Low dose of external exposure among returnees to former evacuation areas: a cross-sectional all-municipality joint study following the 2011 Fukushima Daiichi nuclear power plant incident

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Abstract
There is little information on the radiation dose levels of returnees to areas once designated as legal no-go zones, after evacuation orders were lifted subsequent to the 2011 Fukushima Daiichi nuclear power plant incident. This study used individual radiation dosimeter monitoring and a location history survey to conduct the most recent dose assessment of external exposure among returnees to former no-go zones. We specifically determined correlation and agreement
between external doses and the air dose rate in residential areas and quantified both uncertainty and population variability of the observed data using Monte Carlo (MC) simulation methods. A total of 239 voluntary participants across ten municipalities were analysed; their representativeness of all affected municipal populations was confirmed in terms of air dose rate distribution in residential areas. We found that individual doses were statistically significantly correlated with the air dose rate based on government airborne monitoring. This implies that airborne monitoring can provide sufficient information for understanding dose levels among such returnees. The MC simulations demonstrated that the mean of the annual dose in 2019 (including natural background doses) was 0.93 (95% uncertainty interval 0.53–1.76) mSv, with limited variation between municipalities. As of 2019, this implies that doses from external exposure were very low among returnees and would be associated with a very low likelihood of physical effects according to current scientific consensus. However, these results should be taken with caution due to several study limitations, including selection and participation biases. Regardless, its findings will enhance societal debates about how both individual-dose and government airborne monitoring practices should operate in the future and how the government can improve the public outlook for radiation doses in incident-affected areas.

Supplementary material for this article is available online

Keywords: Fukushima nuclear incident, Japan, no-go zone returnees, radiation, external exposure

(Some figures may appear in colour only in the online journal)

1. Introduction

The incident at the Fukushima Daiichi nuclear power plant (operated by the Tokyo Electric Power Company (TEPCO)) following the massive 9.0-magnitude earthquake and tsunami on 11 March 2011 resulted in an environmental outflow of radioactive materials. As such, radiation exposure and contamination have become important social issues in Japan [1]. International organisations (e.g. the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), World Health Organization (WHO), and International Atomic Energy Agency (IAEA)) and research institutes have estimated both the internal and external radiation doses received by the Japanese population through various modelling methods and viewpoints; many records have thus been established [2–7]. At the same time, many local governments and Japanese research institutions have measured the actual radiation-exposure levels of affected residents using personal dosimeters and whole-body counting machines [8–10]. These records have been publicly reported on their respective websites. Such evaluations are also continually published.

More than eight years have passed since the Fukushima nuclear incident. The recovery process is now at a crossroads, with many decision makers supporting the early return of evacuees. In the weeks immediately after the incident, mandatory evacuation orders were issued to areas both within 20 km of the nuclear power plant and with exceptionally high radiation-exposure levels (hereafter referred to as no-go zones) [11]; over 100,000 people were either forced to evacuate elsewhere within Fukushima Prefecture or move completely
outside its confines [11, 12]. These orders have progressively been lifted in areas meeting the three following requirements: (1) additional annual radiation doses (referring to those attributable to the incident but not including exposure from natural sources) are deemed less than 20 mSv; (2) the infrastructure and life-related services essential to daily life have generally been restored through sufficiently advanced decontamination work (centred on the living environment for children); and (3) related discussions have been held with prefectures, municipalities, and residents [13]. Thanks in part to the successful decontamination efforts by local governments [14], evacuees have begun returning to their homes in former no-go zones near the nuclear power plant. However, this excludes areas where radiation levels remain relatively high compared with the radiation levels in surrounding areas.

Termination of protective action (e.g. the lifting of evacuation orders) is not sufficient to motivate evacuees to return home or rebuild their communities [15, 16]. Such efforts also require timely, high-quality dose assessments for returnees. This is essential for enhancing societal debates and risk communication regarding the governmental ability to improve the overall outlook on radiation doses. Only then will community reconstruction be securely commenced. It is also imperative to ensure that future dose estimations and evaluations conducted by the government and/or international bodies are solid and trustworthy. This will steady long-term community reconstruction plans and preparations for future nuclear incidents.

Recent research efforts have estimated dose levels among individuals returning to former no-go zones through a variety of modelling methods [17, 18]. However, few dose assessments have been conducted based on actual measurements. For one, we conducted a 2017 study to monitor individual doses among returnees to a very limited number of areas in Fukushima Prefecture, finding low levels with a very low likelihood of physical effects [19]. Following these results, this 2019 study expanded the coverage area to all no-go zones; we measured dose levels among returnees, while simultaneously assessing location information on an hourly basis through a questionnaire survey.

