Title	From Hiroshima and Nagasaki to Fukushima 2: Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima
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Citation	Lancet. 386(9992): 479-488
Issue Date	2015-08-01
URL	http://ir.fmu.ac.jp/dspace/handle/123456789/1575
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DOI	10.1016/S0140-6736(15)61106-0
Text Version	author

The Atomic Bomb at 70 Years -Nuclear disaster and health- 2: Impact of nuclear accidents on health and society – a review of health effects of radiation and other problems arising in the aftermath of nuclear accidents with special emphasis on the Fukushima accident

Abstract

Currently, 437 nuclear power plants are in operation around the world to meet increasing energy demands. Unfortunately, major nuclear accidents have occurred over the last 6 decades, i.e. the Kyshtym (1957, Russia), Windscale Piles (1957, England), Three Mile Island (1979, USA), Chernobyl (1986, Russia) and Fukushima accidents in 2011. The impacts of nuclear disasters on individuals and societies are diverse and enduring. The accumulated evidence about the radiation health effects on atomic bomb survivors and other radiation-exposed victims has formed the basis for national regulations concerning radiation protection. Past experiences has indicated, however, that common issues were not necessarily physical health problems directly attributable to radiation exposure; they were associated with psychological and social aspects in the affected populations. Evacuation and long-term displacement also created severe health-care problems in those who are most vulnerable, such as hospitalized patients and elderly people. An open and joint learning process is essential to prepare and minimize the impact of future nuclear accidents.
(159 words)

Key words

nuclear disaster, health effects, radiation exposure, evacuation, psychological impacts

Key messages

- Currently, 437 nuclear power plants (NPPs) are in operation around the world; half are located in areas more densely populated than the area of the Fukushima Daiichi NPP, suggesting a severe nuclear accident would affect a large number of people.
- Although major nuclear accidents are uncommon, there have been five in the past six decades, resulting in not only severe health effects attributable to radiation exposure but also other serious health issues.
- In addition to the severe health effects of radiation exposure (i.e., acute radiation syndrome and an increased incidence of cancer), a critical issue following the Chernobyl accident was adverse effects on mental health, which has also been observed following the Fukushima accident.
- The Fukushima accident revealed severe health risks of unplanned evacuation and relocation for vulnerable population such as hospitalised patients and elderly people requiring nursing care, as well as a failure to respond to emergency medical needs at the NPP. Furthermore, displacement of a large number of people has created a wide range of public health care and social issues.
- Health care professionals should balance the protection from radiation with other health risks when addressing problems arising in a nuclear disaster.

Search strategy and selection criteria section

We conducted a systematic review of the published literature and documents in PubMed, Medline, CiNii, and Google Scholar with search terms “Kyshtym accident”, “Windscale Piles accident”, “Chernobyl accident”, “Three Mile Island accident” or “Fukushima accident”, and “radiation disaster”, “nuclear accident, evacuation” or “evacuation of hospital, disaster” together with “Fukushima”. We also examined the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation for the Chernobyl and Fukushima accidents and those published by the United States and Japanese government on the Three Mile Island and Fukushima accidents, including references cited in these reports. For the empirical data, we could not identify peer-reviewed articles or reports on the latest results from the Fukushima Health Management survey and thus decided to review those on its official web site. With regard to the impact on mental health, we searched PubMed, Medline, CiNii, Google Scholar and reviewed published studies in addition to employing the above-mentioned methods, with search terms “mental health” and “nuclear disaster”, and “stigma”, “PTSD” or “psychiatric disorder” together with “nuclear disaster” or “atomic bombing”. We also reviewed non-peer reviewed literature including the media using the terms such as “radiation stigma” and “Fukushima” for other socio-behavioural issues. We also assessed the regulations and legislations on radiological protection using the International Commission on Radiological Protection and official documents published by the United State and Japanese governments.

Introduction

Since the atomic bombings of Hiroshima and Nagasaki—one of the most tragic events in the human history, accumulated evidence on the radiation effects on atomic-bomb survivors and other radiation-exposed victims has formed the basis for national and international regulations on radiation protection.[1] The peaceful use of nuclear energy has been pursued since December 1953 when US President Eisenhower delivered "Atoms for Peace" speech,[2] and many nuclear power plants (NPPs) have been built around the world to meet increasing energy demands. Unfortunately, though, severe nuclear accidents occurred,[3] resulting in negative health effects directly attributable to radiation as well as various indirect health and social impacts.[4-6] Currently, 437 NPPs are in operation around the world, and more will be constructed as developing countries are seeking for efficient and stable energy sources.[7] A severe accident at one of these plants would affect a large number of people.[8]

This paper describes previous major nuclear accidents, with a special emphasis on the Fukushima accident in 2011. We assess not only medical but also psychological and societal issues related to major nuclear accidents. We then summarise the lessons learned and major policy implications. We conclude the paper by discussing better preparedness with the aim to minimise the health effects of radiation and to cope with other critical health-care and social needs after such accidents.

