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Assessment of the Risk of Medium-Term Internal Contamination in Minamisoma City, Fukushima, Japan, after the Fukushima Dai-ichi Nuclear Accident

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Short title: Risk of Internal Radiation Contamination in Fukushima

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Abstract

Background: The Fukushima Dai-ichi nuclear disaster, the first level-7 major nuclear disaster since Chernobyl, raised concerns about the future health consequences by exposure to and an intake of radionuclides. Factors determining the risk and level of internal radiation contamination after a nuclear accident, which are a key to understanding and improving current nuclear disaster management, are not well studied.

Objective: This study aims to investigate both the prevalence and level of internal contamination in residents of Minamisoma, and to identify factors determining the risk and levels of contamination.

Methods: A program assessing internal radiation contamination using a whole body counter (WBC) measurement and a questionnaire survey was implemented in Minamisoma, between October 2011 and March 2012.

Results: Approximately 20% of the city population (8,829 individuals) participated in the WBC measurement for internal contamination, of which 94% responded to the questionnaire. The proportion of participants with detectable internal contamination was 40% in adults and 9% in children. The level of internal contamination ranged from 2.3 to 196.5 Bq/kg (median, 11.3 Bq/kg). Tobit regression analysis identified two main risk factors: more time spent outdoors, and intake of potentially contaminated foods and water.

Conclusions: This study suggests that with sensible and reasonable precautions, people may be able to live continuously in radiation-affected areas with limited contamination risk. To enable this, nuclear disaster response should strictly reinforce food and water controls with dissemination of evidence-based and up-to-date information about avoidable contamination risks.

Introduction

On March 11, 2011, the Fukushima Dai-ichi nuclear power plant in northeast Japan was substantially damaged by the Great East Japan Earthquake and its subsequent tsunami (World Health Organization 2013). Approximately 900 PBq of radionuclides, including 500PBq of Iodine-131 (I^{131}) and a total of 20 PBq Cesium isotopes (Cs^{134} and Cs^{137}), were released into the atmosphere contaminating over 1800 km^2 of land (The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission 2012; Tokyo Electronic Power Company 2012). Although the amount of radionuclides released was just one sixth of that from the Chernobyl accident (Taira et al. 2013), people in areas affected by the disaster received annual effective doses up to 5 mSv, which was equivalent to the standard fixed five years after the Chernobyl accident for recommended relocation (Nuclear Energy Agency 2002; Taira et al. 2013; World Health Organization 2013). Accordingly, the disaster has raised concerns about the long and short-term health consequences of radiation within Japan and worldwide.

Confronted with the disaster, the Japanese government immediately mandated several evacuation orders: On March 12, the 20 km-radius area around the plant was denoted as a Restricted Area with compulsory evacuation (Ministry of Economy Trade and Industry 2011). Subsequently, a 20-30 km zone became an Evacuation-Prepared Area in case of Emergency, and due to asymmetric deposition of radioactive fallout, a few villages in the 20-50 km zone were re-designated as Deliberate Evacuation Areas (Prime Minister of Japan and his Cabinet 2011; Yoshida and Takahashi 2012). In order to mitigate the effects of internal contamination, radiological contaminant tests were also implemented on March 17 to restrict distribution of radio-contaminated foods (Ministry of Health Labour and Welfare 2011a). The government's preparedness and response plans have been criticized for being inadequate and based on limited knowledge of nuclear disaster management: many residents were not informed of the disaster until the evacuation day, and some were left with the entire decision-making responsibility without information to make wise decisions on evacuation (The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission 2012). A lack of clear guidelines confused residents about the best evacuation process, and also when to return home. Thus within the same city, residents' individual evacuation history and behavior resulted in potentially different initial and chronic exposure periods as well as exposure mechanisms, giving the researchers an opportunity to identify individuals at high risk of internal contamination, and to provide lessons for the management of chronic internal contamination risk both in the affected areas in Fukushima and in the aftermath of future nuclear accidents.

There are currently no comprehensive assessments of risk factors for internal contamination after a major nuclear accident, and the available estimates are limited in scope and timeliness. The earliest published assessments of cesium contamination after the Chernobyl accident used data collected one year after the initial radiation release (Holmberg et al. 1988; Koch et al. 1992; Rabitsch et al. 1991), and were not conducted in populations from the areas closest to the accident. Assessments of residents of the areas closest to the Chernobyl plant were delayed for four years or more after the accident (Bernhardsson et al. 2011; DeVita et al. 2000; Takano 1994), and the period from 1986-1989 has been characterized as "information difficult to obtain" (Saenko et al. 2011a). Most of the studies conducted after this period suffered from significant methodological flaws: some did not assess risk factors for contamination directly, though some assessed levels of contamination in foods associated with the surveyed populations (Leppanen et al. 2011); most had small sample sizes; and some used forensic samples that contained no information about lifestyle habits or risk behaviors (Rabitsch et al. 1991). Despite these limitations, most of these studies identified high levels of internal cesium contamination even a year after the Chernobyl accident (Bernhardsson et al. 2011; Koch et al. 1992; Leppanen et al. 2011; Rabitsch et al. 1991), and many suggested inhalation of radionuclides deposited on external surfaces (Holmberg et al. 1988) and/or consumption of contaminated food as the main risk factors for internal contamination (Anspaugh et al. 1988). Better understanding of these risk factors using data from a large community cohort surveyed as close as possible to the radiation release incident is necessary to develop better methods for internal contamination risk mitigation.

