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

Arifumi Hasegawa, Koichi Tanigawa, Akira Ohtsuru, Hirooki Yabe, Masaharu Maeda, Jun Shigemura, Tetsuya Ohira, Takako Tominaga, Makoto Akashi, Nobuyuki Hirohashi, Tetsuo Ishikawa, Kenji Kamiya, Kenji Shibuya, Shunichi Yamashita, Rethy K Chhem

437 nuclear power plants are in operation at present around the world to meet increasing energy demands. Unfortunately, five major nuclear accidents have occurred in the past—ie, at Kyshtym (Russia [then USSR], 1957), Windscale Piles (UK, 1957), Three Mile Island (USA, 1979), Chernobyl (Ukraine [then USSR], 1986), and Fukushima (Japan, 2011). The effects of these accidents on individuals and societies are diverse and enduring. Accumulated evidence about radiation health effects on atomic bomb survivors and other radiation-exposed people has formed the basis for national and international regulations about radiation protection. However, past experiences suggest that common issues were not necessarily physical health problems directly attributable to radiation exposure, but rather psychological and social effects. Additionally, evacuation and long-term displacement created severe health-care problems for the most vulnerable people, such as hospital inpatients and elderly people.

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Department of Radiation Disaster Medicine (Prof A Hasegawa MD), **Fukushima Global Medical Science Center** (Prof K Tanigawa MD), **Department of Radiation Health Management** (Prof A Ohtsuru MD), **Department of Neuropsychiatry** (Prof H Yabe MD), **Department of Disaster Psychiatry** (Prof M Maeda MD), **Department of Epidemiology** (Prof T Ohira MD), **and Department of Radiation Physics and Chemistry** (Prof T Ishikawa PhD), **Fukushima Medical University, Fukushima, Japan; Department of Psychiatry, National Defense Medical College, Tokorozawa, Japan** (J Shigemura MD); **Department of Radiation Emergency Medical Assistance Team Medical Section** (T Tominaga MD), **National Institute of Radiological Sciences, Chiba, Japan** (M Akashi MD); **Department of Global Health Policy, Graduate School of Medicine, University of Tokyo, Tokyo, Japan** (Prof K Shibuya MD); **Department of Emergency and Critical Care Medicine** (N Hirohashi MD), **and Department of Experimental Oncology, Research Institute for Radiation Biology and Medicine** (Prof K Kamiya MD), **Hiroshima University, Hiroshima, Japan; Department of Radiation Medical Sciences, Atomic Bomb Disease Institute, Nagasaki University, Nagasaki, Japan** (Prof S Yamashita MD); **and Cambodia Development Resource Institute, Phnom Penh, Cambodia** (Prof R K Chhem PhD)

Introduction

Since the atomic bombings of Hiroshima and Nagasaki—some of the most tragic events in human history—accumulated evidence about effects of radiation on atomic bomb survivors and other radiation-exposed people has formed the basis for national and international regulations for radiation protection.[1] Peaceful use of nuclear energy has been pursued since December, 1953, when US President Eisenhower gave his Atoms for Peace speech,[2] and many nuclear power plants (NPPs) have been built around the world to meet increasing energy needs. Unfortunately, major NPP accidents have occurred,[3] resulting in negative health effects directly attributable to radiation and various indirect health and social effects.[4–6] 437 NPPs are in operation worldwide, and more will be constructed as developing countries

Key messages

- 437 nuclear power plants (NPPs) are in operation around the world; at least one-third are located in areas more densely populated than the area of the Fukushima Daiichi NPP, suggesting that a major nuclear accident would affect a large number of people
- Although severe nuclear accidents are uncommon, five have taken place in the past, resulting not only in health effects attributable to radiation exposure, but also in other serious health issues
- In addition to health effects of radiation exposure (ie, acute radiation syndrome and increased incidence of cancer), adverse effects on mental health were reported after the Fukushima Daiichi and Chernobyl NPP accidents
- The Fukushima Daiichi NPP accident showed the health risks of unplanned evacuation and relocation for vulnerable people such as hospital inpatients and elderly people needing nursing care, and failure to respond to emergency medical needs at the NPP
- Displacement of a large number of people has created a wide range of public health-care and social issues

Search strategy and selection criteria

We searched 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”. Additionally, we examined the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation for the Chernobyl and Fukushima accidents and reports published by the US and Japanese Governments on the Three Mile Island and Fukushima accidents, including references cited in these reports. For empirical data, we could not identify peer-reviewed articles or reports of the latest results from the Fukushima Health Management Survey and thus reviewed those on the official website. For effects on mental health, we searched PubMed, Medline, CiNii, and Google Scholar and reviewed published studies, with search terms “mental health” and “nuclear disaster”, with “stigma”, “PTSD” or “psychiatric disorder” together with “nuclear disaster” or “atomic bombing”, in addition to use of the above-mentioned methods. Additionally, we reviewed non-peer-reviewed literature, including the media, with the terms “radiation stigma” and “Fukushima” for other sociobehavioural issues. We assessed the regulations and legislation for radiological protection using the International Commission on Radiological Protection and official documents published by the US and Japanese Governments.