Past major nuclear accidents

Over the last 7 decades, more than 440 major radiation accidents occurred worldwide. Majority of them were related to radiation devices and radioisotopes with limited consequences.[9] Although uncommon, 20 criticalities including the Fukushima accident occurred, resulting in significant influences on people and environment. In the meantime, the International Nuclear and Radiological Event Scale (INES) was developed as a worldwide tool to understand the significance of nuclear and radiological events.[3] Until the Fukushima accident, four major nuclear accidents had been rated as INES level 5 or greater. They include; Kyshtym (1957, Russia), Windscale Piles (1957, England), Three Mile Island (1979, USA), and Chernobyl (1986, Russia) as described below (Table).

The Kyshtym accident

Soon after the Second World War, liquid radioactive wastes dumped from the nuclear facilities, the Mayak Nuclear Materials Production Complex (PA "Mayak") in the southern Urals, Russia and, caused serious contamination of the Techa River and the vicinity of the nuclear compound.[10] On September 29, 1957, a serious accident occurred at the PA "Mayak" called Kyshtym accident. Failure in the cooling system used for the concrete tanks containing highly active nitrate-acetate wastes caused a chemical explosion, resulting in a huge release of chemicals and radioactive fission products into the atmosphere and disposition of these materials onto the surrounding area. An area of 105km length and 8-9km width was contaminated with Sr-90. More than 10,000 people were eventually evacuated.[11] This accident was rated as level 6 on the INES scale (Significant release of radioactive material).[3]

Windscale Piles accident

On October 10, 1957, a fire broke out in the Windscale Piles, a nuclear reactor designed to produce plutonium at Windscale Works, Sellafield, in the UK, and irradiated uranium oxide particles were released.[11,12] Although no citizens were evacuated, a milk distribution was banned in an area stretching from 10 km north of Windscale Works to 20 km to the south. This was the first severe accident of a nuclear facility which led to a large discharge of radionuclides including I-131 and was rated as INES level 5 (limited release of radioactive material).[12]

Three Mile Island accident

The Three Mile Island (TMI) accident was the first major NPP accident to advise the evacuation of residents. On March 28, 1979, troubles in the cooling systems of the TMI-2 reactor resulted in the release of large amounts of vaporized coolant into the atmosphere.[13] Pregnant women and preschool children living within a 5-mile (8-km) radius of the plant were advised to evacuate. Two days later, a plan was made to expand the evacuation zone to a 10-mile and then a 20-mile (32-km) radius; the population subject to evacuation increased from 27,000 within a 5-mile radius to 700,000 within a 20-mile radius.[14] In the preliminary evacuation plan, evacuation was believed necessary only for a 5-mile radius of the TMI,[14] where there were just three nursing facilities and no hospitals. Within the 20-mile radius of the TMI, there were 14 hospitals and 62 nursing facilities.[14] Fortunately, the reactor was brought under control, and hospital evacuation was avoided. Although the health effects of radiation exposure to residents were negligible, the TMI accident, which was also rated INES level 5 (Severe damage to reactor core), highlighted such challenges as evacuating hospitals and nursing homes in the event of nuclear accidents.[14,15]

Chernobyl accident

The Chernobyl accident in 1986 was the worst nuclear accident in history and was the first accident to be rated INES Level 7 (Major release of radioactive material). Among 600 workers involved with the emergency response, 134 workers developed acute radiation syndrome (ARS), resulting in 28 deaths.[4] In all, 220,000 residents were evacuated. One of the most significant public health effects of radiation was an increased incidence of thyroid cancer in pediatric residents. Ingestion of contaminated dairy products was the main route for absorbing radioactive iodine.[4] Increased cancer incidence due to low-dose exposure has not been established.[4] The Chernobyl accident, however, revealed other serious issues not directly attributable to radiation health effects: i.e. long-term psychosocial effects.[5]

The Fukushima Daiichi NPP accident

Japan previously operated 54 NPPs along its coasts.[16] The occurrence of a compound disaster, in which an earthquake, tsunami, or other natural phenomenon would cause such a critical event as an NPP accident, was perhaps inevitable in such a seismically active country. The 6.8-magnitude Chuetsu offshore earthquake in 2007 caused a leakage of contaminated water from the spent-fuel pool of the Kashiwazaki-Kariwa NPP. The event did not develop into a critical accident, but it was a precursor to the disaster at the Fukushima Daiichi NPP.[17]

On March 11, 2011, a 9-magnitude earthquake occurred off the east coast of Japan, generating massive tsunamis, which severely damaged coastal areas and claimed 18,470 lives (15891 deaths, 2579 missing as of May 8, 2015).[18] The Fukushima Daiichi NPP was the only NPP to lose its core cooling capacity entirely after the disaster, which caused severe damage to the nuclear cores and led to an INES Level 7-rated accident. Consequently, substantial amounts of radioactive material escaped into the environment.[19,20]

Japan's response to the Fukushima Dai-Ichi accident

While all-out efforts were being made to cool the nuclear fuels, the government progressively issued emergency evacuation orders between March 11 and 13 to residents living within a radius of 3, 10, and 20 km of the NPP (Figure 1). Most of residents living within the 20-km radius had been evacuated by March 15, when the strongest radioactive plume was released.[21]

Hydrogen explosions occurred at Reactor No. 1 on March 12 and Reactor No. 3 on March