Due to this scarcity of studies conducted in the immediate aftermath of past disasters, a method for identifying individuals at high risk of internal contamination after a nuclear accident is not yet defined (Hatch et al. 2005a; Saenko et al. 2011b; Upton 1981). From October 2011, the Voluntary Internal Radiation Exposure Screening (VIRES) program has been conducted in Minamisoma, Fukushima with the ultimate goal of monitoring the long-term health risks of the residents (Minamisoma Municipal General Hospital 2014). This study expands on the initial report of baseline exposure prevalence (Tsubokura et al. 2012) using the data collected in the first year after the incident to investigate both the prevalence and levels of measurable internal contamination amongst the participants, and also to identify risk factors for the levels of internal contamination.

Methods

Study setting

Minamisoma, a coastal city located 14-38 km north of the Fukushima Dai-ichi nuclear plant, is one of the most radioactively-contaminated regions in Fukushima, and is covered by all three evacuation zones (Supplemental Material Figure S1) (The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission 2012; World Health Organization 2012). Of 146,520 evacuees from Fukushima prefecture, 61,710 (42%) were from this city. A year after the disaster, even after the return of some residents, the population had dropped from its pre-disaster level of about 72,000 to below 43,000 with 32% aged over 65 (Maeda 2012; Statistics Bureau Director General for Policy Planning & Statistical Research and Training Institute 2010).

Data collection

From October 1, 2011 to March 11, 2012, the VIRES program was conducted free of charge for residents aged six and above at the Minamisoma Municipal General Hospital. A program notification was sent to each household b of the general population, including former residents who had evacuated elsewhere but could be traced using the city's family registry (Ministry of Justice 1962). All families officially resident in Japan are registered in such a family registry, which is used for public welfare and statistical purposes. Through collaboration with the Minamisoma municipal authorities, this registry could be used to distribute information about the screening program (Minamisoma city 2014). Because participation in this study was voluntary and based on self-referral, it was not possible to randomize, counter-balance or in any way adjust for any bias that would be induced by subject self-selection over time. The ultimate goal of the program is to continuously collect data of Minamisoma residents to eventually monitor the long-term health consequences in the population. A Fastscan Model 2250 whole body counter (WBC, Canberra, Inc. USA) (Canberra Industries Inc 2014), shielded against background radiation, was used to detect total body activity of radionuclides. Calibration of the machine is conducted regularly based on the method suggested by the company (Bronson et al. 1984).

With a two-minute scan, the detection limits were 210 Bq for Cs^{134} and 250 Bq for Cs^{137}. The WBC could only measure Cs^{137} and Cs^{134} and not I^{131}, due to its short half-life of eight days, while the half-lives of Cs^{137} and Cs^{134} are 30 and 2 years respectively (Christodouleas et al. 2011; Napier 2012; Yasunari et al. 2011). Measurements were made in total body activity (Bq) and concentration by body weight (Bq/kg).

A self-reported questionnaire was administered, and its contents were restructured in December 2011 to shift the focus from the risks associated with external exposure to internal contamination: Questionnaire A (October 1 to December 14, 2011; N=4,045) asked about occupation (Outdoor, Indoor, Unemployed, Students, Housewife or Others), hours spent outdoors in the first week of the disaster (less than 5 hours or more than 5 hours), and changes in daily activity (diet and physical exercise). Questionnaire B (December 15, 2011 to March 11, 2012; N=4,236) asked questions about whether respondents select certain food produce from the supermarket based on the possible radio-contamination risk at point of origin, or simply use local farms. It also asked whether respondents use bottled water when drinking and cooking, as opposed to tap or well water, to reflect government concerns about possible contamination of drinking water (Ministry of Health Labour and Welfare 2011b). Both questionnaires also asked hours spent outdoors before and after the disaster as a proxy measure of external exposure to radiation (less than 5 hours or mode than 5 hours). These questionnaires were administered by the nurses and doctors managing the radiation assessment process, and took only a few minutes to complete with the assistance of the attending staff. No member of the population answered both questionnaire A and B.

Statistical analysis

The median and range for basic radiation contamination data (total body contamination (Bq) and concentration by body weight (Bq/kg)) were presented. Chi-squared tests were used to compare proportions. Throughout the paper, the term "prevalence" is used to denote the proportion of individuals detected with internal contamination above the detection limit of the WBC machine.

