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PAPER

What's better for our health? Conducting protective actions during a nuclear emergency or accepting a certain radiation dose?

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Abstract

The threat caused by ionising radiation has resulted in the establishment of strict radiation protection guidelines. This is especially true for severe nuclear power plant (NPP) accident scenarios, which may involve the release of significant amounts of ionising radiation. However, we believe that the fine balance between the benefit of a certain protective action (e.g. evacuation) and its risks is not always accounted for properly. Deaths and mental health problems have been associated with protective actions (e.g. evacuation) implemented in the response to the Fukushima Daiichi (NPP) accident in 2011. The protective actions were implemented consistent with international recommendations, to reduce radiation-induced health effects, even though the off-site effective doses were too low to indicate that there would be any discernible radiation-induced health effects. In this paper, we will provide a first step for the development of tools to evaluate the risk of protective actions versus the radiation-induced health risk. Over 50 papers were selected as useful from more than 600 reviewed papers to characterise the health impact of protective actions taken during different emergencies (including, technical and natural emergencies). An analysis was performed comparing the radiation-induced health effects averted by protective actions with the health effects associated with the protective actions. We concentrated our analysis on deaths and mental health problems associated with protective actions compared with the inferred radiation-induced deaths averted by the protective actions. Our analysis is stated in terms of absolute risk (cases per 1000) of health effects to allow for a direct comparison. It indicates that taking protective actions consistent with dose criteria typically used in many countries could result in more excess deaths than the inferred radiation-induced deaths prevented, as well as resulting in mental health problems. We identified that residents of facilities for long stays and the elderly are particularly vulnerable and a significant number of the deaths among the general public are associated with a lack of emergency preparedness provisions.

1. Introduction

A major nuclear power plant (NPP) accident may exhibit massive consequences for health as well as for the fabric of society (Steinhauser *et al* 2014, 2019). However, not all effects are directly correlated to radiation dose. The off-site effective doses during the Fukushima Daiichi nuclear power plant (FDNPP) accident (Japan, 11 March 2011) were too low to indicate that there would be any discernible increased incidence of radiation-induced health effects among exposed members of the public or their descendants (UNSCEAR 2014), even if no protective actions were taken. However, there were deaths (Nomura *et al* 2013, Yasumura 2014, Morita *et al* 2017, Reconstruction Agency Japan 2019), increases in morbidity (e.g. diabetes, hypertension, atrial fibrillation) (Satoh *et al* 2015, Suzuki *et al* 2015, Fukushima Medical University 2018, Nomura *et al* 2021), mental health problems (Maeda *et al* 2014, Yabe *et al* 2014) and other effects (e.g.

economic) (Cabinet Office Japan 2012). These adverse effects have been attributed to protective actions (e.g. evacuation) taken consistent with international recommendations, to reduce radiation-induced health effects. Thus *justification*—to do more good than harm—one of the fundamental principles of radiological protection, is not being realised. To a certain extent, this is because no tools were provided to allow the risk of protective actions to be put into perspective relative to the risk from radiation exposure. In this paper, we will provide a first step for the development of such tools by presenting a comparison, based on available information, of the radiation-induced health risk with the protective action health risk.

2. Methodology

More than 600 papers were reviewed to characterise the health impact of protective actions taken during different emergencies (including, technical and natural emergencies). Relevant papers were identified from the Fukushima Medical University library of 'Selected Papers on Disaster and Radiation' (Fukushima Medical University 2021), reviews of the references of important papers, as well as independent searches by the authors. There were 90 papers identified as relevant and over 50 selected as useful based on the criteria that: (a) they examine protective actions, dislocations or radiation-induced health consequences, and (b) the data are useable (e.g. results presented in absolute risk). We concentrated our analysis on deaths and mental health problems associated with protective actions compared with the inferred radiation-induced deaths averted by the protective actions. Our analysis is stated in terms of absolute risk (cases per 1000) of health effects to allow for a direct comparison.

