Shaping global health protection policy following nuclear disasters: learning from Japan's 2011 Fukushima Dai-ichi Nuclear Power Plant Incident

A PhD thesis presented by

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Abstract

Japan's 2011 Fukushima Dai-ichi Nuclear Power Plant Incident displaced more than 150 thousand people due to a release of radioactive material, highlighting the challenges facing us regarding radiation dose assessment and effective countermeasures (especially evacuation) when responding to a major incident.

The overall aim of my PhD project was to inform the design, preparation, and delivery of measures to manage health risks of a major nuclear disaster, by adding evidence to fill knowledge gaps using data collected following the Fukushima nuclear incident. The emergency phase of the incident (i.e. within the first few hours/days) has been assessed elsewhere, so my focus was the post-emergency phase (i.e. in the days/months/years following the incident).

To meet this aim, and building on a review of the relevant literature, I identified key research questions linked to the radiological and non-radiological health protection aspects in the context of the Fukushima incident. I was primarily interested in understanding 1) the potential challenges concerning the assessment of levels of external radiation exposure (the dominant exposure pathway) in children in the post-emergency phase following the Fukushima incident, and 2) the potential benefits and health risks of the post-incident evacuation in adults.

The study areas are Minamisoma City and Soma City in Fukushima Prefecture, Japan, located 14–38 and 35–50 km from the Fukushima nuclear plant, respectively. Various primary and secondary datasets were used in my PhD project, including: measured levels of external radiation exposure; data on post-incident daily behaviour patterns; air dose rate data; measured levels of internal/body radio-contamination; early incident response patterns; nursing home data with evacuation records; and public health check-up data. A variety of statistical approaches to analyse these data were applied.

Key findings concerning the evaluation of external radiation exposure in children included: (a) an average three-fold disagreement between the measured dose and that estimated from Japan's government dose reconstruction model, with the model overestimating it; (b) air dose rates at places where children spend most of the day being the significant predictors of the dose; and (c) poor compliance with radiation dosimeters among children (only 7.3% used the dosimeters properly). With

respect to the potential benefits and health risks of early evacuation of adults, findings included: (d) limited effectiveness of early evacuation on reducing internal exposure risk; (e) a substantial mortality impact of initial evacuation (vs. non-evacuation); and (f) increased risk of long-term hyperlipidemia associated with evacuation.

Overall, these findings indicate that the latitude for improving the evaluation of external radiation exposure in children in the post-emergency phase of a major nuclear incident is wide; dose reconstruction models should be developed that ensure a more realistic representation of external exposure risk factors, and factors influencing the proper use of direct measurements (using an individual radiation dosimeter) must be better understood. In addition, there is scope for reducing post-incident evacuation-related health risks; disaster planning must emphasise well-planned evacuation, with satisfactory arrangements for appropriate transportation, places to evacuate to safely, and include the long-term strategies for mitigating the evacuation-related health risks.

The evidence presented in this PhD thesis will help the government, local authorities, health planners, and disaster coordinators to develop better optimized radiological and non-radiological protection policies to minimise health risks of future nuclear incidents.

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Declaration of originality and conflict of interests, and statement of copyright

I hereby declare that this work if my own and that no part has been copied from any other individuals' work. There are no conflicts of interest to declare.

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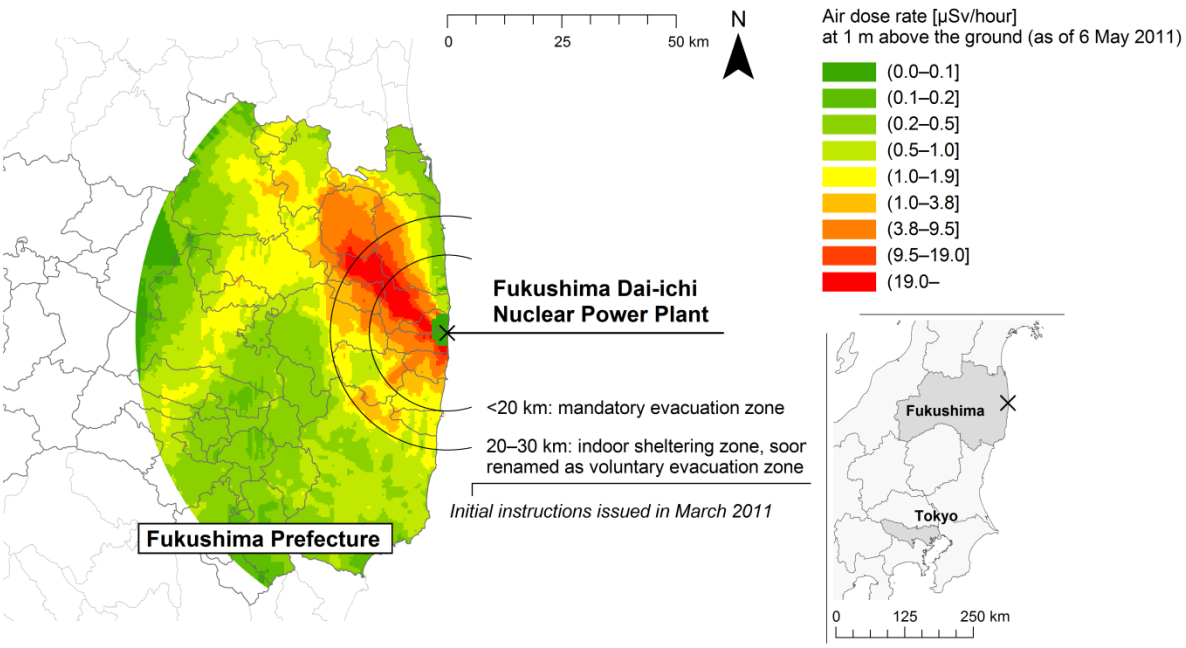
ALT/GPT	alanine aminotransferase/glutamic pyruvic transaminase
AST/GOT	aspartate transaminase/glutamic oxaloacetic transaminase
BMI	body mass index
Bq	becquerel
CART	classification and regression tree
CI	confidence interval
Cs-134	cesium-134
Cs-137	cesium-137
DBP	diastolic blood pressure
EHI	Employee's Health Insurance
Gy	gray
HbA1c	hemoglobin A1c
HDL-C	high-density lipoprotein
HR	hazard ratio
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LDL-C	low-density lipoprotein
LEHI	Late Elders' Health Insurance
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MHLW	Ministry of Health, Labour and Welfare
MMGH	Minamisoma Municipal General Hospital
NHI	National Health Insurance
OR	odd ratio
RR	relative risk
SBP	systolic blood pressure
SD	standard deviation
Sv	sievert
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization

1 Introduction

1.1 Japan's 2011 Fukushima Dai-ichi Nuclear Power Plant incident

At 2:46 PM on Friday 11th March 2011, Japan's northeast area was ravaged by a massive tsunami (the 2011 Great East Japan Earthquake and Tsunami); a magnitude 9.0 earthquake unleashed a wall of water roughly 250 miles long which slammed into the northeast coast, killing more than 18,000 people (including about 2,500 missing) and wrecking whole towns.[1] This damage triggered a nuclear incident at the Fukushima Dai-ichi Nuclear Power Plant, located on the coast of Fukushima Prefecture facing the Pacific Ocean (Figure 1).[2] This incident was classified as a level-7 nuclear incident—a level previously reached only once in the Chernobyl nuclear incident in 1986 in Ukraine.[3]

Figure 1: Map of Fukushima Prefecture and location of Fukushima Dai-ichi Nuclear Power Plant



Note: The base map indicates the air dose rate (including the natural dose from the ground) as of 6th May 2011, measured by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan—the first post-incident measurement by MEXT.[4]

The plant had six operating nuclear reactors at the time, which were designed by General Electric (GE), and maintained by the Tokyo Electric Power Company (TEPCO). All shut down automatically when the earthquake occurred. Subsequent inspection proved no significant damage to any reactors from the earthquake. However, three reactors lost power at 3:42 PM on the day,[5] about one hour after the

earthquake, when the entire site was flooded by the tsunami.[5] Unless indicated otherwise, I define 'post-incident' as the periods after this date and time in the thesis. This disabled back-up emergency generators on site and so a heat exchanger where the heat produced by the nuclear fission is captured and transferred to sea water stopped.[5] As a result, the reactors lost the ability to maintain proper cooling functions, which led to the meltdown of the uranium fuel rods inside of reactors,[5] and subsequent hydrogen explosions. Due to these explosions, radionuclides were released to the environment, including Xenon-133 (about 19 exa/10^{18} becquerel [EBq]),[6] Iodine-131 (about 500 peta/10^{15} becquerel [PBq]), Cesium-134 (Cs-134) (about 10 PBq), and Cesium-137 (Cs-137) (about 10 PBq).[7] The Bq is a unit used to measure a radioactivity.

1.2 Incident response by the Japan's central government

On the day following this incident (12th March 2011), the Japanese government issued a mandatory evacuation order for those living within a 20 km radius of the nuclear plant,[8] and over 80 thousand people from this 20 km zone were forced to move elsewhere within the Fukushima Prefecture, or move out of this prefecture.[8] On 15th March 2011, an indoor shelter instruction was given to residents in the 20 to 30 km zone, and on 25th March 2011 a voluntary evacuation was declared in the zone.[8] The geographical scope of these initial instructions is shown in Figure 1. Due to the non-uniform distribution of radioactive fallout, some areas outside the 20 km zone where the annual cumulative dose might exceed 20 mSv/year, were also designated as mandatory evacuation zones on 22nd April 2011.[8] This initial evacuation measure was based on one of the three recommendations by the International Commission on Radiological Protection (ICRP) Publication 103 for constraints for planned exposure situations and/or reference levels (in either acute or annual dose) for emergency and existing exposure situations: 1 mSv or less; greater than 1 to 20 mSv; and greater than 20 to 100 mSv, depending on characteristics of the exposure situation.[9] For emergency exposure situation where planned actions taken to reduce exposure would be disruptive, ICRP recommends (while recognising that in the emergency situation, the dose may exceed the upper values for the reference level unavoidably) selection of a reference level in the range of 20 to 100 mSv; and suggest development of protection strategies to reduce exposures to as low as reasonably achievable below the reference level by action on the exposure pathways.[9,10]

Radiation exposure can be external (from gamma photons, x-rays, neutrons, or high-energy beta particles emitted from a source outside the body), internal (from sources inside the body), or both external and internal. Radiation dose accumulates from various exposure pathways.[3] As radioactive materials can stay in the food chain through the contamination of rice, meat, fish, vegetables, fruits,

milk, groundwater, etc., and can be easily ingested by humans, in order to prevent the commercial distribution of contaminated foodstuffs, the Ministry of Health, Labour and Welfare (MHLW), Japan established the provisional regulation values for foodstuffs on 17th March 2011.[8] From 21st March 2011 onwards, shipping restrictions on foodstuffs were imposed, in case foodstuffs contaminated in excess of the provisional regulation values were identified via radiological contamination inspection implemented by Fukushima Prefecture and the neighbouring prefectures.[8]

1.3 Public concern and research interest after the incident

Radiation exposure is a public health issue, associated with acute radiation syndrome, gastrointestinal and/or hematologic morbidity and mortality, and long-term risks of disorders including, e.g. eye cataracts and tumours. In the case of the Chernobyl incident, acute radiation injuries in acute phase and thyroid cancer in the paediatric population were reported.[11] Following the Fukushima incident in Japan, health threats have arisen in the radiation-contaminated areas; and external and internal radiation exposure is the major public concern.[2,12-16] here, it should be noted that international bodies, such as United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), World Health Organization (WHO), and International Atomic Energy Agency (IAEA), have concluded that the predicted risk of lifetime cancer following the Fukushima incidence is very low in the general public, except for the most exposed infants and children in the Fukushima Prefecture as well as some workers at the Fukushima Dai-ichi Nuclear Power Plant, in whom thyroid cancer cases exceeding the norm are expected based on model calculations.[17-20]

Owing to the quick response by the Japanese central government and local authorities,[21] such as foodstuff contamination management, which includes radiation inspection of foodstuffs circulating the market,[22,23] and screening for internal contamination using whole-body radiation counters,[24] internal contamination among the majority of the population in the contaminated areas was marginal.[24-31] Accordingly, as many international bodies and other experts acknowledged, a large proportion of the cumulative dose can be attributed to external radiation exposure, particularly in the current, post-emergency phase of the incident.[18-20,29] As such, external radiation exposure has currently received increasing policy/research interest to reduce the doses arising from external irradiation. Accurate understanding of the external dose levels is fundamental to properly evaluate the effectiveness of radiation protection policies,[32,33] and to assess the need for establishing further safety precautions in Japan.[32,33] Understanding the effectiveness of policies enacted in Japan can also be used to help shape more resilient, radiological protection policy, regulation, and application for the future nuclear incidents.

The health effects of the Fukushima incident are not limited to those due to radiation exposure.[34] A particular concern of the health effects of post-incident early evacuation as a countermeasure to the incident was documented briefly in the latest UNCSEAR report.[35] A major disaster often requires evacuation of a large population, which exerts a powerful influence on individual vulnerability to psychological stress, and forces changes in socioeconomic status (e.g. employment, income, etc.) which impact people's health.[36-45] The Fukushima incident is no exception. As mentioned earlier, following the incident the Japanese government issued several evacuation instructions for those living around the Fukushima nuclear plant, and many moved hundreds of km away from their homes, some moved several times.[46] Of those who were forced to evacuate, and despite some lifting of the evacuation instructions, more than 50 thousand were still subject to a range of evacuation measures as of February 2018.[47]

Following the Fukushima incident, evacuation-related health effects were reported in terms of both mortality and morbidity.[48] For example, according to the National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission—the first independent commission chartered by the National Diet in the history of Japan's constitutional government—of 850 patients who evacuated from the seven hospitals located in the 20 km mandatory evacuation zone, 60 people died within one month following the incident, of which 48 deaths occurred during the evacuation transportations.[8] Also, Yasumura et al. (2012) revealed that a total of 1,770 evacuees from 34 nursing homes within the 20 km mandatory evacuation zone experienced approximately 2.4 times higher mortality risk when compared to mortality data from the previous year.[49] The Fukushima Health Management Survey, a post-incident prefecture-wide project managed by Fukushima Medical University (a public university in Fukushima Prefecture) with a primary goal of monitoring the long-term health of the affected residents,[50] also demonstrated that the incidence of diabetes was significantly greater among evacuees than among non-evacuees in the 1.6 years following the incident.[51] In retrospect, the significant increase in mortality and morbidity after the evacuations can be contrasted with the likely limited acute radiation damage.[24,52-54]

Better understanding of the issues regarding radiation dose assessment and effective countermeasures (especially evacuation) when responding to a major incident is the basis of risk reduction policy and action for a major nuclear incident. In this regard, there is significant scope to learn lessons from Japan's Fukushima nuclear incident.[55]

1.4 Aim and objectives of the PhD project

The aim of my PhD project was to inform the design, preparation, and delivery of measures to manage health risks of a major nuclear incident, by adding further evidence to fill knowledge gaps on both radiological and non-radiological protection aspects of a major nuclear incident. Note that, given the limited time frame of data available, the context of this thesis is the post-emergency phase (i.e. in the days/months/years following the incident), and I do not address the emergency phase (within the first few hours/days).

To meet this aim, through my PhD project, I pursued two main objectives:

Objective (1) To better understand potential challenges concerning the assessment of levels of external radiation exposure (the dominant exposure pathway) following the Fukushima incident, and;

Objective (2) To better understand the potential health risks and benefits of the post-incident evacuation.

In this thesis, I first discuss the recent challenges following the Fukushima incident through a review of the relevant literature (Chapter 2 Literature review), and from this review identify key research questions and areas that address the two objectives above in the context of the Fukushima incident (Chapter 3 Key research questions).

2 Literature review

In this chapter, first of all, I discuss what is already known on radiological and non-radiological protection aspects of major nuclear incidents, including the Fukushima incident, and then structure the challenges following the Fukushima incident around the two main objectives of my PhD project: (1) challenges concerning the assessment of levels of external radiation exposure and (2) benefits and health risks of the post-incident evacuation.

For the literature search, no restrictions were placed on article type, study design, study population, study period, outcome measures, etc., but only journal articles published in English and Japanese were considered. The following international databases were searched from their dates of inception to February 2018: Ovid MEDLINE(R) In-Process & Other Non-Indexed Citations and Ovid MEDLINE(R) (1946 to February 2018). I also searched Ichu-Shi, the database of the Japan Medical Abstract Society (from inception (1964) to February 2018).[56] Ichu-Shi includes studies written in Japanese and published in Japanese journals, and occasionally feature an English summary. The search strategies are described in Box 1.

Box 1: Search strategies.

- Ovid MEDLINE(R) In-Process & Other Non-Indexed Citations and Ovid MEDLINE(R)

Search terms
((radiation and (risk or health) and (incident or accident or disaster)) not (animals not humans)).ti,ab.

- Ichu-Shi

Search terms
(事故/AL and (被曝/AL or 被ばく/AL or 健康被害/AL or 健康影響/AL or 健康リスク/AL)) and (PT=原著論文)

A total of 1,474 and 294 articles were identified from the international and domestic databases, respectively, and were carefully screened and reviewed. In addition, key personnel and organizations working in disaster risk management for health, including members of the various networks of disaster researchers and policymakers, were contacted to identify additional references and resources. The UNSCEAR, WHO, and IAEA reports related with the Fukushima incident were also reviewed.[17-20,35,57,58]

2. 1 Evidence before this project: radiation exposure and countermeasures

2.1.1 Radiation exposure pathways and assessment methodologies

An assessment of the doses received after a release of radioactive material into the environment requires data on a number of aspects, including measured levels of radionuclides in the environment (e.g. air, soil, sediment, and drinking water) as well as in plants and animals that may serve as food for humans,[59] estimated amounts of radioactive materials released, atmospheric dispersion and deposition patterns, the nature of subsequent possible transfer in the environment, and the habits, behaviours, and locations of the population for whom doses are being assessed. Dose assessment is primarily based on these data (of often limited availability), with consideration of all possible exposure pathways.

Following a major nuclear incident, people will be exposed to radioactive material by several pathways. The major exposure pathways are: external exposure from radionuclides deposited on the ground (groundshine); external exposure from radionuclides in the radioactive plume (cloudshine); internal exposure from inhalation of radionuclides in the radioactive plume (inhalation); and internal exposure from ingestion of radionuclides in food and drinking water (ingestion). In the case of the Fukushima incident, the most contributing exposure pathways vary with location and distance from the sources of contamination (i.e. the Fukushima Dai-ichi Nuclear Power Plant), time periods following the incident, age of person exposed, types of organs exposed, etc. For example, in the most affected areas, external exposure from groundshine is the dominant pathway contributing to the effective dose (defined below) over the life time, while the dose to the thyroid of an infant in the affected areas over the first year following the incident mostly arose from inhalation of radioactivity in the plume, and less from external irradiation from the ground.[52] On the other hand, with increasing distance from the site the ingestion pathway becomes the main contributor to the lifetime effective dose.[20] More detailed case studies are described in the below section.

Another dose assessment method includes direct individual dose measurements,[60] which are usually performed using an individual radiation dosimeter for determining the external dose level,[18] or using anthropogammametry (i.e. whole body counting (WBC)), which estimates the levels of radioactivity of radionuclides within the body at the time of measurement.

The dosimetric endpoint of the assessment of radiation exposure is often effective dose and equivalent dose, expressed in the Sievert (Sv). Theoretically, the effective dose is calculated by

summing the absorbed dose (the amount of energy absorbed by that organ or tissue, usually expressed in the gray [Gy]) to each of the radiosensitive organs multiplied by the appropriate radiation weighting factor (that varies by radiation type) and tissue weighting factor (that takes into account the radiosensitivity of various tissues and organs).[9,61] The effective dose cannot be measured directly by the dosimetory services (e.g. individual radiation dosimeter and airborne monitoring). Instead, it can be estimated from other quantities, such as the personal dose equivalent (Hp(d)) and ambient dose equivalent (H*(d)). The ICRP Publication 103 defines Hp(d) and H*(d) as "*the dose equivalent in soft tissue (commonly interpreted as the 'ICRU sphere'—a body defined by the International Commission on Radiation Units and Measurements (ICRU), which approximately corresponds to the human body with regard to the absorption of the energy of ionizing radiation) at an appropriate depth, d, below a specified point on the human body*" and "*the dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of d on the radius vector opposing the direction of the aligned field*", respectively.[17]

Principal radionuclides released from the Fukushima Dai-ichi Nuclear Power Plant were Xenon-133 (about 19 EBq),[6] Iodine-131 (about 500 PBq), Cs-134 (about 10 PBq), and Cs-137 (about 10 PBq).[62] For the Fukushima incident, the great majority of the doses received from inhalation and ingestion were expected in the first year. This is particularly the case for Iodine-131 in the emergency phase (within the first few hours/days) of the incident due to their short physical half-life. The physical half-life is the period of time for one-half of a radioactive isotope to decay, which ranges from a few microseconds to billions of years, depending on the radioactive isotope. The biological half-life is the period of time required to eliminate one-half of the radioactivity from the body. For instance, the physical half-life of Cs-134 and Cs-137 is two years and 30 years, respectively, but their biological half-life is shorter (about four months). Meanwhile, the physical half-life of Iodine-131 is only one week, which is much shorter than its biological half-life of about four months

2.1.2 Case studies for the patterns of dose with regard to exposure pathway, time of exposure, and radionuclide in Fukushima

Within Fukushima Prefecture, in the areas with high ground deposition density (excluding evacuation zones), including part of Minamisoma City (one of the study areas of my PhD project—details below), the contribution of external dose from deposited radionuclides (groundshine) to effective dose was dominant in the first year: over half of the dose in adult, children, and infants, was due to external exposure (groundshine) and the majority of the remainder was due to ingestion, while there was some

contribution from inhalation.[18,63] According to Terada et al. (2012), in Minamisoma City, the majority of the radioactive cesium was deposited on 15th to 16th March 2011.[64]

The relative contribution to effective dose from ingestion in the first year in Fukushima Prefecture varied because the dose due to ingestion reflected concentrations of radionuclides averaged over much larger areas than the doses from other pathways—uniform absolute contribution across the prefecture.[18,63] In areas of Japan far away from Fukushima Prefecture, effective doses due to ingestion predominated for most, including neighbouring, prefectures.[18,63]

The major contributor to the dose to the thyroid in the first year was internal exposure due to inhalation and ingestion of Iodine-131.[18] In Fukushima Prefecture, approximately one third of the dose to the thyroid of infants in the first year was due to inhalation and two thirds due to ingestion.[18] The estimated doses to the thyroid for adults in the first year were about 30% of those for infants.[18] These doses were mostly received over the first few weeks after the incident.[18] Meanwhile, in prefectures neighbouring Fukushima Prefecture, ingestion was the dominant exposure pathway for the doses to the thyroid of infants in the first year; the contribution of the inhalation pathway ranged from a few per cent to about 30%.[18]"

2.1.3 Dose estimates and radiological health effects following the Fukushima incident

According to UNSCEAR, estimated average effective doses in the first year following the Fukushima incident to members of the public living outside of any evacuation zones in Fukushima Prefecture were ranged from 1.0 to 4.3 mSv for 20-year-old adults (who were chosen to represent all adults), depending on district.[18] These values are doses in addition to the natural background dose from the universe and the ground. Estimated effective doses for 1-year-old infants (who were chosen to represent all infants younger than 5 years old) in this area were about twice as high (2.0–7.5 mSv, depending on district). For adults and infants who were living in evacuation zones, the estimated average effective dose received ranged from 1.1 to 9.3 mSv and from 1.6 to 13.0 mSv, respectively, depending on evacuation scenarios.[18] Those living in neighbouring prefectures and elsewhere in Japan were estimated to have received comparable or lower doses.[18] The contribution of external dose from deposited radionuclides (groundshine) to these estimated doses was dominant.[18] Lifetime effective doses resulting from the incident that could be received by adults continuing to live in the Fukushima Prefecture have been estimated to be just over 10 mSv on average.[18]

Radiation injuries occurring in the acute phase, and thyroid cancer in infants, were reported following the 1986 Chernobyl incident.[48] However, as of now, no radiation-related deaths or acute diseases have been reported among the general public in Japan or in workers at the Fukushima Dai-ichi Nuclear Power Plant (hereinafter referred to as plant workers). As well-acknowledged by UNSCEAR, WHO, and IAEA, and by other experts, both the doses received in the general public in the first year of the incident, and the estimates for their lifetimes, are generally low.[17-20,52,65] Discernible increased incidences of radiation-related health effects are not expected among exposed members of the public and their descendants.[17-20] An increased risk of developing thyroid cancer and other thyroid disorders can be inferred in infants and children and some plant workers.[18] More than 160 additional plant workers were estimated to have received effective doses of over 100 mSv, predominantly from external exposures.[18] These plant workers also might be in an increased risk of cancer in the future. However, it may be difficult to statistically verify the increase among them in practice due to the low background rates of cancer incidence. As of today, some papers highlighted possible increase in the prevalence of thyroid cancer in areas of Fukushima Prefecture,[66-68] but there are also many concerns about possible over-diagnosis of thyroid cancer because of sensitive thyroid screening of the general population with ultrasound, initiated because of the incident.[69-72]

The various estimations of doses received post-incident were carried out at different times and with different methodologies by different bodies, including WHO and IAEA. The WHO estimates were considered generally higher than those of UNSCEAR.[19] This is primarily because they were early dose projections based on very limited data following the incident (as of September 2011). Also, WHO's estimates were based on mostly conservative assumptions,[20] such as that foods containing higher-than-median levels of radioactivity (which are not allowed on the market) were consumed regularly.[20]

The dose estimates by UNSCEAR and WHO were constrained by limited availability of direct radiation measurements of individual doses incurred by people, and were primarily calculated using dose reconstruction models based on the limited (but best available) data on environmental conditions and food contamination. IAEA's estimates partially benefited from the availability of additional data on direct measurements of dose to people, including data from the Fukushima Health Management Survey.[50] Although these differences make a detailed, robust comparison difficult, the dose estimates of UNSCEAR, WHO, and IAEA are largely consistent in showing that doses received following the Fukushima incident were generally low, and below the lowest level of dose band of 20 to 100 mSv (acute or annual) for the reference level in emergency exposure situation of the ICRP 2007 recommendations.[9,19]

2.1.4 Countermeasures

During a nuclear emergency, different public health protective actions (countermeasures) are implemented at different times. In the emergency phase, countermeasures that aim at preventing the acute, short-term radiation exposure include evacuation, sheltering, pre-distribution of stable iodine (if radioactive iodine is involved), personal decontamination, and food and drinking water restrictions are imposed.[20] Evacuation is most effective when performed as a precautionary action before an airborne release takes place.[73] Sheltering (to remain indoors with the doors, windows, and ventilation sealed) provides shielding against external exposure from radionuclides in the radioactive plume (cloudshine) and radionuclides deposited on the ground (groundshine). The protection against inhalation exposure (internal exposure) by sheltering would be much less than external exposure due to air exchange between the indoor and outdoor environments.[20] Stable iodine intake is only effective for internal exposure to the thyroid gland that results from radioactive iodine,[74] but it cannot reduce exposure that results from other radioactive materials (e.g. radioactive cesium). Food and drinking water restrictions aim at banning from the market those foodstuff commodities produced in highly contaminated areas, which reduce the risk of ingestion of contaminated foodstuff. Decisions to implement these countermeasures are based on nuclear power plant conditions, amount of radioactivity actually or potentially released into the environment, as well as weather conditions (including wind speed and direction, and precipitation), and other factors.[75]

In the post-emergency phase, when the availability of environmental monitoring data is likely to have increased, to further reduce doses in the long-term perspective, other countermeasures may be implemented. Temporary relocation is the non-urgent movement of people from contaminated areas to temporary housing to reduce the risk of chronic radiation exposure. It can be a continuation of the evacuation.[20] If it is not foreseeable to return within a couple of years after relocation, relocation can be considered as permanent.[20] Area decontamination is the complete or partial removal of contamination in soil, water, plants, etc. by a deliberate physical, chemical (e.g. acid and alkaline permanganates solutions), or biological process (e.g. phytoremediation).[18]

In the case of the Fukushima incident, administration of stable iodine for iodine thyroid blocking was not implemented uniformly.[8] However, other countermeasures to protect the public performed well and significantly reduced the radiation exposures that could have been received.[18,76] This was particularly the case for evacuation instructions, which was estimated to have reduced the effective doses by up to 50 mSv for adults in the first year of the incident, according to UNSCEAR.[18]

2.1.5 Non-radiological health effects of countermeasures

Major nuclear incidents, including the 1979 Three Mile Island nuclear incident in the United States, the 1986 Chernobyl incident in Ukraine, and the 2011 Fukushima incident in Japan, have common issues that were not directly related to the physical effects of radiation exposure. Non-radiological health effects, such as mental health issues and lifestyle-related, chronic illnesses (such as diabetes, cardiovascular disease, and stroke), are significant in the general population (including children, hospital patients, decontamination workers, etc.), but have not been as well addressed as radiological health risks after major nuclear incidents.[34,35,77-84]

Extreme examples include the loss of life due to the evacuation of vulnerable population (e.g. hospital patients and elderly, nursing home residents), particularly observed in the Fukushima incident.[49,85] Some studies following past nuclear incidents also suggested that severe mental health problems have risen among those who performed evacuations,[86-88] although it was not evident whether they were due to evacuations. Those who evacuated in response to governmental evacuation instructions have become less physically active, consumed more alcohol, and had difficulty in sleeping after the incident.[89] In addition, because evacuees were forced to change several aspects of their lifestyles, such as dietary habits, physical exercise, sleep, smoking cessation, etc., chronic health risk factors (e.g. obesity, diabetes, hyperlipidemia, and hypertension, which are largely preventable) would be expected to increase.[51,90,91]

2.2 Challenges surrounding the assessment of external radiation exposure levels

After a major nuclear incident, radiation exposure is a primary public concern.[92] In these situations, robust assessment of the exposure levels is fundamental for evaluating the radiation risks to human health and the environment.[24,54,93-95] Accurate understanding of the exposure levels is also important for properly evaluating the effectiveness of radiation protection policies, such as decontamination activities and evacuation instructions, for assessing the need for establishing further safety precautions, and for monitoring post-incident health risks to promote future well-being.[32,33] This understanding can also be leveraged to help shape more resilient radiological protection policy, regulation, and application for future nuclear incidents. Currently, in the post-emergency phase of the Fukushima incident, as international bodies (UNSCEAR, WHO, and IAEA) and other experts acknowledge, external radiation exposure is the most significant contributor to the dose received

among the public.[18-20,29,52] As such, external radiation exposure received increasing policy/research interest to reduce the radiation doses.

2.2.1 Agreement between direct measurements and modelled estimates of external exposure dose

Several intergovernmental bodies such as UNSCEAR and WHO have developed dose estimation models to assess radiation exposure levels and risks to human health.[18,20] The Japanese government also developed its own dose reconstruction model to assess the levels of radiation exposure, which was primarily applied to the adjustment of the evacuation instruction (i.e. the designation of evacuation zones, and subsequent lifting of the designations) and decontamination plans.[96,97] However, there are some concerns regarding the potential disagreement between direct measurements and modelled estimates of external radiation exposure, which was acknowledged by IAEA and other experts.[19,98-101] This disagreement may exist because of model uncertainties due to limited or incomplete knowledge or information, as well as limitations in both temporal and spatial data coverage of measured levels of radionuclides in the environment.[52] For example, for external exposure, the disagreement may come from uncertainty in the radiation reduction functions, which are primarily determined by the degree of shielding from exposure provided by home, school, or work buildings,[102-104] by human behaviour patterns, and the living environment.[101] External walls of buildings can prevent the entry of not only sources of radiation (i.e. radionuclides), but also radiation itself. The effect of the building shielding on external exposure risk is highly dependent on the type of building materials (e.g. concrete, brick, and wood).[60] For example, after the 1986 Chernobyl incident, UNSCEAR showed that a brick house had a higher radiation shielding effect on external exposure risk than a wooden house.[60] These uncertainties were clearly mentioned in the UNSCEAR and WHO reports about the Fukushima incident.[18,20] In addition, the estimation presents individual-, district-, or prefecture-level dose averages for representative members of the public; therefore, there remains uncertainty in how accurately the data used for the estimation represents the spatial distribution of the radionuclides for each measurement level.[18] Other sources of uncertainty have been discussed elsewhere.[18,20,105] However, following the Fukushima incident and other past radiological incidents, no research has been conducted to evaluate the agreement between direct measurements and modelled estimates of external radiation exposure.

2.2.2 Potential risk factors for external radiation dose

Given that direct measurements can only indicate the individual-level dose at the monitored time point, modelled estimates must be used to assess long-term district-level or prefecture-level dose.[105]

Therefore, despite possible disagreements between the direct and modelled dose, the modelled estimation is an important exposure evaluation approach for managing the aftermath of a nuclear incident.[106,107] A robust investigation into individual-level potential risk factors (behaviours and living environment) that are associated with external radiation dose is needed to provide a reliable evaluation of external exposure using accurate model estimates under more appropriate exposure scenarios.