This study was designed to provide the latest dose assessments for external exposure among returnees to former no-go zones based on an individual dose monitoring method. We specifically determined both correlation and agreement between our external dose measurements and the air dose rates in residential areas, as determined through government airborne monitoring. We then quantified uncertainty and population variability for the observed data using Monte Carlo (MC) simulation methods. The results will not only be useful for further developing the Fukushima return policy, but will also inform future individual-dose and government airborne monitoring operations.

2. Materials and methods

2.1. Data collection

2.1.1. Setting of evacuation order. The central Japanese government designated a 20 km radius from the Daiichi nuclear plant and a 10 km radius from the Daini nuclear plant as a legal no-go zone on 12 March 2011; a mandatory evacuation order was issued at that time [11]. Referring to areas where the additional annual dose levels may reach 20 mSv, this zone was updated and expanded to the northwest on 22 April 2011 due to the uneven distribution of radioactive fallout (figure 1). There were also other local spots where an additional dose of 20 mSv y$^{-1}$ was expected. These were designated as ‘specific spots recommended (advisory) for evacuation’ (SSRE) on 16 June 2011.
In addition to the SSRE, a total of 12 municipalities were designated as no-go zones, either in whole or part, by the Japanese government (Figure 1). As the figure indicates, these included Minamisoma City, Namie Town, Tomioka Town, Naraha Town, Hirono Town, Tamura City, Kawamata Town, Iitate Village, Katsurao Village, Kawauchi Village, Okuma Town, and Futaba Town. All SSRE prohibitions had been lifted as of December 2014. Further, most evacuation orders issued within the 12 municipalities had been lifted by the government or their respective municipal office as of 12 February 2019 (when our dose monitoring was performed (see 2.1.3.)). Areas where evacuation orders had not been lifted by that time included all of both Okuma and Futaba and parts of Minamisoma, Namie, Tomioka, Iitate, and Katsurao.

Note that some individuals maintained primary residences in no-go zones or were performing work related to the nuclear incident recovery efforts there. For example, although the evacuation orders for Okuma had not been lifted in all areas as of February 2019, some TEPCO employees had received special permission from the municipal office to live in the town. The population of all 12 municipalities (as registered at the municipal office) totalled

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**Figure 1.** Geographical scope of the location of 12 municipalities in Fukushima Prefecture. 1: Minamisoma City, 2: Namie Town, 3: Tomioka Town, 4: Naraha Town, 5: Hirono Town, 6: Tamura City, 7: Kawamata Town, 8: Iitate Village, 9: Katsurao Village, 10: Kawauchi Village, 11: Okuma Town, and 12: Futaba Town. The base map indicates the air dose rate as estimated by the Nuclear Regulation Authority (NRA) airborne monitoring as of 15 November 2018 [42]. The no-go zones indicated on the map were the most extensive as of April 2012 according to either the central government or respective municipal office. As of then, Hirono was outside the no-go zones denoted by the government, but the municipal office had taken the situation into consideration and issued its own evacuation order for all residents on 13 March 2011 in light of the unclear situation in which accurate dose levels could not be ascertained [43]. Similarly, the municipal office of Kawauchi issued its own evacuation order for all residents on 16 March 2011.
182 849 as of 2018, but had been recorded at 210 695 as of 2010 (pre-incident) [20]. Here, the registered population was not equal to the number of actual residents due to evacuation.

2.1.2. Setting of radiation exposure sources, pathways, and levels. Following a major nuclear incident, people are exposed to radioactive materials through 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 dusts and 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 varied with location and distance from the Fukushima Daiichi nuclear power plant, time periods following the incident, etc.

Principal radionuclides released from the nuclear plant were xenon-133 (about 19 exa/10\(^{18}\) becquerel (EBq)) [21], iodine-131 (about 500 peta/10\(^{15}\) becquerel (PBq)), caesium-134 (Cs-134) (about 10 PBq), and caesium-137 (Cs-137) (about 10 PBq) [22]. Maximum doses received from inhalation and ingestion were only expected in the first year. This is particularly the case for iodine-131 in the first few hours to days of the incident because of its short physical half-life (one week). Notably, xenon-133 is a noble gas with a short physical half-life (one week) and is not concentrated in the body [2]. After the first year of the incident, therefore, only doses from Cs-134 and Cs-137, with physical half-lives of two years and 30 years, respectively, could be measured.