The radiological protection principle of justification states that any decision altering a radiation exposure situations (e.g. implementation of protective actions) should do more good than harm and application of this principle needs to involve key stakeholders who may make or respond to such decisions (ICRP 2020). This is only possible if the risks of radiation exposure and the risk of actions taken to reduce radiation risks are presented in an understandable way for the stakeholders (e.g. local officials, the public). Therefore, the aim of this paper is to provide a tool that allows the key stakeholders to balance the health hazards of radiation exposure versus the health hazards of protective actions during planning and response to NPP emergencies, thereby enabling them to make truly risk-informed decisions (Callen and McKenna 2018). Absolute risk, the number of events divided by the number of people in the affected groups, has been found to be the most understandable way to communicate risk (Noordzij *et al* 2017). Therefore, we express the health risks of radiation exposure and protective actions in terms of absolute risk to allow easy and balanced comparison.

Our analysis does not cover the other adverse consequences (e.g. vast economic impact) of the response to the FDNPP accident (Cabinet Office Japan 2012, Hasegawa *et al* 2015, 2016, Hayakawa 2016), which also affects people's lives in the aftermath of an NPP accident.

3. Dose criteria for radiation-induced health effects important for NPP emergencies

There are two types of radiation-induced health effects—severe early (also called deterministic effects, acute effects, prompt effects, and tissue reactions) and late effects (also called stochastic, latent, and delayed effects).

3.1. Severe early radiation-induced health effects

Severe early radiation-induced health effects are those that could be fatal or reduce the quality of life and have a threshold below which the effect does not occur and above which the likelihood of the effect increases steeply with increased dose. Table 1 presents the threshold doses for severe early effects important for NPP emergencies. The threshold dose is the dose at which 5% of those exposed would be expected to suffer the effect (IAEA 2005). These threshold doses are well above protective action dose criteria typically used in many countries (appendix G of European Atomic Energy Community 2014, US Environmental Protection Agency 2017), except possibly for the threshold for effects to the embryo/foetus.

The threshold doses for severe early effects are from reference (IAEA 2005) and should be provided in terms of absorbed dose (Gy). Here we assume that absorbed dose (Gy) is approximately equal to effective dose (Sv) to allow comparisons with protective action criteria that are often given in effective dose. This is reasonable for external radiation important for NPP emergencies.

A study (Otake *et al* 1991) of the survivors exposed prenatally to the atomic explosions of Hiroshima and Nagasaki found a significant increase in severe mental retardation observed only in those exposed in two periods: 8–15 weeks and 16–25 weeks after fertilisation, with 80% of the radiation-related severe mental retardation occurring due to exposure in the 8–15 weeks' period. Furthermore, the International Commission on Radiological Protection (ICRP) concluded that for foetal doses less than 100 mGy there is no

Table 1. Exposed groups and external dose threshold for severe early radiation-induced health effects important for an NPP emergency (ICRP 2000, IAEA 2005).

Exposed group	External dose threshold (Gy) (Sv)	Severe early radiation-induced health effects important for an NPP emergency
General population	2–3	Death due to red bone marrow exposure
	1	Detectable non-fatal effects (e.g. necrosis, hypothyroidism, permanently suppressed sperm count)
Pregnant women (embryo/foetus)	1	Foetal death
	0.1	Discernable reduction in IQ when exposed 8–15 weeks or 16–25 weeks after fertilization

Table 2. Total effective dose (mSv), estimated inferred radiation-induced cancer (late) deaths per 1000 members of the public exposed during an emergency and total cancer deaths expected, including normal German lifetime cancer deaths (RKI & GEKID 2020).

Total effective dose in addition to background (mSv)	Inferred radiation-induced cancer (late) deaths per 1000 exposed	Total cancer deaths per 1000 among exposed members of the public (radiation-induced + normal) as calculated by extrapolation from the LNT model
0	*0*	200
1	*0.05*	200.05
5	*0.25*	200.25
10	*0.5*	200.50
20	*1*	201.00
50	*2.5*	202.50
100	5	205
250	12.5	212.50
500	25	225
1000	50	250

medical justification for terminating a pregnancy. At foetal doses above this level, informed decisions should be made based upon individual circumstances (ICRP 2000).

