REVIEW ARTICLE

An update on radioactive release and exposures after the Fukushima Dai-ichi nuclear disaster

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ABSTRACT. On 11 March 2011, the Richter scale 0.9-magnitude Tokohu earthquake and tsunami struck the northeast coast of Japan, resulting in widespread injury and loss of life. Compounding this tragic loss of life, a series of equipment and structural failures at the Fukushima Dai-ichi nuclear power plant (FDNP) resulted in the release of many volatile radioisotopes into the atmosphere. In this update, we detail currently available evidence about the nature of immediate radioactive exposure to FDNP workers and the general population. We contrast the nature of the radioactive exposure at FDNP with that which occurred at the Chernobyl power plant 25 years previously. Prediction of the exact health effects related to the FDNP release is difficult at present and this disaster provides the scientific community with a challenge to help those involved and to continue research that will improve our understanding of the potential complications of radionuclide fallout.

Received 8 August 2011
Revised 26 March 2012
Accepted 16 April 2012

DOI: 10.1259/bjr/27017231

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On 11 March 2011, the Richter scale 9.0-magnitude Tokohu Earthquake and tsunami struck the northeast coast of Japan, resulting in widespread injury and loss of life. At the time of writing this article (July 2011), the Japanese National Police Agency has confirmed 15 539 deaths and 7014 people remain missing [1].

Compounding this tragic loss of life, a series of equipment and structural failures at the Fukushima Dai-ichi nuclear power plant (FDNP) resulted in the release of many volatile radioisotopes into the atmosphere. The radioactive fallout predominantly consisted of iodine-131 (half-life 8.02 days), caesium-137 (half-life 30 years) and caesium-134 (half-life 2.06 years), but many other fission products such as ^{129m}Te (half-life 33.6 days), ^{129}Te (half-life 69.6 months), ^{136}Cs (half-life 35 days), ^{110m}Ag (half-life 250 days), ^{96}Zr (half-life 64 days), ^{95}Nb (half-life 35 days), ^{140}Ba (half-life 12.7 days) and ^{140}La (half-life 1.68 days) have been detected as minor radionuclides within 300 km of FDNP [2]. ^{131}I remains the greatest radiation health threat to the public, especially to children and adolescents, owing to its physiological uptake in the thyroid gland.

The International Nuclear and Radiological Event Scale (INES) was introduced in 1990 by the International Atomic Energy Agency (IAEA) to enable prompt communication of the impact of a radiation accident on the safety of the population after such an incident. INES scores are designated according to the severity of compromise on local radiological barriers and controls, as well as the severity of population and environmental contamination. The maximum INES score of 7 is designated when there has been a major release of radioactive material, with widespread health and environmental effects requiring implementation of planned and extended countermeasures. This maximum INES score was designated to the incident at FDNP, based on the involvement of multiple reactors and an estimated total activity release of several tens of thousands of terabecquerels of ^{131}I equivalent [3]. An INES score of 7 has been designated to only one other nuclear disaster, which occurred at the Ukrainian Chernobyl power plant on 26 April 1986.

The Chernobyl disaster resulted in widespread health effects including thyroid and haematological malignancies, and non-cancer effects such as cardiovascular diseases, cataracts and many pervasive psychological consequences. There have been an estimated 6000 thyroid cancers to date, which are predominantly found in persons exposed during childhood or adolescent years [4]. Despite similar INES scores, comparison of the Fukushima and Chernobyl nuclear accidents is very difficult, complicated by many differences, some of which are complex. For example, the Japanese Nuclear and Industrial Safety Agency (NISA) currently estimates that the total activity released at the FDNP was approximately 10% of that released during the Chernobyl incident [3] (Tables 1 and 2). Prediction of the health effects of the FDNP accident is therefore difficult.

Health effects

Radiation workers

A total of three FDNP workers regrettably died during their attempts to mitigate radioactive fallout after the

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Table 1. Assumed discharge from Fukushima Dai-ichi plant compared with the reference discharge from Chernobyl nuclear plant

Isotope	Estimated discharge from Fukushima Dai-ichi plant: Estimated by NISA	Estimated by NSC	Reference discharge from Chernobyl nuclear plant
Iodine-131	1.3×10^{17} Bq	1.5×10^{17} Bq	1.8×10^{18} Bq
Caesium-137	6.1×10^{15} Bq	1.2×10^{16} Bq	8.5×10^{16} Bq

NISA, Nuclear and Industrial Safety Agency; NSC, Nuclear Safety Commission.
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accident. These deaths have been attributed to non-radiation-related causes, and no lethal or serious health effects due to radiation have been reported to date in any member of the public [5]. This is in great contrast to the Chernobyl nuclear disaster, where 134 rescue and plant workers suffered acute radiation sickness, resulting in 28 radiation-related deaths within 4 months of the accident [6]. Myelosuppression was the major cause of death in these Chernobyl workers, despite prompt aggressive treatment, including 13 bone marrow transplants [7].

Three FDNP workers were hospitalised with non-stochastic radiation burns from inadvertent exposure to contaminated water in a turbine well on site [5]. Exposure levels to FDNP workers were reported in the summary of the recent international expert fact-finding mission by the IAEA. The agency reported that approximately 30 FDNP workers had been exposed to effective doses of between 100 and 250 mSv, and that higher internal radiation doses may have been sustained by radiation workers during the early days of the incident [5]. A news release by NISA on 10 June 2011 confirmed that significant internal thyroid radiation exposures were sustained by two employees, with effective doses estimated at 590 and 540 mSv, respectively [8].