Tobit regression analysis was used to determine risk factors for the levels of internal contamination. Tobit regression is an analysis method that adjusts standard linear regression models for the left-censoring effect of the WBC sensitivity, which creates a large proportion of zero values for participants with levels of contamination below the detection limit of the WBC. In conventional ordinary least squares (OLS) regression, these participants would be treated as having zero contamination, when in fact it is likely that they have some positive contamination at a level below the detection limit of the machine. Tobit regression adjusts for the effect of this lower limit on the model estimates. Because there were some outliers in the data, the Tobit regression analysis was conducted on the natural logarithm of the internal contamination data. This means that all coefficients are in log-space, and have been exponentiated in presenting regression results. This means that all the results represent multiplicative changes in internal contamination level corresponding to a unit change in the predictor. In order to model concentration (Bq/kg) rather than activity (Bq/body), we included the natural logarithm of weight as an offset in the tobit model. This is equivalent to modeling the ratio of total body exposure and weight, but does not require the definition of a variable lower limit in the Tobit regression. The regression was adjusted for test month, gender, age and height, and run on three datasets with slightly different sets of risk factor covariates: the whole sample, Questionnaire A, and Questionnaire B. Covariates were selected on the basis that previous studies of exposure risks after the Chernobyl accident identified the possibility that they would be related to either inhalation of airborne radionuclides, or consumption of contaminated food or water (Anspaugh et al. 1988). In addition, basic variables known to be associated with total body activity of internal concentration, such as height and age, were also included in the model selection process.

A variant backward-stepwise model-building method was used: first, a model was built for the overall data using a standard backwards-stepwise method (Armitage et al. 2002), and using a standard exclusion criterion of p-values greater than 0.05. All confounders identified in this model were then included in the data analysis on questionnaires A and B, and retained in these models regardless of their significance. Confounders specific to questionnaires A and B, however, were excluded using the same standard backwards-stepwise process. All the data were analyzed using Stata/MP 12 (Stata/MP 2013).

Ethics and informed consent

The institutional review board of the Institute of Medical Science, University of Tokyo, approved the study, and informed consent was collected from all the participants before the study was conducted (Study codes: 23-46-0113).

Results

Population characteristics

A total of 8,829 individuals participated in the VIRES program during the study period (20% of the population a year after the disaster). Due to missing informed consent forms or questionnaire data, 548 individuals were excluded, leaving a complete dataset of 8,281 individuals (94% of the initial enrollment).

By October 2011, approximately 43,000 residents (65% of the total registry) remained living in Minamisoma, while 6,400 participants of the program (77% of the data sample) answered that they stayed in the city (Supplemental Material, Table S1: The registry only provides the dataset with number rounded to the nearest hundred). The data sample accounted for approximately 12% of the total city population under the registry. Comparison of age distributions between the data sample and the city's family registry indicated that in both sexes there is an overrepresentation of those aged 10 to 19 years, and an underrepresentation of those aged above 60 years (Supplemental Material, Figure S2, S3). There was no significant difference in the number of women attending in the early period of the study (October – November) compared to the later period (December – March) compared to men (chi-squared statistic 1.39, p-value=0.2).

The sample consisted of 7,214 adults (4010 female; median age [range], 46 [16-94]- years), and 1,067 children (536 female; median age [range], 11 [6-15] years) (Table 1). After the accident over 87% of the respondents spent less than five hours outdoors per day, compared to 80% before. During the early phase (October 1, 2011 to December 14, 2011), over 70% of the participants answered that they were not careful about the origin of a food product when purchasing at the supermarket, and close to 50% were drinking tap water instead of bottled water (Supplemental Material, Table S3). Later in the study (December 15, 2011 to March 11, 2012), more than half were then purchasing their food products at a supermarket by paying extra attention to their origin, and close to 70% were consuming non-tap water (Supplemental Material, Table S3).

Levels of internal radiation contamination

A total of 2,969 individuals (2,874 adults [39.9% of the adult sample], 95 children [8.9% of the child sample]), 35.9% of the total sample, had some level of detectable internal contamination. The difference in the proportion of adults and children with levels of internal contamination above the detection limit of the WBC machine was statistically significant (chi-squared statistic=396.72, $p<0.001$). Similarly, differences in observed proportions were statistically significant by sex (chi-squared statistic=771.58, $p<0.001$) and by occupation (chi-squared statistic=256.77, $p<0.001$) (Table 2).

The majority of individuals had contamination concentrations between 0 and 20 Bq/kg, and concentration above 50 Bq/kg was very rare (Figure 1). A clear declining trend in both monthly averaged concentration and detection rate during the study period was observed, with the detection rate below 1.6 % in March 2012 (Table 1). Note that the trend observed here is simply a monthly average of the detection rate, not a follow-up of the same individuals, and because this is a cross-sectional study the declining trend is not necessarily indicative of declining contamination levels within individuals.