	Kyshtym[10,11]	Windscale Piles[11,12]	Three Mile Island[13,14,15,16]	Chernobyl[4,5]	Fukushima[6,17–19]
Location	Kyshtym, Chelyabinsk Oblast, Russia (then USSR)	Sellafield, UK	Dauphin county, PA, USA	Chernobyl, Ukraine (then USSR)	Fukushima, Japan
Date	Sept 29, 1957	Oct 10, 1957	March 28, 1979	April 26, 1986	March 11, 2011
Type of accident	Chemical explosion of containment tank of liquid radioactive wastes at military installation	Fire of nuclear reactor at military installation designed to produce plutonium	Partial core melt at civilian nuclear reactor	Core explosion and fire at civilian nuclear reactor	Core melt-through; three reactor cores damaged; three reactor buildings damaged by hydrogen explosions
Release of radioactivity	100 000 TBq (^{144}Ce and ^{144}Pr: 66%; ^{95}Zr and ^{95}Nb: 24.9%; ^{90}Sr and ^{90}Y: 5.4%)	^{131}I: 740 TBq	Noble gases [mainly 133Xe]: 370 000 TBq; ^{131}I: 0·55 TBq	^{131}I: 1 760 000 TBq; ^{137}Cs: 85 000 TBq	^{131}I: 100 000–500 000 TBq; ^{137}Cs: 6000–20 000 TBq
Contaminated area	Area contaminated with ^{90}Sr: 1000 km^2 (>74 kBq/m^2); 15 000 km^2 (>3·7 kBq/m^2)	No specific information on contaminated area available	No specific information on contaminated area available	Area contaminated with ^{137}Cs: 10 000 km^2 (>560 kBq/m^2); 21 000 km^2 (>190 kBq/m^2)	Area contaminated with ^{137}Cs: 600 km^2 (>560 kBq/m^2); 2000 km^2 (>190 kBq/m^2)
INES level	6	5	5	7	7
Affected population	10 180 residents evacuated; 270 000 lived in contaminated area	No evacuation ordered	195 000 residents living within 32 km evacuated voluntarily	115 000 residents evacuated in 1986 (220 000 subsequently evacuated by 1992); 270 000 lived in contaminated area	170 000 residents evacuated (20 000 evacuated voluntarily)
Dose estimates	Average effective dose of residents: 170 mSv (preceding evacuation); 520 mSv (effective dose equivalent)	Maximum estimated thyroid doses of residents: the order of 10 mGy (adults); 100 mGy (children)	Maximum effective dose: 40 mSv (emergency worker); effective dose of residents living within 80 km: 0·015 mSv (average); 0·85 mSv (maximum)	Workers with acute radiation syndrome: <2·1 Gy (41 people); 2·2–4·1 Gy (50 people); 4·2–6·4 Gy (22 people); 6·5–16·0 Gy (21 people); average thyroid dose of residents: 349 mGy (adult evacuees); 1548 mGy (preschool children evacuees); 138 mGy (adults in contaminated areas); 449 mGy (preschool children in contaminated areas)	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 about accident by government	Poor preparedness before accident; milk distribution banned 10 km north of Windscale Works to 20 km to the south	Scarcity of information about nuclear power plant condition and evacuation plan; no effective plan for hospital and nursing care facility evacuation	Restriction of information about accident by government; delay in implementation of public protection; long-term psychological issues	Severe health effects of evacuation and relocation of hospital inpatients and elderly people needing nursing care; psychosocial issues after accident; poor risk communication

USSR=Union of Soviet Socialist Republics.

Table 1: **Past severe nuclear accidents (International Nuclear and Radiological Event Scale level 5 or higher)**

Correspondence to:
Prof Koichi Tanigawa, Fukushima Global Medical Science Center, Fukushima Medical University, 1 Hikariga-oka, Fukushima 960-1295, Japan
tanigawa@fmu.ac.jp

seek efficient and stable energy sources.[7] A major accident at one of these NPPs would affect many people.[8] The effects of nuclear accidents are not limited to the health effects of radiation, extending to social and psychological effects. Health-care professionals need to understand that a wide range of health risks arise after nuclear accidents in order to properly address these issues.