2.2.3 Compliance with the proper use of individual radiation dosimeters

In addition to modelling exposure, direct measurement can be a desirable approach to dose assessment to respond to concerns of individuals in affected areas as direct measurement can indicate the individual-level doses at the time that people were monitored. Moreover, as for children, who are at the greatest risk for future health issues following radiation exposure, parents can make sure their children's dose levels are assessed on a timely basis by the direct measurement, which may help ease their concerns about radiation exposure risk in their children, though there is no scientific evidence to support this explanation. Direct measurement can be relatively easy to perform with fewer scientific uncertainties, and can consider any individual specifically.[106,108] However, there is a great concern that children, who are at the greatest risk for future health issues following radiation exposure, do not necessarily use the individual dosimeters properly. Such non-compliance may present an obstacle to the direct measurement approach because it likely influences the measurement values, but no previous study has assessed compliance with the proper use of radiation dosimeters. Hence, to better understand issues associated with the use of individual dosimeters, assessment of characteristics of children who do not use the dosimeters properly, and evaluation of errors generated by the improper use of the dosimeters, is of great importance for appropriate evaluation of the measured dose.

2.3 Challenges surrounding the post-incident evacuation

Most evidence of health impacts of nuclear incidents relates to radiological protection aspects. The evidence on non-radiological protection aspects, such as non-radiological health consequences of countermeasures to reduce the risk of radiation exposure, are scarce. However, questions about the safety of the evacuation of people, especially vulnerable populations such as the elderly, are of paramount importance to not only residents, but also medical and welfare institutions,[109-111] whose emergency response to a nuclear incident are often controversial.[85,112] The initial report on this topic following the Fukushima incident from Fukushima Medical University suggested a unplanned, early evacuation with high overall mortality risk.[85] The benefit of evacuation following a nuclear incident needs to be balanced with the risks of evacuation.[113] Also, the potential non-radiological health

impacts of evacuation following a major nuclear incident have not been well-evaluated. Particularly, no Chernobyl study was found from the literature search that assessed health impacts of evacuation.[114]

2.3.1 Effectiveness of early evacuation on reducing the risk of internal radiation exposure

While it is well known that evacuation is an effective early countermeasure to reduce the risk of acute external radiation exposure,[18,60,115] there is no previous study that addressed the effectiveness of evacuation on the internal radiation exposure risk.

Similarly to the situation following the Chernobyl incident,[116] following the Fukushima nuclear incident, the acute intake (inhalation and ingestion) of radionuclides in the emergency phase of the incident was the primary source of internal radiation exposure.[52,54] Assessment of the effectiveness of early evacuation on reducing internal exposure risk is essential to establish effective incident-response preparations, considering the balance between benefits and risks of evacuation.

2.3.2 Potential mortality risk of early evacuation

Safe evacuation is of paramount importance in any disaster setting. In the case of the four recent storms in the United States (Hurricanes Katrina and Rita in 2005, and Hurricanes Gustav and Ike in 2008), the evacuation of elderly nursing home residents resulted in increased mortality and morbidity.[40,111,117] Dosa et al. (2012) demonstrated that after these hurricanes, among the 36,389 nursing home residents exposed to the storms, mortality and hospitalization risk increased two- and four-fold, respectively, 90 days after the evacuation in comparison with the prior two non-hurricane years, independent of other risk factors, including age, sex and race.[40]

Evacuation of medical facilities in response to a disaster threat is typically performed with staff who may not be familiar with the residents.[117] Staffing, supplies, equipment, transportation, individual identification of residents, transfer of records, and responding to family inquiries are prepared in the limited hours leading up to the departure, so facility-specific factors may have a strong influence on the mortality and morbidity associated with evacuation.[118] Experience in the immediate aftermath of Hurricane Katrina also showed that even the best plans of specific facilities may be insufficient to prevent significant morbidity and mortality under a generalized infrastructure collapse, and that support from government both before and after a disaster is essential.[119]

Given the importance of disaster- and facility-specific factors in determining the success of disaster plans, and the possibility of significant increases in mortality and morbidity due to evacuation, it is important to conduct detailed epidemiological assessments of the safety of evacuation procedures in the aftermath of Japan's Fukushima incident.

In this context, and prior to this PhD work, I performed comparative analyses before and after the Fukushima incident evacuation.[120] I evaluated mortality risks among residents admitted to nursing homes located 20 to 30 km from the Fukushima nuclear plant (i.e. outside the 20 km mandatory evacuation zone, but within the indoor sheltering zone), and which were evacuated after the incident due to shortages of care staff and essential medical supplies.[120] I reported that compared to the period before the incident, the overall relative mortality incidence after the incident was 2.68 (95% Confidence Interval (CI): 2.04–3.49), with a substantial variation across the facilities.

This previous study was restricted to the analysis of data from residents who evacuated, but because there was no control group (i.e. non-evacuees) it was not possible to investigate whether the observed increased mortality was associated with stress from the incident, facility-specific evacuation processes, or care quality at evacuation sites. Inclusion of data on non-evacuees were needed to more adequately estimate the impact on mortality risk of experiencing the incident versus evacuation.

2.3.3 Potential long-term chronic health risk of evacuation

It is known that the influence of disasters on chronic heath persists beyond the initial disaster period, affecting people's health for years, regardless of event type and health outcome studied.[44] Past major disasters have demonstrated that socioeconomic factors have the potential to influence the likelihood and/or severity of disaster impacts on long-term health,[121,122] as they generate differential exposure to health-compromising conditions and differential vulnerability in terms of pre-existing health conditions and material resource availability, and thus, determine differential consequences on people's health in the longer term.[123] In this context, it should be noted that post-disaster evacuation can have socioeconomic impacts via dramatic changes in behavioural factors (e.g. smoking, alcohol, dietary practices, etc.), and social-environmental and psychosocial circumstances (e.g. financial loss, property loss/damage, living without family, loved ones, etc.); thus exert a powerful influence on people's health.[36-45]

seven years after the Fukushima incident, the acute health impacts of evacuation (i.e. impacts occurring in the initial days and months) have been reported, including by the Investigation

Commission appointed by the National Diet of Japan.[8] However, the long-term health consequences, i.e. those occurring years after the incident and evacuation, have not been well documented,[35] and are thus less well known. Some studies have evaluated health impacts of evacuation in the 1–2 year period following the incident.[51,91,124,125] One year after the incident, elevated values of metabolic markers, including body mass index (BMI), blood pressure, glucose metabolism, lipid metabolism, and liver function, were demonstrated in evacuees by Satoh et al. (2015) and Tsubokura et al. (2012), suggesting worsening chronic health conditions long term.[51,126] Yabe et al. (2014) showed that two years after the incident, the proportion of adult evacuees who scored above the K6 psychological distress index cut-off point (≥13) for general mental health was four to five times higher than that of the pre-incident general population in Japan.[89]

These long-term impacts of evacuation are hard to establish because of the scarcity of information on the present health status of affected residents, due to expensive research/survey costs and difficulty in tracking individuals over time.[127,128] However, better understanding of the health impact of evacuation and the potential risk factors that influence the evacuation-related health risks are essential for disaster risk reduction, and necessary if we are to design and deliver effective measures, improve long-term health outcomes from disasters including nuclear incidents, and build strong community resilience.

3 Key research questions

Again, the overall aim of my PhD project was to inform the design, preparation, and delivery of measures to manage health risks of a major nuclear incident, by adding further evidence to fill knowledge gaps on both radiological and non-radiological protection aspects of a major nuclear incident.

To meet the aim, and based on research gaps identified in the literature review presented above, as well as data availability and my focus on the post-emergency phase of the incident (see below), I identified the following six key research questions:

Objective 1

To better understand potential challenges concerning the assessment of levels of external radiation exposure following the Fukushima incident:

Question 1: (a) how accurately does the Japanese government's dose reconstruction model estimate the annual external radiation dose among school children 18 to 30 months after the incident, and (b) what uncertainties exist in the model leading to the potential disagreement with the measured dose?

Question 2: how do the behavioural patterns of school children influence external dose 18 to 20 months after the incident?

Question 3: (a) what are the characteristics of school children who do not use the dosimeters correctly, and (b) how much error is generated by improper use of the dosimeters 18 to 20 months after the incident?

Objective 2

To better understand the potential benefits and health risks of the post-incident evacuation:

Question 4: what are the relationships between early evacuation and levels of internal radiation exposure among adults four months after the incident?

Question 5: how much did the mortality risk differ between evacuees and non-evacuees among nursing home residents after the incident?

Question 6: how much did evacuation affect long-term chronic health after the incident?

The study areas of my PhD project are Minamisoma City and Soma City in Fukushima Prefectures, Japan, located 14–38 and 35–50 km from the Fukushima nuclear plant, respectively (details below). The study designs employed were, for Question 1–4 retrospective observational cross-sectional studies, for Question 5 a retrospective observational cohort study, and for Question 6 a retrospective observational longitudinal design. Nine datasets were used in my PhD project, summarised in Table 1 below. The majority of these datasets (including, e.g. radiation exposure data) were secondary data stored in the city office/hospital or nursing homes. Other data (e.g. behaviour and response pattern data) are primary data that I collected as part of a team via surveys in collaboration with the city office/hospital. Note that these are not publically accessible data. Air dose rate data are also secondary, but open access data, published by Ministry of Education, Culture, Sports, Science and Technology of Japan or the government of Fukushima Prefecture, Japan.

Table 1: Summary of selected data used for the PhD project

	Data description [source]	Data type	Data owner	Date of the measurements
Objective 1				
Questions 1–3	Measured levels of external radiation exposure in school children [external radiation exposure screening]	Secondary data	Minamisoma City office and Minamisoma Municipal General Hospital, Fukushima	Between 1st September 2012 and 30th November 2012
	Post-incident daily behaviour pattern in school children [survey]	Primary data	Minamisoma Municipal General Hospital, Fukushima	Between 1st September 2012 and 30th November 2012
	Air dose rate [airborne monitoring]	Secondary data/open access	Ministry of Education, Culture, Sports, Science and Technology of Japan	Between 22nd and 28th June and between 31st October and 16th November 2012
	Air dose rate at schools [school monitoring]	Secondary data/open access	The government of Fukushima Prefecture	Between 19th June and 11th July 2012
Objective 2				

Question 4	Measured levels of internal/body radio-contamination in adults [internal radiation exposure screening]	Secondary data	Minamisoma City office and Minamisoma Municipal General Hospital, Fukushima	Between 11th and 29th July 2011
	Early incident response pattern in adults [survey]	Primary data	Minamisoma Municipal General Hospital, Fukushima	Between 11th to 29th July 2011,
Question 5	Nursing home data with evacuation records [medical records]	Primary data (for evacuation records) and secondary data (for other clinical records)	Nursing homes in Minamisoma City and Soma City, Fukushima	Between 31st August 2011 and 2nd February 2012 for Minamisoma City and between 3rd and 25th September 2013 for Soma City
Question 6	Public health check-ups data in adults [public health check-ups]	Secondary data	Minamisoma City office and Soma City office, Fukushima	Between 1st June and 31th October in 2008, 2009, 2010, 2011, 2012, 2013, and 2014
	Air dose rate [airborne monitoring]	Secondary data/open access	Ministry of Education, Culture, Sports, Science and Technology of Japan	Between 31st May and 2nd July 2011; between 22nd and 28th June 2012; between 27th August and 28th September 2013; and between 1st September and 7th November 2014

Note that, given the limited time frame of these data, the context of this thesis is the post-emergency phase of the incident (i.e. the days/months/years following the incident). Detailed explanation of each dataset (e.g. settings and populations, data collection, data analysis, limitations of the data, etc.) can be found in the corresponding sections below where each research question is addressed in turn.

4 Methods

Objective 1

To better understand potential challenges concerning the assessment of levels of external radiation exposure following the Fukushima incident

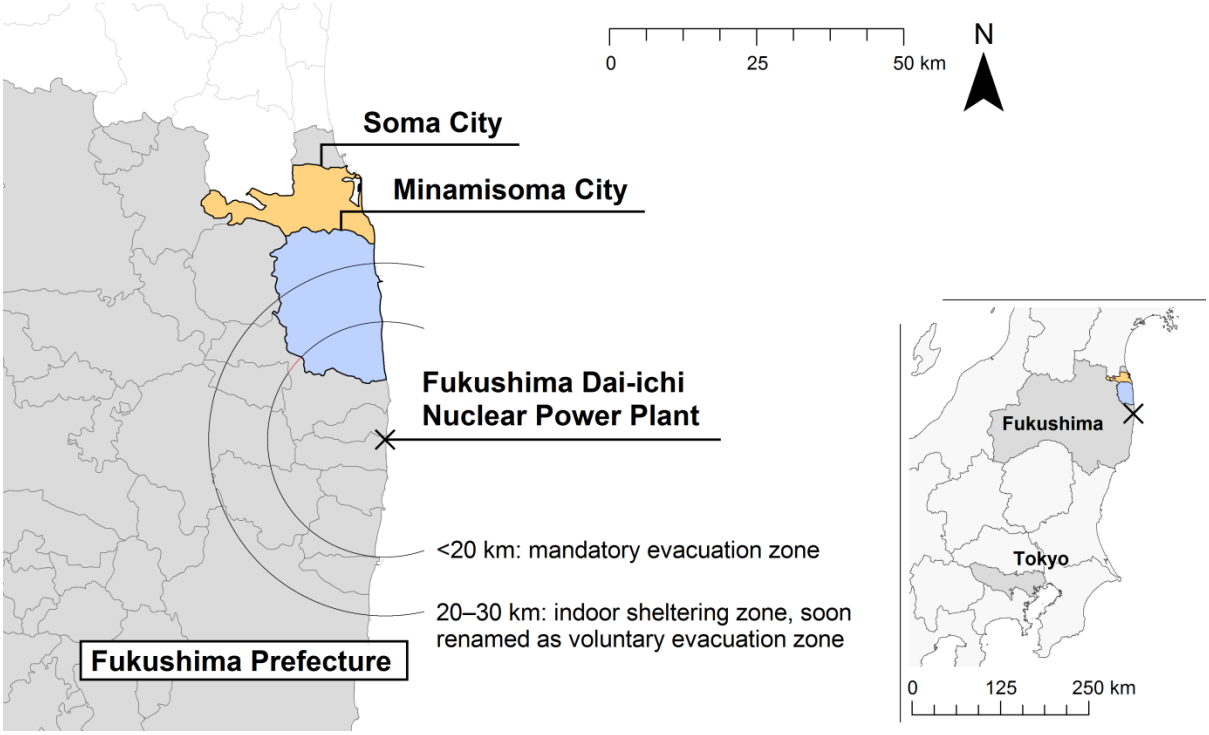
4.1 Question 1: (a) how accurately does the Japanese government's dose reconstruction model estimate the annual external radiation dose among school children 18 to 30 months after the incident, and (b) what uncertainties exist in the model leading to the potential disagreement with the measured dose?

4.1.1 Settings and populations

In response to public concern over radiation exposure following the Fukushima nuclear incident, the city of Minamisoma (located 14–38 km from the nuclear plant, with the pre-incident population of 71,494 as of February 2011[129]: Figure 2), Fukushima Prefecture, Japan, launched a voluntary external radiation exposure screening program in October 2011. This program was free of charge for all infants, school children (aged 7–18), and pregnant women who were registered in the Minamisoma family registry. Notification about the program was sent to each school, and the information also disseminated using the city's public magazine. The screening program was conducted once every three months. In each program, the city office sent a radiation dosimeter (Glass Badge: GD-450, Chiyoda Technol Corp., a privately owned Japanese company that manufactures and sells radiation products used in medicine, pharmacology, biology, agriculture, and other fields[130]) to individuals or infants/students' guardians (typically parents) who gave the city office consent to participate in the program. An instruction manual was sent to each participant explaining that the dosimeter needed to be hung from the user's neck all day, except when the user was at home, when the dosimeter could be placed near the user. At the time of this measurement campaign, levels of internal radiation exposure appeared to be marginal among most Minamisoma residents;[17,24,25,30,53,131,132] therefore, the possibility that the Glass Badge measured radiation from radionuclides inside the body was considered negligible. After the three months of the program, the dosimeters were returned to the city office, and the Minamisoma Municipal General Hospital (MMGH) processed the data, including the measured doses of external radiation exposure as well as participants' demographic information,

which were then stored in the city office. The number of participants in each three-monthly program was about 2,500 in 2011–2012, including about 2,000 school children. Note that although overall aggregated results of the screening are published in the official website of the city office, other individual data was not made publically available.

Figure 2: Location of Minamisoma City and Soma City



This was a retrospective observational cross-sectional study. I considered the data for all primary, secondary, and high school children (aged 7–12, 13–15, and 16–18, respectively) who participated in the fourth screening program, which took place between 1st September 2012, and 30th November 2012 (n=1,956, representing approximately 30% of total school children in the city). The choice of this target population and study period was determined by the particular public concerns for radiation exposure in children, and data availability of the post-incident daily behaviour pattern survey (described in the below section) that the city office staff, MMGH staff, and I jointly created, and which was also administered by MMGH as a part of the screening program performed in this period only for school children. Because the original data (i.e. Glass Badge screening data and daily behaviour survey data) stored in the city office contained personally-identifiable address information, the city office staff anonymised and de-identified the data for my research, before I accessed and used it.

For the analyses, from the 1,956 school children, I excluded those who had missing basic characteristic data or who lived outside Minamisoma City or adjacent areas (n=298) to avoid misbalancing the

unobserved participant characteristics and behaviour patterns among different dwelling regions and to minimise possible bias in the subsequent analyses. I then excluded children with low adherence to the equipment instructions (see below section), specifically those who did not wear the Glass Badge during school commuting hours or while outdoors (n=1,138). Therefore, a total of 520 children were analysed, representing approximately 7% of all school children in the city at the time of the measurement.

4.1.2 Data collection

Measured levels of external radiation exposure

The collected Glass Badge data includes the three-month measured dose and the basic demographic characteristics of the participants (sex, school-level, dwelling area [rural or urban: urban areas were defined as an area with ≥4,000 people per square kilometre], and home location information (longitude and latitude).

The outcome of the Glass Badge measurement is a dose equivalent at a tissue depth of 1 cm (Hp(10)). The Hp(10) values obtained in the conditions of the affected areas in the Fukushima Prefecture are known to be comparable with the effective dose of isotropic (ISO) or rotational (ROT) irradiation geometries.[105,133-135]

The dose attributed to natural sources, including the universe (including cosmic rays) and the ground (including Radon-222), was automatically subtracted from the original Glass Badge measurements by default. The Glass Badge data obtained represent therefore the 'additional' dose due to the Fukushima incident. The subtracted value was set as 0.54 mSv/year (0.062 μSv/h), which were the average values obtained from 20 Glass Badges with a measurement time of 35 days that were placed at Oarai, Ibaraki Prefecture, Japan—located more than 100 km south of the Fukushima nuclear plant—before the incident. The 'additional' dose of some participants was below zero after this automatic subtraction of the background dose, causing a left-censoring effect at zero mSv. Note that the range of the accuracy of the Glass Badge measurement of cumulative dose over 35 days was ±4 %.[136]

Post-incident daily behaviour patterns

In response to public concern about risk behaviours among children exposed to radiation, Minamisoma City also conducted a questionnaire survey for school children. This bespoke survey was created by the city office staff, MMGH staff, and me. The questionnaire was simple. There were no open questions but only multiple-choice questions (except for name, date of birth, and home address)

and to each question the participants had the opportunity to circle only one from the offered alternatives. The survey was administered by MMGH as a part of the screening program performed between 1st September 2012 and 30th November 2012, only for school children. The questionnaire was completed by 1,956 (100%) of the screening participants in this period, by the children, or, more typically, by their parents/guardians. This survey data was linked to the screening data, and the answer sheet was instructed to be returned to the city office along with the child's Glass Badge. This survey questioned children's daily behavioural patterns at home (e.g. the room in which most daytime hours were spent), during the commute to school (e.g. school commuting time), at school (e.g. seat position in the classroom), and after school or on weekends (e.g. place where most after-school hours were spent). In addition, the survey included questions on the conditions in which the Glass Badge was worn: e.g. if the Glass Badge were worn during school commuting hours, at school, at home, outdoors, and when sleeping. This allowed for an assessment of the degree of adherence to the Glass Badge equipment instructions.

Air dose rate at home (dwelling location)

I also considered the air dose rate at the participants' household. Data were collected from the official website of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). After the Fukushima incident, MEXT has irregularly conducted airborne monitoring in the contaminated areas. As of February 2018, the monitoring has been performed 11 times within an 80-km radius of the nuclear plant. The flight altitudes were approximately 300 m above the ground, and the values expressed by the monitoring are the averages of the measured values in approximately 600-m-diameter circles below the aircraft. The width of the flight path of the aircraft was about 1.85 km. The air dose rates at a height of 1 m above ground are measured in terms of the ambient dose equivalent (H^*10)[137] and includes the natural dose from the ground. Monitoring results are open access and freely downloadable as a CSV file from the official website of the MEXT, and the data contains the air dose rates [μSv/h] and the associated monitoring points (longitude and latitude).

To calculate the air dose rate at the middle date (15th October 2012) of the fourth Glass Badge screening program (1st September and 30th November 2012), I used a linear time interpolation method on data from fifth and sixth MEXT monitoring programs, which measured air dose rate on between 22nd and 28th June and between 31st October and 16th November 2012, respectively.[138,139] Linear interpolation estimates a value by connecting two adjacent known values with a straight line. This method works best when the function of a value (e.g. radioactive decay function) is not anticipated to change quickly between these known values.

The air dose rate at each participant's dwelling location was assessed using the following methods. The air dose rates at each monitored 600-m-diameter circle were averaged across a 500-m^2 mesh based on the Japan Profile for Geographical Information Standards (elevation and slope angle fourth mesh data) released by the Ministry of Land, Infrastructure and Transport.[140] Then, each dwelling location was defined as the mesh area where the participant's home was located. Then, each screening participant was linked to one of the mesh areas by the MMGH staff under my guidance, which enabled me to estimate the air dose rate at each participant's dwelling location.

Air dose rate at school

Air dose rate at participants' schools was also considered. Note that Fukushima Prefecture carried out radiation monitoring between 19th June and 11th July 2012 for each school in Minamisoma City.[141] This monitoring campaign measured the ambient dose equivalent (H*10), which included the natural radiation background from the ground. The data included the air dose rate at a height 1 m above the ground within the school grounds, at the main gate, and at the building entrance/exit. All results are open access and freely downloadable as a CSV file from the official website of Fukushima Prefecture.

Ethics statement

Ethical approval was granted by the ethics committee of MMGH, under authorization number 25-08. The ethics committee agreed that written consent was not required for each participant in the study. The original participant data contained personally-identifiable location information (longitude and latitude), but the data was subsequently anonymised and de-identified prior to the data analyses. A scanned copy of the approval with English translations is in APPENDIX A.1.

4.1.3 Data analysis

Measured annual additional effective dose

Unless indicated otherwise, I present the Glass Badge measured dose in terms of additional dose due to the Fukushima incident. To express additional dose in terms of annual levels, I simply multiplied the three-month Glass Badge measured dose values by four. Again, the outcome of the Glass Badge measurement is a dose equivalent at a tissue depth of 1 cm (Hp(10)). The Hp(10) values obtained in the conditions of the affected areas in the Fukushima Prefecture are known to be comparable with the effective dose of isotropic (ISO) or rotational (ROT) irradiation geometries.[105,133-135] This means that the outcome measurements of the measured and modelled dose are comparable (see below 'Modelled annual additional effective dose'). Note that effective doses are principally not measurable.

Therefore, operational quantities for dosimetric measurements are generally used, which enable a sufficiently accurate dose determination with satisfactory information on the radiation fields and with consideration of the varying radio-sensitivity of different organs/tissues, and body shielding (if individual dosimeters are used).[133,142]

Modelled annual additional effective dose

I used the following model developed by the central government to estimate the annual additional effective dose,[96,97] E_i [mSv/year], for a person of age k at dwelling location i: where D_i is the air dose rate [μSv/h] at location i at a height 1 m above flat ground; D_{nat} is the air dose rate [μSv/h] from natural sources; F_k is the conversion coefficient from the air dose rate to the effective dose for a person of age k; T_{out} and T_{in} are fractions of time spent outdoors and indoors in a day, respectively; and β is the shielding coefficient, which is referred to as the ratio of the on-site indoor-external radiation level to the on-site outdoor-external radiation level.

$$E_{i,k} = (D_i - D_{nat}) \times F_k \times (T_{out} + T_{in} \times \beta) \times 24 \times 365$$

I employed air dose rate data obtained by MEXT for D_i, which includes the natural dose from the ground (section 4.1.2). I used the value of 0.04 μSv/h for D_{nat}, which is a pre-incident national average exposure from the ground (and is the value used by the government).[96] The fraction of the time spent outdoors, T_{out}, and the time spent indoors, T_{in}, were set at 8/24 and 16/24, respectively, and the shielding coefficient β was set to 0.4 (again, these are the values used by the government).[96] This government model does not consider age. The conversion coefficient F was set to 1.0 as used by the government. [96] In this model, the radiation reduction coefficient refers to $T_{out} + T_{in} \times \beta$, i.e. 0.6.

Measurement error adjustment for measured dose

Given that the presence of measurement errors would cause biased parameter estimates and lead to erroneous analytical outcomes to various degrees,[143] I first adjusted for measurement errors in the measured dose by introducing error-corrected estimates based on the regression predictions approach.[144] Namely, I derived a predicted value for each participant based on the regression of raw Glass Badge measurements of the annual dose against the demographic characteristics of the participants, such as sex, school-level, and dwelling area, as well as the air dose rate at dwelling location, which were assumed to be associated with measurement errors. This 'adjusted' measured dose was applied in all following data analyses. Due to the imprecision of the Glass Badge measurements, the 'raw' measured dose of some participants was below zero after automatically

subtracting the background doses; hence, for the adjustment, I employed the Tobit multiple regression models, which estimate the linear relationships between the model parameters by adjusting for the left-censoring effect of the Glass Badge.

Ratios of modelled versus measured dose

To assess the level of agreement between the modelled and 'adjusted' measured values of the annual effective dose, the ratio of the modelled to measured doses was calculated for each participant. Given the quantization error of the Glass Badge measurements and the MEXT monitoring, an accuracy of two significant digits was accepted to present the results. Mean ratios in different groups, based on sex, school-level, and dwelling location, were compared using an un-paired t-test and one-way ANOVA, where p-values less than 0.05 were regarded as significant.

Radiation reduction coefficient

The government's dose estimation model employs a radiation reduction coefficient of 0.6 uniformly across all populations under the assumption that people spend 8 hours outside and 16 hours inside in a building with a shielding effect of 0.4 in a day. However, different radiation attenuation functions were expected for the characteristics of different residents, which may lead to different ratios of the modelled to the measured doses among the study participants.

To examine the potential variability in the reduction coefficient for the participants, I calculated each participant's reduction coefficient using the following equation:

$$R = G \div \left((D - D'_{nat}) \times F_k \times 24 \times 365 \right)$$

where R is the radiation reduction coefficient; G is the regression-adjusted Glass Badge measurements of the annual dose [mSv]; D is the air dose rate [μSv/h] measured by the MEXT monitoring at each participant's dwelling; and F_k is the conversion coefficient from the air dose rate to the effective dose for a person of age k. I employed 0.05 μSv/h for D'_{nat}, which is a pre-incident Minamisoma City-specific average of the background dose from the ground [μSv/h].[137] Given that the radiation shielding effects of body tissues depend on body size, the conversion coefficient from the ambient dose equivalent to the effective dose increases as age decreases, according to Yamaguchi et al. (1994).[145] Therefore, the conversion coefficient for the age group of this analysis (7–18 years) was obtained from the following linear function of age k, which was expressed and validated by the National Institute of Radiological Sciences (NIRS), Japan:[146]

$$F_{k<16} = F_{k\geq16} \times (-0.0144 \times k + 1.27)$$

The conversion coefficient for those participants over age 16, $F_{k\geq16}$, was set to 0.6 as suggested by Akahane et al. (2013).[146] Next, the reduction coefficient distribution among the participants was visualized using histograms and univariate kernel density estimation, which was based on a Gaussian kernel with an optimal bandwidth.

Finally, a multiple linear regression model was developed to estimate the associations of the radiation reduction coefficient with the characteristics and behaviour patterns of the participants during the measurements, adjusting for different equipment adherence. School-specific air dose rate (i.e. air dose rate at a height 1 m above the ground within the school grounds, at the main gate, and at the building entrance/exit) measured in terms of ambient dose equivalent at 10 mm depth (H*10) were also incorporated into the model. The final model was used to predict the adjusted reduction coefficient, which was plotted against significant variables to allow for visual inspection of their associations. The regression model construction in these analyses was based on a backward-stepwise procedure, variables with p-values greater than 0.05 were removed.[147] A backward-stepwise regression starts with all the candidate variables in the model, and then continues to remove the least significant variables until all the remaining variables are statistically significant. The partial F-test was used to verify the entry and removal of variables from the model. The heteroskedasticity of the residuals in the model was examined using the White and Breusch-Pagan tests.

Data analysis, including the spatial data formatting, were conducted using STATA/MP 13, R 3.0.2, and ArcGIS 10.2.

4.2 Question 2: how do the behavioural patterns of school children influence external dose 18 to 20 months after the incident?

4.2.1 Settings, populations, and data collection

This was a retrospective observational cross-sectional study. Because Questions 1–3 employed the same data (measured levels of external radiation exposure in school children [external radiation exposure screening], post-incident daily behaviour pattern in school children [survey], and air dose rate: Table 1), descriptions for settings and populations and data collection can be referred to the section 4.1.1 and 4.1.2 above.

As with Question 1, out of the 1,956 school children who participated in the fourth screening program, I excluded those missing data on household address or those who lived outside of Minamisoma City or in its adjacent areas (n=298). I further excluded those who did not adhere to the Glass Badge equipment instructions (i.e. those who did not wear the Glass Badge during school commuting hours or while outdoors: the 'low-adherence group', n=1,138), leaving 520 children (the 'high-adherence' group) from 33 schools (representing approximately 7% of all school children in the city at the time of the measurement) for the analysis.

4.2.2 Data analysis

Explanatory analysis

In this analysis, to support clinical and policy interpretations and to aid understanding when reporting to the general public (as suggested by the city office), unless indicated otherwise, the Glass Badge measurements of 'total' dose i.e. that includes the natural background dose from the universe and the ground was used. To achieve this, the subtracted background dose of 0.14 mSv/3 months was re-added to the collected data).[148] Accordingly, the data were left-censored at 0.14 mSv.

The three-month Glass Badge measurements of dose among the participants were compared by demographic characteristics. The Glass Badge measurements were expected to contain quantization errors, therefore, as with Question 1, an accuracy of two significant digits might be considered appropriate for presenting the results. However, I accepted an accuracy of three significant digits in this analysis because the participants' three-month dose was not large, and the potential difference in dose by demographic characteristics might not be able to be distinguished at only two significant digits.

The behaviour survey results were investigated by school-level because the behavioural patterns were expected to exhibit substantial differences by school-level. To compare proportions between groups, Chi-squared tests were used. The mean differences between two groups were evaluated using un-paired t-tests, and for multiple comparisons, a one-way ANOVA was applied, followed by a Scheffe's post hoc test. P-values less than 0.05 were regarded as statistically significant.

Regression modelling

To evaluate the relationships between behavioural patterns among school children and radiation dose, a Tobit regression analysis was conducted, which allowed the estimation of linear relationships, adjusting for the left-censoring effect of the Glass Badge measures.[149] The natural logarithm was applied to the dependent variable (dose) as the distribution was log normal, with some school children showing relatively higher dose levels. Since the regression coefficients for each of the independent variables were computed on a logarithmic scale, I used the exponentiated forms of the coefficients when presenting the regression results, which indicate the multiplicative change in the dose level per unit increase in each explanatory variable. In this analysis, the Tobit model was extended by regarding 'school' as a random variable, reflecting unobservable random differences among the populations in each school. Construction of the regression model was based on a backward-stepwise procedure with a p-to-remove value of 0.05.[147] The partial F-test was used to verify the entry and removal of variables from the model.

Data analysis, including the spatial data formatting, were conducted using STATA/MP 13, R 3.0.2, and ArcGIS 10.2.

4.3 Question 3: (a) what are the characteristics of school children who do not use the dosimeters correctly, and (b) how much error is generated by improper use of the dosimeters 18 to 20 months after the incident?

4.3.1 Settings, populations, and data collection

This was a retrospective observational cross-sectional study. Because Questions 1–3 for the objective 1 employed the same data (measured levels of external radiation exposure in school children [external radiation exposure screening], post-incident daily behaviour pattern in school children [survey], and air dose rate: Table 1), descriptions for data collection can be referred to the section 4.1.1 and 4.1.2 above .

Of the 1,956 school children that participated in the fourth screening program, I excluded those for whom basic data, including household address, were missing (n=319), and I analysed the remaining 1,637 children, representing approximately 24% of all school children in the city at the time of the measurement.

4.3.2 Data analysis

Regression modelling and projection

As with Question 2, for easier clinical and policy interpretations and to aid understanding in the general public (as suggested by the city office), unless indicated otherwise, the Glass Badge 'total' dose that includes the natural background dose from the universe and the ground were used (i.e. the subtracted background dose of 0.14 mSv/3 months was re-added to the collected data.[148] Accordingly, the data were left-censored at 0.14 mSv.