Risk factors for internal radiation contamination

"Overall, the levels of internal contamination gradually declined from October to March (Table 3: $p<0.001$). Also the level was 59% lower in women than men (Table 3: $p<0.001$), and 34% lower in children than in adults (Table 3: $p<0.001$), suggesting contamination risk was lower in children even after adjusting for weight and the detection limit of the machine. Height and age were also risk factors for higher contamination with older and/or taller individual having a higher levels of contamination (Table 3). Regardless of home address within Minamisoma more time spent outdoors significantly increased the internal contamination concentration by 38% (Table 3: $p<0.001$). These findings were consistent with the other findings in Table 4. For instance outdoor workers had a higher contamination level when compared to indoor workers, housewives and the unemployed (Table 4). The use of tap water and not taking precautions to the source of food (rice and vegetables) when purchasing from the supermarket were the second identified risk factors that significantly increased the contamination level (Table 5). Unexpected results were increased contamination risk for those who reported purchasing non-Fukushima produced mushrooms from the supermarket.

Discussion

The objective of this large scale cross-sectional study was to assess the levels and risks of internal contamination after the Fukushima Dai-ichi nuclear accident. Minamisoma was the first municipality to adopt the WBC for internal contamination screening, and also the first to provide it as a form of medical examination (Tsubokura et al. 2012). This study is also unique in its use of the WBC in combination with detailed evacuation history and behavioral data, which provided an opportunity to assess not only the levels of, but also risk factors for internal contamination (The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission 2012; Yasumura et al. 2012).

The study showed the proportion of participants with detectable internal contamination was 40% in adults and 9% in children. Their level of internal contamination ranged from 2.3 to 196.5 Bq/kg, and contamination above 50 Bq/kg was very rare. A year after the disaster in March 2012, the overall detection rate had dropped from 60 % to less than 10 % with the average cesium concentration below 2 Bq/kg. These substantial declines were more noticeable amongst children, which may be due to differences in metabolizing radioactive materials, or due to differences in risk behaviors (Hatch et al. 2005a; Napier 2012). Such variation in overall contamination level amongst adults and children was also apparent in studies conducted after the Chernobyl disaster (Hatch et al. 2005a). As opposed to findings from previous studies (Hatch et al. 2005b), contamination risk by gender differed in this study, especially amongst adults, with higher prevalence of internal contamination in males (52% vs. 22%; Table 2) but slightly higher concentration levels in women who were exposed (median level 12 Bq/kg in women vs. 10 Bq/kg in men; Table 2). It is not clear whether such difference is caused by biological or behavioral factors or is an artifact of the detection limit of the machine (Hatch et al. 2005a). It is possible, for example, that women are in general more careful about exposure risks, but that a small minority have higher exposure risks. We did not find women were more likely to attend the program earlier in the study, so this difference in contamination risk is unlikely to be due to selection bias induced by sex-related differences in WBC assessment time.

The study also identified two main risk factors for internal contamination: duration of time spent outdoors and intake of potentially contaminated foods and water. Paying more attention to the place of origin of foods, especially of vegetables and rice, significantly reduced contamination risk. Previous studies have also shown that contaminated groundwater, fruits, vegetables and milk are the important risk factors for internal contamination (Hatch et al. 2005a; Ministry of Health Labour and Welfare 2011b; Muck 1997; Napier 2012; Smith et al. 2000; Takatsuji et al. 2000). Mushrooms are also an important food product to consider, as they can accumulate a large amount of radionuclides through their slow decontamination process (Kalac 2001). In this study, selection of non Fukushima-produced mushrooms significantly increased the contamination risk, contrary to expectations. This may be because respondents who can recall paying extra attention to mushroom preparation may have very high levels of daily mushroom consumption. Although reduction in contamination level observed due to food and water intake was substantial and thus such behavioral measures may reflect the effectiveness of food control, this effect may also be a reflection of how careful an individual has been since the disaster. For example, the purchase of non Fukushima-produced rice was associated with contamination reduction, but rice on sale during the study was from the previous year's harvest and could not have been radiologically contaminated. These variables may therefore reflect respondents' overall concerns, rather than a specific benefit arising from consumption of specific products. Frequency of hand washing and gargling (two common Japanese personal hygiene practices) were also associated with reductions in the contamination risk, but may be variables that reflect on overall levels of concern about radiation and health, rather than direct risk factors for internal contamination.

The finding of low prevalence of and low levels of internal contamination was unexpected, considering the amount of radionuclides released, the duration of release, and the severity of soil contamination (World Health Organization 2012; Yoshida and Takahashi 2012). Although we are not aware of malignancy amongst children or acute health problems, it is difficult to predict the future well-being of residents because an assessment of iodine contamination was not possible due to its short half-life, and the health consequences of low-dose radiation contamination are still unknown (Tsubokura et al. 2012; World Health Organization 2013; Yasumura et al. 2012). It has been estimated that in most of the affected areas, with estimated effective doses of 10-50mSv (The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission, 2012), the increase in the relative lifetime risk of leukemia, breast cancer, all solid cancers and thyroid cancer for an exposed infant would be approximately 7%, 6%, 4%, and 70%, respectively (World Health Organization 2013). Nonetheless even such a large increase in the relative risk becomes a small increase when converted to absolute risk (World Health Organization 2013). Therefore large-scale follow-up studies on internal contamination levels, such as the VIRES program, are vital to better understand the long-term effects of a nuclear disaster and to monitor the effect of decontamination and public health measures.