14 injuring 16 emergency workers. It was difficult for the injured to access medical services since local emergency medical institutions had either closed or were barely operating.[22] (Panel 1)

Radiation exposure to emergency and recovery workers

In response to the accident, several thousand workers—mostly contractors—performed on-site emergency operations.[19] According to a 2013 TEPCO report, under 1% of all such workers were found to have been exposed to a radiation dose (effective dose, combined external and internal sources) of 100 mSv or higher; the average dose was 11.9 mSv (Figure 2)(Panel 2). Among 173 workers whose exposure dose exceeded 100 mSv, 86% were skilled TEPCO workers. The dose rates of six emergency workers exceeded 250 mSv; however no worker received a radiation exposure dose beyond 1000 mSv.[26] Notably, most of the injuries or illnesses were not related to radiation exposure (Panel 3). The maximum exposure dose among JSDF personnel and firefighters involved in the emergency operation was 81.2 mSv.[28]

Thus, no acute effects of radiation exposure such as ARS have been observed following the Fukushima accident. In this sense, protection of emergency workers from radiation may have been achieved. However, for those with radiation exposure greater than 100 mSv, a small increase incidence of cancer attributable to radiation exposure may be expected.[6,29,30]

Radiation exposure to Fukushima Prefecture residents

In a nuclear accident, exposure to radioactive materials takes several pathways: external exposure from radionuclides deposited on the ground (groundshine) or in the radioactive cloud (cloudshine), and internal exposure from inhalation of radionuclides or by ingesting food or water.[30]

Early radiation exposure

According to reports released in August 2014, estimated external effective doses for between March 11 and July 11, 2011 were no more than 2 mSv in 94% of the respondents (mean dose, 0.8 mSv).[31,32] The maximum external exposure was 25 mSv, and most doses occurred soon after the accident.[33] However, exposure to radioactive iodine is a major concern, particularly among paediatric residents.[4] In Fukushima, tap water, food, and raw milk were tested soon after the accident, and distribution restrictions were implemented for food, including dairy products.[19,34] Unlike with the

Chernobyl accident, incorporation of radioactive iodine in Fukushima is believed to have been mainly via inhalation.[6,35] The maximum dose rate of exposure occurred after the massive radioactive plume was released on March 15.[20] Based on System for Prediction of Environmental Emergency Dose Information (SPEEDI) data, the maximum average thyroid dose in the most affected district was estimated to be approximately 80 mGy for 1-year-old infants—the age-group most vulnerable to radioactive iodine.[6]

Direct measurement of internal radiation doses was, however, possible only for a limited number of evacuees owing to the difficult circumstances after the accident. According to a report using thyroid monitors for 62 evacuees from the 30-km zone, maximum and median thyroid equivalent doses in adults of 33 and 3.6 mSv, respectively, and 23 and 4.2mSv in children.[36] Another study employing a whole-body counter determined that detectable iodine activity was found in 25% of 196 evacuees and medical support members who remained in the 20- to 30-km indoor-sheltering zone. Their maximum thyroid equivalent dose and median dose were 18.5 and 0.67 mSv, respectively.[35,37] In the World Health Organization (WHO) preliminary estimation, exposure dose in the first year was extrapolated from measurements as of mid-September 2011.[30] Due to the Dose Expert Panel's timeframe, updated data of dose estimation were not incorporated. Therefore in the WHO's assessment, the dose estimates and assumptions were deliberately made so as to minimize underestimation of potential health risks, i.e., err on the side of caution. The report showed that the greatest risk was found among paediatric females exposed in the most heavily exposed areas in Fukushima Prefecture. The excess absolute risk for these people was estimated to be small, but, they had a comparatively high relative increase in lifetime risk due to the low baseline risk estimated for this area.[38] The WHO's Health Risk Assessment (HRA) report recommended continuing monitoring children's health due to these risks.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2013 report relied principally on data and literatures available before the end of September 2012.[6] This report, may have overestimated actual exposures due to the limited available information at this time. The assessment of radio contamination of the thyroid through direct methods found doses 3-5 times lower than those estimated by the Committee.[6] Based on these potential over-estimates, the UNSCEAR report identified the potential increased risk of thyroid cancer among pediatric residents of the districts with the highest estimated average radiation exposure and recommended close monitoring and follow-up of affected children.

Stable iodine tablets are one recommended radiation protection measures.[39] In the early stages following the accident, there was confusion as to whether residents needed the tablets.[19] However, estimations of thyroid tissue equivalent doses suggest no need for the stable iodine tablets.[19] High iodine intake through daily seaweed ingestion in the Japanese diet may suppress the incorporation of radioactive iodine by the thyroid gland.[40] Nonetheless, public concern over the initial thyroid exposures has led to the implementation of a screening program for all children in Fukushima, while there is ongoing debate in the Japanese medical community about the ethical aspects of this program, as well as its implications for overdetection and overtreatment of thyroid abnormalities.[41]

Radiation exposure after acute phase

In Fukushima, municipalities have monitored the radiation dose from external exposure using a simple measurement device, such as a glass badge. Based on the results of a glass badge test conducted from September to November 2011 in Fukushima,[33,42] the first year dose was calculated to be around 2.1 mSv in the northern part of Fukushima Prefecture.