Within this analysis, the following sub-analyses were conducted:

Sub-analysis A: To identify the factors associated with improper use of the Glass Badge for specific time periods in a day (commuting time, at school, after school, at home, outdoors, and at bedtime), a logistic regression model was constructed for each time period. The outcome measure was binary (1: not used, 0: equipped); thus, the regression results present the exponentiated form of the computed regression coefficients of each independent variable, indicating the change in the odds (i.e. the odds ratio (OR)) of non-use for a unit increase in the variable.

Sub-analysis B: To assess how much ‘error’ in the measured dose is generated by the improper use of the Glass Badge, I used the following method. First, using the data from those who used the

dosimeters properly (i.e. the participants who used the dosimeters during all time periods in a day), I estimated a regression model that specified the relationships between the measured dose and the covariates. To build the model, a Tobit model was applied to the data, which enabled estimation of the linear relationships among variables, adjusting for the left-censoring effect of the Glass Badge. Given the potential outliers among the school children (i.e. those who showed higher dose levels), the natural logarithm of the dose was used for the dependent variable. Second, I predicted the 'expected' dose values of those who used the dosimeters improperly by fitting their parameters in this prediction model. Finally, the predicted dose and measured dose of each individual were compared in terms of the ratio of the measured to predicted values. Thus, in this study, the difference between the measured dose and regression estimates of the 'expected' dose are referred to as an 'error' due to non-use.

For regression modelling in these analyses, as previously, model selection was performed using a backward-stepwise method with p-to-remove set to >0.05.[147] The partial F-test was used to verify the entry and removal of variables from the model. Variables that were known or suspected risk factors (e.g. sex) were incorporated into the final model regardless of their statistical significance.

Robustness of the regression prediction

To assess the prediction accuracy of the Tobit model constructed for estimating the 'expected' dose in children who improperly used the Glass Badges, I built another prediction model using the classification and regression tree (CART) method. The CART method is a non-parametric method that does not require any assumptions regarding the distributions of the input data.[150] Then, I compared the pseudo R-squared values from the CART model pruned by ten-fold cross-validation—the most common approach to find the optimal tree size—with the deviance criterion rule to those from a Tobit model in order to examine which model provided a better dose prediction.

Data analysis, including the spatial data formatting, were conducted using STATA/MP 13, R 3.0.2, and ArcGIS 10.2.

Objective 2
To better understand the potential benefits and health risks of the post-incident evacuation

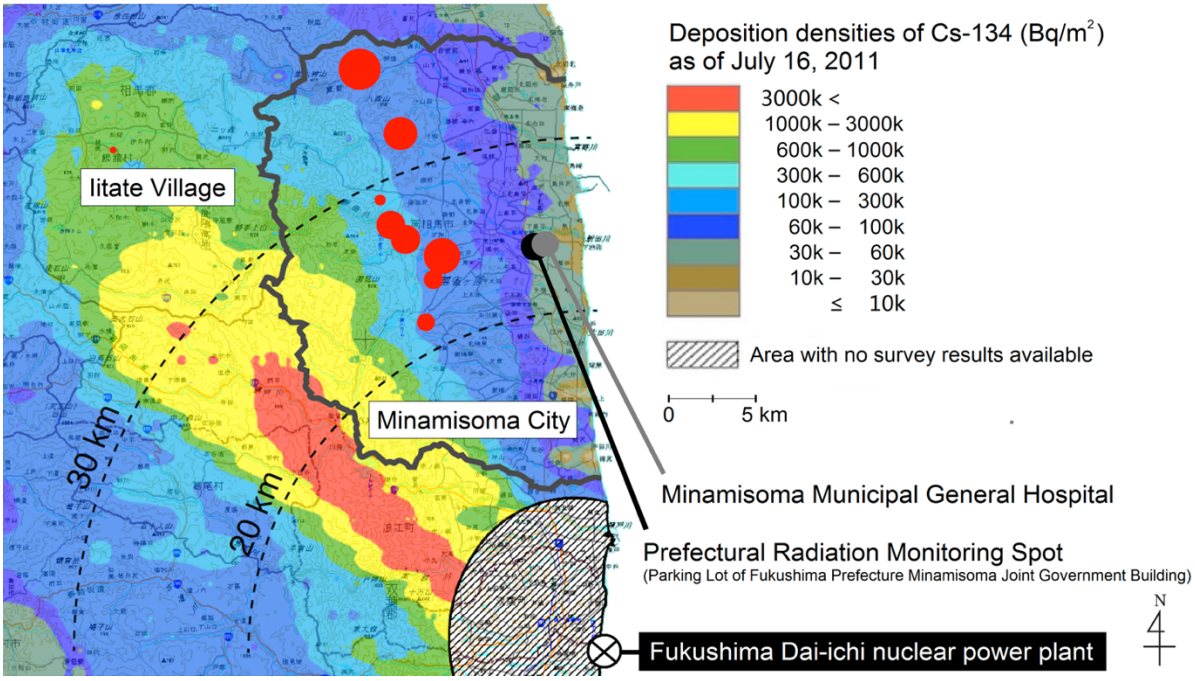
4.4 Question 4: what are the relationships between early evacuation and levels of internal radiation exposure among adults four months after the incident?

4.4.1 Settings and populations

The research site in this analysis is Minamisoma City. This city was one of the most radiation-contaminated regions, and straddles two different initial evacuation zones declared by the Japanese government. On 12th March 2011, an area within a 20 km radius of the nuclear plant was denoted a restricted area with mandatory evacuation. On 15th March, an indoor restriction order was issued for the 20–30 km zone. As of August 2011, of 146,520 evacuees from Fukushima Prefecture, 61,710 (42%) were from Minamisoma City.[151]

In response to public concerns over radiation exposure following the Fukushima nuclear incident, MMGH launched a voluntary internal radiation exposure screening program in mid-July 2011, using a WBC (whole-body counting) unit installed after the incident. This program has been administered by MMGH, and is free of charge for Minamisoma residents, by appointment only. When the WBC monitoring started in July 2011, appointments were booked more than a half year in advance. Because of the large number of pre-booked appointments, residents could not usually participate in the monitoring more than once until March 2013. Notification of the screening program was sent to all individuals who lived in Minamisoma City at the time of the incident, identified using the city's family registry. The MMGH website and the city's public relations magazine were also used to disseminate program information. The locations of MMGH, relative to the nuclear power plant, are shown in Figure 3.

Figure 3: Location of Minamisoma Municipal General Hospital, prefectural radiation monitoring spots, and distributions of the study participants



Note: The base map indicates the Cs-134 deposition as of 16th July 2011. Note that this deposition map is not an indicative of inhalation or ingestion risks of Cs-134 as the deposition levels are not necessarily related to internal levels of contamination.[131] The red circles show the geographical distribution of the study participants, where the circles are proportional to the number of subjects living in each district.

Internal exposure screening was performed using a chair-type WBC (Anzai Medical Co., LTD, Japan), installed in a bus-like vehicle located in the parking lot of MMGH.[152] A sodium iodide (NaI) detector (5-inch diameter × 3-inch thickness) was mounted on the back of the chair, and from that location, was able to count gamma isotopes efficiently,[152] with a scanning time of one minute. The chair-type WBC provided insufficient shielding against background gamma rays (described below), and was only used between 11th to 29th July 2011, and occasionally (very rarely) in August and September 2011. It was replaced by a better-shielded standing-type WBC (FASTSCAN Model 2251, Canberra Inc., United States) on 26th September 2011. Principal radionuclides released from the Fukushima Dai-ichi Nuclear Power Plant were Xenon-133 (about 19 EBq),[6] Iodine-131 (about 500 PBq), Cs-134 (about 10 PBq), and Cs-137 (about 10 PBq).[62] However, Xenon-133 and Iodine-131 were already undetectable when the screening was launched due to their short physical half-lives (one week). Therefore, only Cs-134 and Cs-137, with physical half-lives of two years and 30 years, respectively, could be measured. Note that although overall aggregated results of the screening are published in the official website of the city

office, other individual data is not open to the public (i.e. not accessible for everyone), except for those specially permitted by the city office to undertake analyses (including this) ethically approved by MMGH.

This was a retrospective observational cross-sectional study. For Question 4, in order to assess the levels of internal radiation exposure following the Fukushima incident, I used the data of the internal radiation screening program performed at MMGH in July 2011, four months after the incident and the month the screening program began. Given the data availability of early incident response pattern survey (described in the below section) that the MMGH staff created, I did not consider screening data of August and September 2011. I restricted the data for those over 16 years of age because the biological half-life of Cs-134 (the time taken for half of the radioactive material to be eliminated from the body through biological processes) is about 110 days for adults, but is shorter in children, and wide individual differences were expected.[153] The pre-incident populations (at February 2011) aged over 16 in the city was 61,105, about 85% of the total population. Because the original screening data stored at MMGH contained personally-identifiable address information, the MMGH staff anonymised and de-identified the data for my research.

The original dataset comprised 525 screening participants. The small number of participants in July 2011 can be explained by manpower constraint at MMGH and equipment shortage (WBC); there was only one WBC at July 2011. Owing to missing evacuation data, four participants were excluded, leaving 521 participants. Two children under age 16 were also excluded. In total, data from 519 participants were analysed, representing approximately 1% of pre-incident total population aged over 16 in the city.

4.4.2 Data collection

Data correction for the measurement of internal radiation exposure

The collected internal screening data includes the measurement of internal radiation exposure (described below) and the basic demographic characteristics of the participants (age, sex, weight, and height). Measurements from the chair-type WBC (used in the study period: July 2011) could not be employed directly in the present analyses because the WBC machine's shielding against background gamma rays was insufficient. Given that the human body partially shields such environmental background radiation, the measurements were significantly influenced by examinees' physical characteristics, such as weight and height. To solve this problem, Hayano et al. (2014) developed a phenomenological model that considered physical parameters, including body thickness and body fat,

to reliably compensate for the body-attenuated background radiation, and corrected the measurement data by subtracting the estimated body-attenuated background for each individual.[152] Detailed information about the correction method and its verification can be found in Hayano et al. (2014).[152] The detection limit of this WBC was set at 3σ, i.e. 800 Bq/body, where σ indicates the standard deviation standard deviation (SD) of the corrected measurement.[152] A threshold of 3σ is commonly used as the detection limit as nearly all the values of the measurement uncertainty fall within its range, and are thus censored.

MMGH has, then, stored this corrected data along with the original measurement data at MMGH. Again, note that although aggregated data of the corrected measurement of internal radiation exposure are published in Hayano et al. (2014),[152] individual-level data are not publically available. For this analysis I was specially permitted by the city office to use these corrected measurement data at the individual-level. Since large statistical errors in Cs-137 data were found in the process of the correction,[152] only Cs-134 data were able to be used in this analysis.

Early incident response pattern survey

In July 2011, MMGH conducted a questionnaire survey for all screening participants. This survey was created by the MMGH staff. The questionnaire included only multiple-choice questions (except for name, date of birth, and home address) asking participants about their occupation, commuter time to office/school, hours spent outdoors before and after the incident, and evacuation date and site (evacuation outside/inside Fukushima Prefecture or non-evacuation). Other questions pertained to changes in daily precautionary activities following the incident, which may reveal risk factors for internal contamination, such as whether or not the participants wore masks, washed hands/gargled, avoided certain foods, avoided tap water, and washed vegetables. The survey was administered by MMGH as a part of the internal radiation screening program in July 2011. So, I also used this survey data, which was linked to the internal radiation screening data for each individual. Participants were instructed to complete the questionnaire during the waiting time for WBC measurement, and the response rate of the survey was 100%.

Ethics statement

Ethical approval was granted by the ethics committee of the Institute of Medical Science, The University of Tokyo, Japan, under authorization number 23-46-0113. Written informed consent was obtained from all the participants included in the study. Scanned copy of the approval with English translations is found in APPENDIX A.2.

4.4.3 Data analysis

Regression modelling

To evaluate relationships between early evacuation and the levels of internal contamination of Cs-134, I employed Tobit regression analysis. Since the WBC has limited detection capability, results from some screening participants fell below the detection limit and produced zero measurement values. Tobit models are an appropriate analytical technique in this analysis because they allow for estimating linear relationships between model parameters adjusting for such left-censoring effects.[149] In addition, because of the positive skew in the data (due to the left censoring, and small number of individuals with relatively high exposure levels) the natural logarithm of the Cs-134 value, body burden [Bq/body], was employed as the dependent variable. Accordingly, the regression results present the exponentiated form of the computed coefficients for each independent variable, indicating the multiplicative change in the Cs-134 contamination level for a unit increase in each variable. Moreover, for easier clinical and policy interpretations, I considered body concentration [Bq/kg] rather than body burden [Bq/body] by using the natural logarithm of weight as an offset in the models. The offset restricts the coefficient of weight to a value of 1 and allows us, theoretically, to move weight to the left side of the equation to transform body burden into body concentration.[149] For a detailed explanation of this approach, see APPENDIX B.

I conducted two separate regression analyses:

Regression 1: To evaluate the effects of early evacuation on the levels of Cs-134 body concentration [Bq/kg] four months following the incident, the Cs-134 body concentration of individuals who evacuated early were compared to those of individuals who did not.

Regression 2: To evaluate the impact of the timing of early evacuation on the levels of Cs-134 body concentration [Bq/kg] four months following the incident, the Cs-134 body concentration were compared by evacuation date in March. In order to eliminate the influence of chronic ingestion of contaminated foodstuff as much as possible, only data of those who evacuated to areas outside Fukushima Prefecture within half a month of the incident were included.

For these regressions, independent variables considered were: age at WBC measurement; height; examination date (measured in days after the nuclear incident). Other covariates were categorised as follows: sex (male and female); occupation (outdoor worker, indoor worker, unemployed, housewife, and other); time spent outside per day after the incident (<5 hours and ≥5 hours); and daily

precautionary activities, including wearing masks, washing hands/gargling, avoiding certain foods, avoiding tap water, and washing vegetables ('yes' vs 'no' for each). In addition, evacuation location (no evacuation, evacuation inside Fukushima Prefecture, and evacuation outside Fukushima Prefecture) and evacuation date in March (11th to 19th, and after 20th) were considered for Regression 1 and 2, respectively. As a sensitivity analysis, I used different classifications of evacuation date (for example, the first week following the incident or later, before 20th and after 20th).

Selection of variables was based on the backward-stepwise method with p-to-remove of >0.05.[147] Covariates of primary interest, including evacuation type and experience of disaster, were entered into the models regardless of their significance as long as stable models were obtained. The partial F-test was used to verify for the entry and removal of variables from the model.

Cumulative detection rates of Cs-134 over time

Finally, to further assess the relationship between the Cs-134 levels of internal contamination four months following the incident and early evacuation (to inside/outside the Fukushima Prefecture) as well as timing of the evacuation, I plotted detection rates among those who did not evacuate (Group 1) and evacuees (Group 2) by date of evacuation. For example, the Group 1 analytical dataset contained everyone present before the incident (on 10th March), then everyone except those who evacuated on 11th March, and so on over time. On the other hand, the Group 2 dataset contained evacuees from 11th March, then, in addition, those who evacuated on 12th March, and so on over time. If early evacuation helped reduce international contamination levels, then it is conceivable that individuals who left early should have lower Cs-134 detection rates than those who remained, and as evacuees drop out of the Group 1 dataset, over time, by date of evacuation, the detection rates in individuals among the remaining group (Group 1) increases. Otherwise, the detection rates would remain constant over time. Then, if earlier evacuation supported a larger reduction in internal contamination levels, the detection rates in individuals among evacuees (Group 2) are expected to increase over time, by date of evacuation.

Data analysis, were conducted using STATA/MP 13.

4.5 Question 5: how much did the mortality risk differ between evacuees and non-evacuees among nursing home residents after the incident?

4.5.1 Settings and populations

This was a retrospective observational cohort study. Among all the eight nursing homes in Minamisoma City, five facilities were involved in this analysis, where a total of 328 residents were admitted at the time of the Fukushima incident, representing about 60% of all nursing home residents in the city at the time of the incident; data of these facilities were used in my earlier survival analysis published in early 2013.[120] Among the remaining three nursing homes, one, a rehabilitation facility with a capacity of 58 people, had insufficient data on evacuation for inclusion in the study; one, a 60-person intensive care home, refused to participate; and one facility, a rehabilitation facility with capacity for 100 people, was not able to participate because it was wrecked by the tsunami, all residents were killed and records were destroyed in the tsunami. For this comparative analysis, to provide additional information on non-evacuees, I collected data as part of a team from the only two facilities in Soma City, located to the north of Minamisoma, and 35–50 km from the Fukushima nuclear plant, neither of which conducted evacuation. A total of 198 residents were admitted in these facilities in Soma at the time of the incident. All residents who had been admitted to one of these seven facilities in Minamisoma/Soma between 11th March 2006 and 11th March 2011 were included in this analysis. The locations of Soma and Minamisoma, relative to the Fukushima nuclear power plant, are shown in Figure 2. Note that there are two main types of nursing homes in Japan: intensive care homes and rehabilitation facilities. Four of the facilities in Minamisoma were intensive care homes, which provide people seeking the end of life option with general care as well as more choice about where they would like to live and die. One facility in Minamisoma and both in Soma were rehabilitation facilities for the elderly, which make efforts to improve health such that residents might then rehabilitate at home and improve their quality of life. Both facility types admit residents regardless of their care-levels and health conditions.

After excluding one person with missing entry records, I employed data from 500 elderly residents from the two nursing homes in Soma, representing nearly 100% of all residents who had been admitted to the facilities in the five years before the incident. Adding to the previously obtained data from 715 residents (59%) from five of eight nursing homes in Minamisoma, this analysis employed data from 1,215 participants.

4.5.2 Data collection

Demographic and clinical data

I obtained data on residents' demographic and clinical characteristics, and entry records (age and sex at death, withdrawal, or end of study period), which were extracted from their medical records by nursing home staff. These data included care-level on a scale of 1 to 5, measuring severity of care needs based on the Japanese Category of Condition of Need for Long-Term Care.[155] This scale is an indicator of severity of disability and does not necessarily reflect health condition,[156] which determines the eligibility to receive services under the long-term care insurance system. To be certified to receive insurance for long-term care, people need to apply to the municipality where they reside. The care-level is then determined and certified by the municipality on the basis of a computer-based evaluation of a 74-item questionnaire on activities of daily living and a written statement from the applicant's family physician. The care-level is re-evaluated every two years. In order to support clinical and policy interpretations, I defined residents with care-level of 1 to 4 as requiring low/moderate care and those with care-level of 5 as requiring high care, as with the definition in Nomura et al. (2013).[120] No reliable records of the cause of death were able to be obtained. As the diagnostic tests can be tailored to the clinical syndrome, in the absence of proper medical records post-disaster, the diagnosis of the cause of death is a particular challenge.

Evacuation records

Residents in the facilities in Minamisoma experienced multiple evacuations. I obtained data of their evacuation histories, which were tracked by nursing home staff on the basis of my request until between 31st August 2011 and 2nd February 2012, depending on the facility. These evacuation histories comprised date and site of the evacuations. The additional data from Soma's two nursing homes followed residents until 3rd and 25th September 2013, respectively. These facilities in Soma did not conduct evacuation, except for one self-evacuee (n=1, 0.5%). Evacuation distances were calculated using the Google Maps API with R software version 2.15.0. I measured the distance between the nursing home (or previous evacuation site for subsequent evacuations) to the evacuation site as the shortest distance on a public road. Finally, a vice-president of MMGH and I conducted in-depth, open-ended unstructured interviews with the nursing home presidents and staff who experienced the disaster (2–3 staff for each nursing home, selected by its president), asking for reasons why they evacuated or did not evacuate.

Ethics statement

Ethical approval was granted by the ethics committee of the Institute of Medical Science, The University of Tokyo, Japan, under authorization number 25-16-0712. The ethics committees agreed that written consent was not required for the participants. A scanned copy of the approval with English translations is found in APPENDIX A.3.

4.5.3 Data analysis

Hazard Ratio

To assess the evacuation-related mortality risk, I employed Cox proportional hazards regression model. I conducted two separate Cox multiple regression analyses:

Analysis 1: To evaluate the mortality risk of the early evacuation itself, I undertook a comparative analysis of survival between non-evacuees and evacuees. To adjust for the potential effect on mortality of experiencing the incident, I used both pre- and post-incident data. Data of those who survived beyond the date of the incident (i.e. 11th March 2011) were divided into pre- and post-incident periods, indicating non-incident-exposed data and incident-exposed data, respectively.

Analysis 2: To evaluate the stage-specific evacuation mortality risk (non-evacuation vs. initial evacuation from the original facility vs. subsequent evacuations), I investigated the post-incident data.

All covariates identified in my previous study,[120] such as care-level, and basic variables known to be associated with mortality, such as age and sex, as well as covariates of primary interest, such as evacuation type and experience of incident, were entered into the models regardless of their significance as long as stable models were obtained. For both analyses, selection of variables were based on the backward-stepwise method with p-to-remove of >0.05.[147] A covariate indicating potential seasonal variations in mortality (defined by season at death/withdrawal from the facility, excluding those who censored), was also examined. The partial F-test was used to verify the entry and removal of variables from the model. In these analyses, the Cox models were extended by regarding 'facility' as a random variable, reflecting unobservable random differences in the populations in each nursing home.

Pre- and post-incident survival probability curve and relative incidence

Kaplan-Meier product limit method was used to assess survival probability. The probability of survival by city was plotted against the time of follow-up. The Wilcoxon test was used to test whether there was a difference in survival before and after the incident. In addition, to assess the impact of the incident on mortality among the residents in Soma, pre- and post-incident relative mortality incidence

was calculated. First, each participant's person-years were calculated as the time between the date of admission to the facility and the end of the study period, death or withdrawal. Then, person-years were divided into pre-and post-incident periods, and mortality incidence density was calculated for both periods as the number of deaths divided by sum of person-years. Finally, the relative mortality incidence was calculated as the ratio of pre- and post-incident mortality incidence densities.

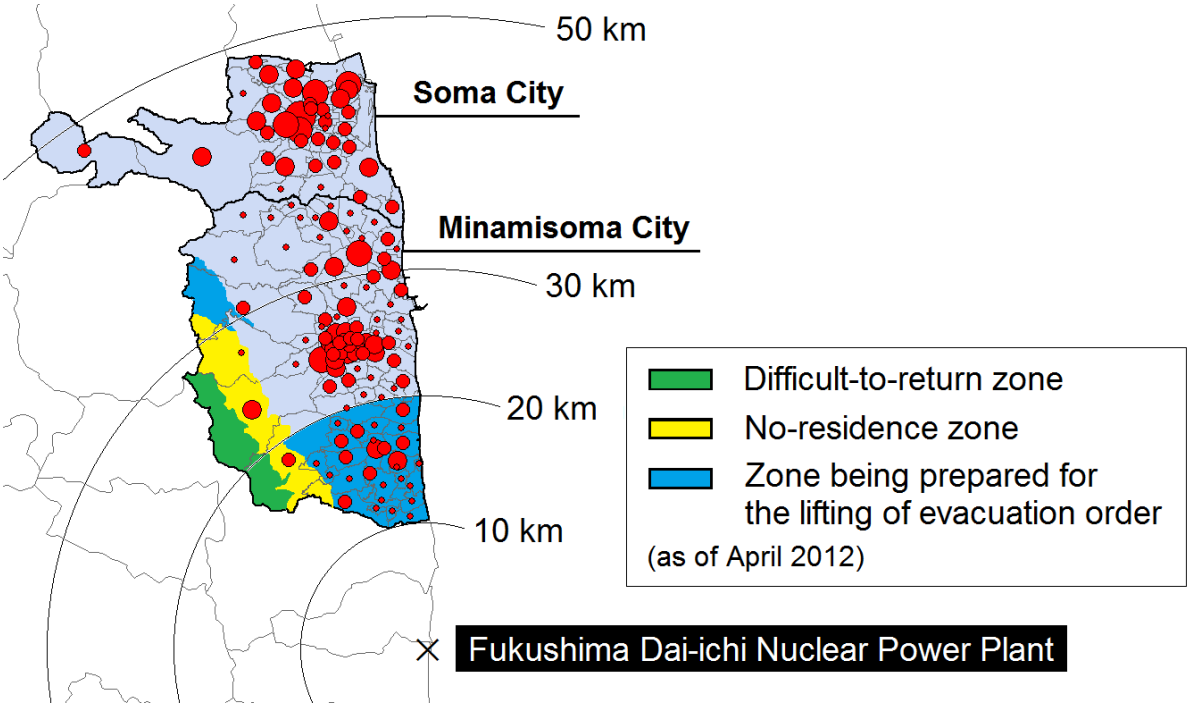
Data analysis were conducted using STATA/MP 13.

4.6 Question 6: how much did evacuation affect long-term chronic health after the incident?

4.6.1 Settings and populations

The study sites in this analysis are again Minamisoma City and Soma City. As mentioned above, on 12th March 2011, a 20 km radius from the nuclear plant was denoted by the central government as a restricted area with mandatory evacuation.[8] Minamisoma therefore straddles the initial mandatory evacuation restriction zone (where about 17 thousand people had lived, representing 24.7% of the total population of Minamisoma),[129] while Soma was entirely outside this zone. The pre-incident populations (at February 2011) of Minamisoma and Soma were 71,494 and 38,054, respectively.[129,157] On 22nd April 2011, the mandatory evacuation zone was expanded slightly to the northwest based on the measured dispersion of highly radioactive fallout (Figure 4), and on 16th April 2012, this mandatory evacuation zone was reclassified into three zones in line with air dose rates (Figure 4): (1) difficult-to-return zone; (2) no-residence zone; and (3) zone being prepared for the lifting of the evacuation order. With frequent small changes, this evacuation instruction is still in effect today. The geographical scope of this 2012 instruction is shown in Figure 4.

Figure 4: Geographical scope of the evacuation instructions around Minamisoma City and Soma City as of April 2012



Note: The mandatory evacuation zone is divided into the (1) Difficult-to-return zone (in green), where the annual dose of radiation is expected to be 50 mSv or more and people are not allowed to return

home until at least March 2017; (2) no-residence zone (in yellow), where the annual dose is expected to be 20–50 mSv and people can temporarily return home in the area, but staying overnight is prohibited; and (3) zone being prepared for the lifting of evacuation order (in blue), where the annual dose is expected to less than 20 mSv and people can temporarily return home in the area, but staying overnight is prohibited.

This was a retrospective observational longitudinal study. I employed a data from public health check-ups (described in the below section), administered by the Minamisoma and Soma City offices from 2008 to 2014, and compared post-incident data (2011–2014) to pre-incident 'baseline' data (2008–2010). A total of 11,279 individuals aged 40–74 (the eligible age group for public health check-ups: details below) participated in the check-ups between 2011 and 2014. After excluding those who did not take a check-up before the incident (n=4,873), I was left with 6,406 individuals with pre- and post-incident data, representing roughly 15% of total population in the age group of 40–74 years in the cities. There was a significant difference in sex distribution between included and excluded individuals (59.3% vs. 55.6% female, $p<0.001$). The included individuals were more likely to have hypertension in 2011, 2012 and 2013 than excluded individuals (52.5% vs. 46.1% in 2011, $p<0.01$; 52.2% vs. 46.8% in 2012, $p<0.001$; 52.0% vs. 49.0% in 2013, $p<0.05$), while post-incident prevalence of diabetes and hyperlipidemia did not differ between excluded and included individuals. Definitions of these disease outcomes were described below.

4.6.2 Data collection

Public health check-ups

There are three main types of health insurance in Japan—Employee's Health Insurance (EHI), National Health Insurance (NHI), and Late Elders' Health Insurance (LEHI). EHI is provided to employed workers (company employees) and their dependents, insured by many insurers (number of insurers in Japan >1,500) mostly depending upon the size of the company.[158] Meanwhile, NHI is designed for people who are not company employed (hence not eligible to be members of EHI) and aged less than 74, and who are insured by municipal governments (villages, towns, and cities: n>1,800 across the country).[158] Those not eligible for EHI or NHI, including self-employed persons aged over 75, are enrolled in the LEHI, insured by prefectures.[158] Public health check-ups are performed annually as part of the NHI system on a voluntary basis for those aged 40–74 at designated community centres and medical institutions during June to October, with records of the check-ups maintained by the municipalities.[158] A health check-up notification is sent to each household every year, based on the city's family registry. The check-up information is also disseminated using each city's public relations magazine. The check-

up comprises a physical examination, blood sample test, and self-report medical history and lifestyle survey. I requested from the municipal offices of Minamisoma City and Soma City the public health check-up data of all the participants for the years 2008–2014, which were available at the time of request. The municipal office staff anonymized the original records and provided them to me.

In 2012, a total of 23,291 (out of the total population of 66,385 [35.1%]) and 11,098 (out of 36,479 [30.4%]) persons were enrolled in NHI in Minamisoma and Soma, respectively,[159] which represent 41.3% and 36.7% of the age group of less than 74 years in the cities.[129,160] These figures are roughly equivalent to those at the national level of 34.0% in 2012.[161] During the study period of 2008–2014, annually approximately 2,500 and 2,000 persons aged 40–74 participated in the public health check-ups in Minamisoma and Soma, respectively, representing about 8% and 12% of the age group of 40–74 years in the cities.[129,160] Because the total number of those who are aged 40–74 in the NHI system is not available in both cities, it is unknown what percentage these figures of 2,500 and 2,000 represent among the same age group in the NHI system in the cities.

The distribution of health check-up participants are show in Figure 4, in which the data of 2010 was presented by way of example. The red circles show the geographical distribution of these health check-up participants, where the circles are proportional to the number of participants living in each district. The analysed dataset included age and sex; clinical characteristics and blood test results from the physical examination; and family disease history, surgical history, treatment history, and lifestyle information from the self-report survey. In addition, I considered district-level radiation levels (see below 'Air dose rates at home (dwelling location)') as an additional variable.

As outcome measures in this analysis, I considered diabetes, hyperlipidemia, and hypertension, which are largely preventable. To define each outcome I used the clinical guidelines for disease diagnosis or self-reported medication use: HbA1C of ≥6.5% or use of antihyperglycemic agents for diabetes; low-density lipoprotein cholesterol (LDL-C) of ≥140mg/dl or use of antihyperlipidemic agents for hyperlipidemia; and systolic blood pressure (SBP) of ≥140mmHg, diastolic blood pressure (DBP) of ≥90mmHg, or use of antihypertensive agents for hypertension.[162-164] I considered only those who participated in the check-ups both at baseline and in one or more target years because some people moved to or from Minamisoma and Soma before or after the incident. Note that not every individual had a check-up every year. For individuals who took the check-ups several times in a year, data from the first check-up in each year was considered.

Air dose rate at home (dwelling location)

Data on air dose rate at each participant's dwelling location was collected from the official website of MEXT. Detailed explanation of this data can be referred to the section 4.1.2 as the same data source for air dose rate was used in Questions 1–3.

I considered the results of the third MEXT monitoring performed between 31st May and 2nd July 2011; fifth monitoring between 22nd and 28th June 2012; seventh monitoring between 27th August and 28th September 2013; and ninth monitoring between 1st September and 7th November 2014 for the radiation levels for the years 2011, 2012, 2013, and 2014, respectively.[165]

Ethics statement

Ethical approval was granted by the ethics committee of the Institute of Medical Science, The University of Tokyo, Japan, under authorization number 25-40-1011. The ethics committees agreed that written consent was not required for the participants in the study. A scanned copy of the approval with English translation is found in APPENDIX A.4.

4.6.3 Data analysis

Subgroup classification

I classified the participants into two subgroups by evacuation status: evacuees and non-/temporary-evacuees. Based on the pre-incident district-level address, those who were living in the districts denoted compulsory evacuation after the incident (i.e. all the evacuation areas highlighted in Figure 4) were defined as evacuees. Participants who were living outside the compulsory evacuation zones were defined as non-/temporary-evacuees (including voluntary temporary-evacuees). Note that because evacuees usually do not declare their change of address to the city office after their evacuation, the address recorded in the city resident registers collected from the post-incident health check-ups indicated not the evacuation site, but pre-incident dwelling site. Post-incident addresses of the evacuees were not known.

Comparison of clinical characteristics between evacuees and non-/temporary-evacuees

To examine the impact of evacuation on chronic health, I compared clinical characteristics between evacuees and non-/temporary-evacuees by year. In addition, the pre- and post-incident relative risk (RR) of diabetes, hyperlipidemia and hypertension were calculated with adjustment for age by

evacuation status and year, in order to compare change of the disease prevalence after the incident between evacuees and non-/temporary-evacuees. Baseline risk was defined as the average disease prevalence from 2008 to 2010. If an individual took a health check-up more than once in these three years, their more recent data was used in calculating the baseline.

Regression modelling

I conducted regression analyses to assess the impact of evacuation on chronic health, adjusted for covariates. The regression models were constructed separately for diabetes, hyperlipidemia, and hypertension using post incident data (2012 to 2014). Note that because the health check-up in 2011 was performed only months after the incident, many unobserved factors (e.g. environmental, social, and economic factors) that potentially influence disease risk might exist in 2011, and/or variables included in the regression models might have different functions in 2011 than other years. Hence, to prevent possible bias on regression coefficients, I excluded data from 2011 from the analysis. Since every participant had more than two check-ups during the study period, the regression models included a random effect at individual level to control for the fact that the same individual's data were correlated.

