Relationship between the Residual Cesium Body Contents and Individual Behaviors among Evacuees from Municipalities near the Fukushima Daiichi Nuclear Power Plant

RELATIONSHIP BETWEEN THE RESIDUAL CS BODY CONTENTS AND INDIVIDUAL BEHAVIORS AMONG EVACUEES FROM MUNICIPALITIES NEAR THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

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Abstract

To support estimations of early individual internal doses to residents who suffered from the 2011 accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP), we have sought to utilize whole-body counter (WBC) measurement results of subjects who lived in municipalities neighboring the FDNPP at the time of the accident. These WBC measurements started several months after the accident; the targeted radionuclides were ^{134}Cs and ^{137}Cs. Our previous study had analyzed the relationship between the residual Cs contents of individuals and evacuation behaviors in the period immediately after the accident for residents of Namie-town, one of the most radiologically affected municipalities. Those results suggested that the first major release event at the FDNPP on 12 March caused significant exposure, particularly to those who delayed evacuation on that day. The present study expanded its scope to include subjects from four towns neighboring the FDNPP (Namie, Futaba, Okuma, and Tomioka) to gather additional evidence of the exposure that took place on 12 March. Additionally, we investigated the relationship between individual Cs doses and subjects' destinations following the largest release event on 15 March. The study population was 1,145 adults. We first divided the subjects into two evacuation groups depending on the distance from the FDNPP and their evacuation whereabouts (25-km boundary) as of 15:00 on 12 March: the G1 group (≥25 km) and the G2 group (<25 km). We further divided these two group subjects into seven subgroups based on the subjects' destinations as of 0:00 on 16 March. Our four main findings are as follows. (1) The ^{137}Cs detection rate was significantly different between the G1 and G2 groups of Namie-town and Futaba-town, but not for those of Okuma-town and Tomioka-town. This result corresponds to the plume passage (flowing toward the northwest to the north) in the afternoon of 12 March and supports our previous study. (2) The upper-percentile committed effective doses (CEDs) of the G2 groups were higher than those of the G1 groups for all four towns, although the between-group difference varied with the town. The highest CEDs were found in the G2 group of Futaba-town, and the lowest CEDs were in the Namie-town G1 group: 0.16 mSv and 0.04 mSv at the 90th percentile, respectively. The CEDs for both the G1 and G2 groups were relatively high for Okuma-town and Tomioka-town compared to those of the G1 group of Namie-town, although the former subjects were expected to be less exposed on 12 March and then evacuated to remote places, as did the residents of the other towns. (3) The CEDs of the G1 subgroup that evacuated outside Fukushima Prefecture were extremely low, suggesting that these subjects were little exposed on both 12 and 15 March. However, the CEDs of the same G1 subgroup were rather higher than those of the corresponding G2 subgroup for Futaba-town and Okuma-town. We thus speculate that the WBC measurements were likely to have been affected by the contamination occurring in the second-round temporary reentry (except for the Namie-town residents). (4) The analyses of the Namie-town evacuees indicated that the area including the middle and northern parts of Fukushima Prefecture was relatively more affected by the major release event on 15 March. In conclusion, the early Cs intake due to the FDNPP accident remained detectable in the WBC measurements of certain present subjects; however, further analyses of the available data are necessary for a full understanding of the WBC measurement results.

Key words: Fukushima Daiichi; whole-body counter (WBC) measurement; Cs; committed effective dose (CED)

INTRODUCTION

Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant (FDNPP) was damaged by the 9.0–9.1-magnitude Tōhoku earthquake and subsequent tsunami on 11 March 2011, which were followed by an enormous release of radioactive materials into the surrounding environment due to the serious damage of nuclear reactor cores by the loss of cooling functions (NAIIC 2012). Consequently, large territories in northern Japan including Fukushima Prefecture were heavily contaminated with radionuclides, and some of the territories remain difficult-to-return areas where the projected annual external dose is >50 mSv (Fukushima Prefecture 2022). It is vital to assess the health effects of radiation exposure due to the 2011 nuclear accident, not only for the emergency workers at the FDNPP site but also for residents living in Fukushima Prefecture. Great efforts to determine the precise dose assessment for Fukushima residents have been made by several Japanese research groups, and the common view drawn from their studies is that the radiation exposure doses of Fukushima residents were low in general (Ishikawa 2017; UNSCEAR 2021).

