency exposure situation, the existing exposure situation and a planned exposure situation are represented.

to the 'Manual for First Responders to a Radiological Emergency' published by the IAEA [48].

Essential public health actions are depicted in Fig. 1 for 'emergency exposure situations', 'existing exposure situations' and 'planned exposure situations', as defined by ICRP [49]. In an emergency situation, evacuation and food control during the early phase of the emergency response contributes to mitigating human exposures to radioisotopes after the nuclear disaster. Monitoring radio-contamination data during the emergency exposure situation, such as monitoring of radioactivity concentrations in air, radioactive contamination of surfaces, internal contamination of a nasal smear and thyroid internal exposure, are essential for accurate estimation of the effective doses. Under the existing exposure situation, there have been major concerns about public health and the future of the Fukushima children due to internal exposure caused by food consumption and external exposure during daily life. In order to return to their hometown, decontamination was carried out in radiation-affected areas to reduce the existing radiation exposure dose. For the people who live in these affected areas, we should provide accurate radiological evaluations of sustainable living conditions, including assessments based on their respective lifestyles and livelihoods. In the preparation phase, evacuation and monitoring systems should be planned in cooperation with local communities. Strategies for responding to a nuclear disaster should be developed by the stakeholders in preparation for a future nuclear disaster.

All aspects of daily life in Fukushima have been affected by the nuclear disaster. The rich agricultural environment of Fukushima has been ruined. Although members of the public were exposed to low levels of radiation from Fukushima incident, we should continue to support risk communication activities in Fukushima about the public health ethics perspective under the existing exposure situations so

that public health is protected. We need to tackle radiological preparedness planning for public health in case of future nuclear disasters under preparation phase.

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