I compared disease risk in evacuees versus non-/temporary-evacuees using logistic regression. The radiation level in the residential areas may be a significant factor confounding the evacuation effect because radiation levels may have a strong relationship with psychological stress/anxiety, known to be associated with chronic health conditions.[166,167] However, because the post-incident addresses of the evacuees were not identified, it was impossible to adjust for post-evacuation radiation level. Therefore, to better understand the effect of radiation levels on disease risk, I modelled the associations between the disease risks and radiation levels in non-/temporary-evacuees. Note that in this analysis I included district as a random effect to take into account geographical similarities/differences in the response values for the regressions.

Variables initially entered into the regression models were chosen based on the univariate analyses. Additional model selection was performed using backward-stepwise method with p-to-remove of >0.05.[147] The partial F-test was used to verify the entry and removal of variables from the model. Variables that were known- or suspected- risk factors (e.g. family history) were incorporated into the final model regardless of their statistical significance.

Data analysis, including the spatial data formatting, were conducted using STATA/MP 13 and ArcGIS 10.2.

5 Results

5.1 Question 1: (a) how accurately does the Japanese government's dose reconstruction model estimate the annual external radiation dose among school children 18 to 30 months after the incident, and (b) what uncertainties exist in the model leading to the potential disagreement with the measured dose?

5.1.1 Subject characteristics

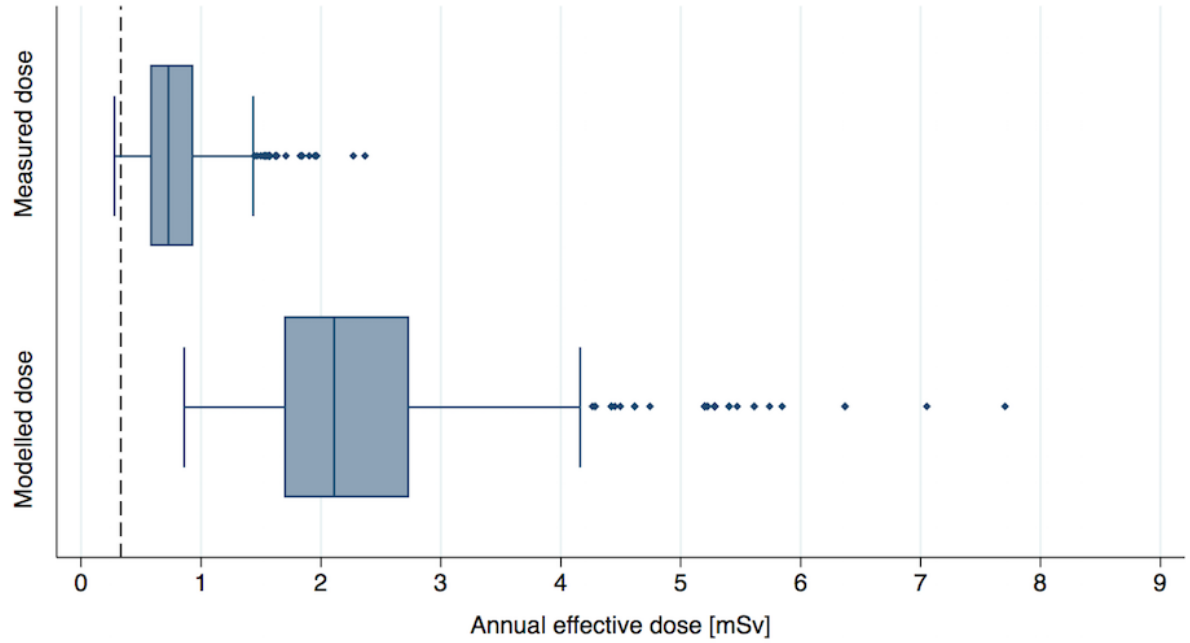
Table 2 describes the subject characteristics (n=520) and mean values of air dose rate at participant's dwelling locations including natural background radiation from the ground, measured and modelled annual effective dose, and ratio of the modelled to measured dose. The air dose rate [μSv/h] ranged from 0.2 to 1.5 (mean: 0.5; SD: 0.2). The inter-quartile range of the measured and modelled dose is shown in Figure 5. The annual average radiation effective dose 18 to 30 months following the incident was 0.8 mSv (SD: 0.3) for direct measurement and 2.4 mSv (SD: 1.0) for the modelled estimation.

Table 2: Subject characteristics in Question 1, air dose rate at dwelling location, annual modelled and measured (using Glass Badge) additional effective dose, and ratio of the modelled to measured dose: mean (standard deviation)

Characteristics	Number	Air dose rate [μSv/h]	Modelled [mSv]	Measured [mSv]	Ratios
Sex					
Male	235	0.5 (0.2)	2.4 (1.1)	0.8 (0.3)	3.1 (1.7)
Female	285	0.5 (0.2)	2.3 (1.0)	0.8 (0.3)	3.0 (1.5)
School-level					
Primary	344	0.5 (0.2)	2.3 (0.9)**	0.7 (0.3)***	3.2 (1.5)***
Secondary	95	0.5 (0.2)	2.6 (1.1)**	0.9 (0.3)***	2.9 (1.6)***
High	81	0.5 (0.2)	2.5 (1.3)**	1.0 (0.4)***	2.6 (1.6)***
Dwelling area					
Rural	369	0.5 (0.2)**	2.5 (1.2)**	0.8 (0.4)	3.1 (1.8)*
Urban	151	0.4 (0.1)**	2.1 (0.4)**	0.8 (0.1)	2.8 (0.7)*
Total	520	0.5 (0.2)	2.4 (1.0)	0.8 (0.3)	3.0 (1.6)

Note: Air dose rare includes natural radiation background from the ground. Modelled dose is based on the government reconstruction model. Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with ≥4,000 people per square kilometre. * $p<0.05$, ** $p<0.01$, *** $p<0.001$ by un-paired t-test (male and female; rural and urban) and one-way ANOVA (primary, secondary, and high) among different groups.

Figure 5: Box plots of the distributions of modelled and measured (using Glass Badge) annual additional effective dose 18 to 30 months following the incident



Note: The dotted line on y-axis at y = 0.33 mSv indicates the level of the background dose from the ground, for reference, which was measured by the Glass Badge at Oarai, Ibaraki Prefecture, Japan, before the Fukushima nuclear incident. Modelled dose is based on the government reconstruction model. Note that both the modelled and measured additional dose presented do not include this background dose.

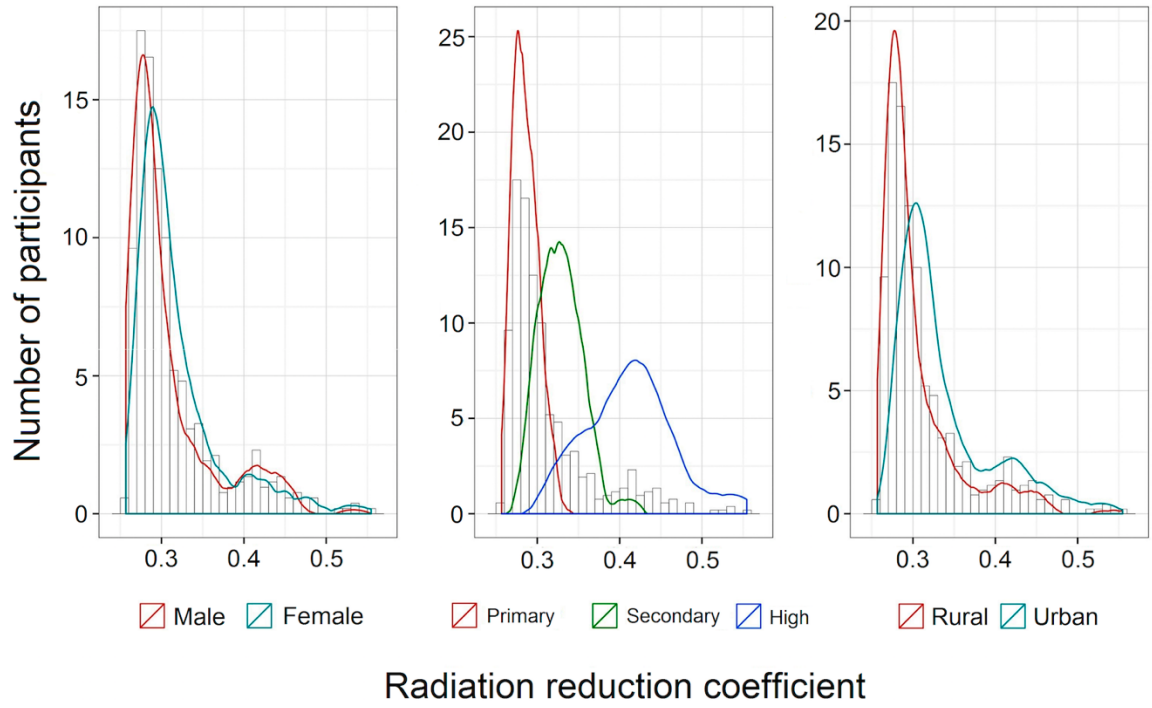
5.1.2 Ratios of modelled versus measured annual effective dose

The modelled annual effective dose was higher than the measured dose in 95% of the participants. The average ratio of the modelled dose to the measured dose among the participants was 3.0 (SD: 1.2) (Table 2), and significantly varied by school-level ($p<0.001$) and dwelling area ($p<0.05$).

5.1.3 Radiation reduction coefficient

Figure 6 shows the histogram of the reduction coefficient with kernel density functions. The mean reduction coefficient was 0.3 (SD: 0.1), which significantly varied by sex ($p<0.05$), school-level ($p<0.001$), and dwelling area ($p<0.001$). Overall, no participants had a reduction coefficient more than 0.6, which is the value used in the government dose estimation model under the assumption that people spend 8 hours outside and 16 hours inside in a building with a shielding effect of 0.4 in a given day.

Figure 6: Histogram of the radiation reduction coefficient with kernel density functions by participants' characteristics (sex, school-level, and dwelling area)



Note: Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with ≥4,000 people per square kilometre.

The air dose rates at schools (mean: 0.2, 0.2, and 0.1 μSv/h; SD: 0.1, 0.1, and 0.0 at main gate, an entrance/exit, and ground, respectively for all school level: Table 3) were substantially lower than those at participants' dwellings (mean: 0.5 μSv/h; SD 0.2 for all participants' dwellings: Table 2) potentially because of decontamination efforts at school, such as weeding, soil scraping or soil replacement.[168] Note that since the Fukushima incident, some municipalities in Fukushima started their own efforts to reduce radiation exposure with the emphasis on children.[168] These parameters were considered in the regression model to estimate the associations of the radiation reduction coefficient with the characteristics and behaviour patterns of the participants, presented below.

Table 3: Air dose rate at schools and decontamination works

	Primary	Secondary	High	Total
Air dose rate [μSv/h]: mean (SD)				
School main gate	0.2 (0.1)	0.2 (0.0)	0.3 (0.1)	0.2 (0.1)
School entrance/exit	0.2 (0.0)	0.2 (0.0)	0.2 (0.1)	0.2 (0.1)
School ground	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)
Soil surface decontamination work: number (%)				
Not completed	13 (4)	0 (0)	15 (21)	28 (6)
Completed	331 (96)	95 (100)	55 (79)	481 (94)

Note: Air dose rare includes natural radiation background from the ground. SD: standard deviation.

The results of the multiple linear regression analysis are shown in Table 4. The White and Breusch-Pagan tests indicated that heteroskedastic residuals were present in the model ($p<0.001$ for both), so robust Huber-White standard errors were employed to establish sufficient statistical significance to allow for heteroskedastic residuals. The following variables were incorporated into the final analysis model: reciprocal-transformed air dose rate, school-level, sex, and behaviour patterns (i.e. the floor in the home where participants spend the majority of the daytime hours and where they sleep at night, commuting time, and time spent outdoors after school or on weekends), adherence indicators (i.e. hours the Glass Badge was worn on a school day and during the weekend), air dose rate in school grounds, and whether soil surface decontamination had been completed in the school. Note that detailed explanation of the behaviour pattern survey results are presented in Question 2.

Table 4: Multiple linear regression model of the relationship between the radiation reduction coefficient and the demographic characteristics and behaviour patterns

Variable	Coefficient	95% CI	P-value
Air dose rate at dwelling location [per μSv/h (reciprocal form)]	0.02	0.01–0.02	<0.001
School-level			
Primary	Ref.		
Secondary	0.05	0.04–0.05	<0.001
High	0.13	0.12–0.14	<0.001
Sex			
Male	Ref.		
Female	0.01	0.01–0.01	<0.001
Floor of room where most daytime hours were spent			
1st floor	Ref.		
2nd floor or higher	0.00	0.00 – 0.01	0.3
Floor of sleeping location			
1st floor	Ref.		
2nd floor or higher	0.00	0.00–0.01	0.6
Commuting time [hour]			
Less than 0.5	Ref.		
More than 0.5	0.00	-0.01–0.00	0.3
Time spent outdoors after school [hour]			
Less than 0.5	Ref.		
0.5–1.0	0.00	-0.01–0.00	0.4
1.0–2.0	-0.01	-0.02–0.00	0.2
More than 2.0	0.00	-0.02–0.01	0.4
Time spent outdoors on a weekend [hour]			
Less than 0.5	Ref.		
0.5–1.0	0.00	-0.01–0.00	0.6
1.0–2.0	0.00	-0.01–0.01	0.9
2.0–4.0	0.00	-0.01–0.00	0.3
More than 4.0	0.00	-0.02–0.01	0.7

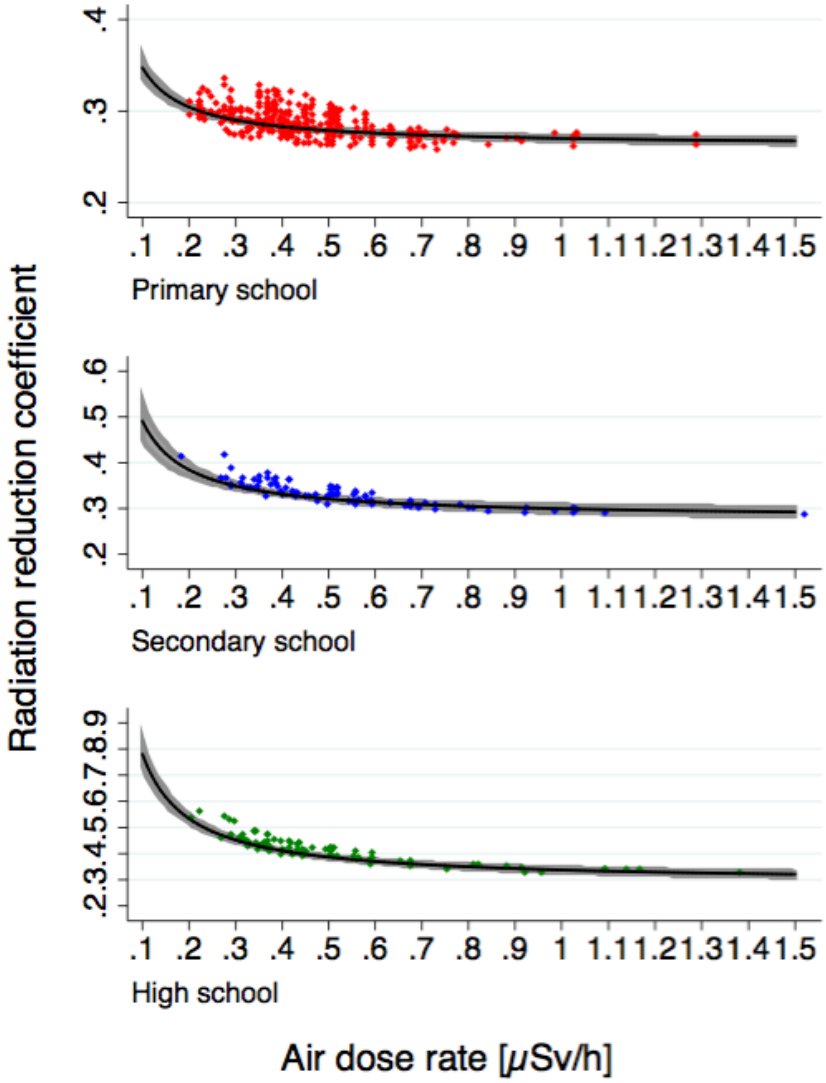
Hours worn on a school day	0.00	0.00–0.00	1.0
Hours worn on a weekend	0.00	0.00–0.00	1.0
Air dose rate in school ground [per μSv/h]	0.00	0.00–0.00	<0.001
Soil surface decontamination			
Not completed	Ref.		
Completed	0.01	0.00–0.02	0.3

Note: Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively.

I observed a substantial negative correlation between the reduction coefficient and the air dose rate at dwelling location ($p<0.001$), which may indicate that the difference between air dose rate indoors and outdoors at a household was larger in areas with higher air dose rate levels. In other words, the radiation exposure risks indoors might be suppressed even in areas with higher air dose rate levels, possibly due to decontamination efforts and countermeasures to reduce the exposure risk indoors. There were also slight differences in reduction coefficient by school-level (coefficient: 0.05 for secondary school children ($p<0.001$) and 0.13 for high school children ($p<0.001$) in reference to primary school children) after adjusting for behaviour patterns, including time spent outdoors after school or on weekends. This suggests secondary and high school children might be exposed to more radiation than primary school children (in keeping with the measured dose: Table 2) which might be due to unobserved/unadjusted school-level-specific factors, such as extracurricular activities, including clubs and sports. Sex and air dose rate in the school ground also had significant relationships with the reduction coefficient, but their effect sizes were nearly zero.

Figure 7 shows the regression prediction of the adjusted radiation reduction coefficient against air dose rate based on the model presented in Table 4. Because I observed substantial associations between the reduction coefficient and school-level, the prediction estimates were established by school-level. The radiation reduction coefficient tended to converge at around 0.3 irrespective of school-level as the air dose rate increased. Regarding lower air dose rates (below 0.2–0.3 μSv/h), there was a steep decrease in radiation reduction coefficient with increasing air dose rate (Figure 7).

Figure 7: Regression prediction of the adjusted radiation reduction coefficient with 95% confidence bounds separated by school-level against air dose rate at dwelling location [µSv/h]



Note: Each dot indicates one participant. Air dose rate includes natural radiation background from the ground. Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively.

5.2 Question 2: Dependence of external radiation dose on behavioural patterns among school children 18 to 20 months after the incident

5.2.1 Subject characteristics

Demographic characteristics of the 520 participants included in this analysis are shown in Table 5. No significant differences in these characteristics were observed between the school-levels.

Table 5: Subject characteristics in Question 2: number (%)

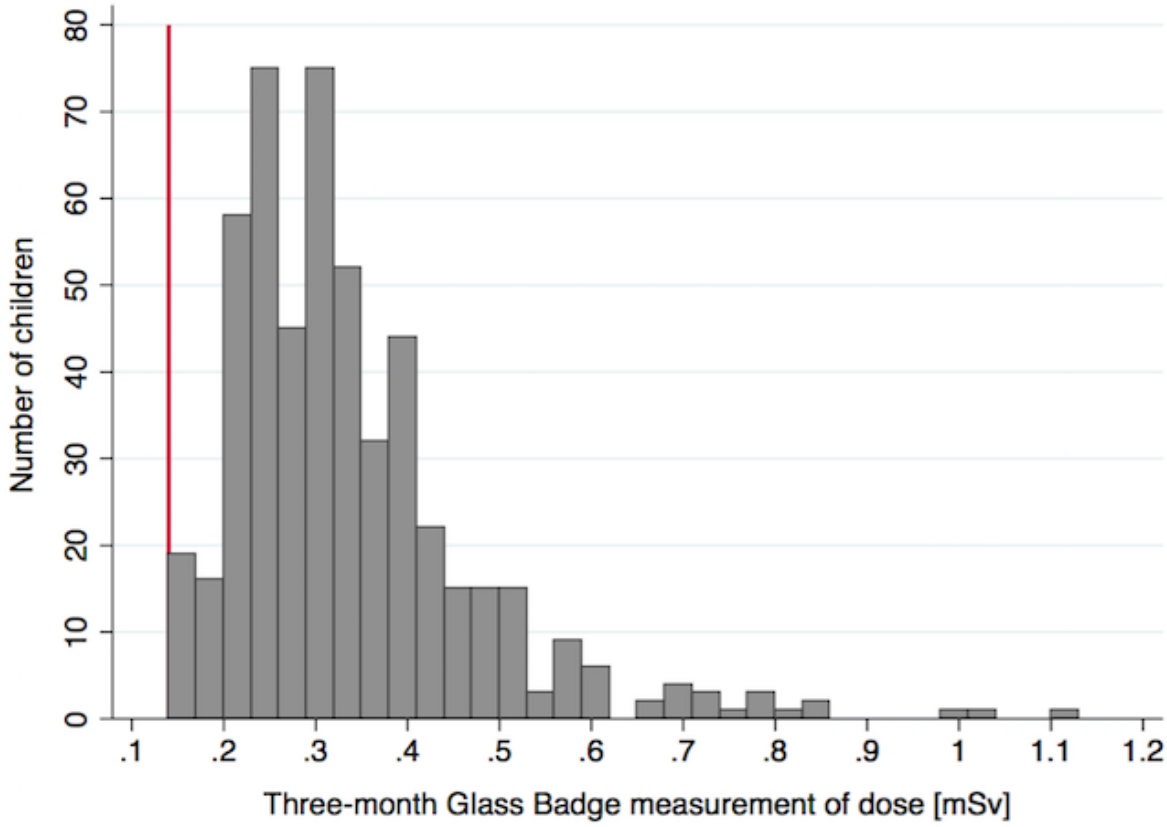
Characteristics	Primary	Secondary	High	Total
Sex				
Male	163 (47.4)	35 (36.8)	37 (45.7)	235 (45.2)
Female	181 (52.6)	60 (63.2)	44 (54.3)	285 (54.8)
Dwelling area				
Rural	252 (73.3)	64 (67.4)	53 (65.4)	369 (71.0)
Urban	92 (26.7)	31 (32.6)	28 (34.6)	151 (29.0)

Note: Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with ≥4,000 people per square kilometre.

5.2.2 Glass Badge measurements of dose

The distribution of dose measured via Glass Badge over the three-month study period is shown in Figure 8, illustrating the left-censoring at 0.14 mSv. Table 6 presents the measured dose by participant characteristics. The mean dose for all 520 individuals was 0.34 mSv (SD: 0.14). High school children showed significantly higher doses than primary school children by 0.06 mSv ($p<0.05$) and secondary school children by 0.02 mSv ($p<0.001$). Differences by sex and dwelling areas (rural or urban) were not observed.

Figure 8: Histogram of the three-month Glass Badge measurement of dose 18 to 20 months following the incident



Note: The red line on the x-axis at x = 0.14 mSv indicates the background dose and the left-censoring effect of the Glass Badge measurement (which includes this background dose). The bin width is 0.03 mSv.

Table 6: Three-month measurements of total dose [mSv] using Glass Badge: mean (standard deviation)

Characteristics	Dose [mSv]
Sex	
Male	0.34 (0.13)
Female	0.34 (0.14)
Dwelling area	
Rural	0.34 (0.14)
Urban	0.33 (0.12)
School-level*	
Primary	0.32 (0.14)
Secondary	0.36 (0.11)
High	0.38 (0.12)

Note: This dose incudes the natural background radiation dose. Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with

≥4,000 people per square kilometre.* p<0.001 by ANOVA: significant differences were observed between primary vs. secondary (p<0.05) and primary vs. high (p<0.001) by Scheffé's test.

5.2.3 Behavioural survey results

Differences in behaviour by school-level were explored (Table 7). With regard to behaviours at home (Table 7: Part 1), significant differences were observed in terms of the room where most of the daytime hours were spent (p<0.001). While 29.4% of the secondary and 37.5% of the high school children spent most daytime hours in their own rooms, 89.6% of the primary school children spent the majority of their time in a living (family) room. There were also differences by school-level regarding the room where children slept (p<0.001). For behaviours while commuting to school (Table 7: Part 2), both the commuting time and the commuting means differed by school-level (p<0.001). Primary children were found to be more likely to travel to school by car (80.2%), with a commute time of less than 30 minutes for 91.4%. For 45.7% of the high school children, the commute time to school was more than 30 minutes. For behaviours at school, a difference was observed in places where most lunch breaks were spent, times partaking in outdoor exercise per week, and outdoor/indoor sports club/culture club (p<0.001 for all) (Table 7: Part 3). For behaviours after school and on weekends, place (indoor or outdoor) and hours outside after school significantly differed by school-level (Table 7: Part 4).

Table 7: Behavioural patterns of the study participants by school-level: number (%)

	Primary	Secondary	High	Total
Part 1: At home				
Attempted to reduce the exposure risk				
No	226 (68.1)	58 (63.7)	55 (71.4)	339 (67.8)
Yes	106 (31.9)	33 (36.3)	22 (28.6)	161 (32.2)
Learned countermeasures from parents				
No	135 (42.5)	39 (45.9)	37 (50)	211 (44.2)
Yes	183 (57.5)	46 (54.1)	37 (50)	266 (55.8)
Room where most daytime hours were spent***				
Living (family) room	302 (89.6)	60 (70.6)	50 (62.5)	421 (82.4)
Own room	35 (10.4)	25 (29.4)	30 (37.5)	90 (17.6)
Floor of room where most daytime hours were spent				
1st floor	266 (81.8)	64 (73.6)	56 (72.7)	386 (78.9)
2nd floor or higher	59 (18.2)	23 (26.4)	21 (27.3)	103 (21.1)
Place to sleep***				
Living (family) room	44 (13.2)	8 (8.7)	4 (5.0)	56 (11.1)
Own room	196 (58.9)	69 (75.0)	73 (91.3)	338 (66.9)
Other	93 (27.9)	15 (16.3)	3 (3.8)	111 (22.0)
Floor of place to sleep				

1st floor	133 (40.7)	34 (38.6)	24 (30.4)	191 (38.7)
2nd floor or higher	194 (59.3)	54 (61.4)	55 (69.6)	303 (61.3)
Part 2: During Commute				
School commuting time [hour]***				
Less than 0.5	309 (91.4)	80 (85.1)	44 (54.3)	433 (84.4)
More than 0.5	29 (8.6)	14 (14.9)	37 (45.7)	80 (15.6)
School commuting means***				
Bus	19 (5.6)	2 (2.2)	1 (1.5)	22 (4.4)
Car	271 (80.2)	44 (47.3)	16 (23.9)	331 (66.5)
Bicycle	6 (1.8)	23 (24.7)	37 (55.2)	66 (13.3)
Walk	42 (12.4)	24 (25.8)	13 (19.4)	79 (15.9)
Part 3: At school				
Seat position in the classroom				
Window area	89 (26.9)	26 (29.5)	23 (30.3)	138 (27.9)
Center area	153 (46.2)	34 (38.6)	29 (38.2)	216 (43.6)
Passage area	54 (16.3)	22 (25.0)	19 (25.0)	95 (19.2)
Not decided	35 (10.6)	6 (6.8)	5 (6.6)	46 (9.3)
Number of times outdoor exercise was done per week***				
Zero	35 (11.5)	33 (41.8)	12 (16.0)	80 (17.5)
Once	78 (25.7)	16 (20.3)	25 (33.3)	119 (26.0)
Twice	99 (32.6)	15 (19.0)	22 (29.3)	136 (29.7)
More than thrice	92 (30.3)	15 (19.0)	16 (21.3)	123 (26.9)
Place where most lunch break hours were spent***				
Indoors	186 (56.9)	83 (95.4)	76 (97.4)	345 (70.1)
Outdoors	141 (43.1)	4 (4.6)	2 (2.6)	147 (29.9)
Outdoor sports club***				
No	320 (93.0)	74 (77.9)	66 (81.5)	460 (88.5)
Yes	24 (7.0)	21 (22.1)	15 (18.5)	60 (11.5)
Indoor sports club***				
No	290 (84.3)	54 (56.8)	57 (70.4)	401 (77.1)
Yes	54 (15.7)	41 (43.2)	24 (29.6)	119 (22.9)
Indoor culture club***				
No	311 (90.4)	68 (71.6)	65 (80.2)	444 (85.4)
Yes	33 (9.6)	27 (28.4)	16 (19.8)	76 (14.6)
Part 4: After school and on weekends				
Place where most after-school hours were spent*				
Indoors	319 (97.0)	89 (100.0)	72 (92.3)	480 (96.8)
Outdoors	10 (3.0)	0 (0.0)	6 (7.7)	16 (3.2)
Hours spent outdoors after school [hour]**				
Less than 0.5	199 (60.3)	49 (52.7)	31 (39.7)	279 (55.7)
0.5–1.0	102 (30.9)	31 (33.3)	28 (35.9)	161 (32.1)
1.0–2.0	18 (5.5)	9 (9.7)	10 (12.8)	37 (7.4)
More than 2.0	11 (3.3)	4 (4.3)	9 (11.5)	24 (4.8)
Place where most daytime hours were spent on weekends				
Indoors	291 (91.8)	85 (96.6)	74 (96.1)	450 (93.4)
Outdoors	26 (8.2)	3 (3.4)	3 (3.9)	32 (6.6)

Hours spent outdoors on weekends [hour]				
Less than 0.5	104 (31.2)	34 (39.5)	34 (43.6)	172 (34.6)
0.5–1.0	103 (30.9)	27 (31.4)	18 (23.1)	148 (29.8)
1.0–2.0	73 (21.9)	13 (15.1)	19 (24.4)	105 (21.1)
2.0–4.0	38 (11.4)	10 (11.6)	4 (5.1)	52 (10.5)
More than 4.0	15 (4.5)	2 (2.3)	3 (3.8)	20 (4.0)
Glass Badge equipment adherence				
Hours worn on a school day: mean (SD)	10.22 (4.12)	13.38 (6.22)	12.99 (5.55)	11.18 (4.95)
Hours worn on a weekend: mean (SD)	7.24 (6.12)	10.64 (8.39)	10.44 (7.50)	8.28 (6.90)

Note: * p<0.05, ** p<0.01, *** p<0.001 by Chi-squared test. SD: standard deviation.

5.2.4 Relationship of behavioural patterns to the dose

Results of the multiple Tobit regression model, including a random effect for schools, are shown in Table 8. In this analysis, variables that were considered of public interest were incorporated into the final model regardless of their statistical significance. These results indicate that behaviours related to outdoor activities, such as commuting hours and means of transport, number of outdoor class exercises per week, outdoor sports clubs, and hours spent outdoors after school and on weekends, had no statistically significant relationship with dose over the three-month period. Meanwhile, a 0.1 μSv/h increase in air dose rate at dwelling location was associated with a 10% increase in measured dose (p<0.001). A 2% increase in the dose per 0.01 μSv/h increase in the air dose rate at the school ground was observed (p<0.05). In addition, after adjusting for covariates, the dose in students sitting in the central areas in classrooms were lower by 10% than in students sitting in the window seats (p<0.01).

Table 8: Multiple Tobit regression model with a random effect for schools

Variable	Relative increase in dose (95% CI)
Air dose rate levels	
Air dose rate at dwelling location [per 0.1 μSv/h]	1.10 (1.08–1.12)***
Air dose rate in the school ground [per 0.01 μSv/h]	1.02 (1.00–1.03)*
Basic demographic characteristics	
Age	1.01 (0.99–1.03)
Sex	
Male	Ref.
Female	1.03 (0.97–1.09)
Dwelling area	
Rural	Ref.
Urban	1.04 (0.97–1.12)
School-level	
Primary	Ref.
Secondary	1.08 (0.94–1.25)
High	1.06 (0.87–1.31)
Behavioural patterns at home	

Room where most daytime hours were spent at home	
Living (family) room	Ref.
Own room	1.11 (0.99–1.23)
Floor of room where most daytime hours were spent at home	
1st floor	Ref.
2nd floor or higher	0.90 (0.82–1.00)
Place to sleep	
Living (family) room	Ref.
Own room	1.00 (0.90–1.12)
Other	1.11 (0.99–1.25)
Floor of place to sleep	
1st floor	Ref.
2nd floor or higher	1.01 (0.94–1.09)
Behavioural patterns during commute	
School commuting time [hour]	
Less than 0.5	Ref.
More than 0.5	1.00 (0.90–1.11)
School commuting means	
Bicycle or walk	Ref.
Car	0.97 (0.90–1.04)
Bus	0.93 (0.79–1.10)
Behavioural patterns at school	
Seat position in the classroom	
Window area	Ref.
Center area	0.90 (0.84–0.97)**
Passage area	0.95 (0.87–1.03)
Not known	0.95 (0.85–1.07)
Number of times outdoor class exercise was done per week	
Zero	Ref.
Once	1.06 (0.96–1.16)
Twice	1.01 (0.92–1.11)
More than thrice	1.04 (0.94–1.14)
Outdoor sports club at school	
No	Ref.
Yes	1.00 (0.91–1.11)
Behavioural patterns after school and on weekends	
Hours spent outdoors after school [hour]	
Less than 0.5	Ref.
0.5–1.0	1.03 (0.97–1.10)
More than 1.0	0.98 (0.89–1.09)
Hours spent outdoors on weekends [hour]	
Less than 0.5	Ref.
0.5–1.0	0.98 (0.91–1.06)
1.0–2.0	1.04 (0.96–1.13)
More than 2.0	0.96 (0.87–1.07)

Note: The relative increase in dose shown includes mutual adjustment for all other variables in the table. Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with ≥4,000 people per square kilometre. * p<0.05, ** p<0.01, *** p<0.001. CI: confidence interval.