Past major nuclear accidents

During the past seven decades, more than 440 major radiation accidents have occurred worldwide. Most were related to radiation devices and radioisotopes with small effects.[9] Although uncommon, major accidents at nuclear facilities, including criticality accidents or NPP accidents, occurred, substantially affecting people and environments. The International Nuclear and Radiological Event Scale (INES) was developed as a worldwide method to understand the extent of nuclear accidents.[3] Until the Fukushima Daiichi accident, four major nuclear accidents had been rated as INES level 5 (limited release of radioactive material) or higher, including Kyshtym (Russia [then USSR], 1957), Windscale Piles (UK, 1957), Three Mile Island (USA, 1979), and Chernobyl (Ukraine [then USSR], 1986) (table 1).

Kyshtym

The Mayak Nuclear Materials Production Complex (Kyshtym, Chelyabinsk Oblast, Russia [then USSR]) was put into operation in 1948. This complex housed uranium-graphite reactors and radiochemical facilities for plutonium production, separation, and reprocessing of waste fuel from nuclear reactors.[10]

On Sept 29, 1957, a serious accident occurred at this complex, known as the Kyshtym accident. Failure in the cooling system used for the concrete tanks containing highly active nitrate and acetate wastes caused a chemical explosion, resulting in release of chemicals and radioactive fission products into the atmosphere and deposition of these materials in the surrounding area. An area of 105 km by 8–9 km was contaminated with ^{90}Sr. 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

On Oct 10, 1957, a fire started in the Windscale Piles, a nuclear reactor designed to produce plutonium at Windscale Works (Sellafield, Cumbria, UK), and irradiated uranium oxide particles were released.[11,12] Although no citizens were evacuated, milk distribution was banned in an area 10 km north of Windscale Works to 20 km to the south. This accident was the first major accident of a nuclear facility leading to a large discharge of radionuclides including ^{131}I, and was rated as INES level 5.[3]

Three Mile Island

The Three Mile Island accident was the first major NPP accident to result in evacuation of residents. On March 28, 1979, failure of the cooling systems of a reactor resulted in release of large amounts of vaporised coolant into the atmosphere.[13] Pregnant women and preschool children living within an 8 km radius of the plant were advised to evacuate. 2 days later, a plan was made to expand the evacuation zone to a 16 km radius, and then to a 32 km radius; the evacuated population increased from 27 000 within an 8 km radius to 700 000 within a 32 km radius.[14] In the preliminary evacuation plan, evacuation was thought to be necessary for only an 8 km radius of Three Mile Island,[14] which included only three nursing facilities and no hospitals. The 32 km radius included 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 accident, which was rated INES level 5 (with severe damage to reactor core), highlighted challenges such as evacuation of hospitals and nursing homes after NPP accidents.[14,15]

Chernobyl

The Chernobyl accident in 1986 was the worst nuclear accident in history and the first to be rated INES level 7 (major release of radioactive material). Among 600 workers involved in the emergency response, 134 workers developed acute radiation syndrome (ARS), resulting in 28 deaths.[4] 220 000 residents were evacuated. One of the most substantial public health effects of radiation was increased incidence of thyroid cancer in children living nearby. Ingestion of contaminated dairy products was the main route of absorption of radioactive iodine.[4] Increased cancer incidence owing to low-dose exposure has not been established.[4] However, the Chernobyl accident showed other serious issues not directly attributable to radiation health effects—eg, long-term psychosocial effects.[5]

Fukushima Daiichi

Japan previously operated 54 NPPs along its coasts.[20] The occurrence of a compound disaster, in which an earthquake, tsunami, or other natural phenomenon causes a critical event such as an NPP accident was perhaps inevitable in such a seismically active country. The magnitude 6·8 Chuetsu offshore earthquake in 2007 caused leakage of contaminated water from the spent-fuel pool of the Kashiwazaki-Kariwa NPP. The accident did not become critical, but was a precursor to the accident at the Fukushima Daiichi NPP.[21]

On March 11, 2011, a magnitude 9 earthquake occurred off the east coast of Japan, generating tsunamis that severely damaged coastal areas and resulted in 15 891 deaths and 2579 missing people as of May 8, 2015.[22] The Fukushima Daiichi NPP was the only NPP to lose its core cooling capacity wholly after the disaster, which caused severe damage to the nuclear cores and led to an INES level 7 rated accident. Substantial amounts of radioactive material were released into the environment.[23,24]

Japan's response to the Fukushima Daiichi NPP accident

Although efforts were made to cool the nuclear fuels, the government progressively issued emergency evacuation orders between March 11 and March 13, 2011, to residents