3.2. Late radiation-induced deaths

Late radiation-health effects (stochastic effects) occur by chance and the probability they will occur is proportional to the dose.

We infer the risk of fatal radiation-induced cancers using the linear-non-threshold (LNT) model and the ICRP fatal radiation risk coefficient of 5% (50 deaths per 1000 exposed) at 1 Sv (ICRP 2007) which is typically used as a basis for the development of protective action strategies. This model assumes the risk of radiation-induced cancer deaths is linearly proportional with the dose and projects risk to zero dose. However, cancer deaths at doses below about 100 mSv effective dose are not consistently discernible, even after careful study of many thousands of exposed individuals over their lifetimes (ICRP 2005, UNSCEAR 2011, Shore *et al* 2019, US Nuclear Regulatory Commission 2020). The assumption of risk at low doses is not scientifically validated and fatal risk at low-doses is unknown (ICRP 2007). According to United Nations Scientific Committee on the Effects of Atomic Radiation: 'Statistically significant elevations in risk are observed at doses of 100–200 mGy and above and epidemiological studies alone are unlikely to be able to identify significant elevations in risk much below these levels' (UNSCEAR 2011).

Table 2 presents in (mSv) the approximate inferred late radiation-induced cancer deaths per 1000 exposed members of the public exposed during an emergency assuming the LNT model. The table also shows the total cancer deaths per 1000 members of the exposed public including the normal German lifetime cancer death rate of about 20% expected among the public, (200 lifetime deaths per 1000, average among age groups for males and females) (RKI & GEKID 2020). The shaded values are for doses at which radiation-induced cancer deaths would not be discernible. The table highlights the need to recognise that typically members of the public annually receive between 1 and 13 mSv (UNSCEAR 2010) from background sources of exposure, such as cosmic radiation, and any exposure during an emergency will in addition to this background.

It is important to note that the increase in mortality risk from common factors such as smoking and obesity may be greater than that from radiation exposure over this entire dose range (Smith 2007, McCormack and Boffetta 2011). Some of these factors (e.g. obesity), as observed after the FDNPP accident (Hasegawa *et al* 2016), can be influenced by implementation of protective actions and resulting dislocations.

4. Deaths and mental health problems associated with protective actions

4.1. Early deaths from protective actions

The protective actions taken to avert radiation exposure during an NPP emergency include evacuation, sheltering, iodine thyroid blocking, relocation and restrictions on food and drinking water. Dislocation, while not a protective action, can be a consequence of most of these protective actions and refers to people moving to and residing in a different location from their usual residence. We focus on evacuations and dislocations resulting from protective actions as they probably caused most of the deaths and other health effects among the public during the FDNPP accident (Callen and McKenna 2018).

Studies (US Nuclear Regulatory Commission 2005, 2008) of evacuations in the USA showed the death risk during evacuation of the public who do not need support is about the same as that during normal road travel. There were 60 US evacuations examined in the studies involving about 15 million people, which found less than 10 early deaths (absolute risk of 0.0007 per 1000) during travel. Therefore, in our analysis we only considered evacuations of those who needed support.

4.1.1. General population

Table 3 presents our estimates of the death risk among the general population associated with dislocations. This estimate was derived based on the disaster related death (DRD) estimates for the Great East Japan Earthquake from (Reconstruction Agency Japan 2012). A DRD is defined as a death caused by the deterioration of underlying medical problems due to poor medical access or illnesses arising from poor living environments, such as temporary shelters, in a disaster (Hasegawa *et al* 2016). The DRDs are official estimates of deaths among the general public located in areas evacuated and dislocated during the FDNPP accident. The national total of DRDs was more than 1600 (as of 31 March 2012) and they are often referred to in reports and peer-reviewed papers as an indication of the adverse impact of the response to the accident. However, the DRDs are uncertain since they are related to the eligibility of condolence money and disability payments and are not supported by analysis of death risk before and after the dislocations (Government of Japan 1973, Callen and McKenna 2018). The authors used the DRD data with adjustments to make them more appropriate for analysing deaths associated with protective actions and dislocations.