This study has several limitations: First and most importantly, the study was not implemented until more than 200 days after the accident, and the biological half-life of cesium is only 100 days. This means that initial contamination levels had declined significantly by the time we commenced WBC measurements. Nonetheless, the VIRES program still offers an important opportunity for early assessment of internal contamination risks. At 250 days from the accident the internal contamination received through direct inhalation of the plume had declined to about 8% of its initial value, but with a detection limit of 210 Bq our machine was still able to identify cesium contamination in individuals who had ingested at least 2500 Bq during the accident. Experience in Chernobyl suggests that quantities much larger than this can be identified in those initially exposed (World Health Organization 2013). Negative results are also important in this context, since after more than three half-lives have elapsed negative results can only occur if ongoing ingestion of cesium contaminants is not occurring – an important finding for those living within 30km of a crippled nuclear power plant.

The WBC was not designed for use with children, which prevented accurate contamination assessment under the age of six. Our study is subject to selection bias towards the most highly concerned individuals with obvious risk factors, or a bias towards the most health conscious in the community who exercise additional caution against radiation contamination even though they might be at low risk. This selection bias may partly explain the sudden drop in radiation contamination levels observed in November 2011, with limited further change in subsequent months (Table 3). Third, due to space constraints on the design of the questionnaires, detailed information about types of foods and water, and the precise amount of consumption were not possible to obtain. Therefore, some of the questions are subjective, and should be seen as a proxy measure of the amount of foods and water consumption or potential for exposure to externally consumed radionuclides rather than precise measurements of this risk. Fourth, it was not possible to assess iodine contamination in this study, because the short half life of iodine meant that the exposure period for this isotope had largely passed by the time the VIRES programme commenced. In addition to the lack of data on the level of internal I-131 contamination, the relative proportions of I-131 and cesium in the environment likely vary depending on the site in Minamisoma, so it is not possible to estimate the levels of iodine contamination in this study. This is unfortunate, because iodine was also the most poorly understood radio-contaminant released after the Chernobyl accident, but also the radio-contaminant most clearly linked to negative health effects (Saenko et al. 2011c). The pattern observed after the Chernobyl accident is likely to be repeated in Minamisoma, but sadly the large contribution of I-131 to committed effective dose has been completely overlooked in this study (Saenko et al. 2011a). This means that estimates of committed maximum radiation dose will be underestimated due to absence of knowledge of this data. Nuclear disaster response plans need to be improved to ensure that iodine internal contamination estimates can be conducted in the immediate aftermath of the disaster, and effective monitoring to be implemented immediately rather than after periods of months.

Another limitation of this study is the method used for statistical analysis. Because the data are left-censored by the detection limit of the WBC machine, we used Tobit regression for statistical analysis, but Tobit regression has several flaws which reduce its usefulness and validity. The concept of residuals is not well defined in Tobit regression, and methods for testing model validity are not available given the slightly unusual truncated nature of the conditional distribution of outcomes. The method also treats the detection limit as a fixed and non-stochastic limit, which is appropriate for many economic applications but may not be correct for radiological assessment equipment with inherent machine error at this lower boundary. Commonly-accessible implementations of Tobit regression also do not allow a varying left-detection limit, though this is defined in the original description of Tobit regression, and this required us to fit weight as an offset, a method that ultimately enables us to estimate the effect of risk factors on activity (measured in Bq/Kg) but is not as good as modeling body activity directly. Finally, mid-way through the study, the questionnaire contents were changed as concerns about contamination risk shifted from immediate environmental sources of internal radiation contamination (such as inhalation of wind-borne particulates) (Questionnaire A) to avoidable ingestive sources of internal contamination (water and food) (Questionnaire B). Hence external exposure risk assessment was only possible for the first three months and not for the entire year.

Implications for disaster response

This study was conducted under challenging circumstances in a town experiencing rapid population changes after a devastating disaster that was responsible for the death of just over 1% of the population of the town. From our experience, we have been able to identify some key lessons for researchers and health care workers responding to such a nuclear accident under very difficult circumstances, some of which are detailed here.

- *Maintain independence*: Independence bolsters the trust that the local community has in our work, and enables us to attract a wider range of individuals to the screening program, as well as ensuring that our results are believed and accepted when reported back to the local community.
- *Provide feedback to the community*: One of the authors (Tsubokura) is involved in a regular program of radiation health seminars in Minamisoma, instructing residents on how to avoid further internal contamination. This program is informed by our research, informs us of the residents' main risk behaviors, and enables our research to directly inform the community who are involved in it. Through this community feedback we ensure the program is sustainable and of benefit to the local community, and identify new areas of research that may be necessary.