In the WHO's preliminary dose estimation, a lifetime cumulative dose of twice the first year dose was assumed based on a reference first year dose for all organs/tissues.[30,38] The doses estimated for subsequent years in Fukushima City were generally consistent with this assumption. For example, in the case of Fukushima City, the mean annual dose estimated from the glass badge measurement decreased from 0.56 mSv in 2012 to 0.44 and 0.32 mSv in 2013 and 2014, respectively.[42] Thus, the lifetime dose beyond the first year in Fukushima City may be around 2 mSv, consistent with the assumptions of the WHO's preliminary dose estimation.

Radioactive cesium intake by ingesting food is the primary concern among residents living in radiation-affected areas.[43] Whole-body counter assessments of internal radiation levels in residents of Minamisoma City, close to the Fukushima Daiichi NPP, found levels of internal exposure that were too high to be due only to initial exposure,[44] and a subsequent study of risk factors for internal contamination found an association with food type and attention to food preparation.[45] Radioactive cesium has been detected in mushrooms, wild vegetables, such meat as boar and birds in fields where the ambient dose was relatively high.[46] Radioactive cesium has also been detected in some types of preserved food, such as dried persimmons. It has been detected in marine products from river mouths in areas with relatively high ambient doses and in fish from coastal waters near the Fukushima Daiichi NPP.[46] Residents in areas closest to the nuclear power plant can be exposed to very high levels of internal contamination even after a year since the accident through the consumption of these foods,[47] and interventions to educate these residents and change food consumption practices can lead to rapid declines in internal contamination, indicating the importance of food–and especially wild foods– as a contamination pathway. Also, a simple radioactivity inspection is conducted prior to cooking food for school lunches in many regions.[48,49] In Fukushima, the radioactive cesium detection level of fast track screening is usually 5-10 Bq/kg, and actual levels in tested foods were far lower.[50-52] An assessment by the Ministry of Health, Labour, and Welfare in spring 2012 reported low additional internal exposure due to radioactive cesium intake at 0.0022 mSv / year in Fukushima.[53]

Non-radiation-related events in Fukushima

The major impacts of a severe nuclear accident are not limited to the health effects of radiation. Significant non-radiation related health disorders and psychological disturbances were observed among the affected population following the Chernobyl accident.[5] The Fukushima accident underscored the importance of non-radiation-related issues, such as evacuation and long-term displacement of vulnerable people, and mental, psychological, and social factors.

Evacuation of hospitals and nursing-care facilities

Approximately 2,200 inpatients and elderly people at nursing-care facilities were rapidly evacuated before March 14, 2011. During or soon after evacuation, however, more than 50 inpatients and elderly people at nursing-facilities died[19] from causes such as hypothermia, deterioration of underlying medical problems, and dehydration. The lack of medical support before, during, and after the evacuation was a major reason for the loss of life during the evacuation, and emphasizes the danger of unprepared evacuation for vulnerable populations.[54]

Effect of relocation, displacement, and changes in living environment

By May 2011, approximately 170,000 residents had been evacuated (voluntarily for about 20,000).[19] The evacuation and relocation had various negative effects, particularly on the elder requiring nursing care and hospitalized patients.[55-57] After the accident, the mortality rate among evacuated elderly people requiring nursing care increased about 3-fold in the first 3 months after evacuation and remained about 1.5-fold higher afterward compared with before the accident.[54,58,59] Women accounted for 70% of the deaths: many of them were over 75 years old, and the main cause was pneumonia. Repeated relocation and the frequent changes in living environment posed significant adverse effects on the elderly people's health.[59] Their deaths were caused indirectly by the earthquake and tsunamis and were therefore certified by the local government as disaster-related deaths (DRDs).[60] The DRDs in Fukushima accounted for 56% (1793 of 3,194 in total) of all DRDs in the entire Tohoku region.[61] Changes in the living environment also influenced those not evacuated. Families and communities became separated owing to differences in perceptions of radiation risk[62]; friction occurred between evacuees and residents of the evacuation destinations; mental and physical changes in the residents through the impact on their lifestyle and overall spirits were observed.[63-67]

Mental health problems and poor health perceptions after NPP accidents

Understandably Fukushima residents feared the invisible radiation exposure, even though external and internal doses were very low compared with the Chernobyl accident.[65,68] After the Chernobyl accident, similar problems were reported, and the media disseminated misleading information on increased thyroid cancer among citizens.[69] The psychological impact on adults was most strongly associated with their risk perception.[70] The Chernobyl Forum held in 2006 reported that the studies of adults from the areas contaminated with radioactivity found a two-fold increase in posttraumatic stress disorder (PTSD), and other mood and anxiety disorders and significantly poorer subjective ratings of health.[70] Based on these findings, the Forum concluded that adverse effects on mental health were the most serious public health issue after the accident. Likewise, the significant impact of the Fukushima accident on mental health was found in a survey about mental health and lifestyle conducted among residents of evacuation zones.[71] The survey identified the great difficulties of evacuee families, who were separated and obliged to move to unfamiliar areas after the accident—similar to those observed among Chernobyl evacuees.[68,72,73] The Fukushima mental health survey employed the Kessler six-item psychological distress scale (K6) to assess psychological distress (scores >20 denote significant, and 13-19 mild to moderate problems). The proportion of adult respondents with K6 $\geq$13 was 14.6% in 2011 and 11.9% in 2012,[71] much higher than the usual state of approximately 3%.[74] Although only a minority of people responded to the questionnaire, these results suggest that problems in mental health persist among adult Fukushima evacuees.