We derived our estimate of three early deaths per 1000 of the general population based on the 711 DRDs recorded within 6 months after the accident for the entire Fukushima Prefecture, as provided in (Reconstruction Agency Japan 2012), assuming they were among the 189 797 registered residents (Fukushima Pecture 2011) in the 11 evacuated municipalities of Fukushima Prefecture (NAIIC 2012). The DRD data were adjusted to be more appropriate for analysing deaths associated with implementation of protective actions by: (a) considering only the DRDs reported during the first 6 months following the accident, and (b) removal of 18% of the DRDs due to causes not related to protective actions or dislocations, such as deaths from the physical or mental load of the impact of the earthquake and tsunami (Reconstruction Agency Japan 2012). Six months was selected as the cut-off period for inclusion of deaths as being associated with the implementation of protective actions or dislocations because of a by law passed in Japan after the 2004 Niigata-Chuetsu earthquake, which states that deaths after 6 months should not be considered disaster related. The national government of Japan presented this approach as a reference example to other local governments after the Great East Japan Earthquake, see attachment 3 of Ministry of Health, Labor & Welfare, Japan (2011).

It is worth noting that almost 40% of the DRDs in Fukushima Prefecture occurred within 3 months after the accident and more than 90% of the deaths occurred in those over 66 years old (Reconstruction Agency Japan 2012, 2019). Importantly, we estimate about 60% of the DRDs causes cited in (Reconstruction Agency Japan 2012), such as delay in receiving medical treatment and conditions during transportation, could possibly have been alleviated by prior emergency preparedness provisions.

4.1.2. Residents of facilities for long stays and the elderly

Deaths risk associated with protective actions (evacuation and sheltering) and dislocations for residents of nursing homes and facilities for the institutionalised elderly are presented in table 3. The 17 deaths per 1000 for deaths resulting from dislocations is based on comparisons of the deaths risk (/1000) before and within the first 90 d following evacuation and resulting dislocations of: (a) the 36 389 residents of nursing homes in response to oncoming hurricanes in the USA (Dosa *et al* 2012), and (b) the 1770 institutionalised elderly persons during the FDNPP accident (Yasumura 2014). The death risk (/1000) for both studies was consistent at 15.9 and 18.32 respectively (Dosa *et al* 2012, Yasumura 2014). Deaths seem to have occurred, despite medical care being provided during and after evacuation (Dosa *et al* 2012). This shows the importance of the possible increased death risk among this group being recognised in emergency preparedness response arrangements.

Table 3. Summary of absolute risk of deaths (/1000) by population type, action taken during the FDNPP accident and key findings related to the deaths (Dosa *et al* 2012, Reconstruction Agency Japan 2012, Tanigawa *et al* 2012, Yasumura 2014, Hasegawa *et al* 2015, 2016, Shimada *et al* 2018).

Population type	Action	Absolute risk (per 1000) of death	Key findings
General population	Dislocation	3	≈40% occurred within 3 months ≈90% occurred in those over 66 years old ≈60% were due to causes that could possibly be alleviated by prior emergency preparedness provisions
Residents of facilities for long stays and the elderly	Dislocation	17	Occurred despite providing medical care during and after evacuation
	Evacuation (during transportation)	60	Occurred during or shortly after transportation when needed support was not provided
Vulnerable patients sheltered in a hospital	Sheltering	2–3 times higher than for those who were evacuated with needed support	Occurred due to needed support not provided during sheltering

The 60 deaths per 1000 is for evacuations without needed support provided. This is based on the FDNPP accident experience involving about 50 deaths during evacuation of 840 patients (60/1000) from hospitals or nursing care facilities located within 20 km of the FDNPP. These deaths occurred during or shortly after transportation of the patients (Tanigawa *et al* 2012, Hasegawa *et al* 2015, 2016). Transportation was very early in the response and was without providing needed medical and other support. These deaths were due to factors such as hypothermia, dehydration, and deterioration of underlying medical problems (Tanigawa *et al* 2012, Hasegawa *et al* 2016). However, later evacuations of about 500 patients from hospitals and nursing facilities were carried out without any deaths during or shortly after their movement when needed support was provided (Hasegawa *et al* 2015, 2016).