The most recent evidence indicates that today’s external exposure through groundshine (from deposited Cs-137) is the dominant pathway contributing to an effective dose in the Fukushima Prefecture [3, 23–25]. Internal exposure via contaminated food (ingestion) and dust (inhalation) is very low [26]. A voluntary internal exposure test conducted in Minamisoma City in early 2019 showed less than 1% and 0.03% detection rates of Cs-137 and Cs-134, respectively [27]. Our 2017 study demonstrated that the average annual additional effective dose in 2017 among returnees was 0.4 mSv [19], which contrasted significantly with the relatively low doses attributed to natural sources such as the universe (e.g. cosmic rays) and ground (known to be about 0.54 mSv y\(^{-1}\) in Japan) [8].

2.1.3. Dose monitoring. This was a cross-sectional study. We conducted dose monitoring between 12 and 25 February 2019 for individuals living in 11 of the 12 municipalities (Futaba was excluded as a no-go zone in its entirety). We used individual radiation dosimeters (i.e. D-shuttles from Chiyoda Technol Corp., a privately owned Japanese company that manufactures and sells radiation products used in medicine, pharmacology, biology, agriculture, and other fields [28]; hereafter referred to as either the D-shuttle or dosimeter). Although Okuma was also a no-go zone as a whole at that time, several TEPCO employees were living in the town. While they were not considered in this study’s analysis (as this was beyond its scope), we conducted dose monitoring in this area in consideration of the need to assess these individuals.

An instruction was provided to each monitoring participant, all of whom were told that the dosimeters must be secured around the neck throughout the workday. When at home, participants were allowed to simply carry the dosimeters unless they wished to remove them while sleeping or bathing. Internal radiation exposure was not the dominant pathway contributing to an effective dose in Fukushima at the time these dose measurements were taken [3, 23–25]. As such, we considered that contributions to the dosimeter-measured radiation were predominantly the result of external exposure (i.e. groundshine) rather than
exposure due to radionuclides inside the body. All dosimeters were collected and processed by the authors after two weeks of monitoring.

Participation in this monitoring process was voluntary. To minimise the burden on the local residents associated with the monitoring participation, including the wearing and carrying of dosimeters, we mainly targeted public servants, such as municipal staff and firefighters. As such, the authors visited areas such as municipal offices and fire stations to recruit participants. This study was thus subject to both selection and participation biases. Each participant received a 3000 JPY (approximately 28 USD) gift card for participating in the monitoring.

2.1.4. Study participants. A total of 279 individuals participated in this study’s dose monitoring procedure, including municipal staff \((n = 176)\), firefighters \((n = 19)\), residents involved in reconstruction activities \((n = 69)\), and TEPCO employees \((n = 15\) in Okuma; excluded from analysis). Dose data from two individuals were excluded due to human error when extracting information from the dosimeter (i.e. data from one individual were overwritten by data from another). To meet our study objective, we did not analyse data from individuals living in areas where evacuation orders had not been lifted as of 12 February 2019 (e.g. Okuma) or where orders had not been denoted post-incident (e.g. parts of Minamisoma, Tamura, and Kawamata). As a result, we finally analysed data from a total of 239 participants across ten municipalities. Collected D-shuttle data included two-week measured doses (see 2.1.5.) and basic demographic characteristics from each participant (e.g. sex and post-incident residential address at Oaza-level (an administrative municipal unit)). The address records of one participant were treated as missing due to unreliability.

2.1.5. Measured levels of external radiation exposure. The outcome of a D-shuttle measurement is a dose-equivalent at a tissue depth of 1 cm \((Hp(10))\), which includes doses attributed to natural sources such as the universe and ground (i.e. 0.54 mSv y\(^{-1}\) on average at the population level \([8]\)). Because the \(Hp(10)\) values obtained from the affected areas in Fukushima Prefecture were comparable with the effective dose of isotropic (ISO) or rotational (ROT) irradiation geometries \([29–32]\), we regarded individual doses measured by D-shuttle units as practical indicators of effective doses from external radiation exposure. The number of datapoints per participant is \(24\) h \(\times\) 14 days = 336; a total of 80 304 datapoints were taken from the 239 participants of this study. Unless otherwise indicated, the individual doses presented in this study include natural background doses from the universe and ground.

2.1.6. Location information. This study’s monitoring process included a questionnaire survey to confirm location information on an hourly basis (i.e. where each participant was during each hour and whether they were indoors or outdoors). These location records were then classified into the eight following categories for analysis: within the residential municipality (indoors (Area 1) or outdoors (Area 2)), outside the residential municipality but within former no-go zones (indoors (Area 3) or outdoors (Area 4)), outside former no-go zones but within Fukushima Prefecture (indoors (Area 5) or outdoors (Area 6)), outside Fukushima Prefecture (Area 7), and unknown or unclassified (Area 8).