Note that although a significant difference was found in the mean dose by school-level (Table 6), the statistical significance of this difference disappeared after adjusting for covariates in the regression analysis (Table 8). Therefore, I analysed the school-level differences in air dose rate at dwelling location and school (Table 9). As explained in Question 1 above (section 5.1.3), air dose rate at dwelling location was significantly higher than that at school, potentially because of decontamination efforts at school, such as weeding, soil scraping or soil replacement.[168] Statistically significant differences in air dose rates at dwelling location and school were observed by school-level. In particular, air dose rate at primary and secondary school was much lower than that at high-school, which might be explained by the city's particular emphasis on younger children for decontamination efforts. Therefore, these results may indicate that the differences in the measured dose by school-level might be mostly explained by the school-level differences in air dose rates at dwelling location and school.

Table 9: Air dose rate at a height of 1 m above ground at dwelling location and school [μSv/h]: mean (standard deviation)

	Primary	Secondary	High	Total
Dwelling location*	0.47 (0.17)	0.54 (0.21)	0.52 (0.25)	0.49 (0.20)
School main gate**	0.21 (0.06)	0.22 (0.05)	0.30 (0.07)	0.22 (0.06)
School entrance/exit***	0.16 (0.05)	0.17 (0.03)	0.25 (0.10)	0.17 (0.06)
School ground****	0.11 (0.03)	0.11 (0.02)	0.15 (0.04)	0.11 (0.03)

Note: The air dose rate includes the background dose from the ground. * $p<0.001$ by ANOVA: significant differences were observed between primary vs. secondary ($p<0.01$) by Scheffé's test; ** $p<0.001$ by ANOVA: significant differences were observed between primary vs. secondary ($p<0.05$), primary vs. high ($p<0.001$), and secondary vs. high ($p<0.001$) by Scheffé's test; *** $p<0.001$ by ANOVA: significant differences were observed between primary vs. high ($p<0.001$) and secondary vs. high ($p<0.001$) by Scheffé's test; **** $p<0.001$ by ANOVA: significant differences were observed between primary vs. high ($p<0.001$) and secondary vs. high ($p<0.001$) by Scheffé's test.

5.3 Question 3: (a) what are the characteristics of school children who do not use the dosimeters correctly, and (b) how much error is generated by improper use of the dosimeters 18 to 20 months after the incident?

5.3.1 Subject characteristics

The demographic characteristics of the participants (n=1,637) are summarized in Table 10. The majority of the participants were primary school children (65.2%), and the majority lived in a rural area (an area with <4,000 people per square kilometre) (69.0%). There was a fairly even split by sex (52.4% female). The mean air dose rates at a height of 1 m above the ground at dwelling location, on the school grounds, at the main gate and at the building entrance/exit of the school were 0.49, 0.11, 0.22, and 0.17 μSv/h, respectively (Table 9).

Table 10: Subject characteristics in Question 3: number (%)

		Numbers (%) of non-users				
Characteristics†	Total	To school	At school††	At home	Outdoors	At bedtime
School-level						
Primary	1,068 (65.2)	55 (5.2)	287 (28.3)	785 (73.5)**	537 (50.3)**	788 (73.8)***
Secondary	371 (22.7)	23 (6.2)	115 (33.1)	239 (64.4)**	211 (56.9)**	232 (62.5)***
High	198 (12.1)	11 (5.6)	55 (29.4)	127 (64.1)**	83 (41.9)**	113 (57.1)***
Sex						
Male	779 (47.6)	44 (5.7)	233 (31.7)	546 (70.1)	401 (51.5)	527 (67.7)
Female	858 (52.4)	45 (5.2)	224 (27.6)	605 (70.5)	430 (50.1)	606 (70.6)
Dwelling area						
Rural	1,130 (69.0)	69 (6.1)	316 (29.8)	814 (72.0)*	566 (50.1)	798 (70.6)
Urban	507 (31.0)	20 (3.9)	141 (29.0)	337 (66.5)*	265 (52.3)	355 (66.1)
Total	1,637	89 (5.4)	457 (29.5)	1,151 (70.3)	831 (50.8)	1,133 (69.2)

Note: Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with ≥4,000 people per square kilometre. * p<0.05, ** p<0.01, *** p<0.001 by Chi-squared test for each column by characteristics. † Chi-squared tests for each row by characteristics were all statistically significant with p<0.001. †† Note that those who did not wear/bring the Glass Badge to school were not included in the 'at school' column.

5.3.2 Profiles of school children who improperly used the Glass Badge

Only 119 children (7.3%) wore the Glass Badge during all time periods (commuting time, at school, after school, at home, outdoors, and at bedtime) in a day (i.e. used the dosimeters properly). As shown in Table 10, a large gap between use at home and use at school was observed. Many did not properly use the dosimeters (i.e. not hung from the neck, or not keep nearby) when they were at home (70.3%)

and sleeping (69.2%). On the other hand, most of the children wore the dosimeters to school (94.6%), and they were also likely to use the dosimeters at school (70.5%).

Table 11 shows the results of logistic regression analyses to assess the covariates associated with non-use of the dosimeters. After adjusting for covariates, school-level was significantly associated with non-use at home, outdoors, and at bedtime. Younger children (i.e. primary/secondary school children) were significantly less likely to wear the dosimeters during these time periods/at these locations than high school children. Other significant factors associated with non-use of the dosimeters were the air dose rate at dwelling location, sex, membership in outdoor sports clubs, and hours spent outdoors on weekends. Children living in areas with a higher air dose rate at dwelling location had lower odds of non-use at school (OR: 0.91 per 0.1 μSv/h increase; 95% CI: 0.85–0.98; $p<0.05$), indicating that children who had higher air dose rate levels at home were more likely to wear the dosimeter at school. Females had lower odds of non-use at school than males (OR: 0.74; 95% CI: 0.59–0.94; $p<0.05$). Those who belonged to outdoor sports clubs were less likely to use the dosimeters when they were outdoors (OR: 1.38; 95% CI: 1.00–1.90; $p<0.05$). Similarly, the odds of non-use among children who spent more than 2 hours outdoors on weekends was 1.53 times higher than that of those who spent less than 30 minutes outdoors (95% CI: 1.14–2.06; $p<0.01$), indicating that children who spent more time outdoors were less likely to wear the dosimeters outdoors. Likelihood of wearing the dosimeters to school was not associated with any variables.

Table 11: Odds ratio and 95% confidence interval of non-use of the Glass Badge for specific time periods in a day

Variable	To school	At school	At home	Outdoors	At bedtime
Air dose rate at dwelling location [per 0.1 μSv/h]	0.89 (0.78–1.02)	0.91 (0.85–0.98)*	0.98 (0.92–1.04)	0.97 (0.91–1.02)	0.94 (0.88–1.01)
School-level					
Primary	0.94 (0.42–2.12)	1.32 (0.76–2.28)	1.09 (0.75–1.58)	1.79 (1.25–2.56)**	1.23 (0.85–1.80)
Secondary	0.66 (0.30–1.45)	0.86 (0.53–1.37)	1.68 (1.19–2.36)**	1.39 (1.02–1.91)*	2.00 (1.42–2.81)***
High	Ref.	Ref.	Ref.	Ref.	Ref.
Sex					
Male	Ref.	Ref.	Ref.	Ref.	Ref.
Female	0.89 (0.57–1.38)	0.74 (0.59–0.94)*	1.11 (0.89–1.38)	1.01 (0.82–1.24)	1.20 (0.94–1.53)
Dwelling area					
Rural	Ref.	Ref.	Ref.	Ref.	Ref.
Urban	0.67 (0.39–1.15)	0.87 (0.66–1.14)	0.77 (0.61–0.98)*	1.06 (0.85–1.32)	0.81 (0.62–1.06)
School commuting time [hour]					
Less than 0.5	Ref.	–	–	–	–
More than 0.5	0.87 (0.43–1.78)	–	–	–	–
School commuting means					
Walk/bicycle	Ref.	–	–	–	–
Car	1.43 (0.81–2.50)	–	–	–	–
Bus	1.94 (0.74–5.12)	–	–	–	–
Sports clubs (outdoors)					
No	–	Ref.	–	Ref.	–
Yes	–	0.73 (0.51–1.04)	–	1.38 (1.00–1.90)*	–
Sports clubs (indoors)					
No	–	Ref.	–	–	–
Yes	–	0.88 (0.66–1.18)	–	–	–
Seat position in the classroom					
Window area	–	Ref.	–	–	–
Centre area	–	1.08 (0.81–1.42)	–	–	–
Passage area	–	0.97 (0.69–1.36)	–	–	–
Not decided	–	1.06 (0.68–1.65)	–	–	–

Room where most daytime hours were spent at home					
Living (family) room	–	–	Ref.	–	–
Own room	–	–	1.22 (0.84–1.77)	–	–
Floor of room where most daytime hours were spent at home					
1st floor	–	–	Ref.	–	–
2nd floor or higher	–	–	0.85 (0.61–1.17)	–	–
Hours spent outdoors on weekends [hour]					
Less than 1.0	–	–	–	Ref.	–
1.0–2.0	–	–	–	1.01 (0.79–1.29)	–
More than 2.0	–	–	–	1.53 (1.14–2.06)**	–
Sleeping place					
Living (family) room	–	–	–	–	Ref.
Own room	–	–	–	–	0.88 (0.58–1.34)
Floor of sleeping place					
1st floor	–	–	–	–	Ref.
2nd floor or higher	–	–	–	–	0.89 (0.68–1.17)

Note: Primary, secondary, and high school children are aged 7–12, 13–15, and 16–18, respectively. Urban areas are defined as an area with ≥4,000 people per square kilometre. * p<0.05, ** p<0.01, *** p<0.001.

5.3.3 Comparison of measured dose versus regression estimates of dose

The data from the 119 children who properly used the Glass Badges at all times/locations was employed to construct the dose prediction model. The estimated final model included the following variables: air dose rate at dwelling location and on school grounds, sex, dwelling area (urban/rural), school-level, floor of room where most daytime hours were spent at home, floor of sleeping place, seat position in the classroom, and hours spent outdoors after school and on the weekend. Using this model, the 'expected' dose values of the remaining children (n=1,518) were predicted. The measured and predicted doses are compared in Table 12. Note that the time-period-specific comparison (to school, at school, at home, outdoors, or at bedtime) employed those who reported non-compliance during the specified time period. Although the overall comparison showed no statistically significant difference between the measured and predicted doses, time-period-specific comparisons of 'to school' and 'outdoors' showed significant differences. The mean measured dose of those who wore the dosimeters to school was higher than their predicted dose by 0.04 mSv ($p<0.01$: paired t-test), representing a 13% difference from the predicted value. In addition, the measured dose of children who did not wear the dosimeters outdoors was 0.01 mSv lower than the predicted dose on average ($p<0.05$), indicating a 3% difference.

Table 12: Comparison of the three-month measured dose (using Glass badge) and regression estimates of total dose: mean (standard deviation)

	Number	Measured dose [mSv]	Estimated dose [mSv]	Ratios
Overall	1,518	0.33 (0.11)	0.33 (0.09)	0.99 (0.35)
Time period				
To school	89	0.37 (0.14)	0.32 (0.07)	1.13 (0.43)**
At school	457	0.32 (0.10)	0.33 (0.09)	0.98 (0.31)
At home	1,151	0.33 (0.11)	0.33 (0.09)	0.99 (0.34)
Outdoors	831	0.32 (0.10)	0.33 (0.09)	0.97 (0.33)*
At bedtime	1,133	0.33 (0.11)	0.33 (0.09)	0.99 (0.35)

Note: The presented dose includes the natural background radiation dose. * $p<0.05$, ** $p<0.01$ by paired t-test. The time-period-specific comparison employed those who reported non-compliance during the specified time period.

5.3.4 Robustness of the regression prediction

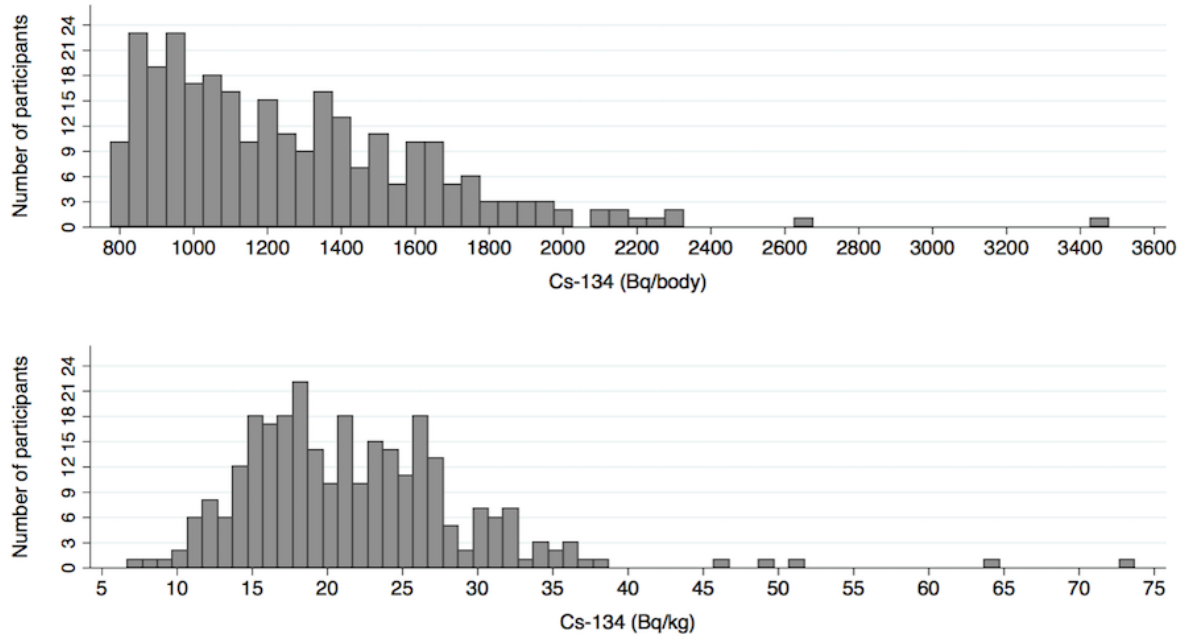
The pseudo R-squared values from the Tobit model were compared with those derived from the CART model pruned by ten-fold cross-validation with the deviance criterion rule to assess the prediction accuracy of the Tobit model. As a result, I obtained pseudo R-squared values of 0.86 for the Tobit model and 0.70 for the CART model, indicating that the Tobit model was slightly more predictive.

5.4 Question 4: what are the relationships between early evacuation and levels of internal radiation exposure among adults four months after the incident?

5.4.1 Subject characteristics

The geographical distribution of the study participants (n=519) is shown in Figure 9. In the screening program, 279 participants (53.4%) had detectable levels of Cs-134 contamination (≥800 Bq/body). Histograms of Cs-134 [Bq/kg] among the participants with detectable levels are shown in Figure 9.

Figure 9: Distribution of Cs-134 burden [Bq/body] (top) and body concentration [Bq/kg] (bottom) detected among participants



Note: The bin width is 50 Bq/body and 1 Bq/kg, respectively.

Table 13 shows participant characteristics. The mean age of the participants was 56.0 with SD of 17.7, and 54.9% were female. Thirty percent of the participants usually worked outdoors, and the percentage of participants who spent more than 5 hours outdoors per day dropped from 27.4% before the incident to 11.9% after the incident. In terms of early evacuation, 40.3% of the participants evacuated to areas outside Fukushima Prefecture, 44.7% evacuated within the Prefecture, and 15.0% did not evacuate at all following the incident. This pattern of evacuation location (i.e. to areas outside vs. inside the Prefecture) did not differ by age (p=0.21: ANOVA) or sex (p=0.06: Chi-squared test), although there was a significant association between evacuation status (i.e. evacuated or not) and

occupation (p=0.03: Chi-squared test) with outdoor workers less likely to evacuate. The relationship between evacuation location and evacuation date is presented in Table 14, showing that earlier evacuation tended to be within Fukushima Prefecture, and later evacuation predominantly outside the prefecture. Regarding daily precautionary activities following the incident, while many participants wore masks (62.8%) and washed their hands and gargled (62.4%), fewer participants gave additional consideration to selection or preparation of foodstuffs or use of tap water (21.2% and 22.4%, respectively).

Table 13: Subject characteristics in Question 4

Characteristics	Number (%)
Sex	
Male	234 (45.1)
Female	285 (54.9)
Age at test	
16–25	33 (6.4)
26–35	57 (11.0)
36–45	43 (8.3)
46–55	79 (15.2)
56–65	156 (30.1)
66–75	78 (15.0)
76–85	63 (12.1)
86–95	10 (1.9)
Occupation	
Outdoor worker	152 (29.3)
Indoor worker	51 (9.8)
Unemployed	85 (16.4)
Housewife	62 (11.9)
Other	169 (32.6)
Evacuation location	
Outside Fukushima Prefecture	209 (40.3)
Inside Fukushima Prefecture	232 (44.7)
No evacuation	78 (15.0)
Evacuation date in March 2011	
11th	7 (1.4)
12th	59 (11.4)
13th	24 (4.6)
14th	61 (11.8)
15th	63 (12.1)
16th	70 (13.5)
17th	57 (11.0)
18th	60 (11.6)
19th	23 (4.4)
After 20th	17 (3.3)
Commute time to office/school [minutes]	
Less than 30	226 (43.5)
More than 30	79 (15.2)
Time spent outside per day before the incident [hours]	

Less than 5.0	377 (72.6)
More than 5.0	142 (27.4)
Time spent outside per day after the incident [hours]	
Less than 5.0	457 (88.1)
More than 5.0	62 (11.9)
Daily precautionary activities	
Wear masks	326 (62.8)
Wash hands/gargle	324 (62.4)
Avoid certain foods	110 (21.2)
Avoid tap water	116 (22.4)
Wash vegetables	248 (47.8)

Table 14: Cross tabulation of evacuation location and evacuation date in March 2011: number (%)

	Evacuation location	
Evacuation date	Inside Fukushima	Outside Fukushima
11th	3 (1.3)	4 (1.9)
12th	48 (20.7)	11 (5.3)
13th	20 (8.6)	4 (1.9)
14th	49 (21.1)	12 (5.7)
15th	44 (19.0)	19 (9.1)
16th	24 (10.3)	46 (22.0)
17th	22 (9.5)	35 (16.8)
18th	16 (6.9)	44 (21.1)
19th	2 (0.9)	21 (10.1)
After 20th	4 (1.7)	13 (6.2)
Total	232	209

5.4.2 Regression analyses

Table 15 shows the results of Regression 1 using the whole dataset to examine the effect of early evacuation on the levels of Cs-134 body concentration four months following the incident. Covariates that remained in the model were: sex; age at WBC measurement; height; examination date; occupation; time spent outside per day after the incident; evacuation location; and daily precautionary activities.

Table 15: Tobit multiple regression model of levels of Cs-134 body concentration by evacuation location

Variable	Relative level	95% CI	P-value
Sex			
Male	Ref.		
Female	0.96	0.83–1.10	0.6
Age at test [years]	1.00	1.00–1.01	0.1
Height [per 10 cm]	0.90	0.83–0.97	<0.01
Examination date [days after the incident]	0.98	0.97–0.99	<0.001
Occupation			
Outdoor worker	Ref.		
Indoor worker	1.02	0.82–1.25	0.9
Unemployed	0.89	0.76–1.04	0.1
Housewife	1.06	0.89–1.27	0.5
Other	0.98	0.85–1.12	0.7
Time spent outside per day after the incident [hours]			
Less than 5.0	Ref.		
More than 5.0	0.96	0.82–1.12	0.6
Evacuation location			
No evacuation	Ref.		
Inside Fukushima Prefecture	0.88	0.76–1.02	0.1
Outside Fukushima Prefecture	0.86	0.74–0.99	<0.05
Daily precautionary activities			
Wear masks	1.01	0.91–1.12	0.9
Wash hands/gargle	1.02	0.92–1.14	0.7
Avoid certain foods	1.03	0.91–1.16	0.7
Avoid tap water	0.90	0.80–1.02	0.1
Wash vegetables	0.97	0.88–1.08	0.6

Note: CI: confidence interval.

The model indicated that time spent outdoors had no significant relationship with the level of Cs-134 body concentration, but evacuation to areas outside Fukushima Prefecture was statistically significantly associated, although not by much, with the contamination level (relative level: 0.86, in reference to non-evacuation; $p<0.05$).

Table 16 presents results of Regression 2 assessing the impact of the timing of evacuation on the level of Cs-134 body concentration four months following the incident using data of evacuees to areas outside Fukushima Prefecture. Covariates that remained in the model were: sex; age at WBC measurement; height; examination date; occupation; time spent outside per day after the incident; evacuation date; and daily precautionary activities. The evacuation date did not show a significant association with the levels of Cs-134 body concentration, after adjustment for participant characteristics. As a sensitivity analysis, I used different classifications of evacuation date (for example,

the first week following the incident or later, before 20th and after 20th), but similar results were obtained.

Table 16: Tobit multiple regression model of exposure risk by evacuation date

Variable	Relative level	95% CI	P-value
Sex			
Male	Ref.		
Female	1.08	0.89–1.32	0.4
Age at test	1.01	1.00–1.01	<0.05
Height [10 cm]	0.97	0.87–1.09	0.6
Examination date	0.99	0.97–1.00	<0.05
Occupation			
Outdoor worker	Ref.		
Indoor worker	1.24	0.89–1.72	0.2
Unemployed	1.00	0.79–1.25	1.0
Housewife	1.16	0.90–1.51	0.3
Other	0.95	0.78–1.18	0.7
Time spent outside per day after the incident [hour]			
Less than 5.0	Ref.		
More than 5.0	0.86	0.67–1.10	0.2
Evacuation date in March			
After 20th	Ref.		
11th	0.86	0.45–1.65	0.7
12th	1.30	0.84–2.03	0.2
13th	0.93	0.50–1.74	0.8
14th	0.99	0.64–1.55	1.0
15th	1.06	0.70–1.60	0.8
16th	0.99	0.70–1.39	1.0
17th	1.05	0.74–1.50	0.8
18th	0.97	0.68–1.36	0.9
19th	0.82	0.55–1.21	0.3
Daily precautionary activities			
Wear masks	0.93	0.80–1.08	0.4
Wash hands/gargle	0.96	0.81–1.14	0.7
Avoid certain foods	0.99	0.83–1.18	0.9
Avoid tap water	0.96	0.80–1.16	0.7
Wash vegetables	0.98	0.84–1.14	0.8

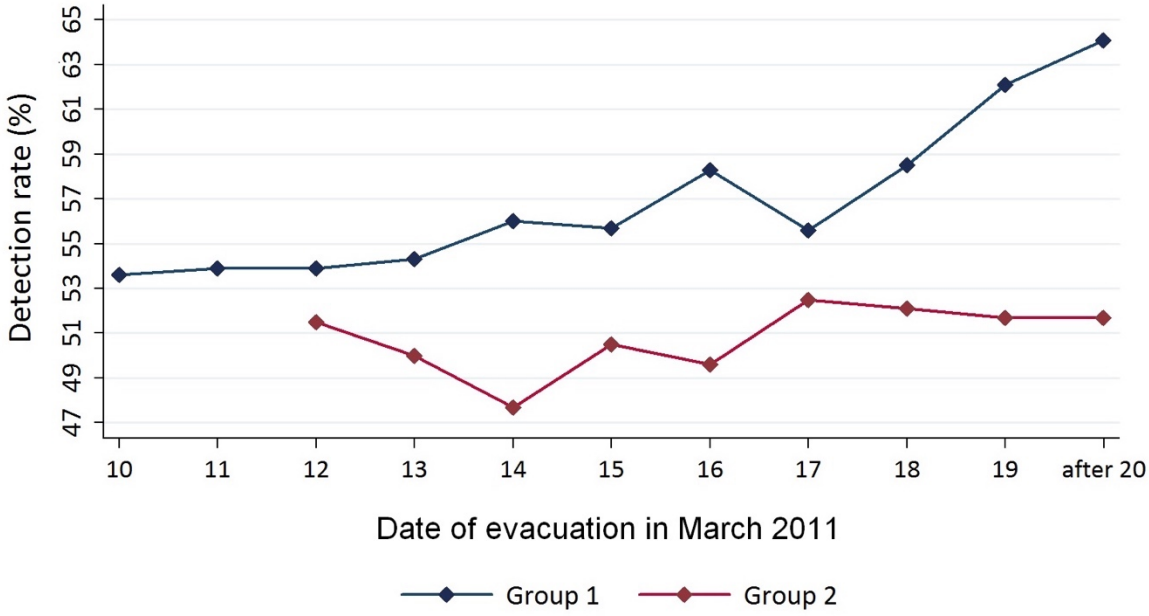
Note: CI: confidence interval.

5.4.3 Cumulative detection rates of Cs-134 over time

Associations between the Cs-134 levels of internal contamination four months following the incident and early evacuation as well as timing of the evacuation, were also investigated through visual inspection of cumulative detection rates of Cs-134 over time (Figure 10). Because of low numbers of evacuees prior to the incident (i.e. those who moved due to the tsunami, but before the Fukushima incident: n=7), I did not include the detection rate on 11th March (28.6%) in Group 2. Group 1 showed

a slightly increasing proportion of participants with detectable levels of Cs-134 contamination as time passed, indicating that evacuation might help in the initial stage of the incident. However, Group 2 did not present a significant increase in rates of Cs-134 detection over time, which might suggest that the timing of evacuation was not important. These findings were supported by the evidence that in the areas with high ground deposition density, the greater contribution to effective dose in the first year was from external exposure from radionuclides deposited (in Minamisoma, mostly on 15th to 16th March 2011) (see section 2.1.2).[18,63,64]

Figure 10: Cumulative detection rates of Cs-134 over time



Note: Group 1 indicates those who did not evacuate. The dataset contained everyone present before the incident (on 10th March), then everyone except those who evacuated on 11th March, and so on. Group 2 contained evacuees on 11th March (not shown), then, in addition, those who evacuated on 12th March, and so on.

5.5 Question 5: how much did the mortality risk differ between evacuees and non-evacuees among nursing home residents after the incident?

5.5.1 Subject characteristics

Subject characteristics (n=1,215) are presented in Table 17. For basic characteristics, such as sex, age, and care-level, between Minamisoma and Soma, a significant difference was observed only in the distribution of care-level (Chi-squared test: $p<0.001$) with Minamisoma residents more likely to be high care.

Table 17: Subject characteristics in Question 5: number (%)

Characteristics	Number of residents admitted between 11th March 2006 and 11th March 2011 (and those who experienced the incident)		
City	Total	Minamisoma†	Soma
Sex			
Male	313 (117)	192 (80)	121 (37)
Female	902 (409)	523 (248)	379 (161)
Age at death/withdrawal or end of study period††			
50–69	46 (29)	30 (21)	16 (8)
70–79	169 (66)	110 (52)	59 (14)
80–89	588 (262)	339 (153)	249 (109)
90 +	411 (169)	236 (102)	175 (67)
Care-level			
Low/moderate	764 (366)	399 (224)	365 (142)
High	450 (160)	316 (104)	134 (56)
Number of death	567 (160)	305 (75)	261 (85)
Person-years			
Pre-incident	2,427	1,543	885
Post-incident	521	188	332

Note: † Pre-disaster data for Facility 4 in Minamisoma included only those who died.[120] †† The age-distributions of residents amongst the seven facilities were statistically different (Chi-squared test: $p<0.01$).

The mean distance from the nuclear plant to the nursing homes was 28 km for Minamisoma and 40 km for Soma. According to the interviews with the presidents/staff, the five facilities in Minamisoma voluntarily evacuated because of lack of nursing staff due to their evacuation and lack of daily necessaries and nursing care equipment, including medicines and medical gas (i.e. oxygen).[92] The initial evacuation took place between 4 and 11 days after the incident (15th to 22nd March 2011), depending on facility.[120] In contrast, the facilities in Soma fortunately received voluntary external supports (such as, supplies including gasoline, food, medication, and sanitary materials) from

individuals, charities, and/or distant welfare facilities, and could therefore provide their residents with relatively normal service. As a result, evacuation was not undertaken at these facilities, and instead, residents sheltered in place.

Descriptive statistics of the variables incorporated into the analytical models are shown in Table 18. Pre-incident, Minamisoma City had a significantly lower hazard ratio than Soma City, after adjusting for covariates, which might reflect the potential city-level difference in residents' health status. Note that Soma had fewer nursing homes per population than Minamisoma (e.g. for >50 years old, 9,083 per facility for Soma versus 4,395 per facility for Minamisoma in 2012),[169,170] meaning that in Soma those admitted to nursing homes were likely to be in relatively worse health than in Minamisoma.

Table 18: Pre-incident mortality by given variables

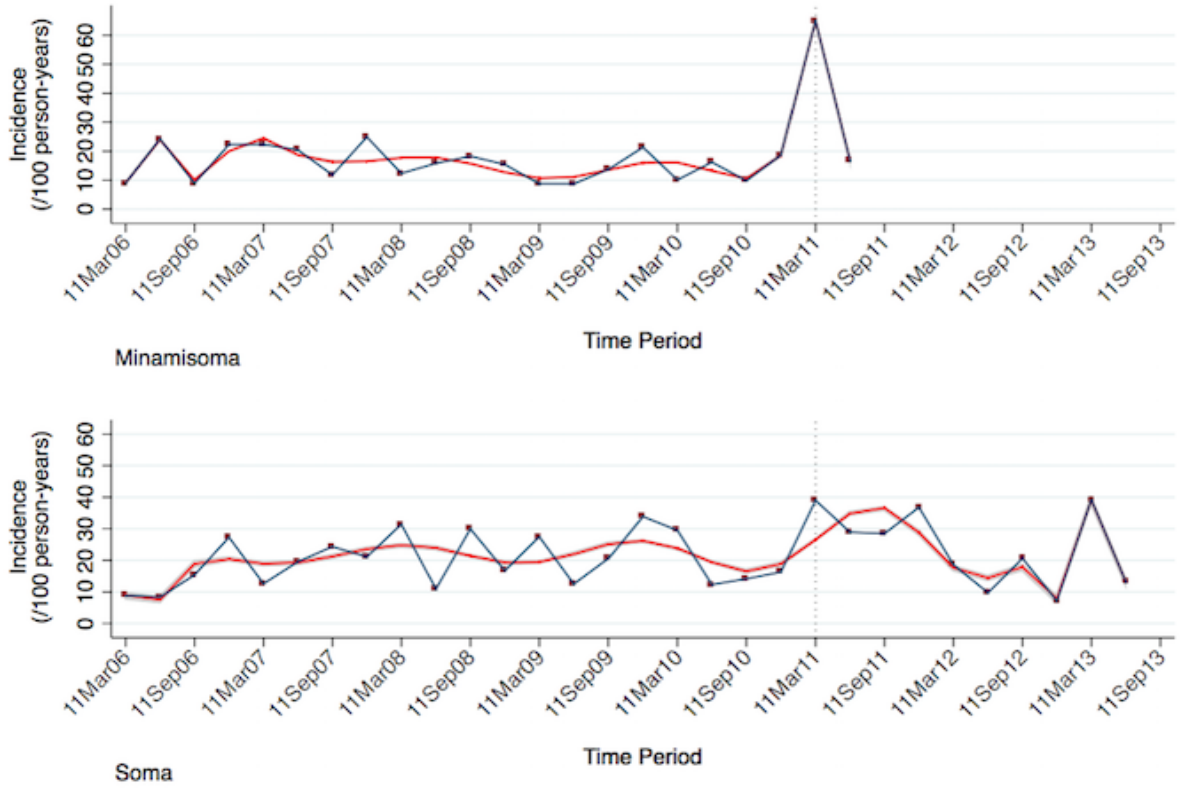
Variable	Hazard ratio	95% CI	P-value
City			
Soma	Ref.		
Minamisoma	0.72	0.52–0.99	<0.05
Sex			
Male	Ref.		
Female	0.70	0.56–0.88	<0.01
Age			
50–69	Ref.		
70–79	0.82	0.41–1.65	0.6
80–89	1.01	0.53–1.96	1.0
90 +	1.31	0.68–2.53	0.4
Care-level			
Low/moderate	Ref.		
High	1.19	0.96–1.75	0.1
Season			
Spring (Mar–May)	Ref.		
Summer (Jun–Aug)	1.00	0.75–1.32	1.0
Autumn (Sep–Nob)	0.85	0.64–1.12	0.2
Winter (Dec–Feb)	0.90	0.69–1.17	0.4
Facility type			
Intensive care home	Ref.		
Rehabilitation facility	0.97	0.70–1.35	0.9

Note: The hazard ratios shown include mutual adjustment for other variables in the table via random-effects regression. CI: confidence interval.

Season had no significant impact on pre-incident mortality (Table 18). Potential underlying temporal trends in mortality were assessed through visual inspection of a time-series of quarterly incidence and a B-spline-curve smoothing method. No temporal effects were detected before the incident, suggesting no strong influence of seasonal or longer-term time trends on mortality incidence after the

incident (Figure 11). There was also no significant difference in pre-incident mortality risk by facility type (i.e. intensive care home versus rehabilitation facility), care-level, or age group, after adjustment for covariates (Table 18).