Chernobyl evacuees who were children at the time of the accident perceived its consequences more seriously than their unaffected colleagues; however, their perceptions were not linked to such mental conditions as depression,[75] suggesting resilience among Chernobyl's young generation.[76] The mental health and lifestyle survey through the Fukushima Health Management Survey investigated the mental health of child evacuees using the Strengths and Difficulties Questionnaire (SDQ). The proportion of SDQ ≥16 in 4- to 6-year-old children and elementary school children (aged 6–12 years) was 24.4% and 22.0%, respectively, in 2011. That was twice the normal,[77] indicating the presence of severe psychological difficulties among child evacuees. However, the proportion of SDQ ≥16 diminished to 16.6% and 15.8%, respectively, in 4- to 6-year-old children and elementary school children in 2012,[71] indicating that resilience among the child evacuees to that observed after the Chernobyl accident.

The Fukushima mental health survey also investigated traumatic factors in the evacuees by employing a PTSD checklist (PCL).[71] The proportions of PCL ≥44 among adults were 21.6% in 2011 and 18.3% in 2012, similar to that for rescue and cleanup workers (PCL ≥50, 20.1%), and greater than that for residents (PCL ≥44, 16%) in lower Manhattan after the World Trade Center September 11 attacks.[78,79] These results indicated the magnitude of traumatic factors in the psychiatric influences among adult evacuees in the Fukushima accident.

Psychological consequences for disaster workers

Workers involved in the clean-up process after Chernobyl (often termed liquidators or cleanup workers) suffered various mental and physical morbidities.[70,80] Following the Fukushima accident, TEPCO workers came under public criticism. Those workers were stigmatized and discriminated against.[81] In a study conducted 2–3 months after the disaster, TEPCO workers who had suffered discrimination or slurs were two to three times more likely to have adverse psychological consequences than those without such exposure.[82] A follow-up study showed both immediate and long-lasting psychological effects of discrimination.[83] These investigations indicate that when workers are rejected from the society they are trying to save, such experiences may lead to ongoing health consequences; longitudinal studies are warranted.

Discordance in families and communities

In addition to the psychiatric problems described above, complex psycho-social issues arose in Fukushima including discordance in families and in society. Displacement, fear of radioactive exposure, compensation, employment, and other personal reasons produced rifts among residents and in communities. Three types of discordance may adversely affect families or communities in this way.[84] First, different perceptions of the radiation risk result in discordance among family members. Parents with young children are especially susceptible to conflicts: mothers may prefer to move to other regions for their children's sake, whereas fathers may be reluctant to do so.[85] Second, interfamilial conflicts in the community result from disparities in governmental restrictions and compensations. Third, frustrations arise between evacuees and residents of communities accepting large numbers of evacuees (e.g., Iwaki). With time, the relationship between evacuees and recipient community members gradually deteriorates because of the undefined period of the evacuees' stay, population increase, and rise in land prices. Discordance may become a difficult issue among Fukushima evacuees and reduce the resilience that the communities once had.

Stigma and self-stigma

Stigma is another issue among the evacuees and may arise through ignorance about radiation. For example, young women in Fukushima are afraid that some people may view them negatively owing to assumptions regarding the effects of radiation on future pregnancy or genetic inheritance.[86] Through such misconceptions, evacuees often try to conceal the fact that they formerly lived in Fukushima.[85] A similar phenomenon was reported among atomic bomb survivors,[87] who often hesitate to talk about their life history and their experiences of the bombing. This is a type of self-stigma, which is induced and reinforced by public stigma. One study has demonstrated that self-stigma causes three different emotional reactions among stigmatized people: righteous anger; loss of self-esteem; and indifference.[82,88] In Fukushima, self-stigma appears to have caused various emotional reactions leading to distress.[85] Since the psychological effects of self-stigma cannot be ignored, it is necessary to develop countermeasures for public stigma to prevent affected people from further stigmatizing themselves.

Lifestyle-related problems

The Fukushima accident forced many evacuees to change various lifestyle aspects, such as diet, physical exercise, and other personal habits. The proportions of evacuees following government direction having less regular physical exercise (less than once/week), drinking excessively (over 44-g ethanol/day), suffering mental problems, and experiencing sleeping difficulties were 51%, 10%, 20%, and 70%,[71,89] respectively. Those proportions were higher than in other areas of Japan.[74] These changes in health-related behaviours have raised concerns over the future risk of cardiovascular diseases among evacuees. According to a longitudinal analysis of the Fukushima Health Management Survey,[90] an increased proportion of overweight individuals (body-mass index > 25 kg/m^2) was significantly higher in evacuees than non-evacuees (31.5% to 38.8% after the accident in evacuees, whereas 28.2% to 30.5% in non-evacuees).[90,91] After the accident, increased prevalence was observed in hypertension (53.9% to 60.1%), diabetes mellitus (10.2% to 12.2%), and dyslipidemia (44.3% to 53.4%) among the evacuees, but not the non-evacuees.[90,91] Based on these results, the local government has promoted health awareness among evacuated residents.[92]