- *Better preparation is essential*: communities located near nuclear power plants need to be prepared for the worst case scenario, and a part of that preparation should include the presence of a WBC machine, and/or the identification of a machine that can be rapidly deployed. Our results would have much more power if we had been able to commence the VIRES program within 100 days of the accident, but this was impossible simply through a lack of local preparation.
- *Ensure assessment is rapid*: The biological half-life of cesium is just 100 days, and that of Iodine even shorter. In addition to timely implementation of assessment, it is essential to be able to rapidly process large numbers of residents in a short time, in order to ensure that the assessment process does not unduly restrict the sample size that can be gathered in the first days of the program, when internal contamination levels will be declining most rapidly. We designed a one page questionnaire, to be conducted in conjunction with a two minute scan, and conducted no blood tests or other health tests. This ensured that we could process large numbers of people rapidly, scanning 3000 people in just two months with only one machine and a couple of staff members. A slower assessment process would significantly reduce the available sample size in the early period of the study when detection is most likely, reducing the ability of the study to effectively assess committed dose or distinguish between acute and chronic exposure.

With the lessons learnt from this study, we hope that communities that live near nuclear power plants will be better able to respond to such accidents in future, with all the benefits for local population health that this rapid response implies.

Conclusion

A nuclear disaster has multiple effects on health: directly by internal contamination; indirectly by psychological disturbance, such as anxiety about unforeseen future and social disruption; or indirectly through changes in lifestyle associated with behavioral changes required to reduce external exposure (Sugimoto et al. 2012; Wind et al. 2011; Yasumura et al. 2012). Unless the latter two are properly managed, they may be more harmful to individuals than the effects of radiation itself (Sugimoto et al. 2012). Past practices in nuclear disaster management have predominantly involved evacuation and relocation, but recent studies from Chernobyl suggest that weak regulation of foods and water was the main cause of the prolonged internal contamination effect and increased cancer incidence (Hatch et al. 2005a; Saenko et al. 2011b). A standard for the minimum airborne radiation level for acute exposure should be clearly noted, but the level of internal contamination is uncorrelated with either external radiation level or with distance to the plant. This is because high levels of airborne radionuclides only persist during the initial stages (Muck 1997). Thus to mitigate the overall effects, the benefits of initial evacuation must be weighed against the long-term social disruption and health consequences of extended evacuation, and where evacuation is considered too dangerous or disruptive, rigorous ongoing monitoring of radiation contamination should be implemented early and maintained throughout the affected communities.

An alternative form of nuclear disaster response plan should include all of the following:

1. The necessity of long-term evacuation should be assessed carefully with its ultimate focus on the risk profile of individual residents;
2. Food and water control should be strictly reinforced with the immediate commencement of radiological contaminant tests and sales restrictions; and
3. Dissemination of evidence-based, clear and up-to-date information on what is known and unknown about methods to reduce internal contamination, should be encouraged for self-protection and to diminish concerns (Napier 2012; Rahu 2003; Ten Hoeve and Jacobson 2012).

While the developed world is shifting towards an anti-nuclear movement, developing nations are in need of nuclear power to support their industrialization. Unless the use of nuclear power is abolished, the chance of another nuclear accident remains. Because nuclear disasters are rare, it is often the case that communities are neither experienced nor prepared for their aftermath (Christodouleas et al. 2011). This research suggests that radiation contamination risks can be identified and may be managed, and that with sensible and reasonable precautions people may be able to continue to live in radiation-affected areas with limited risk of contamination. However, it is imperative that governments in nations with a nuclear industry be aware of the worst-case scenarios, develop a rational and evidence-based emergency response, and be prepared for both the short and long-term effects of radiation contamination.

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Table 1. Demographic characteristics.

Characteristics	Number	Percent
Type of questionnaire		
Type A	4045	48.8
Type B	4236	51.2
Gender		
Male	3735	45.1
Female	4546	54.9
Age category		
Adult (Over 15 years old)	7214	87.1
Child (15 years or less)	1067	12.9
Age distribution		
0 - 9 years	292	3.5
10 - 19 years	1747	21.1
20 - 29 years	658	7.9
30 - 39 years	1239	15.0
40 - 49 years	1176	14.2
50 - 59 years	1205	14.6
60 - 69 years	1133	13.7
70 - 79 years	620	7.5
above 80 years	211	2.6
Test month (2011 - 2012) [a]		
October	1412	17.1
November	1739	21.0
December	1777	21.5
January	1831	21.1
February	1388	16.8
March	134	1.6

Characteristics	Number	Percent
Time spent outside before the disaster		
<5 hours per day	6534	79.4
≥5 hours per day	1697	20.6
Time spent outside after the disaster		
<5 hours per day	7161	86.5
≥5 hours per day	1120	13.5
Occupation [b]		
Outdoor	632	14.9
Indoor	547	12.9
Unemployed	452	10.7
Student	456	10.8
Housewife	469	11.1
Other	1422	32.8
Total sample size	8281	100

[a]Test month (2011-2012) refers to the number of participants attended the screening program in each month. [b]Data on occupation was only collected in Questionnaire A.