Figure 11: B-spline-smoothed trend of incidence pre- and post-incident with 95% confidence bounds



Note: The trends of mortality incidence in Minamisoma and Soma were plotted until the end of August 2011 and the end of August 2013, respectively, the period for which data from all the five facilities in Minamisoma and two facilities in Soma was available. Dotted line at 11th March 2011, the date of the tsunami.

5.5.2 Evacuation history

Table 19 shows the facility-specific evacuation history in Minamisoma City. The average number of evacuations per resident ranged from 1.0 to 3.1, depending on facility.[120] The mean number of evacuations per resident was 2.1 (SD: 1.1). Evacuation distances ranged from 3 km to 325 km (SD: 72) for the initial evacuation, from 3 km to 510 km (SD: 161) for the second evacuation, from 4 km to 872 km (SD: 203) for the third evacuation, and from 8 km to 325 km (SD: 87) for the fourth evacuation. Although the facilities in Soma did not conduct facility-wide evacuation, one person voluntarily evacuated 236 km away from their initial facility.

Table 19: Evacuation history by facility in Minamisoma City

	Facility number				
	1	2	3	4	5
Average number of evacuations	2.9	2.6	3.1	1.7	1.0
Average evacuation distance (km) by stage					
Initial	306	303	325	203	242
Second	238	193	261	238	N/A
Third	209	143	223	97	N/A
Fourth	52	145	161	48	N/A

5.5.3 Comparison between evacuees and non-evacuees

Comparison of survival between the evacuees and non-evacuees was conducted in order to assess the effects of early evacuation on mortality. For this analysis, both pre- and post-incident data were used, indicating non-incident-exposed data and incident-exposed data, respectively. Using these data allowed for adjustment of the effect of 'experience of the incident' on mortality (in other words, different survival before vs. after the incident net of other variables), which then allowed the assessment of the effect of early evacuation itself on mortality.

The results of the multiple Cox proportional hazards regression model with a random effect for facility are shown in Table 20, which is expressed as a multiplicative change (i.e. hazard ratio) in the hazard level for evacuees versus non-evacuees. After variable selection, the final model that I specified was the following:

$$h(t) = h0(t)\exp(\beta1 \times X1 + \beta2 \times X2 + \beta3 \times X3 + \beta4 \times X4 + \beta5 \times X5)$$

where h(t) is the hazard function and h0(t) is the baseline hazard function at time t. Four dummy covariates (X1: city - Minamisoma or Soma, X2: sex - male or female, X3: evacuation - yes or no, and X4: experience of incident - yes or no), and one categorical covariate (X5: age - 50–69, 70–79, 80–89, and 90+), were incorporated into the model. My major interests were comparisons between 'yes' and 'no' with respect to the covariates 'evacuation' and 'experience of incident', effects of which were expressed as β3 and β4, respectively. This model takes into account the time participants have spent in the facilities (with censored data), which enabled us to deal with pre-post incident comparison.

Table 20: Random-effects regression model of survival for evacuation impact (pre- versus post-incident data)

Variable	Hazard ratio	95% CI	P-value
City			
Soma	Ref.		
Minamisoma	0.60	0.49–0.73	<0.001
Sex			
Male	Ref.		
Female	0.63	0.52–0.77	<0.001
Age			
50–69	Ref.		
70–79	1.38	0.78–2.43	0.3
80–89	1.82	1.07–3.07	<0.05
90 +	3.13	1.84–5.31	<0.001
Care-level			
Low/moderate	Ref.		
High	1.66	1.40–1.97	<0.001
Evacuation			
No	Ref.		
Yes	1.82	1.22–2.70	<0.01
Experience of incident			
No	Ref.		
Yes	1.10	0.84–1.43	0.5

Note: CI: confidence interval.

After adjusting for the other covariates, evacuation had a significant impact on mortality risk with a hazard ratio of 1.82 (95% CI: 1.22–2.70). In contrast, experience of the incident itself, did not show a significant association with mortality (hazard ratio: 1.10; 95% CI: 0.84–1.43).

5.5.4 Stage-specific evacuation mortality risk

To explore the stage-specific evacuation mortality risk, I used the post-incident data. After variable selection, the final model that I specified was the following:

$$h(t) = h0(t)\exp(\beta1 \times X1 + \beta2 \times X2 + \beta3 \times X3 + \beta4 \times X4)$$

Two dummy covariates (X1: sex - male or female, and X2: care-level - low/moderate or high), and two categorical covariates (X3: age - 50–69, 70–79, 80–89, and 90+, and X4: evacuation type - none, initial, and subsequent), were incorporated into the regression model. My major interest here was evacuation type, effect of which was expressed as β4. Note that β4 is not a single parameter, but a vector with elements corresponding to two evacuation types (initial evacuation and subsequent evacuation) in reference to non-evacuation.

Results showed a significant effect of initial evacuation versus no evacuation on mortality, with a hazard ratio of 3.37 (95% CI: 1.66–6.81), adjusted for sex, age, and care-level (Table 21). No significant difference between subsequent evacuations and non-evacuation was observed, indicating that the subsequent evacuation had less impact on mortality, or that those most affected by the initial evacuation did not survive long enough to experience subsequent evacuations. Evacuation distance was not significantly associated with mortality, and was dropped from the model. Interaction terms of covariates were incorporated into the model, but were not significant.

Table 21: Random-effects regression model of survival by evacuation stage

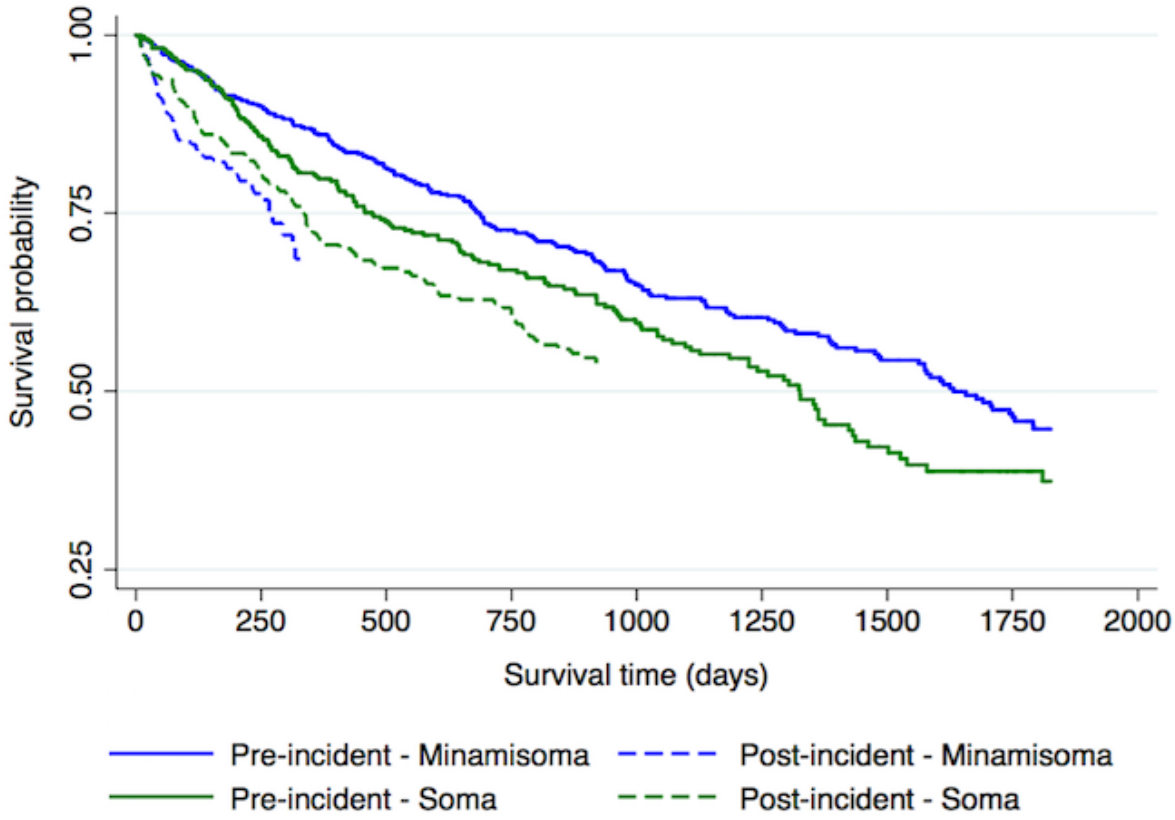
Variable	Hazard ratio	95% CI	P-value
Sex			
Male	Ref.		
Female	0.76	0.52–1.13	0.2
Age			
50–69	Ref.		
70–79	1.39	0.49–3.95	0.5
80–89	1.63	0.65–4.09	0.3
90 +	3.18	1.26–8.01	<0.05
Care-level			
Low/moderate	Ref.		
High	1.89	1.37–2.61	<0.001
Evacuation type			
None	Ref.		
Initial	3.37	1.66–6.81	<0.01
Subsequent	1.93	0.90–4.14	0.1

Note: CI: confidence interval.

5.5.5 Comparison between Minamisoma and Soma for pre- and post-incident survival

Figure 12 shows Kaplan-Meier curves of survival probability for facilities in Minamisoma and Soma before and after the incident. Analysis time for before/after the incident starts from the date of admission to the facility (within the study period) and the date of the incident (i.e. 11th March 2011), respectively. No significant difference in pre- and post-incident survival time was observed in Soma ($p=0.15$), while in Minamisoma the post-incident survival was significantly reduced compared to pre-incident survival ($p<0.01$). A sharp drop in the survival probability in Minamisoma residents was observed in the first to second month following the incident (Figure 12), indicating that many of the deaths occurred soon after the initial evacuation.

Figure 11: Estimated pre- and post-incident survival probability in Minamisoma City and Soma City



5.5.6 Relative mortality risk in Soma City

For residents of the facilities in Soma, there was an increase in mortality within a year of the incident (RR: 1.68; 95% CI: 1.12–2.29) compared to the pre-incident levels, but no significant increase when assessed over the two years after the incident (RR: 1.29; 95% CI: 0.98–1.68).

5.6 Question 6: how much did evacuation affect long-term chronic health after the incident?

5.6.1 Subject characteristics and comparison of clinical characteristics between evacuees and non-/temporary-evacuees

Demographic and clinical characteristics by evacuation status are shown in Table 22. Variables did not differ between evacuees and non-/temporary-evacuees at baseline or in 2011. However, in years 2012 to 2014, BMI and high-density lipoprotein cholesterol (HDL-C) were significantly higher and lower, respectively, in evacuees than non-/temporary-evacuees. Differences in self-report medial history and lifestyle survey by evacuation status are shown in Table 23. Although there were no significant differences between evacuees and non-/temporary-evacuees in treatment history at baseline and in 2011, a significant difference was identified in treatment for hyperlipidemia after 2012, with evacuees significantly more likely to receive outpatient treatment than non-/temporary-evacuees. In addition, differences in lifestyles between evacuees and non-/temporary-evacuees were notable. From 2011, evacuees were significantly more likely to have gained or lost more than 3 kg of their weight over the previous year. From 2012, evacuees were also less likely to feel refreshed after a nights' sleep. In addition, the non-/temporary-evacuees tended to walk faster than evacuees both after 2011 and in the baseline years.

Table 22: Comparisons of subject characteristics between evacuees and non-/temporary-evacuees

	Baseline (2008–2010)		2011		2012		2013		2014	
Characteristics	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees
City of residence: number (%)										
Minamisoma	960 (100)	2,818 (51.7)	216 (100)	832 (29.0)	627 (100)	1,925 (49.5)	657 (100)	2,055 (55.8)	617 (100)	1,990 (55.4)
Soma	0 (0)	2,628 (48.3)	0 (0)	2,038 (71.2)	0 (0)	1,961 (50.5)	0 (0)	1,625 (44.2)	0 (0)	1,601 (44.6)
Total	960	5,446	216	2,870	627	3,886	657	3,680	617	3,591
Demographic characteristics										
Age: mean (SD)	62.0 (6.6)	62.4 (7.1)	64.9 (6.3)	64.8 (7.3)	65.3 (6.4)	65.3 (6.9)	65.5 (6.5)	65.7 (6.6)	66.0 (6.3)	66.3 (6.3)
Sex: number (%)										
Male	404 (41.9)	2,203 (40.5)	95 (44.0)	1,169 (40.7)	267 (42.6)	1,578 (40.6)	281 (42.8)	1,459 (39.7)	254 (41.2)	1,375 (38.3)
Female	556 (58.1)	3,243 (59.5)	121 (56.0)	1,701 (59.3)	360 (57.4)	2,308 (59.4)	376 (57.2)	2,221 (60.4)	363 (58.8)	2,216 (61.7)
Clinical characteristics: mean (SD)										
BMI [kg/m^2]	23.6 (3.2)	23.5 (3.3)	24.0 (3.4)	23.6 (3.3)	24.2 (3.3)***	23.6 (3.4)***	24.0 (3.3)**	23.6 (3.4)**	23.7 (3.4)*	23.4 (3.4)*
Systolic blood pressure [mmHg]	130.5 (16.1)	130.7 (16.3)	130.0 (14.6)	131.7 (16.0)	128.9 (15.5)*	130.7 (16.2)*	128.0 (14.6)	128.7 (15.2)	126.5 (14.1)**	128.4 (14.8)**
Diastolic blood pressure [mmHg]	77.5 (9.5)	77.5 (9.7)	78.0 (11.3)	79.0 (10.2)	76.7 (10.2)	76.9 (10.3)	76.3 (9.2)	75.7 (9.8)	74.6 (9.3)	75.1 (9.6)
HbA1c [%]	5.5 (0.6)	5.5 (0.6)	5.4 (0.5)	5.5 (0.6)	5.6 (0.5)	5.6 (0.6)	5.7 (0.6)	5.7 (0.6)	5.6 (0.6)	5.6 (0.6)
HDL-C [mg/dL]	61.4 (14.4)	61.4 (14.8)	59.8 (14.5)	60.9 (14.7)	56.2 (13.2)***	58.8 (14.3)***	57.9 (13.9)**	59.6 (14.3)**	58.1 (13.8)***	60.3 (14.8)***
LDL-C [mg/dL]	124.9 (30.0)	125.4 (31.0)	126.5 (30.9)	124.4 (31.1)	120.0 (31.1)	122.2 (31.0)	123.5 (30.5)	124.8 (31.0)	121.0 (29.7)**	124.8 (31.2)**
ALT/GPT [IU/L]	22.0 (13.3)	22.7 (18.5)	23.3 (16.5)	24.7 (17.7)	24.2 (16.4)	23.4 (18.2)	23.0 (16.6)	22.1 (19.3)	22.8 (16.4)	22.1 (14.6)
AST/GOT [IU/L]	24.8 (11.5)	25.1 (11.9)	24.8 (8.7)	26.4 (15.0)	26.4 (13.9)	25.7 (12.2)	25.1 (12.2)	24.9 (15.6)	24.6 (10.9)	24.8 (14.7)
γ-GTP [IU/L]	34.0 (40.9)	37.4 (51.4)	35.8 (42.4)	39.3 (56.7)	38.6 (43.8)	36.6 (44.9)	36.8 (51.2)	36.4 (56.4)	34.5 (63.7)	35.8 (55.2)
Urin protein: number (% of positive)	16 (1.7)	115 (2.1)	3 (1.4)	58 (2.0)	6 (1.0)	64 (1.7)	13 (2.0)	59 (1.6)	8 (1.3)	68 (1.9)
Urin occult blood: number (% of positive)	55 (5.7)	319 (5.9)	20 (9.3)	209 (7.6)	17 (2.7)*	184 (4.8)*	30 (4.6)	185 (5.1)	30 (4.9)	163 (4.6)
Urine glucose: number (% of positive)	19 (2.0)	130 (2.4)	2 (0.9)	60 (2.1)	8 (1.3)	89 (2.3)	10 (1.5)	74 (2.0)	14 (2.3)	68 (1.9)
Presence of diseases: number (%)										
Diabetes	74 (7.7)	415 (7.7)	20 (9.3)	226 (8.0)	64 (10.2)	368 (9.5)	86 (13.1)	423 (11.6)	84 (13.6)	399 (11.2)
Hyperlimidemia	430 (44.8)	2,390 (44.3)	109 (50.5)	1,290 (45.2)	336 (53.6)**	1,815 (46.8)**	394 (60.0)***	1,877 (51.2)***	341 (55.3)	1,874 (52.6)
Hypertension	437 (45.5)	2,463 (45.3)	112 (51.9)	1,506 (52.6)	333 (53.1)	2,020 (52.1)	366 (55.7)*	1,888 (51.3)*	297 (48.1)	1,758 (49.2)

Note: SD: standard deviation

Table 23: Comparisons of results of self-report medial history and lifestyle survey between evacuees and non-/temporary-evacuees: number (%)

	Baseline (2008–2010)		2011		2012		2013		2014	
	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees	Evacuees	Non-/temporary-evacuees
Part 1: Medical history										
Surgical history: number										
Esophagus/stomach	12 (1.3)	111 (2.0)	4 (1.9)	62 (2.2)	9 (1.4)	85 (2.2)	6 (0.9)	74 (2.0)	10 (1.6)	75 (2.1)
Duodenum	2 (0.2)	24 (0.4)	0 (0.0)	16 (0.6)	1 (0.2)	16 (0.4)	1 (0.2)	17 (0.5)	3 (0.5)	17 (0.5)
Intestines	11 (1.2)	102 (1.9)	2 (0.9)	59 (2.1)	9 (1.4)	53 (1.4)	11 (1.7)	54 (1.5)	13 (2.1)	60 (1.7)
Chest	11 (1.2)	79 (1.5)	3 (1.4)	46 (1.6)	7 (1.1)	59 (1.5)	13 (2.0)	58 (1.6)	5 (0.8)	32 (0.9)
Family disease history										
Heart disease	163 (17.0)	903 (16.6)	37 (17.1)	499 (17.4)	119 (19.0)	683 (17.6)	120 (18.3)	694 (18.9)	120 (19.5)	682 (19.0)
Cerebrovascular disease	120 (12.5)	788 (14.5)	30 (13.9)	432 (15.1)	88 (14.0)	614 (15.8)	107 (16.3)	570 (15.5)	95 (15.4)	574 (16.0)
Hypertension	342 (35.6)	1,954 (35.9)	77 (35.7)	1057 (36.8)	254 (40.5)	1,424 (36.6)	258 (39.3)	1,433 (38.9)	226 (36.6)	1,368 (38.1)
Diabetes	150 (15.6)	964 (17.7)	24 (11.1)*	495 (17.3)*	120 (19.1)	703 (18.1)	102 (15.5)*	710 (19.3)*	102 (16.5)	716 (19.9)
Hyperlipidaemia	18 (1.9)	107 (2.0)	4 (1.9)	72 (2.5)	17 (2.7)	99 (2.6)	28 (4.3)	109 (3.0)	22 (3.6)	93 (2.6)
Treatment history										
High blood pressure										
None	635 (66.2)	3,665 (67.3)	125 (57.9)	1,748 (62.6)	348 (55.5)	2,194 (58.3)	343 (52.2)	2,088 (56.7)	337 (54.6)	1,966 (55.8)
Receiving outpatient treatment	285 (29.7)	1,596 (29.3)	85 (39.4)	968 (34.7)	256 (40.8)	1,419 (37.7)	286 (43.5)	1,473 (40.0)	258 (41.8)	1,417 (40.2)
Recovered/Left untreated	40 (4.2)	183 (3.4)	6 (2.8)	76 (2.7)	23 (3.7)	148 (3.9)	28 (4.3)	119 (3.2)	22 (3.6)	139 (4.0)
Crebrovascular disease										
None	929 (96.8)	5,297 (97.3)	213 (98.6)	2,702 (96.8)	601 (95.9)	3,631 (96.5)	630 (95.9)	3,549 (96.4)	592 (96)	3,389 (96.3)
Receiving outpatient treatment	19 (2.0)	97 (1.8)	3 (1.4)	67 (2.4)	18 (2.9)	90 (2.4)	19 (2.9)	98 (2.7)	18 (2.9)	95 (2.7)
Recovered/Left untreated	12 (1.3)	50 (0.9)	0 (0.0)	23 (0.8)	8 (1.3)	40 (1.1)	8 (1.2)	33 (0.9)	7 (1.1)	37 (1.1)
Cardiovascular disease										
None	920 (95.8)	5,158 (94.8)	209 (96.8)	2,631 (94.3)	579 (92.3)	3,532 (93.9)	617 (93.9)	3,467 (94.3)	581 (94.3)	3,317 (94.2)
Receiving outpatient treatment	34 (3.5)	227 (4.2)	7 (3.2)	128 (4.6)	41 (6.5)	191 (5.1)	32 (4.9)	183 (5.0)	31 (5.0)	181 (5.1)
Recovered/Left untreated	6 (0.6)	59 (1.1)	0 (0.0)	32 (1.2)	7 (1.1)	37 (1.0)	8 (1.2)	28 (0.8)	4 (0.7)	23 (0.7)
Eye disease										
None	790 (82.3)	4,376 (80.4)	167 (77.3)	2,141 (76.7)	468 (74.8)	2,849 (75.7)	487 (74.1)	2,760 (75)	465 (75.4)	2,578 (73.2)
Receiving outpatient treatment	115 (12.0)	763 (14.72	36 (16.7)	489 (17.5)	112 (17.9)	663 (17.6)	123 (18.7)	702 (19.1)	118 (19.1)	692 (19.6)
Recovered/Left untreated	55 (5.7)	305 (5.6)	13 (6.0)	162 (5.8)	46 (7.4)	250 (6.7)	47 (7.2)	218 (5.9)	34 (5.5)	253 (7.2)
Anemia										
None	893 (93.0)	5,149 (94.6)	209 (96.8)	2,646 (94.8)	599 (95.5)	3,549 (94.4)	628 (95.6)	3,519 (95.6)	580 (94.2)	3,350 (95.1)
Receiving outpatient treatment	6 (0.6)	30 (0.6)	1 (0.5)	18 (0.6)	8 (1.3)	30 (0.8)	5 (0.8)	28 (0.8)	9 (1.5)	36 (1.0)
Recovered/Left untreated	61 (6.4)	265 (4.9)	6 (2.8)	127 (4.6)	20 (3.2)	180 (4.8)	24 (3.7)	133 (3.6)	27 (4.4)	136 (3.9)
Diabetes mellitus										
None	878 (91.5)	5,039 (92.5)	196 (90.7)	2,577 (92.3)	559 (89.3)	3416 (90.8)	585 (89.2)	3,322 (90.3)	541 (87.7)	3,146 (89.4)
Receiving outpatient treatment	71 (7.4)	337 (6.2)	19 (8.8)	191 (6.8)	60 (9.6)	294 (7.8)	67 (10.2)	318 (8.6)	72 (11.7)	344 (9.8)
Recovered/Left untreated	11 (1.2)	69 (1.3)	1 (0.5)	24 (0.9)	7 (1.1)	51 (1.4)	4 (0.6)	39 (1.1)	4 (0.7)	31 (0.9)
Hyperlipidaemia										
None	659 (68.7)	3,869(71.1)	137 (63.4)	1,882 (67.4)	344 (55.0)***	2,377 (63.2)***	357 (54.3)***	2,290 (62.3)***	325 (52.7)***	2,142 (60.8)***
Receiving outpatient treatment	199 (20.7)	982 (18.)	48 (22.2)	609 (21.8)	209 (33.4)***	977 (26.0)***	239 (36.4)***	1,009 (27.4)***	227 (36.8)***	1,032 (29.3)***

Recovered/Left untreated	102 (10.6)	593 (10.9)	31 (14.4)	300 (10.8)	73 (11.7)***	407 (10.8)***	61 (9.3)***	380 (10.3)***	65 (10.5)***	347 (9.9)***
Kidney disease										
None	944 (98.3)	5,287 (97.1)	211 (97.7)	2,706 (96.9)	612 (97.6)	3,632 (96.7)	636 (96.8)	3,547 (96.4)	599 (97.2)	3,395 (96.4)
Receiving outpatient treatment	2 (0.2)	47 (0.9)	0 (0.0)	24 (0.9)	6 (1.0)	47 (1.3)	6 (0.9)	44 (1.2)	8 (1.3)	48 (1.4)
Recovered/Left untreated	14 (1.5)	109 (2.0)	5 (2.3)	62 (2.2)	9 (1.4)	78 (2.1)	15 (2.3)	88 (2.4)	9 (1.5)	78 (2.2)
Respiratory disease										
None	932 (97.1)	5,255 (96.5)	204 (94.4)	2,688 (96.3)	602 (96)	3,606 (95.9)	628 (95.6)	3,536 (96.1)	600 (97.2)	3,365 (95.5)
Receiving outpatient treatment	11 (1.2)	94 (1.7)	9 (4.2)	51 (1.8)	14 (2.2)	100 (2.7)	17 (2.6)	86 (2.3)	7 (1.1)	91 (2.6)
Recovered/Left untreated	17 (1.8)	97 (1.8)	3 (1.4)	53 (1.9)	11 (1.8)	56 (1.5)	12 (1.8)	57 (1.6)	10 (1.6)	67 (1.9)
Gastrointestinal diseases										
None	846 (88.1)	4,693 (86.3)	189 (87.5)	2,369 (84.9)	551 (87.9)*	3,189 (84.8)*	577 (87.8)	3,112 (84.6)	541 (87.7)	30,06 (85.4)
Receiving outpatient treatment	39 (4.1)	279 (5.1)	15 (6.9)	184 (6.6)	23 (3.7)*	231 (6.1)*	38 (5.8)	236 (6.4)	28 (4.5)	206 (5.9)
Recovered/Left untreated	75 (7.8)	469 (8.6)	12 (5.6)	239 (8.6)	53 (8.5)*	340 (9.0)*	42 (6.4)	332 (9.0)	48 (7.8)	310 (8.8)
Colorectal disease										
None	894 (93.1)	5,073 (93.2)	204 (94.4)	2,577 (92.4)	577 (92)	3,448 (91.7)	593 (90.3)	3,366 (91.5)	561 (91.1)	3,174 (90.1)
Receiving outpatient treatment	11 (1.2)	49 (0.9)	2 (0.9)	30 (1.1)	7 (1.1)	46 (1.2)	12 (1.8)	51 (1.4)	8 (1.3)	55 (1.6)
Recovered/Left untreated	55 (5.7)	321 (5.9)	10 (4.6)	182 (6.5)	43 (6.9)	266 (7.1)	52 (7.9)	263 (7.2)	47 (7.6)	292 (8.3)
Liver disease										
None	939 (97.8)	5,284 (97.1)	211 (97.7)	2,717 (97.3)	606 (96.7)	3,649 (97.1)	643 (97.9)	3,579 (97.3)	598 (96.9)	3,412 (96.9)
Receiving outpatient treatment	13 (1.4)	66 (1.2)	3 (1.4)	30 (1.1)	8 (1.3)	62 (1.7)	7 (1.1)	56 (1.5)	6 (1.0)	54 (1.5)
Recovered/Left untreated	8 (0.8)	93 (1.7)	2 (0.9)	45 (1.6)	13 (2.1)	48 (1.3)	7 (1.1)	45 (1.2)	13 (2.1)	55 (1.6)
Gout										
None	918 (95.6)	5,237 (96.2)	210 (97.2)	2,672 (95.7)	601 (95.9)	3,598 (95.7)	621 (94.5)	3,506 (95.3)	576 (93.5)	3,352 (95.2)
Receiving outpatient treatment	19 (2.0)	135 (2.5)	5 (2.3)	87 (3.1)	14 (2.2)	119 (3.2)	26 (4.0)	121 (3.3)	26 (4.2)	122 (3.5)
Recovered/Left untreated	23 (2.4)	72 (1.3)	1 (0.5)	32 (1.2)	12 (1.9)	43 (1.1)	10 (1.5)	52 (1.4)	14 (2.3)	48 (1.4)
Blood disease										
None	959 (99.9)	5,422 (99.6)	216 (100)	2,778 (99.5)	622 (99.2)	3,744 (99.6)	656 (99.9)	3,657 (99.4)	615 (99.7)	3,497 (99.3)
Receiving outpatient treatment	1 (0.1)	12 (0.2)	0 (0.0)	9 (0.3)	3 (0.5)	14 (0.4)	0 (0.0)	18 (0.5)	0 (0.0)	17 (0.5)
Recovered/Left untreated	0 (0.0)	8 (0.2)	0 (0.0)	5 (0.2)	2 (0.3)	3 (0.1)	1 (0.2)	4 (0.1)	2 (0.3)	7 (0.2)
Part 2: Lifestyle related										
Personal habits										
Alcohol										
None or rarely	530 (55.2)	3,105 (57.0)	124 (57.4)	1,628 (58.3)	355 (56.6)	2,128 (56.6)	370 (56.3)	2,111 (57.4)	362 (58.7)	2,084 (58.1)
Sometimes	195 (20.3)	1,092 (20.1)	38 (17.6)	516 (18.5)	113 (18.0)	777 (20.7)	133 (20.2)	751 (20.4)	105 (17.0)	712 (19.8)
Everyday	235 (24.5)	1,248 (22.9)	54 (25.0)	649 (23.2)	159 (25.4)	858 (22.8)	154 (23.4)	818 (22.2)	150 (24.3)	793 (22.1)
Smoking	129 (13.4)	864 (15.9)	27 (12.5)	361 (12.9)	67 (10.7)	475 (12.6)	59 (9.0)**	466 (12.7)**	54 (8.8)*	418 (11.7)*
Lifestyle: number (% of Yes) †										
High weight gain (Q1)[1]	351 (36.6)	1,967 (36.2)	81 (37.7)	998 (35.8)	267 (42.6)**	1,387 (36.9)**	268 (40.9)*	1,349 (36.7)*	251 (40.8)*	1,274 (35.5)*
Moderate intensity exercise (Q2)[2]	286 (29.8)**	1,868 (34.4)**	85 (39.5)	932 (33.5)	209 (33.3)	1,385 (36.8)	243 (37.1)	1,388 (37.8)	228 (37.0)	1,404 (39.2)
Low intensity exercise (Q3)[3]	357 (37.2)	2,033 (37.4)	78 (36.3)	963 (34.6)	224 (35.7)	1,286 (34.2)	229 (34.9)	1,335 (36.3)	204 (33.1)	1,301 (36.3)
Walk speed (Q4)[4]	353 (36.8)***	2,357 (43.4)***	76 (35.4)*	1,203 (43.2)*	209 (33.4)***	1,602 (42.6)***	209 (33.4)**	1,602 (42.6)**	209 (33.4)*	1,602 (42.6)*
Small weight gain/loss (Q5)[5]	183 (19.1)	1,175 (21.6)	64 (29.8)*	646 (23.2)*	229 (36.5)***	943 (25.1)***	184 (28.1)**	855 (23.3)**	158 (25.7)*	780 (21.8)*
Good sleep (Q6)[6]	738 (76.9)	4,185 (77.1)	148 (68.8)	2,030 (72.9)	423 (67.6)**	2,785 (74.0)**	425 (64.8)***	2,645 (72)***	402 (65.3)***	2,611 (72.8)***
Late evening meal (Q7)[7]	230 (24.0)**	1,060 (19.5)**	41 (19.2)	488 (17.5)	133 (21.3)	711 (18.9)	126 (19.2)	614 (16.7)	112 (18.2)	594 (16.6)
Midnight snack (Q8)[8]	113 (11.8)	585 (10.8)	24 (11.2)	273 (9.8)	46 (7.4)	304 (8.1)	42 (6.4)	288 (7.8)	41 (6.7)	283 (7.9)
Breakfast skip (Q9)[9]	51 (5.3)	322 (5.9)	2 (0.9)*	125 (4.5)*	24 (3.8)	181 (4.8)	29 (4.4)	199 (5.4)	32 (5.2)	195 (5.4)

Eating speed (Q10)[10]										
Normal	660 (68.8)	3,571 (65.8)	140 (65.1)	1,807 (64.9)	423 (67.5)	2,484 (66)	434 (66.2)	2,411 (65.7)	403 (65.4)	2,360 (65.8)
Fast	232 (24.2)	1,399 (25.8)	57 (26.5)	744 (26.7)	143 (22.8)	929 (24.7)	174 (26.5)	968 (26.4)	164 (26.6)	938 (26.2)
Slow	68 (7.1)	461 (8.5)	18 (8.4)	234 (8.4)	61 (9.7)	350 (9.3)	48 (7.3)	293 (8.0)	49 (8.0)	289 (8.1)

Note: * p<0.05, ** p<0.01, *** p<0.001 for evacuees versus non-/temporary-evacuees by un-paired t-test for continuous outcomes, and Chi-squared test for categorical outcomes. 1 Q1: Have you gained ≥10 kg since you were 20 years old?, 2 Q2: Have you been exercising at least 2 days per week, at least 30 minutes each at an intensity that causes a slight sweat, for at least 1 year?, 3 Q3: Do you walk for at least 1 hour every day or have equivalent physical activities in your daily life?, 4 Q4: Do you walk faster than people of your age and sex?, 5 Q5: Have you had a weight gain or loss of ≥3 kg over the last year?, 6 Q6: Do you feel refreshed after a night's sleep?, 7 Q7: Do you have an evening meal within 2 hours before bedtime 3 days or more per week?, 8 Q8: Do you eat after the evening meal (have a fourth meal) 3 days or more per week?, 9 Q9: Do you skip breakfast 3 days or more per week?, 10 Q10: How fast do you eat compared to others?