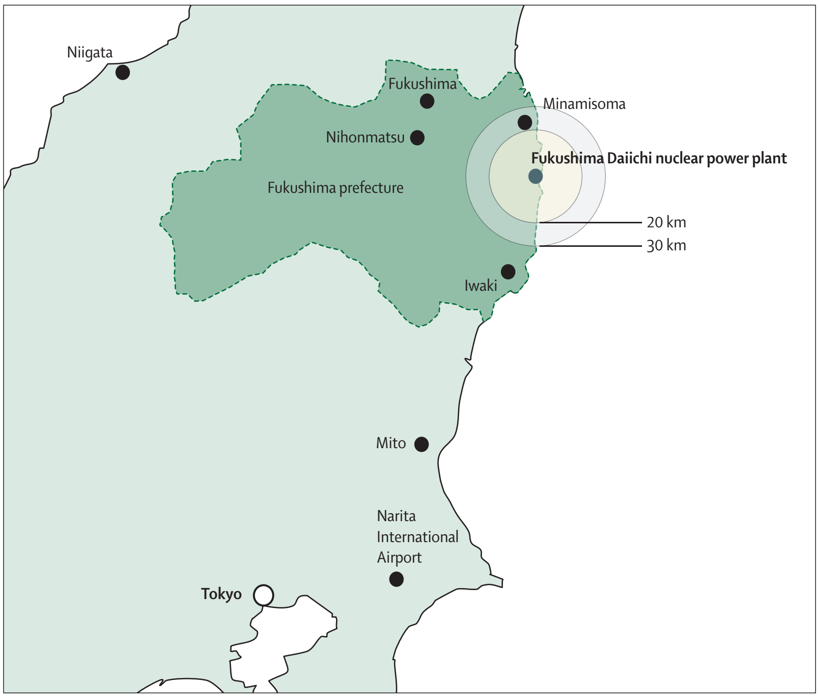

Figure: **Location of Fukushima Daiichi nuclear power plant**
Reproduced from National Diet of Japan, Fukushima Nuclear Accident Independent Investigation Commission,[17] by permission of Fukushima Nuclear Accident Independent Investigation Commission. Residents living within a 20 km radius from the plant were ordered to evacuate on March 12, 2011. Residents living within a 20–30 km radius of the plant were ordered to shelter indoors on March 15, 2011. On March 25, 2011, the national government recommended the residents in this area evacuated voluntarily.

Panel 1: Tokaimura criticality accident and development of radiation emergency medical hospitals in Japan

In September, 1999, a a criticality accident at JCO Company Limited's Tokai Plant in Tokaimura, Tokai, Ibaraki, Japan, occurred when workers inappropriately poured enriched uranyl nitrate solution into a precipitation vessel, triggering fission reactions (known as the Tokaimura criticality accident).[26] The local government advised residents to evacuate the area within a 350 m radius of the plant. Termination of the criticality took 19 h. Three workers were exposed to a massive dose of neutron and gamma ray radiation and developed acute radiation syndrome, resulting in two deaths from an estimated exposure exceeding 6 Gy equivalent. Additionally, 169 JCO employees were exposed to a maximum estimated dose of 48 mSv, 260 emergency workers were exposed to a maximum estimated dose of 9·4 mSv, and 234 residents were exposed to radiation with a maximum dose of 21 mSv. Despite human casualties, no major release of radioactive material was observed, and therefore this accident was graded as International Nuclear and Radiological Event Scale (INES) level 4—ie, an accident with local effects. The Tokaimura criticality accident highlighted the importance of integrated critical care for patients exposed to high-dose radiation. Additionally, risk communication was suggested to be one of the key issues in public relation after a nuclear accident.[27]

After this accident, the radiation emergency hospital system was enhanced, focusing on work-related accidents with high-dose radiation exposure,[25] although not for such large-scale accidents as Fukushima.[17] Accordingly, two referral hospitals were designated tertiary radiation emergency hospitals where advanced treatment for acute radiation syndrome or severe internal contamination was provided. 74 hospitals in prefectures in which nuclear power plants were located were designated as primary or secondary radiation emergency facilities, in which patients could be triaged and treated and then transferred to tertiary hospitals when indicated. Of note, 38 of these hospitals were located within a 30 km radius of nuclear power plants, meaning that these hospitals might lose their function if a major 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 labour conventions, and European directives for radiological protection are based on these recommendations. The ICRP revised its recommendations and updated them as ICRP Publication 103 in 2007.[29] 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 duties involving radiation, such as those undertaken after an accident by workers employed at the plant and by other workers involved 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, some skilled workers are expected to be involved in emergency tasks. Thus, the dose limits are 500–1000 mSv as reference levels to avoid deterministic effects (dose-dependent radiation-induced cell death) for workers in a nuclear power plant accident.