The mean effective dose sustained by the cohort of approximately 600 000 Chernobyl recovery operators known as ''liquidators'' is estimated to be up to 170 mSv, with a large individual variation ranging from <10 to >500 mSv [9]. A cohort of early liquidators who potentially were exposed to internal radioiodine were found to have a statistically significant increase in thyroid cancer risk [10]. Cardis and Hatch recently concluded that evidence also exists for increased risks of leukaemia and other haematological malignancies, and for cataracts among the Chernobyl liquidators [11]. Cardis and Hatch also reviewed evidence suggesting an elevated risk of cardiovascular diseases in later life following exposure to low doses of ionising radiation, a topic recently comprehensively reviewed by the Advisory Group on Ionising Radiation to the Health Protection Agency in the United Kingdom [12]. It is difficult to predict the exact health consequences of those FDNP workers exposed to significant internal radiation from ^{131}I, but psychological consequences are thought likely, and

Table 2. Principle radionuclides released owing to the Chernobyl nuclear plant disaster

Principle radionuclides released owing to the Chernobyl nuclear disaster	Half-life	Activity released (PBq)
Volatile elements		
Iodine-131	8.04 days	~1760
Iodine-133	20.8 h	~2500
Caesium-137	30 years	~85
Caesium-136	13.1 days	36
Caesium-134	2.06 years	~47
Tellurium-132	3.26 days	~1150
Tellurium-129m	33.6 days	240
Intermediately volatile		
Strontium-89	50.5 days	~115
Strontium-90	29.12 years	~10
Rubidium-103	39.3 days	>168
Rubidium-106	368 days	>73
Barium-140	12.7 days	240
Refractory elements		
Zirconium-95	64 days	84
Molybdenum-99	2.75 days	>72
Cerium-141	32.5 days	84
Cerium-144	284 days	~50
Neptunium-239	2.35 days	400
Plutonium-238	87.74 years	0.015
Plutonium-239	24065 years	0.013
Plutonium-240	6537 years	0.018
Plutonium-241	14.4 years	~2.6
Plutonium-242	376000 years	0.00004

Adapted from the study of Saenko et al [6].

future screening should focus on thyroid cancer, haematological malignancy and cataracts.

General population

Adequate information on the radiation exposure to members of the general public is not yet available, and we await data from dose assessments and health surveys of ''at risk'' communities, which have recently been commissioned by the Japanese Government. Deposition of ^{131}I has not been observed at monitoring sites in 47 prefectures surrounding FDNP since 17 May 2011 [13]. Contamination of sea water and the marine environment has occurred by both aerial deposition and by discharges of radioactive liquid from FDNP. Activity levels of caesium isotopes were highest in surface sediments at the near-shore stations close to the reactors. These were between 24 and 320 Bq kg^{-1} for ^{137}Cs in the middle of May 2011 [13], but have decreased by a factor of 1000 since their peak, owing to distribution and dispersion off shore [14]. This dilution greatly lessens the chances of direct impact to humans and marine biota [14].

^{134}Cs and ^{137}Cs contamination has been found in small numbers of routinely sampled seafood, unprocessed tea leaves, shiitake mushrooms and bamboo shoots. One sample of algae collected on 21 May 2011 showed contamination above regulation values for ^{134}Cs/^{137}Cs and I-131 [13]. Radioactivity in tap water exceeded 100 Bq l^{-1} in many prefectures, including Tokyo, leading to widespread drinking water restrictions to selected population subgroups between 21 March and 1 April 2011.

Background radiation exposure in Japan

Members of the Japanese public have an annual effective dose comparable with the worldwide average, which is mainly composed of approximately 1 mSv from natural sources and 2.2 mSv from diagnostic imaging examinations [15].

Exposure reduction

Exposure reduction measures conducted by the Japanese authorities included evacuation of the general public within a 20-km radius of the FDNP, and the restriction of drinking water and food. These measures are commendable and will have significantly decreased the potential health consequences to members of the general public [5]. Early results of paediatric thyroid dose studies, involving 946 children from areas with some of the highest fallout, show minimal thyroid doses of less than 100 mSv [16]. Rapid distribution of potassium iodide tablets in these areas was a crucial precaution taken to decrease ^{131}I thyroid uptake. Japanese children, who consume one of the most iodine-rich diets in the world [16], would on average have already been better protected compared with the children exposed from Chernobyl, who tended to be iodine-deficient [16], and consequently would absorb and retain more ^{131}I.

The mental health effects after the Chernobyl nuclear disaster were significant and protracted, involving a large percentage of the exposed population over their lifespan, sometimes passing on to subsequent generations [17], and may be linked to local culture and poverty. These effects were found by the 2006 Chernobyl Forum Report to be the primary public health consequence of the Chernobyl nuclear disaster [18]. The far-reaching psychological morbidity of toxic exposure is not dose related but may be more important than the cases of cancer diagnosed and treated [19]. In a recent review article entitled ''What have we learnt from Chernobyl? What have we still to learn?'', Thomas et al concluded that ''most importantly, we must learn to report figures to the public in an appropriate manner, and to keep things in perspective'' [17]. This advice is relevant both to the scientific research community and to physicians and, if followed, will help exposed individuals to concentrate on the actual, rather than the perceived, risks of radiation exposure [17].

Future studies on the exposed members of the Japanese public should not only investigate the potential increases in the incidence of thyroid, haematological and other solid malignancies, but should also interrogate the potential non-cancer-related effects of the FDNP disaster, such as an increased incidence of cardiovascular disease, radiation-induced cataractogenesis, and psychological and mental health effects.

Conclusion

Information on the nature of public exposure resulting from the Fukushima nuclear disaster is incomplete at the time of writing. IAEA state that certain Fukushima workers may be at increased risk of developing some radiation-induced health effects [5]. The disaster provides the scientific community with a challenge to help those involved and to continue research that will improve our understanding of the potential complications of radionuclide fallout.

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