5.6.2 Age-adjusted relative risk of diabetes, hyperlipidemia, and hypertension

Table 24 shows the age-adjusted pre- and post-incident RR of each outcome. For diabetes, both evacuees and non-/temporary-evacuees had significantly higher risk in 2013 and 2014 than at baseline. These RRs did not significantly differ between evacuees and non-/temporary-evacuees in any year. For hyperlipidemia, in evacuees, risk was significantly higher in 2012, 2013, and 2014 compared to baseline. In non-/temporary-evacuees, risks were significantly higher in 2013 and 2014. The RR of hyperlipidemia by evacuation status was significantly different in 2012 ($p<0.05$) and in 2013 ($p<0.01$) - the increased risk in hyperlipidemia was significantly greater among evacuees than among non-/temporary-evacuees. For hypertension, the RR was borderline significant in 2013 for evacuees, and significantly reduced in 2014 for non-/temporary-evacuees. The difference of the RR of hypertension between evacuees and non-/temporary-evacuees was not significant in any year.

Table 24: Age-adjusted pre- and post-incident relative risk of the diseases versus baseline (2008–2010) (95% confidence interval)

	Evacuees	Non-/temporary-evacuees	P-value of the difference in row
Diabetes			
2011	1.12 (0.70–1.79)	0.94 (0.81–1.10)	0.5
2012	1.21 (0.88–1.67)	1.11 (0.97–1.27)	0.6
2013	1.55 (1.15–2.09)**	1.33 (1.17–1.52)***	0.3
2014	1.60 (1.18–2.16)**	1.27 (1.11–1.45)***	0.1
Hyperlipidemia			
2011	1.10 (0.94–1.27)	1.00 (0.95–1.05)	0.3
2012	1.16 (1.05–1.29)**	1.03 (0.98–1.08)	<0.05
2013	1.30 (1.18–1.43)***	1.12 (1.07–1.17)***	<0.01
2014	1.20 (1.08–1.32)**	1.14 (1.09–1.20)**	0.6
Hypertension			
2011	1.05 (0.91–1.21)	1.05 (1.01–1.10)	1.0
2012	1.04 (0.94–1.14)	1.03 (0.99–1.07)	1.0
2013	1.10 (1.00–1.21)*	1.01 (0.97–1.05)	0.1
2014	0.94 (0.85–1.05)	0.95 (0.91–0.99)*	0.8

Note: * p<0.05, ** p<0.01, *** p<0.001 for given year versus baseline (2008–2010), adjusted for age.

5.6.3 Regression analyses

Impact of evacuation after adjusted for covariates

The estimated impact of evacuation on disease risk is shown in Table 25. For diabetes, there was no significant difference in risk between evacuees and non-/temporary-evacuees post-incident after adjustment for covariates. I identified a small but significant effect of evacuation on hyperlipidemia risk (OR: 1.18; 95% CI: 1.06–1.32; $p<0.01$). This result is consistent with that shown in Table 24, suggesting that the evacuation effect on hyperlipidemia risk was not entirely accounted for by

potentially confounding covariates. In other words, the evacuation effect persisted after adjustment for potential confounders. An interaction term of 'evacuation' and 'year' variables was examined in the regression model to test for the different evacuation impacts by year, but no interaction was observed (data not shown), suggesting that effect of evacuation was similar in 2012, 2013, and 2014. For hypertension and diabetes, no significant difference in risk between evacuees and non-/temporary-evacuees was identified.

Table 25: Random-effects regression model: odds ratio (95% confidence interval)

Variable	Diabetes[1]	Hyperlipidemia[2]	Hypertension[3]
Demographic characteristics			
Evacuation status			
Non-/temporary-evacuees	Ref.	Ref.	Ref.
Evacuees	1.14 (0.96–1.35)	1.18 (1.06–1.32)**	0.97 (0.86–1.09)
Year			
2012	Ref.	Ref.	Ref.
2013	1.27 (1.10–1.47)**	1.09 (0.99–1.19)	0.95 (0.86–1.04)
2014	1.23 (1.06–1.43)**	1.19 (1.08–1.30)***	0.80 (0.73–0.88)***
City			
Minamisoma	Ref.	Ref.	Ref.
Soma	1.08 (0.95–1.23)	0.86 (0.79–0.93)***	1.00 (0.92–1.09)
Age			
40–64	Ref.	Ref.	Ref.
65–74	1.29 (1.12–1.48)***	1.13 (1.04–1.22)**	2.47 (2.27–2.69)***
Sex			
Male	Ref.	Ref.	Ref.
Female	0.43 (0.37–0.49)***	1.91 (1.75–2.10)***	0.71 (0.65–0.79)***
Clinical characteristics			
BMI	1.13 (1.11–1.15)***	1.07 (1.06–1.09)***	1.18 (1.17–1.2)***
HbA1c [%]	–	1.61 (1.48–1.75)***	–
γ-GTP [IU/L]	–	–	1.00 (1.00–1.00)***
Urine protein			
Negative/trace	Ref.	–	Ref.
Positive	2.96 (2.16–4.05)***	–	2.21 (1.56–3.13)***
Medical records			
Use of medicines			
Diabetes			
No	–	Ref.	Ref.
Yes	–	0.91 (0.77–1.07)	1.45 (1.24–1.69)***
Hyperlipidemia			
No	Ref.	–	Ref.
Yes	2.15 (1.89–2.45)***	–	1.49 (1.36–1.63)***
Hypertension			
No	Ref.	Ref.	–
Yes	1.49 (1.31–1.69)***	1.07 (0.99–1.16)	–
Family disease history			
No	Ref.	Ref.	Ref.
Yes	3.49 (3.08–3.96)***	4.45 (3.35–5.89)***	3.12 (2.87–3.38)***

Lifestyle			
Tobacco use			
No	Ref.	Ref.	Ref.
Yes	1.26 (1.06–1.51)*	0.95 (0.84–1.08)	0.74 (0.65–0.84)***
Alcohol consumption			
None/rarely	Ref.	Ref.	Ref.
Sometimes	0.81 (0.69–0.96)*	0.94 (0.85–1.03)	1.09 (0.99–1.21)
Everyday	0.68 (0.57–0.80)***	0.56 (0.50–0.62)***	1.72 (1.53–1.94)***
Low intensity exercise (Q3)[4]			
No	Ref.	–	–
Yes	1.27 (1.12–1.43)***	–	–
Eating speed (Q10)[5]			
Normal	–	–	Ref.
Fast	–	–	0.90 (0.82–0.99)*
Slow	–	–	0.72 (0.63–0.84)***

Note: * p<0.05, ** p<0.01, *** p<0.001. 1 Surgical history of esophagus/stomach was also adjusted, 2 Surgical history of esophagus/stomach and treatment history of heart disease, kidney disease, liver disease, and blood disease were also adjusted, 3 Treatment history of heart disease was also adjusted, 4 Q3: Do you walk for at least 1 hour every day or have equivalent physical activities in your daily life? 5 Q10: How fast do you eat compared to others?

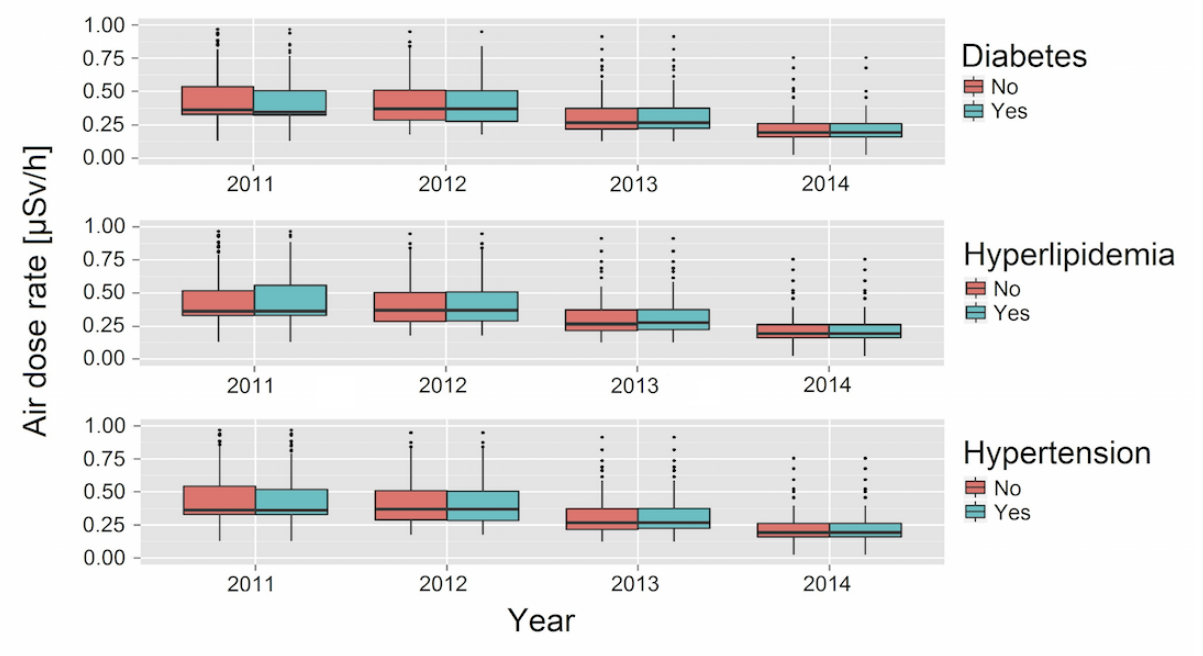
In addition to evacuation, I identified several other covariates associated with disease risk (Table 25). For example, the older age group (65–75 years) was significantly more likely to experience an increase in risk of each disease post-incident than the younger age group (40–64 years). Females had twice the risk of hyperlipidemia as males, while the post-incident risk of diabetes and hypertension were higher in males than females by about 2 and 1.5 times, respectively. As many previous studies have acknowledged,[171-173] family history of disease was significantly highly associated with disease risk for each outcome. Tobacco use and alcohol consumption were also found to be associated with disease risks, although not always in the expected direction, making these results difficult to interpret. Interestingly, hypertension was significantly associated with eating speed; those with slow eating speed were less likely to have hypertension (OR: 0.72, 95% CI: 0.63–0.84, p<0.001).

Impact of air dose rate level as a proxy of stress/anxiety level

Figure 13 shows the distribution of district-level air dose rates at non-/temporary-evacuees' dwelling locations by disease status. After adjustment for covariates, among non-/temporary-evacuees, no significant associations between diseases risk and air dose rate levels [per μSv/h] were observed post-incident for any of the outcomes (OR for diabetes: 0.87, 95% CI: 0.45–1.67, p=0.7; OR for hyperlipidemia: 0.94, 95% CI: 0.61–1.46, p=0.8; and OR for hypertension: 0.85, 95% CI: 0.53–1.34, p=0.5). I conducted sensitivity-analyses by constructing models using air dose rate levels in a

categorical form (quantiles), rather than as a continuous variable, and results were similar. These results indicate that level of radiation exposure did not affect disease risk for these chronic diseases.

Figure 12: Box plots for the distribution of air dose rate at non-/temporary-evacuees' dwelling locations by disease status



Note: The bar represents the median radiation air dose rate. The air dose rate includes the background dose from the ground. The box shows the 25th and 75th centiles. Whiskers are 1.5 times the interquartile range. Outliers are shown by dots.

6 Discussion

6.1 Analysis-specific discussion

6.1.1 Question 1: (a) how accurately does the Japanese government's dose reconstruction model estimate the annual external radiation dose among school children 18 to 30 months after the incident, and (b) what uncertainties exist in the model leading to the potential disagreement with the measured dose?

This was the first study after the Fukushima nuclear incident to compare individual radiation dose measured directly using radiation dosimeters to that modelled using the Japanese government-proposed equation model. I observed a three-fold disagreement on average between the modelled and measured additional external doses in school children in the 18 to 30 months after the incident in Minamisoma City, with the model over-estimating exposure.

The government dose reconstruction model was developed for the evaluation of the dose, which was (and is) applied for the designation of evacuation zones, and subsequent lifting of these designations. It is reasonable to assume that the government model was designed for simple/easy and conservative dose evaluation in the affected areas. However, as pointed out elsewhere,[174,175] more than 80 thousand evacuees from the 20 km mandatory evacuation zone,[8] resulting in substantial evacuation-related mortality and morbidity (both in short- and long-term) with no radiation-related deaths,[48-51] showed that it is hard to affirm that the evacuation instructions (based on this 'conservative' government model), taken to minimize radiation-induced cancer risks, was valid; the dose evaluation for the designation of evacuation zones was not 'conservative'. My work, therefore, addressed the critical issue of the government's overestimation of dose, and highlighted uncertainties associated with this modelling approach to dose estimation.

The causes of the disagreement between the modelled and measured values of the annual effective dose include the conversion coefficient, the radiation reduction coefficient, and participant behaviour, discussed in turn below.

First, the government model employs 1.0 as the conversion coefficient from the air dose to the effective dose without considering the varying sensitivity of different organs and tissues to radiation.

However, several studies have confirmed that the conversion coefficient should be less than 1.0. For example, the conversion should be around 0.6 for adults and children (see section 5.1.3) for air dose rates measured in terms of ambient dose equivalent (H*10) according to Saito et al. (2015).[146,176]

The second potential cause of the difference between the measured and modelled values comes from uncertainties associated with the radiation reduction coefficient. Japan's government model used 0.6 for the reduction coefficient under the assumption that people spent 8 hours outside and 16 hours inside in a building with a shielding effect of 0.4 per day (these values are also used in the WHO's dose reconstruction models).[20] However, the survey reported here showed that most of the participants (school age children) self-reported spending less than 2 hours and 4 hours outdoors after school (95.2%) and on a weekend (96.0%), respectively (Table 7), and 100% of the participants had a coefficient of less than 0.6 (Figure 6), implying that the 'true' reduction coefficient, at least in this sub-group of the population, is much lower than that used in the government model. For example, the mean reduction coefficient in these school age study participants was 0.3, so the underestimated reduction coefficient used in the government model may explain about half of the three-fold discrepancy between the measured and modelled dose. In addition, the regression analysis demonstrated a substantial negative correlation of the reduction coefficient with the air dose rate in participants' dwellings, indicating that that the difference between air dose rate indoors and outdoors at a household was larger in areas with higher air dose rate levels. The radiation exposure risks indoors might be suppressed even in areas with higher air dose rate levels, possibly due to decontamination efforts and countermeasures to reduce the exposure risk indoors. Supportive evidence on this finding comes from the 2014 joint research between NIRS and the Japan Atomic Energy Agency (JAEA) which also reported the potential negative correlation of the building shielding effects with the air dose rate regardless of the building type.[105]

In addition, there were significant associations between school-level and the radiation reduction coefficient after adjusting for covariates, suggesting that behaviour patterns in school are also important indicators for the estimation of radiation exposure.[98]

Limitations

The present study used the best data available at the time (i.e. external radiation exposure screening, post-incident daily behaviour patterns in school children, and air dose rate), and the choice of the data and target population (i.e. school children) was determined from the disaster context. When interpreting the findings, there are several limitations to be considered. First, I measured the three-

month effective dose using a Glass Badge and multiplied the resulting dose by four to obtain an annual dose; therefore, this method ignored the nature of radioactive decay or disintegration (i.e. half-life) of radionuclides during the subsequent nine months, which might lead to a potential overestimation of the annual dose. The government equation model does not consider the half-life of radioactive elements either, so this limitation is unlikely to explain the discrepancy between the modelled and measured dose. The majority of radionuclides released from the Fukushima nuclear power plant were Xenon-133 (about 19 EBq),[6] Iodine-131 (about 500 PBq), Cs-134 (about 10 PBq), and Cs-137 (about 10 PBq),[7] and their radioactive half-lives are five days, one week, two years, and 30 years, respectively. Given that dose attributed to Xenon-133, Iodine-131, and Cs-134 is negligible or modest, respectively, at the time of the study (18 to 30 months after the incident) due to their relatively short half-lives,[18,20] this failure to account for the half-life of the radioactive elements is likely to have limited impact. In addition, because Cs-137 has such a long half-life, the radioactive decay during this one year study was likely marginal.

The second limitation comes from the accuracy of air dose rates measured by MEXT airborne monitoring. The MEXT air dose rates at a height 1 m above ground were measured from a height of 300 m. However, a clear positive correlation with an absolute error of approximately 10–30% in the dose rates between the aircraft measurements and direct ground surveys was demonstrated by JAEA.[177] In addition, the MEXT air dose rates were averaged in 600-m-diameter circles below the aircraft. Therefore, given that the spatial distribution of the radionuclides varies from location to location,[178] the accuracy of the measurements might be influenced by environmental characteristics within each measurement area, such as the presence of geographical gradients and forests.

Third, because the study participants were school children, whose daily lifestyle and living environment might be different from other population groups, I cannot generalize the results of this analysis to the wider affected population.

Finally, it must be noted that the Glass Badge campaign was voluntary, and only those with high adherence to the dosimeter equipment rules (i.e. those who wore the Glass Badge during school commuting hours and while outdoors) were included in the analyses (520 out of 1,956 school children electing to wear Glass Badges during this screening wave). I report in Questions 2 and 3 above, that no significant differences in the behavioural patterns were observed between the low- and high-adherence groups, except in terms of the school commuting time ($p<0.05$: Chi-squared test), which was not a significant variable in the regression analysis (section 5.2.3). Data from children who did not

wear the dosimeters when travelling to/from school and/or outdoors (and who were excluded from this analysis) likely had statistically significant (but clinically insignificant), errors in their measured dose, however improper use of a dosimeter at school, at home, and at bedtime did not appear to generate errors (section 5.3.2). While this gives some confidence that the data of the 520 children included in this analysis might represent the wider participants of the external radiation screening in this analysis period, it is unlikely that they represent the wider population of school children because of the nature of voluntary-based screening. Unfortunately there were no data available for non-participants to address the wider generalizability of these findings. Potential participation bias include that people concerned about radiation exposure might be more likely to participate in the screening and be included in this analysis. Given that people who are concerned about their exposure level might also be more likely to undertake additional countermeasures to reduce their risk of exposure in their daily life, this analysis may underestimate dose in the wider school age population. As a result, the ratio of the average modelled and measured dose and the radiation reduction coefficient might be over and under estimated respectively.

6.1.2 Question 2: how do the behavioural patterns of school children influence external dose 18 to 20 months after the incident?

This was the first assessment to evaluate the relationship between individual behaviours and the measured external radiation dose after the nuclear incident in Japan. The results of this analysis indicate that, after adjusting for covariates, the factors that had a significant relationship with dose were air dose rate at dwelling location and at school (Table 8).

In addition, time spent outdoors while commuting to school, after school, and on weekends were not statistically significantly associated with dose measured over three months using the Glass Badge (Table 8). The majority of the participants did not spend much time outdoors (84.4% spent less than 30 minutes commuting to school, 87.8% spent less than 1 hour outdoors after school, and 85.5% spent less than 2 hours outdoors on weekends (Table 7: Part 2 and 4)). These non-significant results suggest that the effects of outdoor activities over a short period of time on the total dose are likely marginal. Other relevant outdoor activities, such as outdoor class exercise and sports club activities, also had no significant relationship with the measured dose, probably for the reason mentioned above. It is necessary to be careful when generalising my findings beyond this study' participants, e.g. children who spend even more time outdoors. I could not exclude the possibility that if a time longer than, e.g., 2–4 hours, was spent outdoors, a statistically significant increase in dose might be observed.

This finding can be contrasted with current emerging concerns from the public in the Fukushima affected areas. In response to concerns regarding radiation exposure, many activities aiming at reducing the potential/unknown exposure risk in children have been conducted by their parents, schools, and communities. In order to minimize the exposure risk, many schools in the radiation-contaminated areas in the Fukushima Prefecture adopted countermeasures such as placing restrictions on the number of weekly outdoor exercise classes, and other outdoors activities, including club activities after school.[179] Another major concern was the potential presence of areas with exceptionally high external exposure from radionuclides deposited on the ground (groundshine) in the school commuting zones, referred to as 'hot spots'.[180] This concern resulted in 80.2% of parents taking their primary school children to school by car to protect against this radiation (Table 7: Part 2). In addition, 40.1% of the participants who answered the survey believed that they were most exposed to the radiation during the commuting hours. Contrary to these concerns, this analysis demonstrated that exposure risk during outdoor activities and school commuting, which occur over short periods of time, is likely marginal.

Limitations

This analysis is subject to the same limitations described above in section 6.1.1 above. In brief, the external screening program was voluntary, meaning participants in this program may not be representative of the wider population from which they were drawn. In addition individuals with low adherence to the Glass Badge equipment instructions were excluded from the analyses, bringing the percentage of the school children participating in the study down to only 7% in Minamisoma City at the time of the dose measurement. Furthermore, the study population comprised school children whose daily behavioural patterns as well as living environment might differ from the population in other age groups, meaning findings cannot be generalized to the wider population.

6.1.3 Question 3: (a) what are the characteristics of school children who do not use the dosimeters correctly, and (b) how much error is generated by improper use of the dosimeters 18 to 20 months after the incident?

This was the first study evaluating the proper use of individual radiation dosimeters in children, and the effects of improper use on the measured dose after a major radiation-release incident. This analysis shows that only 7.3% of the participants used the Glass Badges properly during the screening period, and I identified some potential reasons for this low compliance. First, it must be emphasized that although only a small percentage of the children used the dosimeters correctly throughout the entire measurement period, most of the children used the dosimeters properly during school hours

(Table 10). Therefore, the low rate of proper use was attributed mainly to non-use when children were at home or outdoors. Possible explanation for this includes that parents were specifically concerned about the radiation exposure of their children at school, where the children spent most of the day away from parental supervision.

Second, primary and secondary school children were significantly less likely to wear the dosimeters at home, outdoors, or at bedtime than high school children (Table 11), suggesting that it is very difficult to encourage younger children to adhere to the appropriate use of the dosimeters, possibly partially because the children found it difficult to handle the small devices.

Third, the air dose rate level at dwelling location and sex were associated with how well the children use the dosimeters (Table 11). My logistic regression analyses confirmed that children who had lower air dose rates at dwelling location were less likely to wear the dosimeters at school. One possible explanation is that because parents were usually aware of the air dose level at their home, and those living in areas with lower air dose rates might be less concerned about the proper use of the dosimeters by their children. The regression analyses also confirmed that male children were less likely to use the dosimeters at school than female children. This result may reflect greater concerns of parents about the risk of radiation exposure for female children in particular, who have also suffered from social stigma that some people might view them negatively owing to assumptions about the radiation effects on future pregnancy or genetic inheritance.[34,181]

Fourth, membership in outdoor sports clubs and hours spent outdoors on weekends were also associated with non-use of the dosimeters outdoors (Table 11). These results imply that children who participate in outdoor activities tend to avoid wearing a dosimeter outdoors, possibly because they felt uncomfortable with it when they played outdoors, and/or that wearing the dosimeter was incompatible with their sports (e.g. contact sports (which might damage the device) or sports requiring specific clothing).

Importantly, the error generated by improper use of the Glass Badge—as defined in the section 4.3.2 , the difference between the measured dose and regression estimates of the ‘expected’ dose are referred to as an ‘error’ due to non-use in this study—was almost zero mSv (ratio: 0.99) overall (n=1,518) with the measured and ‘expected’ dose not being statistically significantly different (Table 12). This result indicates that even if the dosimeters are not properly used throughout the day, an appropriate evaluation of the radiation exposure may be possible.

When children removed the dosimeters, the dosimeters were generally left somewhere inside the home or school. This means that if the dosimeters are removed when children were indoors at home or at school the dosimeters would still detect the radiation emitted from the same environment, likely at similar exposure levels to those experienced by the children. On the other hand, if children do not wear or bring the dosimeters to school, or do not wear them outdoors, the dosimeters would not be co-located with the children, and so may measure different radiation levels due to being located in a different environment. Two possible reasons for the good agreement between the measured and 'expected' dose are: (a) the difference in radiation levels between places where children spent most of the day and places where the dosimeters detected radiation without the child nearby was very small; and (b) although children might not have taken their dosimeters with them when outdoors, most of the children in this analysis did not spend much time outdoors during the screening period.

These assumptions are supported by the fact that when the differences between the measured and 'expected' dose for each time period are compared, statistically significant differences were observed among children who did not wear or bring the dosimeters to school ($p<0.01$), whereas non-use at school or at home and during bedtime did not result in significant errors. Because children spend most of the day at school, if they do not wear or bring the dosimeters to school and the dosimeters are left in the home, the dosimeters measure the radiation in the home for a long period of time while the children are in school. Owing to successful decontamination of schools[182] as well as schools' structural properties, there was a large difference in radiation levels between participants' dwelling location and the school grounds (mean air dose rate of 0.49 and 0.11 μSv/h, respectively: Table 9). As a result, the measured dose of children who did not wear or bring the dosimeters to school, where the radiation level was much lower than at home, were overestimated (ratio: 1.13; difference: 0.04 mSv; $p<0.01$), although this difference may not be clinically important.

The finding that the measured values in those who did not use the dosimeters outdoors were significantly underestimated (ratio: 0.97; difference: 0.01 mSv; $p<0.05$) deserves careful consideration. This underestimate might be attributed to the fact that most of the children in this analysis did not spend much time outdoors during the screening period (87.8% spent less than 1 hour outdoors after school, and 85.5% spent less than 2 hours outdoors on weekends). The magnitude of the difference due to non-use outdoors is determined by the amount of time children spend outdoors when the dosimeters remain indoors, in addition to the difference in indoor and outdoor radiation levels;

consequently, the measured dose may be underestimated, although again this is not likely to be clinically significant.

The major determinant of the total dose is the radiation level at the places where people spend most of the day. Therefore, it is reasonable to think that a major contributor to the magnitude of the errors generated by the improper use of the dosimeters is the difference between the radiation levels in places where children versus dosimeters are located. My study considered school children, who tend to spend most of the day at school or home, and who follow a similar schedule every day. It is necessary to be careful when generalising my findings beyond this school age group, e.g. to children who do not go to school (e.g. preschool children), children on a long holiday or vacation break, and older children who are employed, who will have a very different schedule.

It should be noted that monitoring the daily behaviour of individuals is challenging owing to the technical and practical difficulties, as well as barriers involving privacy issues that make people reluctant to agree to participate in such monitoring exercises. In this context, I would like to emphasise that the external radiation screening by Minamisoma City offered a unique and valuable opportunity to perform the above retrospective studies with sufficient quantitative behavioural data to better understand compliance and behaviours influencing radiation exposure.

Limitations

I have identified several limitations in this analysis. The mean air dose rate at the participants' dwelling location in Minamisoma City during the measurement period was 0.49 μSv/h (range: 0.19 to 2.13 μSv/h), including the natural background dose from the ground. Because the absolute values of the errors generated by improper use of the dosimeters may depend on the air dose rate at each participants dwelling, my findings with regard to the significance of the errors are not generalisable to other areas with higher exposure levels in the Fukushima Prefecture. In addition, in this analysis, I did not adjust the measured dose for the body size of an individual but instead directly used the measured dose as his/her effective dose. It is known that that the body size of an individual affects the accuracy of an individual radiation dosimeter by, at maximum, about 10%, depending on the product type as well as the irradiation geometry in the environment.[183] However, I had no data on height/weight, so was not able to take this into account.

This analysis is also subject to the same limitations described above in section 6.1.1 above. In brief, the external screening program was voluntary, thus participants in this program may not be

representative of the wider population from which they were drawn. In addition, the data of only 119 children who properly used the dosimeters were employed to construct the dose prediction model, which represent about 2% of all school children in the city at the time of measurement. Therefore the regression estimates of the 'expected' dose in the rest of children (who improperly used the dosimeters) may not be representative of the wider school age population. However, despite the small number of samples used for the dose prediction model, the prediction accuracy of the model was high and robust (see section 5.3.4).

6.1.4 Question 4: what are the relationships between early evacuation and levels of internal radiation exposure among adults four months after the incident?

According to previous studies, the greater contribution to effective dose in the first year in the areas with high ground deposition density was from external exposure from deposited radionuclides (groundshine) (see section 2.1.2).[18,63] The present study shows that individuals who evacuated to areas outside Fukushima Prefecture had significantly lower (but not by much) Cs-134 body concentration four months after the incident than individuals who stayed in Fukushima, after adjusted covariates (relative level: 0.86; 95% CI: 0.74–0.99; $p<0.05$: Table 15) .

This modest reduction in Cs-134 body concentration following evacuation might suggest that other mitigation strategies perhaps reduced the body concentration. Possible explanations may include that Fukushima Prefecture and Minamisoma City instituted strong food safety regulations shortly after the incident,[22,23] and therefore, the risk of ingestion of radionuclides in food and drinking water was somewhat mitigated for all residents, irrespective of evacuation status or evacuation location. In addition, in response to the incident, Japanese and prefectural governments launched an initiative to monitor foodstuffs, including drinking water, on 17th March 2011.[22] One week following the launch of the initiative, selected foodstuffs containing radioactivity levels exceeding the provisional regulation values (depending on types of foodstuff and radionuclides—e.g. 200 Bq/kg of radioactive cesium for drinking water and milk; and 500 Bq/kg of radioactive cesium for vegetables, grains, meat, eggs, and fish), were banned from the market.[22]

Challenges to investigate the initial stage of the incident include very limited or non-existent data on early exposure assessment and insufficient quantitative data about resident's daily precautionary behaviours, including evacuations they may have taken.[184] The chair-type WBC installed in July 2011 at MMGH in Minamisoma City was the first WBC unit introduced in Fukushima Prefecture after the

nuclear incident. While other WBC units were installed several months later in other areas of Fukushima, Minamisoma was the only city able to conduct early (but not in the emergency phase) internal radiation exposure assessments, offering me a unique opportunity to assess the effectiveness of early evacuation on the levels of internal radiation exposure four months after the incident.

Limitations

To my knowledge, this is the first assessment of the effectiveness of early evacuation on reducing the risk of internal radiation exposure in the post-emergency phase of the incident. However, there are limitations in this analysis. Data were obtained from volunteers, and therefore, people who were concerned about radiation exposure might be more likely to be included in the study. Gender distribution in the study participants (female: 54.9%: Table 13) was similar to that in the whole population in the city (52.3% as of July 2011[129]). The most frequent age groups were 56–65 years for both the participants and whole population.[129] However, occupation data is not available for the whole population and there were no other data available that might be related to the screening participation behaviour (such as socioeconomic status[185,186]), to address the potential selection bias. Therefore, the screening results would not necessarily represent the levels of internal contamination for the general population in the affected areas. If people who worried about their risk of internal contamination were more likely to care about ingestion of radionuclides in food and drinking water (by avoiding consumption of home-grown foods), the contamination levels in this analysed population may be lower than those in the general population in Fukushima Prefecture, which may underestimate the effects of evacuation to reduce the contamination levels four months after the incident. Alternatively, if people were worried about internal contamination because of their potential ingestion of contaminated foodstuff following the incident, they may be more likely to attend the screening to check their contamination levels, and the contamination levels in this analysed population may be higher than in the general population, which could overestimate the evacuation effects. It was not clear from the available data which direction this bias would work.

In addition, although I reduced the possible effects of chronic ingestion of contaminated foodstuff by considering only those who evacuated to areas outside Fukushima Prefecture within half a month of the incident (Table 16), it was not possible to distinguish between the effects of acute ingestion of contaminated foodstuff and inhalation of Cs-134 in the emergency phase of the incident on the levels of Cs-134 body concentration four months after the Fukushima incident.

Although an assessment of inhalation of Iodine-131 in the emergency phase of the incident would be helpful to evaluate its effects on the thyroid gland, when MMGH initiated the WBC screening in July 2011, Iodine-131's short physical half-life caused it to be undetectable, suggesting that screening of internal contamination should ideally begin within a few days of such an incident, in order to evaluate the potential effects on the thyroid. It must be noted that because the amount of Iodine-131 released to the environment after the incident was much greater than that of both Cs-134 and Cs-137 (500 PBq vs. 10 PBq and 10 PBq, respectively),[62] the inhalation risk of Iodine-131 was significant,[52] and early evacuation may have had a significant effect on reducing this inhalation risk. However, my analysis could not evaluate this. Note that major radionuclides released to the environment after the incident included Xenon-133 (about 19 EBq),[6] but it was disregarded in this analysis as it is noble gas and is not concentrated in the body.[20]

6.1.5 Question 5: how much did the mortality risk differ between evacuees and non-evacuees among nursing home residents after the incident?

This was the first comparative assessment of mortality risk between evacuees and non-evacuees in nursing home residents after the Fukushima nuclear incident. I observed no statistically significant increased mortality risk in those that experienced the incident when comparing pre- and post-incident data (Table 20). However, I found that those who experienced evacuation had a substantially increased mortality risk, with the initial evacuation being associated with approximately three times as many deaths as non-evacuation (Table 21). My work addresses the critical issue of whether to evacuate or shelter in place.