living within a radius of 3 km, 10 km, and 20 km of the NPP (figure). Most residents living within the 20 km radius had been evacuated by March 15, when the strongest radioactive plume was released.[23]

Hydrogen explosions occurred at Reactor 1 on March 12 and Reactor 3 on March 14, injuring 16 emergency workers. Access to medical services for injured workers was difficult since local emergency medical institutions had either closed or were barely functioning (panel 1).[25]

Exposure of emergency and recovery workers to radiation

In response to the accident, several thousand workers—mostly contractors—undertook on-site emergency work.[17] According to a 2013 Tokyo Electric Power Company (TEPCO) report,[28] less than 1% of all such workers were exposed to a radiation dose (effective dose, combined external and internal sources) of 100 mSv or higher; the average dose was 11·9 mSv (panel 2, table 2). Among 173 workers whose exposure dose exceeded 100 mSv, 149 (86%) were skilled TEPCO workers. The exposure dose of six emergency workers exceeded 250 mSv; however, no worker received a radiation exposure dose of more than the reference level recommended by the ICRP, ie, 1000 mSv, to avoid severe deterministic injuries.[28,29] Notably, most injuries or illnesses were not related to radiation exposure (panel 3). The maximum exposure dose among Japan Self-Defense Force (JSDF) personnel and firefighters involved in the emergency work was 81·2 mSv.[31]

Thus, no acute effects of radiation exposure such as ARS were reported after the Fukushima Daiichi NPP accident. Emergency workers seem to have been successfully protected from radiation. However, for emergency workers with radiation exposure of more than 100 mSv, a small increase in incidence of cancer attributable to radiation exposure might be expected.[6,18,32]

Radiation exposure of Fukushima prefecture residents

In an NPP accident, exposure to radioactive materials can occur by several pathways: external exposure from radionuclides deposited on the ground, or in radioactive clouds, and internal exposure from inhalation of radionuclides or ingestion of contaminated food or water.[18]

Early radiation exposure

According to reports in August, 2014, estimated external effective doses between March 11 and July 11, 2011, were no more than 2 mSv in 395 988 (94%) of 421 394 respondents of the survey (mean dose 0·8 mSv).[33,34] The maximum external exposure was 25 mSv, and most doses occurred soon after the accident.[35] However, exposure to radioactive iodine is a major concern, especially among children.[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.[17,36] Unlike in Chernobyl, incorporation of radioactive iodine in Fukushima is thought to have occurred mainly via inhalation.[6,37] The maximum air dose rate occurred after the massive radioactive plume was released on March 15.[23] 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 roughly 80 mGy for infants aged 1 year—the age group most vulnerable to radioactive iodine.[6]

However, direct measurement of internal radiation doses was possible for only a small number of evacuees owing to the difficult circumstances after the accident. According to a report in which thyroid monitors were used for 62 evacuees from the 30 km zone, the maximum thyroid equivalent dose was 33 mSv and the median equivalent dose was 3·6 mSv in adults; the maximum equivalent dose was 23 mSv and the median dose was 4·2 mSv in children.[38] Results of a study using a whole body counter showed that 46 (25%) of 196 evacuees and medical support members who stayed in the 20–30 km indoor sheltering zone had detectable iodine activity. Their maximum thyroid equivalent dose was 18·5 mSv and their median equivalent dose was 0·67 mSv.[37,39] In WHO's preliminary estimation, exposure dose in the first year was extrapolated from measurements as of mid-September, 2011.[18] Owing to the Dose Expert Panel's timeframe, updated data of dose estimation were not incorporated. Therefore in WHO's assessment, dose estimates and assumptions deliberately overestimated potential health risks (ie, erring on the side of caution). Results of the report showed that the highest risk of thyroid cancer was among girls in the most heavily exposed areas in Fukushima prefecture. The excess absolute risk for these people was estimated to be small, but they have a high relative increase in lifetime risk owing to the low baseline risk estimated for this area.[40] WHO's Health Risk Assessment report[18] recommended continued monitoring of children's health because of these risks.