In this study, we examined the relationship between the residual cesium (Cs) body contents of subjects living near the FDNPP at the time of the accident and their evacuation behavior. Our analysis aimed to support estimations of early internal doses of the residents, a challenging task due to the lack of direct human measurements for radioiodines, particularly ^{131}I. The available data on residual Cs body contents were obtained through whole-body counter (WBC) measurements initiated at the end of June 2011, approximately three and a half months after the accident. These measurements were conducted to assess the levels of internal contamination with ^{134}Cs/^{137}Cs in residents from Fukushima municipalities where evacuation orders were issued. As of the end of January 2012, a total of 9,927 measurements had been conducted (Momose et al. 2012). If we can establish that residual Cs body contents originated from intake during the early phase when public exposure to ^{131}I in the environment was significant, we could potentially utilize the results of the WBC measurements for the aforementioned purpose. The early phase is considered to span from the day of the accident to the end of March 2011.

Our previous study (Igarashi et al. 2020) analyzed the above relationship among subjects from Namie-town, one of the Fukushima municipalities heavily affected by radionuclide contamination. The results of our study revealed that the whereabouts of individuals during the afternoon of 12 March was a key factor in the assessment of the internal doses during the early phase. Our findings suggest that evacuees who remained within the 20 km radius of the FDNPP just before a hydrogen explosion event at the reactor building of the FDNPP's Unit 1 at 15:36 on 12 March would have received greater exposure to the radioactive plume released by this event. This plume flowed from the northwest to the north of the FDNPP (Chino et al. 2016), and its passage covered the coastal area of Namie, where the town's population is centered.

The present study expanded its scope to include subjects from four towns neighboring the FDNPP (Namie, Futaba, Okuma, and Tomioka) to gather additional evidence of the exposure that took place on 12 March. We also investigated the relationship between individual Cs doses and subjects' destinations following the largest release event on 15 March.

MATERIALS AND METHODS

Subjects

The subjects of this study were all adults (aged ≥18 years old as of 11 March 2011) who both underwent WBC measurements by the Japan Atomic Energy Agency during the period that ended in January 2012 and provided information about their evacuation behaviors (described later). The recruitment of subjects for WBC measurements was carried out by Fukushima Prefecture. We did not use WBC data of children, due to their considerably low

Cs detection rate. The subjects were from Namie, Futaba, Okuma, and Tomioka, the locations of which are shown in **Fig. 1**. The subjects from Namie had been studied by Igarashi et al. (2020) and were included in the present study to facilitate comparisons with the results from the other three towns. The subjects from Namie and those from the other three towns underwent a re-analysis as described later. The entire areas of Futaba, Okuma, and Tomioka and the east area of Namie are included within the 20-km radius of the FDNPP, which lies on the border between Futaba and Okuma. The Japanese government issued an evacuation order to all residents living within the 20-km radius of the FDNPP at 18:25 on 12 March after a hydrogen explosion occurred at the reactor building of the FDNPP at 15:36 on the same day (NAIIC 2012). **Table 1** provides the age and sex distributions for the subjects of each town. The 1,145 subjects were 233 (20.3%) males and 912 (79.7%) females. Most of the subjects were ≤40 years old: 958 subjects consisting of 175 (18.3%) males and 783 (81.7%) females.