Table 2. Levels of internal contamination in cesium concentration by body weight.

Variable	Number	Prevalence	Median (Bq/kg) [a]	Range (Bq/kg)[a]
Gender				
Male	3735	1939 (51.9%)	10.0	2.5 to 133.2
Female	4546	1030 (22.7%)	12.2	2.3 to 196.5
Age category				
Adult	7214	2874 (39.9%)	11.3	2.3 to 196.5
Child	1067	95 (8.9%)	8.5	2.8 to 37.5
Occupation[b]				
Outdoor	632	471 (74.5%)	16.7	2.7 to 196.5
Indoor	547	244 (44.6%)	10.2	2.6 to 137.9
Unemployed	452	275 (60.8%)	14.1	2.4 to 93.4
Students	456	372 (81.6%)	11.7	2.6 to 57.9
Housewife	469	160 (42.1%)	10.5	2.8 to 53.1
Others	1422	700 (49.2%)	11.4	2.6 to 124.1
Total	8281	2969 (35.9%)	11.3	2.3 to 196.5

[a]Individuals with measurement lower than the detection limits of WBC (below 250 Bq) were excluded from the calculations of medians and ranges. [b]Data on occupation was only collected in Questionnaire A.

Table 3. Tobit multiple regression analysis on overall data (n=8,281).

Variable	Relative change (95% CI)	Standard Error	T statistic	P-value
Test month (2011 - 2012)				
October	1	NA	NA	NA
November	0.38 (0.34, 0.42)	0.05	-20.07	<0.001
December	0.32 (0.29, 0.36)	0.05	-23.14	<0.001
January	0.23 (0.20, 0.25)	0.06	-26.90	<0.001
February	0.18 (0.16, 0.20)	0.06	-28.60	<0.001
March	0.15 (0.11, 0.21)	0.17	-11.20	<0.001
Gender				
Male	1	NA	NA	NA
Female	0.41 (0.37, 0.44)	0.05	-19.94	<0.001
Age category				
Adult	1	NA	NA	NA
Child	0.66 (0.55, 0.79)	0.09	-4.58	<0.001
Height	1.72 (1.07, 2.77)	0.24	2.23	0.02
Age at test	1.21 (1.19, 1.24)	0.01	18.05	<0.001
Time outside after disaster				
<5 hours	1	NA	NA	NA
≥5 hours	1.38 (1.26, 1.51)	0.05	7.05	<0.001

Table 4. Tobit multiple regression analysis on Questionnaire A (n=4,045).

Variable	Relative change (95% CI)	Standard Error	T-statistic	P-value
Test month (2011 - 2012)				
October	1	NA	NA	NA
November	0.40 (0.37, 0.44)	0.05	-19.32	<0.001
December	0.36 (0.32, 0.40)	0.06	-17.92	<0.001
Gender				
Male	1	NA	NA	NA
Female	0.45 (0.40, 0.51)	0.06	-13.28	<0.001
Age category				
Adult	1	NA	NA	NA
Child	0.65 (0.50, 0.85)	0.13	-3.17	0.002
Height	1.34 (0.72, 2.49)	0.32	0.93	0.4
Age at test	1.18 (1.14, 1.22)	0.02	9.70	<0.001
Time outside after disaster				
<5 hours	1	NA	NA	NA
≥5 hours	1.28 (1.13, 1.45)	0.06	3.83	<0.001
Occupation				
Outdoor	1	NA	NA	NA
Indoor	0.69 (0.60, 0.81)	0.08	-4.83	<0.001
Unemployed	0.68 (0.58, 0.79)	0.08	-4.97	<0.001
Students	0.81 (0.65, 1.01)	0.11	-1.89	0.06
Housewife	0.60 (0.51, 0.71)	0.09	-5.94	<0.001
Others	0.72 (0.64, 0.81)	0.06	-5.53	<0.001
Change in daily activity				
Hand wash and gargle	0.84 (0.77, 0.91)	0.04	-4.19	<0.001
Avoid tap water	0.76 (0.70, 0.82)	0.04	-6.47	<0.001
Wash vegetables	1.10 (1.01, 1.20)	0.04	2.25	0.03

Table 5. Tobit multiple regression analysis on Questionnaire B (n=4,236).