Lessons learned from the Fukushima and past severe nuclear accidents

After a nuclear accident, uncertainty over the extent and gravity of the accident results in confusing and contradictory information being issued by various sources, including administrative authorities, operators of the plant, the media, and scientists.[13,14,19,24,93] Restriction of information on the accident may further accelerate public anxiety, leading to proliferation of inaccurate information and public distrust.[94,95] In such a disordered situation, health care professionals are often asked to explain the risks to the community.[96] Information about the accident, including what is clear and what is not, needs to be disclosed by authorities and operators in a timely and organised fashion. Scientific messages based on accumulated evidence from atomic bombings and past nuclear accidents and provided by health care professionals should be used to enhance the public's understanding of the impacts of the accident on the public's health.

The consequences of nuclear accidents vary substantially, ranging from short- to long-term health effects and from direct health to social and psychological effects. In the acute phase of an accident, the serious health effects due to uncontrolled exposure and multi-casualty accidents that require abundant medical resources are major concerns.[4,22] Inadequate protection of the public from radiation exposure may lead to an increased incidence of cancer later in life.[4] Meanwhile, we should be aware of potential adverse health risks accompanying the protective measures themselves; i.e., increased health risks associated with an unplanned evacuation or the relocation of vulnerable populations such as hospitalised patients and the elderly in nursing care facilities,[54,58,59,64] and poor medical responses to life-threatening trauma or illnesses within an evacuation zone around the nuclear facility.[22,27] Following the acute phase, displacing hundreds of thousands of people creates a wide range of public healthcare and social issues that strike at the weakest link of the healthcare and societal system.[89-92] Among these, major psychological consequences are most commonly observed after a nuclear accident.[69-73]

The evacuation for a large population and vulnerable people needs to be carefully planned.[64] Surrogate emergency systems that support local medical responses should be deployed promptly after an accident. Mental and psychological care as well as behavioural and social support for displaced people need to be put in place with coordinated approaches by the government, municipalities, academic organizations and volunteer groups. Finally, general public health services are prerequisite to counteract long-term adverse health effects after a severe nuclear accident.[96] For all of these countermeasures, health care professionals should balance the protection from radiation with other health risks, and make efforts to mitigate the psychological effects that are most strongly associated with the risk perceptions of radiation.[70] These challenging tasks constitute the agenda of future research.
(4349 word)

Contributors

KT, AO, KK, KS, SY and RC set the conceptual framework of the report. AH, KT, AO, HY, MM, JS, TO, TT, MA, TI and NH contributed to drafting. KS, KT, AH and AO did a systematic review and contributed to the critical revision. All authors contributed to the discussion and have seen and approved the final version of the report.

Conflicts of interest

JS reports grants from the Ministry of Health Labour and Welfare of Japan, grants from Senshin Medical Research Foundation, during the conduct of the study; and mental health assistance to the Tokyo Electric Power Company Fukushima Daiichi and Daini nuclear power plant employees according to official requests from Daini and a Japanese Prime Minister Cabinet order to the Ministry of Defense. Other authors declare no conflicts of interest.

Acknowledgment

We thank Dr. Kenneth Nollet, professor and director of the Department of International Cooperation, Fukushima Medical University, for English proofreading. This work was generously supported by Fukushima Medical University, Hiroshima University and Nagasaki University. The views expressed in this report are solely those of the authors.

Panel 1: Tokai-Mura criticality accident and development of radiation emergency medical hospitals in Japan

In September 1999, a criticality accident at the JCO uranium-conversion plant in Tokai-Mura, Japan occurred when workers inappropriately poured enriched uranyl nitrate solution into a precipitation vessel, triggering fission reactions (Tokai-Mura criticality accident).[23] The local government advised residents to evacuate from the area within a 350 m radius of the plant. It took 19 hours to terminate the criticality. Three workers were exposed to a massive dose of neutron and gamma ray radiation and developed ARS, resulting in two deaths from an estimated exposure exceeding 6 Gy equivalent. Besides these 3 workers, 169 JCO employees, 260 emergency personnel and 234 residents were exposed to radiation with maximum estimated doses of 48, 9.4 and 21mSv, respectively. Although there were human casualties, no major release of radioactive materials was observed and therefore this accident was graded as INES level 4, i.e., an accident with local consequences. The Tokai-Mura criticality accident highlighted the importance of integrated critical care for patients exposed to high dose radiation. In addition, risk communication was indicated as one of the key issues in public relation after a nuclear accident.[24]

Base on lessons learned from this accident, the radiation emergency hospital system had been enhanced particularly focusing on work-related accidents with high dose radiation exposure[22], however, not for such large-scale natural disasters as Fukushima.[19] Accordingly, 2 referral hospitals were designated as the tertiary radiation emergency hospitals where advanced treatment for ARS or severe internal contamination was provided. Seventy-four hospitals in prefectures where NPPs were located were also designated as primary or secondary radiation emergency facilities where patients were triaged and treated, then transferred to tertiary hospitals when indicated. Of note, 38 of these hospitals were located within a 30 km radius of NPPs, meaning these hospitals may lose their function if a severe nuclear accident mandates evacuation from the area.