Personal behavior data

The personal behavior data were created from the subjects' self-administered questionnaires used in the Basic Survey mainly for the external dose estimation, one of the core components in the Fukushima Health Management Survey (Yasumura et al. 2012). Details regarding these data are provided elsewhere (Ishikawa et al. 2014). Briefly, the personal behavior data contain the history of the whereabouts of the subject (i.e., the place name and its latitude and longitude), the time spent indoors/outdoors or moving, and the type of building where the subject stayed (e.g., a wooden house or concrete building).

The personal behavior data were provided hourly until 25 March and daily from 26 March to 11 July (only for representative places where the subjects stayed or commuted to each day); however, we found that the data for the latter daily period were missing for most of the subjects. We thus analyzed the hourly data until 25 March. The distances between each of the subjects and the FDNPP at each timepoint were calculated as described (Igarashi et al. 2020).

WBC measurements

Details of the WBC measurements are described elsewhere (Kurihara et al. 2018). These measurements were performed using three WBC units (of two types). The attainable minimum detectable activity (MDA) was approximately 300 Bq for both ^{134}Cs and ^{137}Cs. **Tables 2** and **3** provide the Cs detection rates and the residual Cs body contents (at the time of the measurements) of the subjects from each town. Note that these results cannot be directly compared among the towns because of the differences in the measurement periods (**Fig. 2**); the WBC measurements were performed earliest for residents of Namie (mainly during July and August in 2011) and later for those of the other three towns. The biological half-life of Cs for adults is approximately 100 days (ICRP 1993). Consequently, for a fair comparison of the magnitude of Cs doses among the four towns, it would be reasonable to use an alternative indicator: the committed effective dose (CED) based on a standardized intake scenario. This CED accounts for the variation in the subjects' measurement dates (see the subsection 'Internal dose calculations' below). Our comparison of CEDs was based on the assumption that any additional Cs intake after the early phase was negligible.

Internal dose calculations

The Cs intake, denoted as *I*, and the CED of each subject were calculated using the following equations:

$$I_{134} = \frac{M_{134}}{R_{134}(t)} \quad (1)$$

$$I_{137} = \frac{M_{137}}{R_{137}(t)} \quad (2)$$

$$\text{CED} = I_{134} \cdot e_{134} + I_{137} \cdot e_{137} \quad (3)$$

Where the subscripts 134 and 137 are denoted as ^{134}Cs and ^{137}Cs, respectively; *M* is the residual Cs body content (Bq) from WBC measurements; *R* is the whole-body retention rate (dimensionless) as a function of the time elapsed between intake and measurement; and *e* is the effective dose coefficient of ^{134}Cs or ^{137}Cs (Sv per Bq intake). The values of *R* and *e* are those given for adults defined in an International Commission on Radiological Protection publication (ICRP 1995) in the case of the inhalation of Type F compounds with an AMAD of 1 μm as a default value for public exposure. These values were taken from the database of the MONDAL system (Ishigure et al. 2004) and the ICRP database (ICRP 1998). The intake day for Cs was fixed as 12 March, which represents the earliest plausible intake day under the assumption of an acute intake scenario, ensuring conservative dose estimates. For subjects with Cs levels below the MDA, their residual body contents were treated as zero. As elaborated further, the Cs detection rates among the study subjects were relatively low. Our primary focus was thus on the CEDs derived from the subjects with detectable Cs body contents, facilitating comparisons among the four towns.

Data analyses

The analyses of the WBC data and the personal behavior data are described as follows. The first analysis was essentially the same as that performed by Igarashi et al. (2020): a two-group comparison test based on the distances between the FDNPP and the whereabouts of subjects as of 15:00 on 12 March. In our previous study (Igarashi et al. 2020) we had set the boundary distance to divide groups of subjects at 20 km; in the present study we changed this distance to 25 km. In this context, we designated the 'G1 group' as the subjects whose locations were beyond the specified boundary distance at the aforementioned time, and we designated the 'G2 group' as the subjects whose locations were within the specified boundary distance at the aforementioned time. Fisher's exact test was used to examine differences in the Cs detection rates of pairs of groups, and p-values <0.05 were accepted as significant.