Questionnaires were completed by 100% of analysed participants, who were instructed to return their answer sheets to the respective municipal offices when they were not directly collected with D-shuttle data. The resulting survey data were linked to the monitoring data.
2.2. Analysis

2.2.1. Validating participant representativeness. As noted above, this study was biased due to its recruitment methods. We thus examined the representativeness of all study participants in terms of the air dose rate distribution in residential areas by comparing the percentile rank of the air dose rate in their respective residential areas (at Oaza-level) as of 18 February 2019 with those of the whole population residing in studied former no-go zones. This was the central day of the study period. Air dose data were obtained through airborne monitoring reports released by the Nuclear Regulation Authority (NRA), which included exposure from natural sources of radiation in the ground (known to be about 0.04 μSv h\(^{-1}\) on average at the population level [33]). Unless otherwise indicated, the air dose data presented in this study include the background air dose rate due to natural radiation from the ground. Detailed methods are presented in supplementary text 1 which is available online at stacks.iop.org/JRP/40/1/mmedia.

2.2.2. Dose evaluation

2.2.2.1. Annual and hourly external dose levels among study participants. We estimated the annual and hourly doses from external exposure among study participants by first dividing their two-week dose measurements by the total measurement period (i.e. 14 days). These measurements were then multiplied by 365 (days) or divided by 24 (hours) to achieve annual and hourly doses, respectively. Unless indicated otherwise, average or mean refers to the arithmetic mean in this study.

2.2.2.2. Correlation and agreement between annual external dose and air dose rate in residential areas. We tested for correlations between individual doses and the air dose rate in residential areas by drawing a scatterplot of the hourly external dose levels for each participant (μSv h\(^{-1}\)) against the air dose rates (μSv h\(^{-1}\)) in their respective residential areas as of 18 February 2019 (supplementary text 1); both axes were situated on a logarithmic scale. A Pearson correlation coefficient was also computed for the logarithmic relationship.

We also calculated the ratio of additional doses per hour to the additional air dose rates after subtracting those attributable to natural sources: 0.062 μSv h\(^{-1}\) (i.e. 0.54 mSv y\(^{-1}\)) for individual dose and 0.04 μSv h\(^{-1}\) for the air dose rate [8, 33]. These figures are the population-level average, where there is no distinction between the indoors and outdoors.

2.2.2.3. Quantification of uncertainty. To quantify the uncertainty about the ‘true’ dose due to population variability of the observed data (driven by participants’ recruitment methods), a probabilistic sensitivity analysis was performed using an MC simulation for a hypothetical population of 100,000 residents in the study areas. Mean and standard deviations (SD) of individual dose (μSv/h) by location (see 2.1.5.) and municipality in addition to those for length-of-stay (hours) by location served as input data. These were assumed to follow log-normal and normal distributions, respectively. If the simulated value of length-of-stay by location was accidentally less than zero (which was impossible in reality), it was replaced by zero. It was also proportionately scaled up to 24 h. We accounted for the municipal population distribution at the time of evacuation using population data from the National Census in 2010 [34]. We derived a 95% uncertainty interval (UI) from the 2.5 and 97.5 percentiles of the distribution of values generated by 100,000 iterations of the randomly selected values according to the assumed distributions of all input data.
As a subanalysis, we divided the population into the three subgroups (i.e. municipal staff and two others); doses were simulated in the same way. The two groups other than municipal staff were identified through a cluster analysis on the un-normalised length of stay by location using Ward’s method with a squared Euclidean distance as a measure of homogeneity.

All statistical analyses were conducted using STATA/MP 15, SPSS Statistics 24.0 and Oracle Crystal Ball (version 11.1.2.4.850; Oracle).

2.3. Ethical approval

Ethical approval for this study was granted by the ethics committee of Fukushima Medical University (approval number: General 30249). Individual consent was obtained from all participants.

3. Results

Figure 2 shows a similar distribution of percentile ranks for air dose rates as of 18 February 2019 in the studied residential areas with that of the whole population in studied former no-go zones. This indicated that the study participants were highly representative the population in terms of the air dose rate distribution in residential areas.

Participant demographic characteristics (n = 239 across ten municipalities) are summarised in table 1. A total of 26.8% (n = 64) were female. Most were municipal staff (n = 153, 64.0%). The average length of time spent outdoors was less than three hours per day (table 1). Supplementary table 1 presents these data for those excluded from analysis (n = 39).