	TEPCO	Contractor
<10 mSv	2034	17 164
10–50 mSv	1144	7470
50–100 mSv	553	794
100–150 mSv	118	20
>150 mSv	31	4

Maximum dose 678·8 mSv (external exposure 88·80 mSv; internal exposure 590 mSv). 29 332 workers were involved in operations. Data from the Japanese Ministry of Health, Labour, and Welfare.[28]

***Table 2:* Irradiation dose and number of workers involved with the emergency and recovery operations at Fukushima Daiichi nuclear power plant (March 11, 2011, to Aug 31, 2013)**

Panel 3: Injuries of emergency and recovery workers at Fukushima

By the end of September, 2014, 754 workers received medical treatment at the site. Five deaths were reported: three workers had acute myocardial infarction and cardiac arrest; one patient had aortic dissection; and another person had asphyxia caused by a landslide during construction of a pile foundation. Among the workers, only 12 people had contamination with radioactive substances, which occurred in March, 2011. In 2011–14, heat illness increased in May–July. 88 workers had heat illness; however, no severe cases, such as heatstroke, were reported. To coordinate efforts for emergency medical care and provide an adequate working environment for nuclear power plant personnel, the Emergency Medical System Network was established; its purpose is to examine occupational environments, to institute preventive medicine, especially in summer to avert heatstroke, and to undertake follow-up of workers with chronic illnesses and mental health problems.[30]

The UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2013 report[6] relied mostly on data and scientific literature available before the end of September, 2012. This report might have overestimated actual exposure because little information was available. Assessment of radioactive contamination of the thyroid through direct methods showed doses 3–5 times lower than those estimated by UNSCEAR.[6] On the basis of these potential overestimates, the UNSCEAR report identified the potential increased risk of thyroid cancer among children 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 measure.[41] In the early stages after the accident, confusion existed about whether residents needed the tablets.[17] However, estimated thyroid tissue equivalent doses suggested no need for stable iodine tablets.[17] High iodine intake through daily seaweed ingestion in the

Japanese diet might suppress incorporation of radioactive iodine by the thyroid gland.[42] Nonetheless, public concern about initial thyroid exposure led to implementation of a screening programme for all children in Fukushima, although debate is ongoing in the Japanese medical community about the ethical aspects of this programme and its implications for overdetection and overtreatment of thyroid abnormalities.[43]

Radiation exposure after acute phase

In Fukushima, municipalities have monitored radiation dose from external exposure with a simple measurement device, such as a glass badge. Based on the results of a glass badge test done between September and November, 2011, in Fukushima,[35,44] the first year dose was calculated to be about 2·1 mSv in the northern part of Fukushima prefecture.

In 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 or tissues.[18,40] The doses estimated for subsequent years in Fukushima city were generally consistent with this assumption. For example, in Fukushima city, the mean annual dose estimated from the glass badge measurement decreased from 0·56 mSv in 2012 to 0·44 mSv in 2013 and 0·32 mSv in 2014.[44] Thus, the lifetime dose after the first year in Fukushima city might be around 2·0 mSv, consistent with the assumptions of WHO's preliminary dose estimation.

Radioactive caesium intake by ingestion of food is the main concern among residents living in radiation-affected areas.[45] Whole body counter assessments of internal radiation in residents of Minamisoma city, close to the Fukushima Daiichi NPP, showed internal exposure too high to be due only to initial exposure,[46] and results of a subsequent study[47] of risk factors for internal contamination showed an association with food type and attention to food preparation. Radioactive caesium has been detected in mushrooms, wild vegetables, and meat from boar and birds in fields in which the ambient dose was fairly high.[48] Additionally, radioactive caesium has been detected in some types of preserved food, such as dried persimmons. Radioactive caesium has been detected in marine products from river mouths in areas with fairly high ambient doses and in fish from coastal waters near the Fukushima Daiichi NPP.[48] Residents in areas closest to the NPP can be exposed to very high levels of internal contamination even a year after the accident through consumption of these foods,[49] and interventions to educate residents and change food consumption practices can lead to rapidly decreased internal contamination, highlighting the importance of food—especially wild foods—as a source of contamination.[50] A simple radioactivity inspection is undertaken before cooking food for school lunches in many regions.[51] In Fukushima, the radioactive caesium detection level of fast-track screening is usually 5–10 Bq/kg, and actual levels in tested foods were far lower.[52–54] The Japanese Ministry of Health, Labour and Welfare in March–May, 2012, reported low additional internal exposure owing to radioactive caesium intake at 0·0022 mSv/year in Fukushima.[55]

Effects not related to radiation in Fukushima

The effects of a major NPP accident are not limited to the health effects of radiation. Substantial health and psychological disorders not related to radiation were reported among the population affected by the Chernobyl accident.[5] The Fukushima Daiichi NPP accident highlighted the importance of issues not related to radiation, such as evacuation and long-term displacement of vulnerable people, and mental, psychological, and social factors.