The second analysis was a multigroup analysis based on the subjects' locations as of 0:00 on 16 March. **Fig. 3** depicts the seven geographic areas divided for this purpose, taking into account the wide variety of the subjects' destinations. Data manipulations in this study were performed using Microsoft Excel™ and programs that we created and coded in Python.

RESULTS

Comparison of the Cs dose between the two evacuee groups

The numbers of the G1 and G2 groups totaled 614 and 531, respectively. The two groups were more evenly divided than those in the case of the previous boundary distance setting (20 km), which was beneficial for the subsequent analysis. The ^{137}Cs detection rate was higher in the G2 group (39.5%) compared to the G1 group (23.0%). The detection rates of ^{134}Cs are not shown here since they are similar to those of ^{137}Cs. **Table 4** provides the corresponding data for each town, demonstrating that the ^{137}Cs detection rates were significantly different between the G1 and G2 groups for Namie and Futaba, but not for Okuma or Tomioka.

Fig. 4 compares the CEDs at the 75th-, 90th-, and 95th- percentiles between the G1 and G2 groups for each of the towns. Note that the 50th-percentile (median) CEDs are unavailable for the comparison because of the low Cs detection rate. The CEDs of the G2 group are higher than those of the G1 group for all four towns; however, the difference in CEDs between the two groups was relatively small for Okuma and Tomioka. The highest-dose group was the G2 group of Futaba (0.16 mSv at the 90th percentile). The CEDs of the G1 group of Futaba were also high and were comparable to those of the G2 group of Namie (both 0.13 mSv). The CED of the G1 group of Namie was much lower (0.04 mSv) than those for the other three towns.

Relationship between individual Cs doses and evacuation destinations

Fig. 5 provides the numbers of subjects in each subgroup further divided based on their evacuation destinations (Areas 1–7) for each town as of 16 March (at midnight). Here the original G1 and G2 groups were divided by the 25-km boundary distance, but three individuals who returned their hometowns (except for Tsushima district of Namie) were excluded from the subsequent analyses. **Table 5** summarizes the compositions of the numbers of subjects with/without ^{137}Cs positive detection, along with the ^{137}Cs detection rates for each subgroup of each town; the latter is only for the subgroups with an n-value ≥15. Regarding the G1 subgroups for Area 7 (outside Fukushima Prefecture), the ^{137}Cs detection rate was only 10.5% for Namie, whereas the corresponding rates were relatively high for Futaba (30.4%) and Okuma (30.5%) even though the WBC measurements for these two towns' residents were conducted later compared to Namie (**Fig. 2**). **Fig. 6** compares the 75th-, 90th-, and 95th-percentile CEDs between the G1 (or G2) subgroups, each of which was obtained from the total of subjects from the four towns. As can be seen in the figure, the relationship regarding CEDs between the G1 and G2 groups (i.e., G1 < G2) remains in most of the pairs of the G1 and G2 subgroups with the same destinations.

DISCUSSION

It is crucial to clarify whether or not a residual fraction of the early intake after the FDNPP accident could be detected in the present WBC measurements (starting approximately three and a half months after the March 2011 accident) from the viewpoint of the thyroid dose reconstruction of Fukushima residents, especially those who could be potentially exposed to radioiodines due to the accident. Only a few studies have addressed similar issues (Matsuda et al. 2013; Nomura et al. 2016). Further analyses can be conducted on the results obtained in the present study, as follows.