While I found a statistically significant association between evacuation and mortality risk, I could not ascertain from my data whether the observed impact of evacuation on mortality could be attributed to physical/psychological evacuation burden (due to e.g. inadequate transportation means for nursing home residents and/or long transfer distance, although evacuation distance did not have a significant influence on risk); poor preparations for care-provision at evacuation sites as well as separation from the care staff in the original facility who were familiar with the residents and their care needs, causing e.g. a discontinuity of care; or a combination of these factors.

It is likely that the unplanned initial evacuation in the aftermath of the incident did not permit satisfactory arrangements for appropriate welfare vehicles,[187] and facilities at the initial evacuation sites were potentially not well-prepared for the evacuees' care. Second and subsequent evacuations, which were more likely to have been pre-planned and carefully executed, did not show a significant

impact on mortality risk (Table 21). These data indicate that appropriate evacuation preparations are fundamental to survival of nursing home residents[117,118,188]

Balancing the risks of evacuation with the risk of radiation exposure and associated health impacts in elderly populations requires evaluations such as these to inform the appropriate management of any such incident in the future. This analysis provides evidence that evacuation may not have been the best life-saving strategy for elderly people in Minamisoma. Sheltering in place should be considered as an alternative strategy for disaster planning.[189] However, importantly, particularly for elderly institutionalised residents (such as patients/nursing home residents), the decision of whether or not to evacuate also requires the understanding of the need for evacuation of potentially younger facility staff who might suffer greater consequences (or at least longer term consequences) of radiation exposure. As described in the section 5.5.1, for the facilities in Minamisoma, evacuations were at least partly driven by staffing deficiencies due to staff evacuation.[92] Murakami et al. (2016) simulated the loss of life expectancy (LLE) of nursing home residents and facility staff (about 200 samples for each) in Minamisoma City under the scenarios that they had not evacuated but exposed to the effective dose of 20 mSv or 100 mSv in the first year following the incident.[190] Total LLEs from all solid cancers and leukaemia due to radiation exposure for facility staff were estimated approximately 10 times higher than those for the residents in both scenarios (1,000 vs 100 person days and 5,300 vs 530 person days for 20 mSv or 100 mSv, respectively), although these are 20 to 100 times lower than that in the actual situation (i.e. LLEs due to evacuation) among the residents (11,000 person days).[190]

In addition, in a post-disaster situation where collapsed infrastructure affects the essential conditions for maintaining elderly peoples' health (e.g. lack of daily necessities and nursing care equipments),[191,192] evacuation may be essential/unavoidable regardless of the radiation exposure risk. Another important note includes that statistically significantly higher mortality was observed in residents aged more than 80 years than in those aged 50–69. It is well-known that older persons are more vulnerable and less resilient to disasters than the younger population because of decreased sensory awareness, physical and cognitive impairment, chronic health factors, and socio-economic limitations (e.g. high reliance on social support and fewer transportation options and opportunities).[193,194]

Limitations

The present study had several limitations. Only five of eight nursing homes in Minamisoma were involved in this analysis. As explained in the section 4.5.1, among the rest of the three nursing homes,

one, which is a rehabilitation facility with a capacity of 58 people, had insufficient data quality for inclusion in the study (such as lack of evacuation records); one, a 60-person intensive care home, refused to participate; and one facility, a rehabilitation facility with capacity for 100 people, was not able to participate because it was wrecked by the tsunami, all residents were killed and records were destroyed in the tsunami. This 218 excluded residents represent about 40% of all nursing home residents in the city at the time of the Fukushima incident. There was a possibility that some selection bias was present, but unfortunately the data were not available to test it.

In addition, the regression model that evaluated the stage-specific mortality risk (non-evacuation vs. initial evacuation from the original facility vs. subsequent evacuations) using post-incident data (Table 21), I was not able to adjust for the city effect (i.e. the different mortality between Minamisoma and Soma net of other variables). Post-incident data of Minamisma only contained evacuees and that of Soma only contained non-evacuees. Therefore, a variable of 'city' and 'evacuation type' were highly correlated, and thus were not included in the same regression model to maintain low multicollinearity among the variables.[195] Given that the city effect was statistically significant (Table 18 and Table 20) with Minamisoma more likely to have lower mortality than Soma, the estimated mortality risk of evacuation (drawn from Minamisoma) in this regression analysis might be underestimated.

6.1.6 Question 6: how much did evacuation affect long-term chronic health after the incident?

In this analysis I found that in the three-year follow up of individuals in Fukushima Prefecture there have been significant increases of prevalence of diabetes and hyperlipidemia both in evacuees and non-/temporary-evacuees in comparison with baseline years (RR of 1.27 to 1.60 for diabetes and 1.12 to 1.30 for hyperlipidemia, depending on post-incident year), after adjusting for age. Evacuees had a small but significantly higher risk of hyperlipidemia than non-/temporary-evacuees. Despite high levels of public concern, radiation levels were not associated with these disease risks.

Although many previous studies reported post-disaster increases in hypertension prevalence, adequate control of hypertension should be achievable after a disaster as day-to-day self-blood pressure monitoring is possible using a home blood pressure monitor.[196] In contrast, diabetes and hyperlipidemia are more difficult to control after a disaster; almost all available blood glucose and cholesterol monitoring require invasive procedures, self-monitoring is less accepted by patients, resulting in reduced patient compliance in diabetes and hyperlipidemia monitoring and treatment.[197,198] Previous studies have reported associations between experiences of life-threatening

disaster and reduced chronic health control partially due to interruption of routine medication,[166,199,200] resulting in, for example, worsen circulatory system diseases, such as acute myocardial, cardiovascular, and cerebrovascular diseases.[41,201-203] The findings of this analysis show that, regardless of evacuation, there was a significantly increased risk of diabetes and hyperlipidemia more than three years after the incident. This persistent impact on chronic health indicates the necessity of paying particular attention to the mid- to long-term effects of a disaster on diabetes and hyperlipidemia.

The fact that while evacuees had higher risk of hyperlipidemia than non-/temporary-evacuees, there was no significant difference in diabetes risk between evacuees and non-/temporary-evacuees post-incident may reflect public and clinicians' substantial concern about diabetes. This heightened concern over diabetes, even in the post-evacuation environment (characterised by reduced physical exercise, dietary change, reduced access to medical care, and socioeconomic changes), may have resulted in diabetes risk in evacuees being successfully managed at a similar level as in non-/temporary-evacuees. This didn't appear to be the case for hyperlipidemia, and these findings suggest that all parties involved in local health care should pay more attention to hyperlipidemia control, with a particular focus on evacuees.

Meanwhile, Satoh et al. (2015) found that evacuees had about 1.4 times higher diabetes risk than non-/temporary-evacuees one year after the Fukushima incident after adjustment for covariates.[51] This finding was contrary to the result of the present study which suggested no significant difference in diabetes risk between evacuees and non-/temporary-evacuees post-incident. Given that my study considered those aged up to 74, while Satoh et al. (2015) included people aged more than 75 up to 90, these differences suggest that evacuation may engender differential vulnerability for elderly people in terms of chronic health conditions, depending on the distance of evacuation.

In my study sites, from a few months after the incident, the city offices and municipal hospitals have offered external and internal radiation exposure screening programs for free to city residents using personal radiation dosimeters and whole-body counting machines.[29] I found no significant associations between diseases risks and radiation levels at dwelling location post-incident for any of the diseases, which may indicate that the public's understanding of the potential radiation risk has been fostered and public anxiety about radiation exposure might not be strong enough to influence disease risk. In fact, low risk dietary and lifestyle behaviours were well studied in our study sites.[204] Although residents' dietary patterns might have changed immediately following the incident, with a

potential move to increased meat consumption due to concern over the radio-contamination of soil (vegetables/fruits) and seawater (fishery products),[205] this change was likely temporary. As of the end of 2013, it was known that all foodstuffs, except for mushrooms and mountain vegetables, were at a low risk of radiation contamination and under no governmental shipment restrictions.[204]

Limitations

This analysis has several limitations. First, because the definition of 'evacuees' was those who were living in the districts denoted compulsory evacuation, the 'evacuees' did not include voluntary temporary evacuees who were living outside the evacuation zones. Although in Minamisoma the proportion of people who were forced to evacuate was about 27% of the total population,[129] according to the city office, the population declined to about 10% right after the incident, indicating that approximately 60% of people voluntary evacuated. However, many of these evacuations were temporary and the population has now rebounded to more than 70% of the pre-incident level so far,[206] so I had to assume that many of the voluntary evacuees returned soon after their voluntary evacuation, though I lack reliable data to evaluate this. Therefore, I am differentiating the effect of mandatory evacuation from non-/temporary-evacuation.

Second, the health check-ups were undertaken on a voluntary basis, and only offered to the self-employed aged 40 to 74 years (insured by NHI system), potentially biasing the results, and limiting my ability to generalise to the wider population, especially the different occupation and age groups. Consequently, those insured by other types of health insurance, such as EHI and LEHI (see section 4.6.2), which are mainly intended for employed workers and self-employed persons aged over 75, respectively, were not included as study participants.

Note that as I described in the section 4.6.2, there are more than 1,500 insurers for EHI system across Japan.[158] Companies need to conduct regular health check-up on their employees under the EHI system. Their check-ups data are managed by companies and their insurers. Given it is unknown who are insured by which insurers and who are employed by which companies, I was not able to obtain the health check-up data under the EHI system in Minamisoma and Soma. About 35% and 30% of total population are covered by NHI in Minamisoma and Soma, respectively. Although the percentages of those covered by EHI and LEHI are not available at municipality level, at the national level, approximately 60% are covered by EHI, 10% by LEHI, and 30% by NHI.[207]

Fourth, this analysis cannot rule out the potential effect of temporal trends of the disease prevalence because I did not have any comparison pre- and post-incident for other prefectures that were not affected by the incident. However, according to the Japanese National Health and Nutrition Survey (NHNS),[208] the prevalence of diabetes, hyperlipidemia, and hypertension at national level has not significantly changed since 2006, after adjusting for age. NHNS is a nation-wide stratified random sampling survey on health and nutrition in Japan conducted every November by a household interview and blood sample collection, administered by Japan's MHLW.[209] Although, this NHNS data does not necessarily represent a prefecture- or municipality-level temporal trend on these diseases' burdens in Fukushima Prefecture or Minamisoma/Soma City, I believe the influence of any potential temporal trend was likely small and unlikely to significantly affect my findings. In other words, the comparisons pre- and post-incident in my study should mostly represent the impact of the Fukushima incident.

Fifth, it should be noted that evacuation sites include several housing styles, such as shelters, temporary housing, neighbours/relatives house, or new houses. As of July 2015, according to the official website of Minamisoma City, among the evacuees, 30% were staying at a neighbours/relatives house, 34% were living in temporary housing, and the remaining 36% had obtained their own new house.[206] However, due to lack of data, I was not able to consider these differences in evacuation experience in this analysis. Because different housing situations may create social stratification, which in turn, engender differential exposure to post-evacuation health compromising conditions, further investigation is necessary to clarify which housing styles are more relevant to chronic health issues.

Finally, my study sites suffered not only from the Fukushima nuclear incident, but also the tsunami that ravaged the seacoast areas of the cities right before the incident. Although the dataset of Soma did not include the data of tsunami victims (defined as those who perished directly because of the tsunami), that of Minamiosma contained tsunami victims' data because of the different dataset management/processing by the city offices. Since it was impossible to identify the tsunami victims of Minamisoma in the dataset collected, this analysis was not able to adjust for the health impacts of the tsunami. However, given that the percentage of the tsunami victims in the total population of Minamisoma was only 1% (n=790, including missing persons),[210] the statistical influence of this limitation on the study results is likely to be marginal.

6.2 Overall discussion and policy recommendations

Japan's 2011 Fukushima Dai-ichi Nuclear Power Plant Incident highlights the challenges facing us regarding radiation dose assessment and effective countermeasures (especially evacuation) when responding to a major incident. Better understanding of these challenges is vital to form a solid foundation of disaster risk reduction policy and action for nuclear incidents in the future. In this regard, there is significant scope to learn lessons from Japan's Fukushima nuclear incident.[55]

It must be noted that, given the limited time frame of these data, the context of much of the thesis is the post-emergency phase of the incident, and therefore I could not address the emergency phase (i.e. within the first few hours/days). In collaboration with Minamisoma City and Soma City—the cities most affected by the incident—my PhD project revealed that:

First, on the radiological protection aspects regarding challenges concerning the assessment of levels of external radiation exposure,

(1) there was a three-fold disagreement on average between the modelled (via the central government's reconstruction model) and measured (using an individual dosimeter) additional external effective dose 18 to 30 months after the incident among the school children in the city of Minamisoma, highlighting the government's overestimation of the dose and the uncertainties associated with the dose estimation;

(2) while behaviour related to outdoor activities had no statistically significant relationship with the dose in school children 18 to 20 months after the incident after adjustment for covariates, the air dose rate at dwelling location and school had a positive relationship with the dose in children—a 0.1 and 0.01 μSv/h increase in the air dose rate at dwelling location and school was associated with a 10 and 2% increase in the dose, respectively—implying that the air dose rate at places where school children spend most of their day are the significant predictors of the dose, as opposed to short periods of time spent outdoors;

(3) a low rate of proper Glass Badge use by children (7.3%) was identified 18 to 20 months after the incident, primarily attributed to non-use of the Glass Badge at home and outdoors, rather than at school. However, because of small dose error (less than 1%) due to the improper use of the dosimeters, even if the dosimeters are improperly used, robust evaluation of radiation exposure may be possible.

Second, on the non-radiological protection aspects regarding benefits and health risks of the post-incident evacuation,

(4) the effectiveness of early evacuation on reducing the levels of Cs-134 body concentration among adults (mean age: 56) was limited (an average 14% reduction in evacuees vs. non-evacuees);

(5) early evacuation of nursing home residents was associated with 1.82 times higher mortality after adjustment for covariates, with the initial evacuation from the original care facility associated with a 3.37 times higher mortality risk than non-evacuation;

(6) in the self-employed aged 40–74 years, while significant post-incident increases in prevalence were observed for diabetes and hyperlipidemia regardless of evacuation status (RR of 1.27 to 1.60 and 1.12 to 1.30, respectively, depending on post-incident year) after adjustment for age, the increase in hyperlipidemia was significantly greater among evacuees than among non-/temporary-evacuees (OR: 1.18), adjusted for covariates.

Overall, these findings may indicate that the latitude for improving the evaluation of the external radiation exposure in children in the post-emergency phase of a major nuclear incident is large if a dose reconstruction model can ensure more realistic representation of risk factors for external exposure and/or if the proper use of direct measurements (using individual radiation dosimeter) is thoroughly understood. In addition, there is plenty of scope for reducing post-incident evacuation-related health risks. More endeavours are necessary for disaster planning that can ensure evacuation implementation in well-planned manner with satisfactory arrangements for appropriate transportation and places to evacuate to safely, and that considers the long-term resilience measures for mitigating the evacuation-related health risks.

Developing resilient capacities for preparedness and response to such incidents will require buy-in at all levels (individuals, communities, local and national governments, and globally) to form evidence-based risk reduction policies and action plans for future crises. Based on the findings from my PhD project, I propose the following major actions to improve and increase disaster risk reduction efforts.

(1) Improvement of the external radiation exposure assessment and evaluation in children in the post-emergency phase of a nuclear incident

The modelled dose assessment must remain an important evaluation approach not only for the assessment of radiation exposure levels and risks to human health, but also for, more practically, the adjustment of the evacuation instruction (i.e. the designation of evacuation zones, and subsequent lifting of the designations) and decontamination plans. The Japanese government aims to provide realistic estimates of dose to the Japanese population, but the present study indicated for the first

time that significant overestimations likely occurred as a result of uncertainties due to our lack of knowledge and information regarding the individual's potential risk factors associated with their dose. Based on Questions 1 and 2, with a particular focus on school children, I suggest that:

(1-a) the air dose rate level in dwellings and the behaviour patterns in school where children spend the majority of their daytime hours are the most significant predictors of the dose, rather than outdoor activities over short periods of time. Accurate and timely assessments of air dose rate at dwelling location, and behaviour patterns at school are therefore essential for evaluating exposure risk in children, and should be primary considerations for dose estimation.

It is important to acknowledge that while the government model was designed for simple/easy dose evaluation, it is often a challenge to estimate dose in children, who exhibit unique daily behaviours (e.g. tend to spend much longer hours outdoors than adults), or for those in unique living environments (e.g. those living in building with very poor shielding effects).

Meanwhile, the use of direct measurements (using individual radiation dosimeter) is also beneficial as they can indicate the individual-level doses at the time that people were monitored. It is also reasonable to assume that the direct measurement could help ease parents' concerns about radiation exposure risk in their children by knowing their dose levels on a timely basis. However, the present PhD study indicated that school children did not necessarily use the individual dosimeters properly, which may present an obstacle to the direct measurement approach because it likely influences the measurement values. Therefore, based on Question 3:

(1-b) education of parents, as well as more instructions on the use of the dosimeter, are required, with particular focus on time periods other than school hours; and

(1-c) specific attention to younger children (primary and secondary students) is also needed because of the difficulty in supporting their adherence to the appropriate use of the dosimeters. These age groups might require more specific equipment instructions, and/or a modified device that is designed for their ease of use; however,

(1-d) the possibility that excessive or repeated instructions can be stressful for children and affect their everyday lives should be considered.

(2) Reduction of health risks of post-incident evacuation

It is well acknowledged that early evacuation is an effective early countermeasure to reduce the risk of external exposure in the early phase of a radiological incident.[60,115] Here, I added new evidence to

quantify the effectiveness of early evacuation on levels of Cs-134 in the body (Question 4). The potential benefits and risks of evacuation after a major nuclear incident must be balanced.[113] Importantly, given the potential health risks of evacuation—particularly the acute mortality risks in elderly, care-requiring population that I included in my analysis—the decision to implement early evacuation after a nuclear incident should be made by carefully. Thus, given the findings of Questions 5 and 6, as well as lessons from recent relevant discussions,[55,120,187,211] I highlight the following points regarding effective practice and procedures under mass-displacement disaster scenarios for further discussion, with a view to improving evacuation planning for, especially, elderly institutionalised residents (patients/nursing home residents):

(2-a) Emergency planning and response by health planners, disaster coordinators and facility managers in disaster-prone areas should consider the potential benefits of sheltering in place, and balance these against the risks of early evacuation.[120]

(2-b) Local authorities including municipalities and prefectures can and should play a leading role in both disaster planning and its implementation, and need to:

  (i) be aware of available resources within/beyond their locality in order to secure and dispatch the necessary staff, medical and other supplies (e.g. gasoline, food, and sanitary materials) to the affected facilities in times of disaster;

  (ii) facilitate the continuation of care whilst sheltering in place via advance agreements with all necessary parties to ensure reliable resource supplies during times of disaster; and

  (iii) formulate an evacuation plan, centering on proper arrangements for the safe transportation of elderly residents (e.g. vehicles for disabled persons, medical oxygen cylinders, and paper diapers) and well-preparedness of evacuation sites (e.g. nursing beds and transfers of residents' nursing/medical records) within/beyond their locality.

If a decision is made to evacuate based on balancing the competing risks of disaster exposure and evacuation burden, then:

(2-c) Local authorities should coordinate the movement of elderly residents from the disaster-affected facilities and support their admission to well-prepared, suitable evacuation sites.

Finally, in addition to the acute mortality risks, I also indicated for the first time the evacuation-related risk of hyperlipidemia that persisted longer term (over years). Therefore, I suggest:

(2-d) all parties involved in local health care should pay more attention to year-long hyperlipidemia control, with a particular focus on evacuees: for instance, promoting disease- and target-specific measures at the community or population level, and/or healthy lifestyle activities at the individual level (e.g. weight control, sleep behaviour, and balanced diet), which I identified as differing between evacuees and non-/temporary-evacuees post-incident (Table 23).

6.3 Dissemination of learning from this incident

Because of the unprecedented scale and nature of the Fukushima incident, all attempts and reactions to the incident were new and presented daunting challenges for local communities, financially, technically, and operationally. Since the incident, I have been engaged in community-based research over seven years in Minamisoma City and Soma City, and repeatedly discussed with responsible parties (e.g. city offices, hospitals, and health centres) a range of issues, including, for example, data recording, transfer, processing, and storage, ethical approval, and correspondence to mass media. In doing so, strong friendships and confidences were founded with the communities, which helped to make my series of unique studies possible, and facilitated the sharing of findings that inform the on-going recovery of communities in Fukushima, and inform preparedness and action in future similar events. The outputs from Questions 1–6 described above were published in international peer-reviewed journals,[212-217] and have been communicated with the public and disseminated widely within the relevant scientific community (including the UN system).[218-222] My study findings in this PhD project have informed the design, preparation, and delivery of measures to manage health risks for the Fukushima incident as examples and will support preparedness and action for any future major radiological incidents (e.g. informing the Japan Global Health Working Group (JGHWG) 2016 G7 Summit and Health Ministers' Meeting in Japan).[223]

6.4 Call for a new epidemiologic approach to disaster response

A major limit to learning from this disaster relates to the many limitations and biases described above in sections 6.1. Most of my analyses were reliant on imperfect data, due to small numbers of samples and/or biased populations samples (e.g. due to voluntary participation in the external radiation screening (rather than mandatory participation of all residents) and/or locally specific study designs rather than prefecture-/nation-wide research). In addition, the time frame of data available differed between Questions 1–6: 18–20/30 months after the incident for Question 1–3, 4 months after the incident for Question 4; up to 2.5 years after the incident for Question 5; and 3.5 years after the incident for Question 6. These issues may influence the value of the results, and limit ability to provide comprehensive understanding of the post-emergency phase of the incident and to generalise the

findings to shape future policy. Below I try to address this concern, highlighting how my studies are nonetheless invaluable in providing evidence to support the management of future incidents.[224]

Voluntary-based participation might be the default setting for individual radiation monitoring after nuclear incidents and research in their aftermath is necessarily based on voluntary participants

After the Fukushima incident, for both external and internal radiation exposure screenings, people were voluntarily screened (i.e. “Not get screened” was the default selection and “Get screened” was an active choice). In contrast, thyroid ultrasound examination, offered in every school in Fukushima Prefecture, was designed for children to participate as the default (i.e. “Get screened” was the default selection and “Not get screened” requite active opt-out).

The choice of screening measures can bring both benefits and harms in any situation. Both external and internal radiation screening can reduce radiation exposure by informing participants of risk behaviours. However, participants may react by changing their dietary habits or physical activities for the worse, or experience anxiety, even at low dose levels.[225] Thyroid examination can detect malignancy early, but could also lead to over-diagnosis or psychological distress.[69-72,226] For example, mortality rates due to suicide, accidents, or trauma were high in patients who received thyroid cancer surgery after the 1986 Chernobyl nuclear incident,[227] although it was not evident whether this increase was due to psychological distress after the surgery or to other reasons intrinsic to the country. The balance between benefits and harms depends on dose levels and social screening systems. Default settings for screening determine participation in the screening and therefore can be a key determinant of overall public benefit (or harm).[225] However, when harm outweighs public benefit, participation should not be the default choice, although screening should be made available to those who want to be screened. Authorities should consider the right of residents in affected areas to receive public and medical services after a major disaster, which is an essential element of a democratic society: government and society should acknowledge the right of residents to receive services while at the same time promote overall public health and benefits. A screening system in which voluntary participation is the default choice has an affinity with the philosophy of libertarian paternalism or nudge theory, giving residents options while promoting overall public benefits.[225]

In low dose situations, like Fukushima, mandatory screening for all residents may not be the best option, from a public health perspective. On the other hand, voluntary screening has low participation rates; self-selected participants may not represent the whole population, instead reflecting risk

perception and screening accessibility.[228] Such voluntary participation is not the "gold standard" in traditional, classic epidemiology, which generally requires a large number of samples distributed randomly with a low risk of bias. However, a screening system in a disaster context should not be determined from epidemiologists' specifications - when harms significantly outweigh benefits, epidemiologists and other public health researchers should consider novel ways to increase study generalisability.[229]

To increase study generalizability I used a variety of statistical approaches to analyse data. For instance, in Question 5, I included adjustment for the nursing home-specific elements of each nursing home in the study, and thus it is likely that the other risk factors (i.e. experience of the incident, evacuation type) for mortality that I identified are generalisable beyond the specific nursing homes studied.[212]

Nuclear incidents are rare and research in their aftermath is necessarily locally specific

Although the time frame of data used differed between Questions 1¬6, my PhD project makes important points about the management of the post-emergency phase of radiation-release incidents, which occur very rarely and only in very specific locations and whose potential influence differ over different time frames.[34] In fact, Minamisoma and Soma are the only cities that were heavily affected by the incident in terms of both radiological and non-radiological aspect in the post-emergency phase. Accordingly, all incidence-associated data collected and recorded are invaluable, even if the data are, by necessity, sporadic, incomplete and/or non-representative. My findings above are derived from analyses using the best available data (that covered different groups of population and a wide range of ages and periods affected by the incident) about both radiological protection aspects and non-radiological protection aspects in these local contexts. While in a non-disaster setting a larger and/or more generalizable sample followed continuously from short to long term might be able to be sought, in the post-disaster context these limited available data represent an invaluable material from which to derive outputs which can support better management of similar incidents in the future.

6.5 Concluding remarks

We stand at the crossroads of deciding how to go about building our future towards a disaster resilient society. Nuclear risk is not only an issue facing Japan. The 25 oldest nuclear reactors in Europe are now close to or past their originally envisioned 40 years of operation,[230] and their vulnerability to failure and accidents has been growing, with a reported 50% increase in unexpected incidents between 2000 and 2006.[231] Also, more than two-thirds (74 of 100) of the United States' operating

nuclear reactors have received extended licences permitting 60 years of operation, far beyond their original design lifetimes of 40 years.[230,232] As a result, we are entering a new era of nuclear risk. In this context, it is vital we take lessons from challenges posed by the Japan's Fukushima nuclear incident with respect to not merely radiological protection aspects, but also non-radiological protection aspects (especially the health impacts of evacuation), in order to build resilient capacities at the all levels (individuals, communities, local and national governments, and internationally) for preparedness and response to the future nuclear crises, globally.

Here, my PhD project adds deeper understanding of external radiation dose assessment and effective evacuation when responding to a major incident, which must be the fundamental basis of risk reduction policy and action for a major nuclear incident. The Japan Fukushima incident offers an historic opportunity to make a difference to future response and resilience in nuclear crises, and to support the world in reaffirming that “never again will we have another Fukushima incident”. I hope that the implications for practice derived from my PhD project will be carefully considered at all levels and promote discussions of successful implementation of effective preparedness and response towards risks of nuclear crises.

7 References

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APPENDIX A: Ethics approval

A.1 Authorization number 25-08

Notification letter of ethics examination results

審 査 結 果 通 知 書

Date: 25 March 2014
平成２６年３月２５日

Dear Dr Yukio Kanazawa,
The President of Minamisoma Municipal General Hospital
南相馬市立総合病院
院長　金澤幸夫　様

Dear Dr Kai Ishihara
Chair of Ethics Committee of Minamisoma Municipal General Hospital
南相馬市立総合病院医療倫理委員会
委員長　石　原　　開

承認番号　２５－０８
Authorisation number

研究等名　南相馬市における外部被ばくリスクに関する解析
Project title: analysis of external radiation exposure in Minamisoma city

上記、研究等の計画に関し、委員会での審議の結果、下記のとおり判定しましたので通知します。
Please be informed that we made a decision on the ethics of the research project above.

記

１．判定結果

Decision　承　認　　条件付承認　　不承認

Approval

２．条件の内容等

３．その他

A.2 Authorization number 23-46-0113

平成２４年１月１３日
Date: 13 January 2012

Applicant
Dr Masahiro Kami
申請者　上　昌広　殿

東京大学医科学研究所長
Head of the Institute of Medical Science, The University of Tokyo
清　野　宏
Dr Hiroshi Kiyono

Please be informed that we made a decision on the ethics of the research project below.

Ethics Committee at the Institute of Medical Science, The University of Tokyo
Notification letter of ethics examination results

平成２４年１月１３日
Date: 13 January 2012

所　　長　殿

委員長　吉田進昭
Chair of the committee: Dr Nobuaki Yoshida

審査の結果を次のとおり報告します。

受付番号　２３－４６　　提出日　平成２４年１月１２日
承認番号　２３－４６－０１１３
Application number
研究責任者　上　昌広　特任教授
審査事項　□初回審査　□変更　■修正
Authorisation number
委員会審査日　平成２４年１月１３日　□委員会開催　■迅速審査日
課題名　南相馬市立総合病院にて施行された内部被ばく検査データの後ろ向き解析
Project title: retrospective analysis of data of internal radiation screening conducted in Minamisoma Municipal General Hospital

判定　□ヒトゲノム倫理審査委員会に付議する（□要修正）
Decision
■承認　□条件付き承認　□変更の勧告　□否承認　□非該当
Approval
□修正を要する
□修正不要

勧告あるいは理由

A.3 Authorization number 25-16-0712

Ethics Committee at the Institute of Medical Science, The University of Tokyo

Notification letter of ethics examination results

東京大学医科学研究所倫理審査委員会

審査結果通知書

Date: 12 July 2013

平成２５年７月１２日

Applicant

Division of Social Communication System for Advanced Clinical Research,
the Institute of Medical Science, The University of Tokyo

申請者

Dr Masahiro Kami, a specially-appointed professor

先端医療社会コミュニケーションシステム社会連携研究部門

上　昌広　特任教授　殿

Head of the Institute of Medical Science, The University of Tokyo

Dr Hiroshi Kiyono

東京大学医科学研究所長

清　野　宏

審査番号：２５－１６

承認番号：２５－１６－０７１２

Application number

研究課題：福島原発事故後の高齢者介護施設入所者における避難後の生存解析

Authorisation number

申 請 日：平成２５年７月９日

Project title: analysis of survival analysis of elderly home residents following the Fukushima Dai-ichi nuclear power plant incident

Approval date: 9 July 2015

上記研究計画について、平成２５年６月２０日開催の本委員会における指摘事項の修正を確認し、下記のとおり決定しましたので、ここに通知します。

記

Please be informed that in a committee meeting held on 20 June 2013, we made a decision on the ethics of the research project above.

判定 Decision	承認 Approval	変更の勧告
	条件付き承認	否承認
	□修正を要する □修正不要	非該当

理　由・コメント

A.4 Authorization number 25-40-1011

Ethics Committee at the Institute of Medical Science, The University of Tokyo
Notification letter of ethics examination results

東京大学医科学研究所倫理審査委員会
審査結果通知書

Applicant
Division of Social Communication System for Advanced Clinical Research,
the Institute of Medical Science, The University of Tokyo
Dr Masahiro Kami, a specially-appointed professor

Date: 11 October 2013

申請者

先端医療社会コミュニケーションシステム社会連携研究部門

上　昌広　特任教授　殿

Head of the Institute of Medical Science, The University of Tokyo
Dr Hiroshi Kiyono

東京大学医科学研究所長

清　野　　宏

審査番号：２５－４０

承認番号：２５－４０－１０１１

Application number

研究課題：福島原発事故の影響に関する浜通り周辺地区住民の健康診断データの解析

申 請 日：平成２５年１０月８日

Authorisation number

Approval date: 8 October 2015

Project title: analysis of health check-ups data of residents in the affected areas following the Fukushima Dai-ichi nuclear power plant incident

上記研究計画について、平成２５年９月１９日開催の本委員会における指摘事項の修正を確認し、下記のとおり決定しましたので、ここに通知します。

記

Please be informed that in a committee meeting held on 19 September 2013, we made a decision on the ethics of the research project above.

判　定		
Decision	承認	変更の勧告
	条件付き承認	否承認
	Approval □修正を要する □修正不要	非該当
理　由・コメント		

APPENDIX B: Detailed explanation of a Tobit regression in Question 4

In order to support easier clinical and policy interpretations, I considered body concentration [Bq/kg] rather than body burden [Bq/body]. However, we could not use the natural logarithm of body concentration as the outcome variable in the Tobit regression because of limitations of the statistical software used in the analysis (STATA). Instead, I used the natural logarithm of body burden as the outcome and added natural logarithm of weight as an offset in order to 'theoretically' estimate the model with the body concentration.

I aimed to estimate the model in equation (1) (note that this equation is simplified for the sake of clarity):

$$\ln(\text{Cs/weight}) = a + [\text{covariates}] \quad (1)$$

By the properties of the natural logarithm, the left hand side of (1) can be expanded to obtain

$$\ln(\text{Cs134}) - \ln(\text{weight}) = a + [\text{covariates}],$$

which can be re-arranged as

$$\ln(\text{Cs134}) = a + [\text{covariates}] + \ln(\text{weight}).$$

Which is a model with body burden on the left hand side (the outcome) and weight entered as an offset on the right hand side. This is the regression model I constructed and ran on STATA. This approach was verified in Sugimoto et al. (2014).[149]

There are some advantages to using this approach. If body concentration is analysed as the outcome, every person has a different threshold in the Tobit regression because each subject's individual threshold is the ratio of the WBC's detection limit and weight. However, STATA is not able to handle a variable threshold value in its Tobit regression procedure. However, if I use the natural logarithm of body burden as the outcome and weight as an offset, I can have a fixed threshold of 800 Bq/body for

every subject, and at the same time we can interpret the coefficients as the effect on body concentration per unit increase of the covariate.