Panel 2: Protection of emergency workers from radiation exposure

Most national regulations for radiation protection are based on the 1990 Recommendations of the International Commission on Radiological Protection (ICRP).[1] International standards, such as the International Basic Safety Standards, various international labor conventions, and European directives on radiological protection, are also based on those recommendations. The ICRP revised its recommendations and updated them as ICRP Publication 103 in 2007.[25] According to the new publication, the dose limit for occupational exposure is 100 mSv over 5 years and 100 mSv for emergency work. Occupational exposure of workers occurs during the performance of duties involving radiation, such as those conducted after an accident by workers regularly employed at the plant and by other workers engaged in recovery and rescue operations. Many workers need to be involved in on-site mitigation and other activities. Such workers are subject to internationally established limits for occupationally exposed workers. However, a small number of skillful workers are expected to be involved in emergency tasks. Thus, the dose limits are 500–1000 mSv as reference levels to avoid the occurrence of deterministic effects for workers in an emergency situation.

Panel 3: Injuries of emergency and recovery workers in response to the accident

By the end of September 2014, 754 workers had sought medical treatment at the site. Five deaths were observed: three workers developed cardiac arrest owing to acute myocardial infarction; there was one case of aortic dissection, and another person suffered from asphyxia caused by a landslide during the construction of a pile foundation. Among the workers, there were only 12 cases of contamination with radioactive substances—all of which occurred in March 2011. There was an increase in heat illness in May to July. In all, 88 workers suffered from heat illness; however, no severe cases, such as heat stroke, were reported. To coordinate efforts for emergency medical care and provide an adequate working environment for NPP personnel, the Emergency Medical System Network was established: its purpose is to examine occupational environments, institute preventive medicine, particularly in summer to avert heat stroke, and conduct follow-up of workers with chronic illnesses and mental health problems.[27]

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Table and Figure legends

Table: Summary of past major nuclear accidents

* Prefixes of the SI unit; T (tera): 10^{12}, Bq: becquere

**The INES at nuclear facilities is classified on the scale of seven levels based on the radiation doses to people and widespread release of radioactive materials, violation of radiological barriers and control within an installation, and dysfunction of accident preventing measures.[2]

INES Level 7: major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures

INES Level 6: significant release of radioactive material to require implementation of planned countermeasures

INES level 5: limited release of radioactive material to require implementation of some planned countermeasures, severe damage to reactor core

Figure 1: Location of Fukushima Daiichi Nuclear Power Plant[17]

Figure 2: Irradiation dose and number of workers involved with the emergency and recovery operations at Fukushima Daiichi Nuclear Power Plant (March 11, 2011 to August 31, 2013)[24]

*Max: 678.08mSv (external exposure, 88.08mSv; internal exposure, 590mSv)

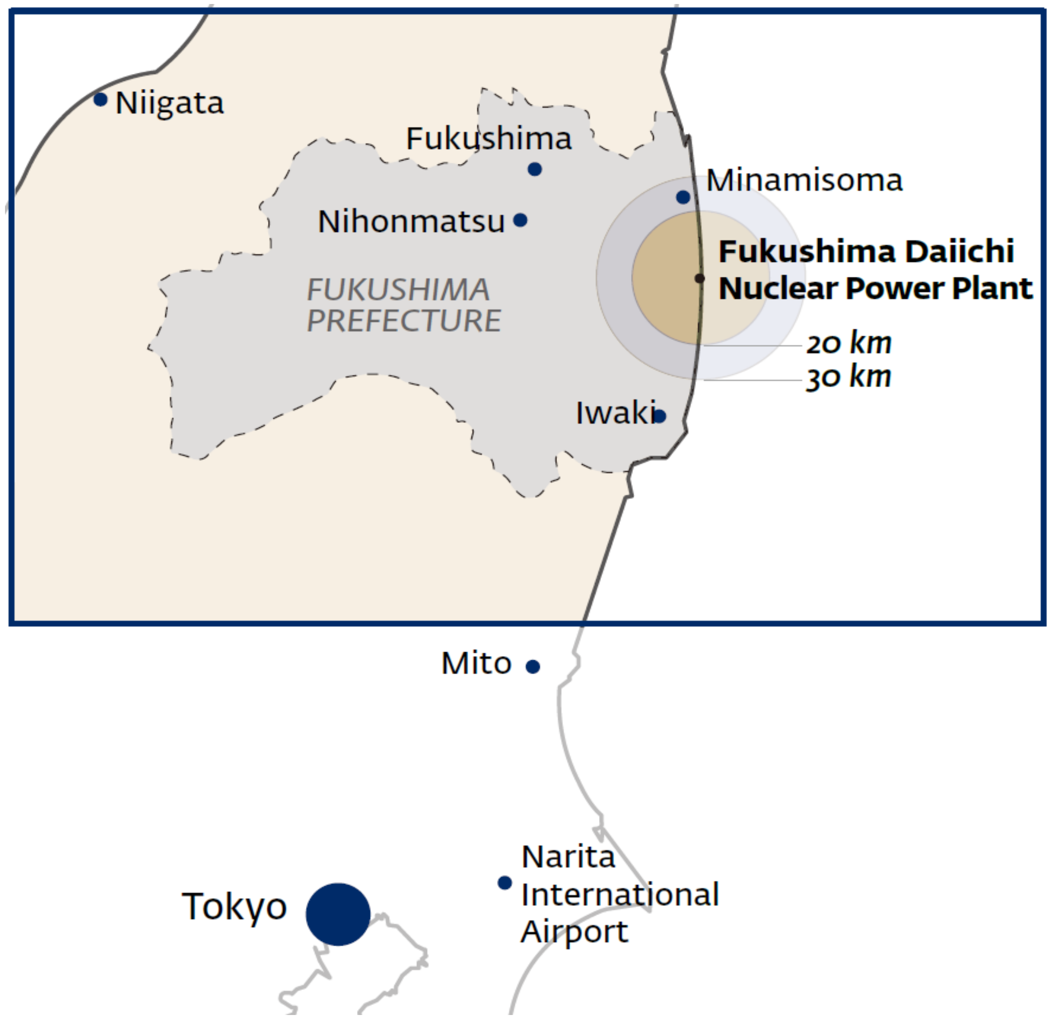
(29,332 workers were engaged in operations)