Evacuation of hospitals and nursing care facilities

About 2200 inpatients and elderly people at nursing care facilities were rapidly evacuated before March 14, 2011. However, during or soon after evacuation, more than 50 hospital inpatients and elderly people at nursing facilities died from causes such as hypothermia, deterioration of underlying medical problems, and dehydration.[17] Absence of medical support before, during, and after evacuation was a major reason for loss of life, and emphasises the danger of being unprepared for evacuation for vulnerable populations.[56]

Effect of relocation, displacement, and changes in living environment

By May, 2011, about 170 000 residents had been evacuated (about 20 000 voluntarily).[17] Evacuation and relocation had various negative effects, especially on elderly people needing nursing care and hospital inpatients.[57–59] After the accident, mortality among evacuated elderly people needing nursing care increased by about three times in the first 3 months after evacuation and remained about 1·5 times higher than before the accident.[56,60,61] Women accounted for 70% of the deaths: many were older than 75 years, and the main cause was pneumonia. Repeated relocation and frequent changes in living environment resulted in substantial adverse effects on elderly people's health.[61] Since the deaths were caused indirectly by the earthquake and tsunamis, they were certified by local government as disaster-related deaths (DRDs).[62] DRDs in Fukushima accounted for 1793 (56%) of 3194 DRDs in the Tohoku region during the first 42 months after the accident.[63] Changes in living environment likewise affected people who were not evacuated. Families and communities became separated owing to differences in perceptions of radiation risk,[64] friction occurred between evacuees and residents of evacuation destinations, and mental and physical changes in the residents were reported, as a result of effects on their lifestyle.[65–69]

Mental health problems and poor health perceptions

Understandably, Fukushima residents feared invisible radiation exposure.[67,70] After Chernobyl, in which external and internal doses were much higher than in Fukushima, similar problems were reported, and the media disseminated misleading information about increased incidence of thyroid cancer among citizens.[71] The psychological effect on adults was strongly associated with risk perception.[72] According to The Chernobyl Forum, held in 2006 (in Belarus and Ukraine), results of studies of adults from the areas contaminated with radioactivity showed that incidence of post-traumatic stress disorder (PTSD) and other mood and anxiety disorders doubled, and people had statistically significantly lower subjective ratings of health.[72] On the basis of these findings, The Chernobyl Forum concluded that adverse effects on mental health were the most serious public health issue after the accident. Likewise, a survey about mental health and lifestyle undertaken among residents of evacuation zones showed the substantial effect of the Fukushima Daiichi NPP accident on mental health.[19] The survey identified the difficulties of evacuee families, who were separated from each other and moved to unfamiliar areas after the accident—similar to those reported by Chernobyl evacuees.[70,73,74] The Fukushima Health Management Survey used the Kessler six-item psychological distress scale (K6) (scores >20 denote substantial problems, and scores of 13–19 denote mild-to-moderate problems). The proportion of adult respondents with K6 scores of 13 or higher was 14·6% in 2011 and 11·9% in 2012[19]—much higher than the proportion of roughly 3% in other parts of the country.[75] Although few 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 effects more seriously than did their unaffected peers; however, their perceptions were not linked to mental health disorders such as depression,[76] suggesting resilience among Chernobyl's young generation.[77] The mental health and lifestyle survey done by the Fukushima Health Management Survey investigated the mental health of child evacuees using the Strengths and Difficulties Questionnaire (SDQ). The proportion of children aged 4–6 years with an SDQ score of 16 or more (ie, substantial risk of clinically significant mental health problems) was 24·4%, and that of children aged 6–12 years was 22·0% in 2011. Twice as many of these children had an SDQ score of 16 or more than did the general paediatric population,[78] suggesting the presence of severe psychological difficulties, such as hyperactivity, emotional symptoms, conduct and peer problems, among child evacuees. However, the proportion of children aged 4–6 years with an SDQ score of 16 or more decreased to 16·6% and that of children aged 6–12 years decreased to 15·8% in 2012,[19] suggesting resilience among the child evacuees similar to that observed after Chernobyl.

The Fukushima Mental Health Survey investigated traumatic factors in evacuees by use of a PTSD checklist (PCL).[19] The proportion of adults with a PCL score of 44 or more (ie, probable PTSD) was 21·6% in 2011 and 18·3% in 2012, similar to that for rescue and clean-up workers (PCL ≥50 20·1%), and higher than that for residents (PCL ≥44 16%) in lower Manhattan after the World Trade Center attacks on Sept 11, 2001.[79,80] These results show the magnitude of traumatic factors in adult evacuees in Fukushima.