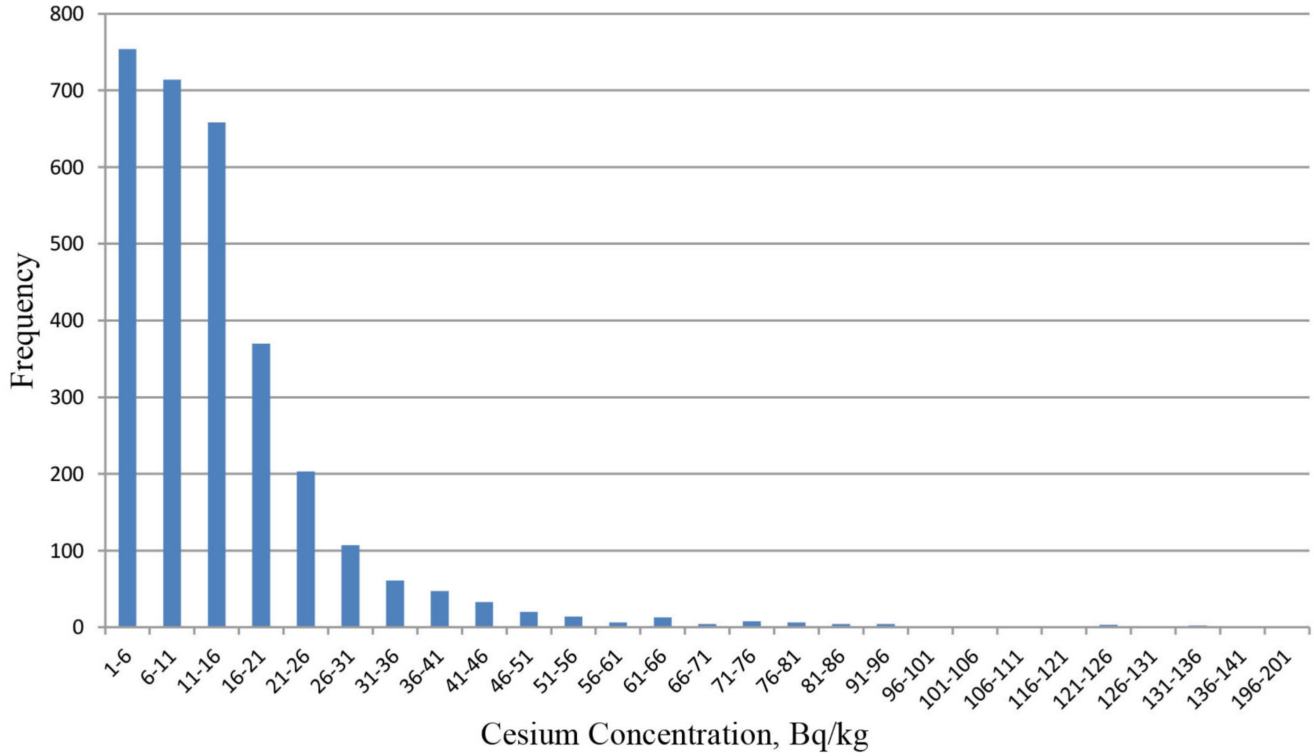
Variable	Relative change (95% CI)	Standard Error	T- statistic	P-value
Test month (2011 - 2012)				
December	1	NA	NA	NA
January	0.73 (0.64, 0.83)	0.07	-4.61	<0.001
February	0.57 (0.49, 0.66)	0.07	-7.75	<0.001
March	0.49 (0.34, 0.70)	0.18	-3.93	<0.001
Gender				
Male	1	NA	NA	NA
Female	0.39 (0.34, 0.46)	0.08	-12.28	<0.001
Age category				
Adult	1	NA	NA	NA
Child	0.63 (0.48, 0.83)	0.14	-3.25	0.001
Height	2.37 (1.10, 5.11)	0.39	2.21	0.03
Age at test	1.24 (1.20, 1.28)	0.02	12.77	<0.001
Time outside after disaster				
<5 hours	1	NA	NA	NA
≥5 hours	1.30 (1.14, 1.48)	0.07	3.87	<0.001
Attention to food and water intake [a]				
Rice	0.86 (0.76, 0.98)	0.06	-2.27	0.03
Vegetables	0.66 (0.55, 0.78)	0.09	-4.73	<0.001
Mushroom	1.25 (1.05, 1.49)	0.09	2.52	0.01
Drinking water	0.87 (0.77, 0.98)	0.06	-2.29	0.02

[a]This refers to purchasing decisions about rice, vegetables and mushrooms. Each line indicates the effect on overall internal contamination levels of purchasing rice, vegetables or mushrooms from outside of Fukushima prefecture, or of drinking only bottled water.

Figure Legend

Figure 1. Histogram of cesium concentration in exposed individuals (n=2,969).

Figure 1.



800
700
600
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400
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200
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0
Frequency
1-6
6-11
11-16
16-21
21-26
26-31
31-36
36-41
41-46
46-51
51-56
56-61
61-66
66-71
71-76
76-81
81-86
91-96
96-101
101-106
106-111
116-121
121-126
126-131
131-136
136-141
196-201
Cesium Concentration, Bq/kg