Furthermore, during the FDNPP accident the death risk among vulnerable patients sheltered in a hospital without needed support (e.g. no heating, staff shortages) was about 2–3 times higher than for those evacuated with needed support (Shimada *et al* 2018). This shows the importance of emergency preparedness provisions to provide such support in an emergency.

4.2. Mental health problems associated with dislocation

A recent study on non-radiological health consequences from evacuation and relocation (US Nuclear Regulatory Commission 2021) found the largest effect to be non-fatal effects, such as the disruption of social support networks, increases in domestic abuse, and memory problems in children, among others. The findings were that nearly 250 per 1000 people displaced potentially suffer from these effects. The analysis found substantial and statistically significant increases in depression, psychological distress, post-traumatic stress disorder (PTSD), sleep problems, and mortality, among others, for evacuated and relocated populations relative to nondisplaced populations.

Our literature review identified numerous important non-fatal health effects that reduce the quality of life. However, we focused our analysis on mental health problems because they are cited as the most serious health effects of the FDNPP accident and include PTSD, stigma, stress, depression, chronic anxiety, and guilt (González *et al* 2013, WHO 2013, Hasegawa *et al* 2016). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) concluded concerning the FDNPP accident that:

> *'No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants. The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported'* (UNSCEAR 2014)

Table 4 presents some of the mental health problems identified among evacuees in studies of the FDNPP accident. It is estimated that there were about 200 per 1000 adults with probable PTSD (Kawakami *et al* 2014, Maeda *et al* 2014, Ohto *et al* 2015) and 120 per 1000 adults were found to have depression (Maeda *et al* 2014, Yabe *et al* 2014). The absolute risk of adults with probable PTSD was estimated assuming a normal lifetime

Table 4. Absolute risk (per 1000) of selected mental health problems associated with dislocations caused by protective actions and perceived risk of exposure to ionising radiation during the FDNPP accident (Kawakami *et al* 2014, Maeda *et al* 2014, Mashiko 2014, Yabe *et al* 2014, Ohto *et al* 2015).

Mental health problems	Absolute risk (per 1000) of mental health problems associated with dislocations caused by protective actions and perceived risk of exposure to ionising radiation
Probable PTSD	200
Depression	120
Psychological distress (children)	120

prevalence of about 1% (10/1000) (Kawakami *et al* 2014). The 120 per 1000 adults with depression was estimated assuming a 3% (30/1000) normal prevalence (Yabe *et al* 2014). Children were reported to exhibit psychological distress at 120 per 1000 (Mashiko 2014, Yabe *et al* 2014). The absolute risk of psychological distress in children was estimated assuming a normal prevalence of about 12% (120/1000) (Yabe *et al* 2014).

Mental health problems have also been identified as possibly the most serious health effect for the Three Mile Island and Chernobyl NPP accidents (Kemeny *et al* 1979, WHO 2006). The major risk factor associated with mental health problems following NPP accidents is the public's perceived risk of radiation-induced health effects (Kemeny *et al* 1979, WHO 2006, Bromet 2012, González *et al* 2013, UNSCEAR 2014). This demonstrates the importance of putting the radiological risks in perspective in a way that the public and decision makers can understand (McKenna *et al* 2015).

Suicides are included in the DRD totals in table 3. However, it is worth noting that there were 83 cases of suicide in Fukushima Prefecture officially certified as disaster-related suicide in the 5 years after the FDNPP accident (Maeda and Oe 2017). A study of the standardised suicide mortality ratio found that it decreased in Fukushima Prefecture during the first 2 years after the FDNPP accident compared with 2010 (Ohto *et al* 2015). Significantly, in 2014 the ratio then exceeded the pre-accident level, despite the fact that in Japan as a whole, suicide prevalence is declining slightly.