Summary measures of external doses are presented in table 2. The individual annual dose rate from external exposure among all 239 participants ranged from 0.44 to 4.33, with a mean value of 0.90 (SD 0.37) mSv. When taken by municipality, the highest mean (SD) of the annual dose was observed in Iitate at 1.12 (0.24) mSv, while the lowest was in Hirono at
Table 1. Participant demographics by municipality ($n = 239$).

| Municipality     | Total participants | Female (%) | Municipal staff (%) | Firefighters (%) | Average time spent outdoors per day (hour) (SD) | Total population$^a$ |
|------------------|--------------------|------------|---------------------|------------------|-----------------------------------------------|---------------------|
| Minamisoma       | 28                 | 14 (50.0)  | 15 (53.6)           | 0 (0.0)          | 2.8 (1.8)                                     | 70,878              |
| Namie            | 33                 | 10 (30.3)  | 20 (60.6)           | 2 (6.1)          | 2.8 (1.6)                                     | 20,905              |
| Tomioka          | 25                 | 2 (8.0)    | 20 (80.0)           | 1 (4.0)          | 2.4 (1.6)                                     | 16,151              |
| Naraha           | 27                 | 7 (25.9)   | 21 (77.8)           | 4 (14.8)         | 2.4 (1.3)                                     | 7,700               |
| Hirono           | 30                 | 4 (13.3)   | 20 (66.7)           | 8 (26.7)         | 2.3 (1.1)                                     | 5,418               |
| Tamura           | 19                 | 8 (42.1)   | 14 (73.7)           | 0 (0.0)          | 2.2 (1.0)                                     | 40,422              |
| Kawamata         | 16                 | 0 (0.0)    | 1 (6.3)             | 0 (0.0)          | 4.3 (2.4)                                     | 15,419              |
| Iitate           | 19                 | 7 (36.8)   | 9 (47.4)            | 0 (0.0)          | 3.0 (1.5)                                     | 6,209               |
| Katsurao         | 21                 | 4 (19.0)   | 20 (95.2)           | 1 (4.8)          | 3.1 (1.3)                                     | 1,531               |
| Kawauchi         | 21                 | 8 (38.1)   | 13 (61.9)           | 3 (14.3)         | 3.2 (2.2)                                     | 2,820               |
| Total            | 239                | 64 (26.8)  | 153 (64.0)          | 19 (7.9)         | 2.8 (1.6)                                     | 187,453             |

SD: standard deviation.

$^a$ Source: The National Census in 2010, performed in October 2010 (before the Fukushima incident) [34].
Table 2. Summary of the measures of effective external doses obtained from D-shuttle dosimeters (including natural background dose).