Psychological effects on emergency and recovery workers

Workers involved in the clean-up process after the Chernobyl NPP accident had various mental and physical morbidities.[72,81] After the Fukushima Daiichi NPP accident, TEPCO workers experienced public criticism owing to post-disaster management missteps, such as delayed information disclosure. These workers were stigmatised and discriminated against.[82] In a study[83] done 2–3 months after the accident, TEPCO workers who had experienced discrimination or slurs were two to three times more likely to have adverse psychological effects than those without such exposure. Results of a follow-up study[84] showed immediate and long-lasting psychological effects of discrimination. These investigations suggest that rejection of workers from the society they are trying to save might lead to ongoing health effects; longitudinal studies are warranted.

Discordance in families and communities

In addition to psychiatric problems, complex psychosocial issues arose in Fukushima, including discordance in families and in society. Displacement, fear of radioactive exposure, compensation, employment, and other personal factors caused rifts among residents and communities. Three types of discordance might adversely affect families or communities.[85] First, different perceptions of the radiation risk result in discordance among family members. Parents with young children are especially susceptible to conflicts: mothers might prefer to move to other regions for their children's sake, whereas fathers might be reluctant to do so.[86] Second, conflicts between families in the community result from disparities in governmental restrictions and compensation. Third, frustrations arise between evacuees and residents of communities to which large numbers of evacuees relocate. With time, the relationship between evacuees and recipient community members gradually deteriorates because of the undefined time period of the evacuees' stay, population increase, and increase in land prices. Discordance might become a difficult issue among Fukushima evacuees and reduce resilience.

Stigma and self-stigma

Stigma is another issue among the evacuees and might arise through ignorance about radiation. For example, young women in Fukushima worry that some people might view them negatively owing to assumptions about the effects of radiation on future pregnancy or genetic inheritance.[87] Owing to such misconceptions, evacuees often try to conceal the fact that they lived in Fukushima.[86] Similarly, atomic bomb survivors[88] often hesitate to talk about their life history and their experiences of the bombing. This effect is a type of self-stigma, which is induced and reinforced by public stigma. Results of one study have shown that self-stigma causes three different emotional reactions: righteous anger; loss of self-esteem; and indifference.[83,89] In Fukushima, self-stigma seems to have caused various emotional reactions leading to distress.[86] Since the psychological effects of self-stigma cannot be ignored, development of counter-measures for public stigma is necessary to prevent affected people from further stigmatising themselves.

Lifestyle-related problems

The Fukushima Daiichi NPP accident caused many evacuees to change various aspects of their lifestyles, such as diet, physical exercise, and other personal habits. After government-directed evacuation, 15% reported mental health problems, and 70% reported experiencing sleeping difficulties.[19,90] Proportions of mental health problems and sleeping difficuties were higher than in other areas in Japan (ie, 3% with mental health problems and 15% with sleeping difficulties).[75] These changes in health-related behaviours have raised concerns about the future risk of cardiovascular diseases among evacuees. According to a longitudinal analysis of the Fukushima Health Management Survey,[91] the proportion of people with a body-mass index of more than 25 kg/m² was significantly higher in evacuees than in Fukushima residents who were not evacuated (31·5–38·8% *vs* 28·2–30·5%).[91,92] After the accident, prevalence of hypertension increased from 53·9% to 60·1%, prevalence of diabetes increased from 10·2% to 12·2%, and prevalence of dyslipidaemia increased from 44·3% to 53·4% among the evacuees, but prevalence did not increase among residents who were not evacuated.[91,92] On the basis of these results, the local government promoted health awareness among evacuated residents.[93]

Conclusions

The effects of NPP accidents vary substantially, ranging from short-term to long-term health effects and from physical health to social and psychological effects. In the acute phase of an accident, serious health effects due to uncontrolled exposure and multicasualty accidents that need abundant medical resources are major concerns.[4,25] Inadequate protection of the public from radiation exposure might lead to increased incidence of cancer later in life.[4] Additionally, potential adverse health risks might accompany the protective measures themselves—ie, increased health risks associated with an unplanned evacuation or relocation of vulnerable populations, such as hospital inpatients and elderly people in nursing care facilities,[56,60,61,66] and poor medical responses to life-threatening trauma or illnesses within an evacuation zone around the nuclear facility.[25,30] After the acute phase, displacement of hundreds of thousands of people creates a wide range of public health-care and social issues.[90–93] Among these issues, major psychological effects are the most commonly observed effects after an NPP accident.[19,71–74]

Contributors

KT, AO, KS, KK, SY, and RKC set the conceptual framework of the report. AH, KT, AO, HY, MM, JS, TO, TT, MA, NH, and TI did the literature search and drafted the report. KS, KT, AH, and AO checked the draft closely and contributed to the critical revision. All authors contributed to the discussion and have seen and approved the final version of the report.

Declaration of interests

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