Some pre-existing mental health problems were also reported to have been exacerbated after the FDNPP accident (Matsumoto *et al* 2014). A study found that the proportion of support-requiring children in Fukushima Prefecture was 21.2% (212/1000) in 2011, significantly higher than the reported 9.5% (95/1000) in the Japanese population who did not experience a disaster (Mashiko 2014). In addition, stigma and prejudice toward those who may have been in the contaminated areas resulted in discrimination, anger, loss of self-esteem, bullying of children, and was still occurring 6 years after the accident (NAIIC 2012, González *et al* 2013, Hasegawa *et al* 2016, Sawano *et al* 2018).

5. Radiation risk compared with protective action risk

Table 5 presents the inferred radiation-induced deaths per 1000 possibly prevented by protective actions triggered by dose criteria that encompasses those used in many countries (appendix G of European Atomic Energy Community 2014, US Environmental Protection Agency 2017). The dose criterion of 100 mSv is shown in bold-italics since it is the lowest threshold for severe, early radiation-induced health effects for an NPP accident (discernible reduction in IQ due to embryo/foetus from exposure 8–15 weeks or 16–25 weeks after fertilisation). Termination of a pregnancy is not medically justified for foetal doses less than 100 mGy and for doses above this level, informed decisions should be made based upon individual circumstances (ICRP 2000).

In addition, to allow easy comparison, table 5 includes our estimates of the absolute risk (per 1000) of deaths and mental health problems associated with dislocations caused by protective actions.

The authors want to emphasise that table 5 is intended to be used as a general tool to compare the absolute risk of radiation-induced deaths with deaths associated with protective actions or dislocations and the mental health problems risk. However, it must be used with caution owing to the variation and uncertainty in estimating such risks (e.g. risks can be age and sex dependent). This has been reflected in the table with separate columns for the elderly and those under 18. Furthermore, there are uncertainties related to the use of radiation-induced cancer death risks based on the LNT model, as well as uncertainties in the reliability of the estimates of the impact of protection actions, which are based on limited, early data. However, table 5 was developed for ease of use and to meet the need for a tool that can be available now to evaluate the risk of protective actions versus the radiation-induced death risks. It was developed based on the best available data and formulated such that it can be easily used as a basis for making informed decisions on emergency preparedness arrangements.

Table 5. Dose criteria for triggering protective actions (mSv), absolute risk (per 1000) for inferred radiation-induced deaths prevented by triggered protective actions, deaths associated with protective actions or dislocations, and mental health problems associated with dislocations and perceived risk of exposure to ionizing radiation (Dosa *et al* 2012, Reconstruction Agency Japan 2012, Kawakami *et al* 2014, Maeda *et al* 2014, Mashiko 2014, Yabe *et al* 2014, Yasumura 2014, Ohto *et al* 2015, Harrison *et al* 2016).

Dose criterion for triggering protective actions (mSv)	Absolute risk (per 1000)						
	Radiation-induced deaths possibly prevented by triggered protective actions			Deaths associated with protective actions or dislocations		Mental health problems associated with dislocations and perceived risk of exposure to ionising radiation	
	General population	Elderly (70 and above)	Under 18	General population	Residents of facilities for long stays and the elderly	General population	Under 18
1	0.05	0.02	0.1	3	17–60	200	120
5	0.25	0.1	0.5				
10	0.5	0.2	1				
20	1	0.3	2				
50	2.5	1	5				
100	5	2	10				

The absolute risk for radiation-induced deaths prevented by triggered protective actions was estimated for the general population, elderly and those under 18 in accordance with (Harrison *et al* 2016). The inferred cancer risk per unit of effective dose for the general population is based on the ICRP fatal radiation risk coefficient, and the inferred cancer risk per unit of effective dose for those 70 and above is about 1/3 of that inferred for the general population, and for those under 18 it is double the risk inferred for the general population.