|                          | Mean (μSv) | SD (μSv) | Median (μSv) | IQR (μSv) | Min (μSv) | Max (μSv) |
|--------------------------|------------|----------|--------------|-----------|-----------|-----------|
| (A) Two-week measured dose |            |          |              |           |           |           |
| Minamisoma               | 37.84      | 26.52    | 32.45        | 8.05      | 22.53     | 166.06    |
| Namie                    | 41.89      | 19.67    | 32.92        | 11.83     | 26.65     | 99.57     |
| Tomioka                  | 33.25      | 11.47    | 29.26        | 15.45     | 17.47     | 59.28     |
| Naraha                   | 31.47      | 8.92     | 30.73        | 6.99      | 21.62     | 69.25     |
| Hirono                   | 28.21      | 4.51     | 28.07        | 4.60      | 16.99     | 39.19     |
| Tamura                   | 28.61      | 3.27     | 28.30        | 4.79      | 23.78     | 35.35     |
| Kawamata                 | 37.18      | 9.52     | 38.10        | 9.02      | 23.98     | 65.17     |
| Iitate                   | 43.05      | 9.32     | 44.32        | 16.32     | 27.89     | 59.70     |
| Katsurao                 | 34.71      | 5.77     | 34.11        | 5.15      | 25.24     | 48.68     |
| Kawauchi                 | 29.11      | 4.45     | 28.21        | 5.65      | 23.07     | 39.60     |
| Total                    | 34.58      | 14.16    | 31.65        | 8.95      | 16.99     | 166.06    |
| (B) Annual dose (mSv)    |            |          |              |           |           |           |
| Minamisoma               | 0.99       | 0.69     | 0.85         | 0.21      | 0.59      | 4.33      |
| Namie                    | 1.09       | 0.51     | 0.86         | 0.31      | 0.69      | 2.60      |
| Tomioka                  | 0.87       | 0.30     | 0.76         | 0.40      | 0.46      | 1.55      |
| Naraha                   | 0.82       | 0.23     | 0.80         | 0.18      | 0.56      | 1.81      |
| Hirono                   | 0.74       | 0.12     | 0.73         | 0.12      | 0.44      | 1.02      |
| Tamura                   | 0.75       | 0.09     | 0.74         | 0.12      | 0.62      | 0.92      |
| Kawamata                 | 0.97       | 0.25     | 0.99         | 0.24      | 0.63      | 1.70      |
| Iitate                   | 1.12       | 0.24     | 1.16         | 0.43      | 0.73      | 1.56      |
| Katsurao                 | 0.90       | 0.15     | 0.89         | 0.13      | 0.66      | 1.27      |
| Kawauchi                 | 0.76       | 0.12     | 0.74         | 0.15      | 0.60      | 1.03      |
| Total                    | 0.90       | 0.37     | 0.83         | 0.23      | 0.44      | 4.33      |
| (C) Hourly dose (μSv)    |            |          |              |           |           |           |
| Minamisoma               | 0.11       | 0.08     | 0.10         | 0.02      | 0.07      | 0.49      |
| Namie                    | 0.12       | 0.06     | 0.10         | 0.04      | 0.08      | 0.30      |
| Tomioka                  | 0.10       | 0.03     | 0.09         | 0.05      | 0.05      | 0.18      |
| Naraha                   | 0.09       | 0.03     | 0.09         | 0.02      | 0.06      | 0.21      |
| Hirono                   | 0.08       | 0.01     | 0.08         | 0.01      | 0.05      | 0.12      |
| Tamura                   | 0.09       | 0.01     | 0.08         | 0.01      | 0.07      | 0.11      |
| Kawamata                 | 0.11       | 0.03     | 0.11         | 0.03      | 0.07      | 0.19      |
| Iitate                   | 0.13       | 0.03     | 0.13         | 0.05      | 0.08      | 0.18      |
| Katsurao                 | 0.10       | 0.02     | 0.10         | 0.02      | 0.08      | 0.14      |
| Kawauchi                 | 0.09       | 0.01     | 0.08         | 0.02      | 0.07      | 0.12      |
| Total                    | 0.10       | 0.04     | 0.09         | 0.03      | 0.05      | 0.49      |

SD: standard deviation; IQR: inter-quantile range. The annual and hourly doses were estimated based on the two-week measured dose: (two-week dose / 14 [days]) × 365 [days]; and (two-week dose / 14 [days]) / 24 [hours], respectively.

0.74 (0.12) mSv. Supplementary table 2 presents these data for those excluded from analysis (including TEPCO employees in Okuma).

The relationship between individual annual external doses and the air dose rate obtained from NRA airborne monitoring reports is shown in figure 3 (A and B plot the individual doses against the air dose rate and additional doses against the additional air dose rate, respectively).
A Pearson correlation coefficient for logarithmic data revealed 0.387 ($p < 0.001$) for A and 0.396 ($p < 0.001$) for B. Most doses fell within a factor of two or three. The mean ($SD$) of the ratio of the additional doses per hour to the additional air dose rate was 0.12 ($0.10$).

Summaries of the input data used in the MC simulations are presented in supplementary table 3 (individual dose by location and municipality) and supplementary table 4 (length of stay by location). We avoided small-sample-size bias in the input data by classifying the original eight locations (Area 1–8) into five groups with similar regression coefficients to individual doses (see supplementary table 5 for the constructed regression model) (Area 1, Areas 2 + 4; Areas 3 + 5; Areas 6 + 8; and Area 7).

Figure 4 shows the box plots of the MC-simulated distributions of annual external doses among a hypothetical population of 100 000 returnees for both the whole population and by each municipality (A) and subgroup (B). The estimated mean of the annual dose of the whole population was 0.93 (95% UI 0.53–1.76) mSv. When taken by municipality, the highest mean dose was observed in Namie at 1.12 (0.52–2.27) mSv y$^{-1}$, while the lowest was in Hirono at 0.73 (0.56–0.96) mSv y$^{-1}$. Similar estimates were produced between the three subgroups. Exact values for the box plots for the whole population are presented in supplementary table 6, while supplementary table 7 shows those for the municipal staff, and supplementary tables

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**Figure 3.** Correlation between individual hourly external doses and air dose rate from airborne monitoring, where natural background sources were considered (A) and not considered (B). (A) External dose per hour versus air dose rate, and (B) additional external dose per hour versus additional air dose rate. Note that axes have different scales for A and B. Each plus (+) symbol indicates an individual data, while blue lines represent the linear regression of the individual dose on air dose rate in logarithmic forms. The grey area represents the 95% confidence interval. Dash (-) and short-dash (-) lines indicate factors of two and three, respectively. One participant was not considered in the figure as their address records were missing. Further, four participants were not included in (B) because their additional annual doses were below zero after subtracting 0.062 μSv h$^{-1}$ (i.e. the background dose from the universe and ground).
8 and 9 show those for clusters 1 and 2, respectively; municipality-specific values are also shown.