Figure

Table

	Kyshtym accident [10,11]	*Windscale Piles accident* [11,12]	*Three Mile Island accident* [13,14,15,93]	*Chernobyl accident* [4,5]	*Fukushikma accident* [6,19,30,71]
Location	Southern Urals, Russia	Sellafield, UK	Pennsylvania, USA	Chernobyl, Russia	Fukushima, Japan
Year	1957 Sep	1957 Oct	1979 Mar	1986 Apr	2011 Mar
Type of accident	Chemical explosion of the containment tank of liquid radioactive wastes at the military installation	Fire of the nuclear reactor at the military installation designed to produce plutonium	Partial core melt at the civilian nuclear reactor	Core explosion and fire at the civilian nuclear reactor	Core melt-through 3 reactor cores damaged 3 reactor buildings damaged by the hydrogen explosions
Release of radioactivety	100,000 TBq (Ce-144+Pr-144: 66%, Zr-95+Nb-95: 24.9%, Sr-90;Y-90: 5.4%)	I-131: 740 TBq	Noble gases (mainly Xe-133): 370,000 TBq I-131: 0.55 TBq	I-131: 1,760,000 TBq Cs-137: 85,000 TBq	I-131: 100,000-500,000 TBq Cs-137: 6,000-20,000 TBq
Contaminated area	Area contaminated with Sr-90 > 74 kBq/m2 (2 Ci/km2) : 1000 km2 > 3.7 kBq/m2 (0.1 Ci/km2): 15000 km2	Milk distribution was banned in an area stretching from 10 km north of Windscale Works to 20 km to the south.		Area contaminated with Cs-137 > 560 kBq/m2: 10,000 km2 > 190 kBq/m2: 21,000 km2	Area contaminated with Cs-137 > 560 kBq/m2: 600 km2 > 190 kBq/m2: 2,000 km2
INES level	6	5	5	7	7
Affected population	10,180 residents evacuated 270,000 lived in the area contaminated		195,000 residents living within 20 miles evacuated voluntarily	115,000 residents evacuated in 1986 (subsequently 220,000 evacuated) 270,000 population lived in "strict control zone" (contaminated area)	213,000 residents evacuated (20,000 evacuated voluntarily)
Dose estimates	Average effective dose of residents: 170mSv preceding evacuation, 520mSv in effective dose equivalent	Maximum estimated thyroid doses of residents Adults: the order of 10 mGy Children: conceivably 100 mGy	Maximum effective dose: 40 mSv (emergency worker) Effective dose of residents living within 50 miles Average: 0.015 mSv Maximum: 0.85 mSv	Workers with acute radiation sickness <2.1 Gy: 41 persons, 2.2 - 4.1 Gy: 50 persons, 4.2 - 6.4 Gy: 22 persons, 6.5 - 16 Gy: 21 persons Average thyroid dose of residents Evacuees: Adults: 349 mGy Pre-school children: 1548 mGy Residents in contaminated area: Adults: 138mGy Pre-school children: 449 mGy	Maximum effective dose: 678 mSv (emergency worker) Maximum thyroid dose: 12 Gy (emergency worker) Maximum effective dose of residents: 25 mSv (external) Maximum average thyroid dose of infants in the most affected district: 80 mGy
Implications	Restriction of information on the accident by the government	Poor preparedness before the accident	Scarcity of information about plant condition and evacuation plan No effective plan for hospital and nursing care facility evacuation	Restriction of information on the accident by the government Delay in implementation of public protection Long-term psychological issues	Severe health consequences in evacuation and relocation of hospitalized patients and elderly people requiring nursing care Psycho-social issues after the accident Risk communication

Figure 1


Niigata
Fukushima
Nihonmatsu
Minamisoma
FUKUSHIMA
PREFECTURE
Fukushima Daiichi
Nuclear Power Plant
20 km
30 km
Iwaki
Mito
Tokyo
Narita
International
Airport