Our estimates presented in table 5 show 3 deaths per 1000 among the general population that are associated with dislocations caused by protective actions, which are comparable to the inferred radiation-induced deaths prevented by protective actions triggered at about 100 mSv. However, at lower doses radiation-induced deaths would not be discernible and deaths associated with protective actions or dislocations are greater than those prevented by the protective actions. For example, implementing water restrictions triggered by a dose criterion of 1 mSv could result in dislocations. As a result, there could be 60 times more deaths among the general population, compared to the inferred radiation-induced deaths prevented by the protective actions.

These disparities could be even greater if the protective actions are not 100% effective, which is likely due to imprecise or conservative dose projections. While the use of conservative dose projections (i.e. assuming the worst case theorised) might lower the risk from radiation exposure, it will also increase the number of people affected by the more likely detrimental health effects associated with the implemented protective actions.

Furthermore, emergency planners should recognise that the actual public exposure at specific times and locations will not be known precisely when protective action decisions need to be made, as demonstrated during the FDNPP accident (Callen-Kovtunova and Homma 2022). However, the range of possible exposures could be estimated in advance, as part of the planning process, for conditions at an NPP and environmental measurements (Callen and McKenna 2018). Such estimates, combined with a tool (e.g. table 5), can facilitate informed decision making.

It is important to note that the 17 deaths associated with dislocation of residents of facilities for long stays and the elderly seem to have occurred despite providing medical care during and after evacuation. There were 60 deaths among this group that occurred during or shortly after transportation, when needed support was not provided.

The radiological protection principle of justification ensures that decisions regarding the implementation of protective actions result in a benefit for the affected people, as these actions can potentially induce significant disruptions (ICRP 2020). The estimates presented in table 5 could aid key stakeholders at the preparedness phase and during a response to evaluate decisions on the implementation of protective actions and assist in placing the risk of exposure to ionising radiation in perspective and possibly alleviate mental health problems associated with the perceived risk of exposure to ionising radiation. Furthermore, to contribute to the well-being of individuals, justification should also include special consideration to vulnerable groups (ICRP 2020). Therefore, our results include the especially vulnerable residents of facilities for long stays and the elderly, with our estimates indicating that evacuations and dislocations of this group could possibly cause many deaths among this group compared to the inferred radiation-induced deaths prevented by the protective actions.

A study (Murakami *et al* 2015) on the risk trade-off between evacuation and radiation used the detriment indicator loss of life expectancy (LLE). It found that the LLE from relocation of nursing-home residents compared to the LLE from radiation exposure was one order of magnitude higher than the LLE due to 20 mSv exposure and double that of the LLE due to 100 mSv exposure, clearly highlighting the prominent risks of evacuating nursing-home residents.

Table 5 also indicates that there could be numerous cases of mental health problems associated with evacuations and dislocation. These problems would most likely be associated with the perceived risk of exposure to ionising radiation.

The radiation-induced deaths prevented by the protective actions triggered at less than 100 mSv, presented in table 5, would not be discernible even after careful study of many thousands of exposed individuals over their lifetimes, even if they occur. However, experience from the FDNPP accident indicates that the deaths to due to protective actions and mental health problems would be observable within months to a year. Importantly, once an emergency is declared, decisions on protective actions on-site and offsite would need to be taken promptly to be effective. Given the short time to react and the numerous uncertainties, these actions should be prepared in advance on the basis of plausible scenarios and adapted as much as possible to the actual situation (ICRP 2020). Table 5 is estimated based on the best available data and on actual experience from previous evacuations and dislocations and could therefore be a first step in determining in advance the actions to be taken based on plausible scenarios.

As noted in (Callen and McKenna 2018) it is also important to take actions to counter the exaggerated fear of radiation exposure that could lead to taking unjustified protective actions and increased mental health problems. Such actions include effective communication with the public during the emergency by placing the health hazards of radiation exposure and protective actions into perspective. Further examples of tools that could be used to place the health hazards of radiation exposure into perspective is given in (McKenna *et al* 2015).