4. Discussion

This was the first study to evaluate dose levels from external exposure among returnees to former no-go zones after the government lifted its evacuation orders, while also considering detailed hourly location information. Individual doses were statistically significantly correlated with the air dose rate reported by NRA airborne monitoring. This finding was consistent with those of previous studies [35, 36] performed outside the no-go zones. Most observed doses fell within a factor of two or three, showing good agreement between the individual dose and air dose rate. Further, the ratio of observed additional hourly dose rates to the additional air dose rate was 0.12. This was also similar to estimates reported in the previous study (0.18) [35]. These findings imply that air dose rate data are sufficient for determining dose levels of individuals in former no-go zones as a whole from an administrative viewpoint.

The government uses its own individual dose-estimation model when considering whether to lift evacuation orders based on the air dose rate (in terms of the ambient dose equivalent). In the government model, an air dose rate of 0.23 $\mu$Sv h$^{-1}$ (or additional air dose rate of 0.19 $\mu$Sv h$^{-1}$) corresponds to an individual additional external dose of 1 mSv y$^{-1}$ assuming that individuals spend eight hours outside and 16 h inside a wooden house with a shielding effect of 0.4 (that is, a radiation reduction coefficient of 0.6) each day [33]. Although caution is necessary because when comparing the air dose rate and exposure dose, a
conversion factor (e.g. 0.6 for adults [37]) needs to be considered, our findings prove that the ratio of the additional dose to the air dose rate was much lower than these government shielding/reduction coefficients. In other words, the government assumption is conservative (i.e. it overestimates the individual dose).

UNSCEAR also has its own external dose estimation model to examine the Fukushima incident. This one largely relies on occupancy factors (i.e. the proportion of time spent indoors and outdoors, which differ according to representative persons of different population groups (e.g. indoor and outdoor workers)) [38]. The UNSCEAR model sets these at 10% (2.4 h per day) for indoor workers and 30% (7.2 h per day) for outdoor workers [38]. Although we had no such data and were not able to classify our study participants into indoor or outdoor workers, they averaged less than three hours per day outside (table 1). Thus, UNSCEAR’s occupancy factors for Japan can be considered applicable for returnees (especially those who work indoors) to former no-go zones.

Among the 239 analysed study participants, the annual external dose including natural background doses (0.54 mSv) was 0.90 mSv on average, with an SD of 0.37 mSv. The MC simulations demonstrated that the mean of the annual dose was 0.93 (95% UI 0.53–1.76) mSv. There were small variations between municipalities, with the highest in Namie at 1.12 (0.52–2.27) mSv y\(^{-1}\) and the lowest in Hirono at 0.73 (0.56–0.96) mSv y\(^{-1}\). According to scientific consensus, these findings indicate that doses from external exposure were already as low as reasonably achievable [39] among returnees. That is, they were sufficiently low to minimise the health risks associated with radiation exposure.

### 4.1. Implications

It is important to evaluate dose levels when optimising risk communication to improve overall risk comprehension and decision making in addition to achieving doses as low as reasonably achievable per the ICRP principle [39]. A good agreement between individual doses and air dose rates based on airborne monitoring supports the topical debate among stakeholders. Individual dose monitoring may be inconvenient for residents because they must continually wear dosimeters. That may not be suitable for dose assessments over a wide area. On the other hand, airborne monitoring may be a promising solution to these issues. NRA conducted periodical (annual in recent contexts) airborne monitoring after the Fukushima incident to estimate doses as a requirement for lifting evacuation orders [13]. Continuous airborne monitoring could provide useful information about the dose levels of returnees to no-go zones. As such, we strongly support its continued implementation.