A relatively straightforward and highly effective protective action are food safety measures. It has been shown (Steinhauser *et al* 2017) that the intense monitoring programme initiated by the Government of Japan was effective in reducing the onset of high doses for the public. Even under worst-case assumptions, no member of the public should have received a thyroid dose through ingestion of contaminated food that would have justified the administration of stable iodine prophylaxis. Due to its high intensity, such a monitoring campaign comes at a high cost, as illustrated by the example of beef monitoring (Steinhauser 2017). It is conceivable that not all NPP countries have the capacity to measure such high numbers of samples over a comparable period of time. Apart from the costs, food monitoring shows little adverse impact on the consumer (but likely on the producers who are affected by radioactive fallout). This may change, however, once high contamination levels threaten the supply of a sufficient amount of food. In this respect, the choice of regulatory limits becomes crucial. After the Chernobyl NPP accident, most common (solid) foods had a maximum permissible level in Europe of 1250 Bq kg^{-1} for radiocesium, whereas the Japanese regulatory limits were much stricter: the maximum permissible level for radiocesium was 500 Bq kg^{-1} in the first year after the accident and 100 Bq kg^{-1} thereafter. As outlined by Merz *et al* (2013), these much stricter limits were not necessarily driven by dose considerations but rather by public pressure, as the Japanese authorities assumed that the entity of foods were contaminated at the maximum permissible limit, which is, of course, not only a super-conservative but also a highly unrealistic assumption. The very strict regulatory limits now pose the risk that they will be demanded by the public after possible future NPP accidents. Depending on the amounts of released radionuclides, it may appear possible that a large fraction of foods may moderately exceed the regulatory limit—however, without causing an unacceptable dose risk. This may jeopardise food supply in affected areas. We argue that accurate knowledge about the actual contamination levels in food (which is only achievable by intense monitoring) are more important than strict regulatory limits.

6. Conclusions

Our analysis shows that taking protective actions consistent with dose criteria typically used in many countries could result in more deaths than the inferred radiation-induced deaths prevented. In addition, the response could result in mental health problems often associated with the perceived risk of exposure to ionising radiation. These adverse effects can result from protective actions taken consistent with international recommendations to avert radiation exposure, even though the radiation-induced health effects avoided would be negligible and not discernible. This failure to do more good than harm and fulfil the fundamental radiological protection principle of justification is because too much emphasis is given to protection of people from the radiation, without due consideration to the impact of the protective action. Our analysis identified that residents of facilities for long stays and the elderly are particularly vulnerable if needed support is not provided during transportation for evacuation or while sheltering. Furthermore, for those dislocated from facilities for long stays and the elderly, deaths seem to have occurred, despite providing medical care during and after evacuation. This highlights the need for protective actions designed specifically to mitigate the health effects for residents for long stays and the elderly, particularly when evacuating, sheltering or dislocating.

Crucially, about 60% of the deaths among the general public could be associated with a lack of emergency preparedness provisions. Furthermore, emergency planners need to recognise that there are several components required to enable informed decision making on protective actions. The actual public exposure at specific locations and times will not be precisely known when protective action decisions need to be made. However, the range of possible exposures could be estimated in advance, as part of the planning process, for conditions at an NPP and environmental measurements. Such estimates, combined with a tool (e.g. table 5), can facilitate informed decision making.

We believe that this analysis should be taken into consideration in radiation protection guidance for severe NPP emergencies to ensure an adequate level of emergency preparedness, and that any protective action will most likely do more good than harm when the risk of the radiation averted and impact of the protective actions are considered. Without these changes, there is the possibility of similar observable deaths associated with protective actions and dislocations to avoid radiation-induced cancer deaths that would not be discernible, should an NPP emergency happen in the future. Importantly, any revisions to the guidance should ensure that the information is presented in a useful and understandable way for the decision maker and the public, as we have presented in table 5. We believe this table is a useful tool that could be adjusted to the needs of a specific country and our analysis provides a first step for the development of such tools.

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