Our study also found that external dose levels among returnees in 2019 were very low on average; the highest observed exposure dose among study participants was 4.33 mSv y\(^{-1}\), which is also very low. These dose levels are associated with a very low likelihood of physical effects. This implies that we are at a stage in which the purpose of individual dose monitoring is shifting. That is, it may no longer be efficient to perform individual dose monitoring among returnees for the purpose of optimising radiation protection and reducing exposure doses in former no-go zones. On the other hand, it may be reasonable to conduct this practice for those who desire it as a risk-communication tool for improving the overall outlook on radiation doses. Individual dose monitoring may also be suitable for identifying people with relatively high radiation doses than others (e.g. outliers) and thus proposing individual countermeasures, if necessary. In the case of this study, we identified one person with an annual dose of 4.33 mSv y\(^{-1}\) in Minamisoma City. We can discuss reasonable countermeasures if this person expresses concern about radiation exposure.
The maximum dose in this study was 4.33 mSv y\(^{-1}\) of a Minamisoma resident. We confirmed the following possible reasons. While the average time spent outdoors per day among the Minamisoma residents was 3.1 h (SD 1.2), this person spent 9.3 h per day during the dose monitoring period. The individual owns persimmon and plum orchards, which are adjacent to the no-go zones where the evacuation order has not been lifted, so the air dose rate is relatively high. Winter (when our dose monitoring was implemented) is the key time for pruning work in orchards, which might have resulted in relatively long outings and high radiation exposure.

### 4.2. Limitations

This study used the best data available for returnees at the time of research (i.e. those achieved through external radiation exposure monitoring and a post-incident life and behaviour survey). However, caution is necessary when interpreting these results due to the nature of the dose monitoring design; study participants included those who were not living in no-go zones at the time of the incident, but newly settled in those zones after the evacuation orders were lifted. In addition, there are several limitations to be considered when interpreting this study’s findings, some of which are the same as described above and which were justified in our prior study (or other studies) that employed radiation dosimeters [8, 19, 40, 41].

First, this study measured a two-week effective dose using D-shuttle dosimeters and multiplied the resulting doses by 365/14 days to obtain annual doses. This method ignored the nature of radioactive decay or the disintegration (half-life) of radionuclides (especially Cs-134 and Cs-137) over the course of a year, which may lead to a potential overestimation of the annual dose.

Second, data for length-of-stay by location (e.g. time spent indoors and outdoors) served as input data for the MC simulation. However, these data were collected in February from mostly public servants. Thus, seasonal variations and occupational variations were not considered in the simulation. For example, farmers visit their fields from spring through autumn, whereas there is no access to (or no need to access) them in winter (when our dose monitoring was implemented). In addition, when residents get used to their new lives after returning, we believe that their range of daily activities also expand, thus affecting exposure doses in both positive and negative directions. However, we could not address these variations and possible future changes in the analyses as the data to quantify them were not available.

Third, the D-shuttle instruction manual explains that dosimeters require removal when undergoing radiation therapy (e.g. computed tomography (CT) scans). However, this study could not rule out other sources of radiation exposure (e.g. air travel or mountain climbing). Further, we could not exclude the possibility that radiation therapy (in which radioisotopes are injected directly into the body) could cause exposure to radioactive substances in the body.

Fourth, study participation was voluntary and subject to both selection and participation biases, and it was impossible to rule out the idea that individual dosimeters may not have been properly equipped per the instructions. However (as confirmed in figure 2), the 239 voluntarily analysed participants were properly representative of the whole municipal-based population in terms of the air dose rate distribution in residential areas. Meanwhile, we were not able to verify the representativeness of behavioural patterns (i.e. those obtained from location information) in achieving reliable data at the whole populational level.

Finally, the exposure from nature sources considered in this study was the population-level average. However, for more precise consideration, residential area-specific values were preferred, but no data were available, and their assessment was outside the scope of this study.
5. Conclusion

No-go zones have not yet been lifted in some areas as of the time of this study. Some of these areas have been designated as ‘specific reconstruction and revitalisation base areas’ (SRRBA), where decontamination is conducted at national expense to lift the current evacuation orders within four to five years. At present, parts of the six municipalities of Namie, Tomioka, Iitate, Katsurao, Okuma, and Futaba have been designated as SRRBAs.

This study demonstrated that air dose rate data are sufficient for understanding the dose levels of individuals in former no-go zones as a whole. Further, the external doses of evacuees who returned to former no-gone zones after the government lifted its evacuation orders were very low at the time of study; by scientific consensus, they would be associated with a very low likelihood of physical effects. It should be particularly emphasised that the expected lifetime doses from the incident in addition to the natural background doses are very small among returnees. This study’s findings will enhance societal debates about how both individual-dose and government airborne monitoring may operate in the future. They should also inform government methods for improving the public outlook about radiation doses in incident-affected areas.

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Contributors

All authors conceived of and designed the study and take responsibility for the integrity of the obtained data and accuracy of the data analysis. MT acquired the data. SN, MM, and MT analysed and interpreted the data. SN and MM conducted statistical analyses and drafted the article. All authors made critical revisions to the manuscript for essential intellectual content and gave their final approval.

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Competing interests

The authors declare no conflicts of interest.

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