The data in **Table 4** suggest that the hydrogen explosion affected mainly the G2 groups of Namie and Futaba. The ^{137}Cs detection rates for the G2 groups were 2–3 times higher than that for the G1 groups of these two towns, whereas the rate was comparable between the G1 and G2 groups of Okuma and Tomioka. This result seems to be attributable to the radioactive plume on 12 March that flowed from the northwest to the north of the FDNPP. Considering both the geographical locations of these four towns (**Fig. 1**) and the main evacuation routes for each town (Akahane et al. 2013), the magnitude of exposure to this plume would be greater in the residents of Namie and Futaba than in those of Okuma and Tomioka. Regarding the subjects in Namie, our previous studies reproduced their exposure situations by superimposing time-series, ground-level air-concentration maps generated by atmospheric transport and dispersion model (ATDM) simulations of the locations of individuals at each timepoint (Kim et al. 2021b, 2022). We were then able to explain the finding by Igarashi et al. (2020) and deduced that the largest release event on 15 March would have less affected most of the Namie residents because they had already evacuated to remote places by that day. This can also be true for the residents of the other three towns. The proportions of subjects who evacuated outside Fukushima Prefecture as of 0:00 on 16 March were found to be comparable among the four towns (data not shown here); however, the CEDs of both the G1 and G2 groups of Okuma and Tomioka were relatively high although most of these subjects were expected to be less exposed on 12 March, as were the G1 group of Namie (**Fig. 4**). The 90th-percentile CED of the Okuma and Tomioka residents is 2–3 times as high as those of the G1 group of Namie. In addition, the CEDs of the G1 group of Futaba were comparable to those of the G2 group of Namie even though the evacuation time and routes of residents on 12 March were similar between these two towns (Zengenkyo 2012).

Regarding the ^{137}Cs detection rate, the relationship between the G1 and G2 groups (i.e., G1 < G2) remained in the subgroups of Namie and Futaba (**Table 5**). Of particular interest among the data is the considerably low ^{137}Cs detection rates found in the G1 group of Namie for Area 6 (7.7%) and Area 7 (10.5%) in contrast to the average of the G1 subgroups of this town (18.8%, **Table 4**), which suggest that these subjects would mostly avoid exposure due to the major release events on both 12 and 15 March. This prediction seems reasonable because Areas 6 and 7 were less contaminated by the released radionuclides. In contrast, the ^{137}Cs detection rate is unexpectedly high in the G1 subgroups of Area 7 for Futaba (30.4%) and Okuma (30.8%) as described before. It is difficult to explain this result based on only the magnitude of exposure in the early phase that is predicted by individual evacuation behaviors.

The differences in the CEDs between the G1 (or G2) subgroups are ambiguous (**Fig. 6**) because of the mixture of the subjects from the four towns with different characteristics. The CEDs for Areas 1–3 are comparable to each other in both the G1 and G2 subgroups; the proportion of subjects from Namie is relatively high in these subgroups (**Fig. 5**). Area 1 includes the heavily contaminated zone northwest of the FDNPP. This zone was generated by wet deposition in the evening of 15 March (Katata et al. 2012); however, there seems to be no correlation between the CEDs and the ground deposition density. Regarding Area 5, more than half of the subjects were from Okuma and Tomioka where the exposure on 12 March is considered small as noted above. The CEDs for Area 5 are higher than those for Areas 1–3 in both the G1 and G2 subgroups. The ^{137}Cs detection rate for Area 5 is also higher, although no significant difference was observed between the G1 and G2 subgroups at 42.9% and 60.0%, respectively (**Table 5**). On 15 March, a major radioactive plume started releasing toward the south of the FDNPP along the coastal region in the early morning and reached the neighboring prefectures. High aerial concentrations of ^{131}I and Cs were temporarily observed at sites in Ibaraki Prefecture (located south of the FDNPP) in the morning of 15 March (Takeyasu et al. 2012). As a result, Area 5 is expected to be most affected by the release event on that day. In addition to the above findings, it is of particular interest that the CEDs of the G1 subgroups of Area 7 are much higher than those of the G1 subgroups of Area 6 and are rather comparable to those of the other destinations. To clarify the cause of this, the CEDs for Area 7 were further examined for each town (**Fig. 7**). We observed that the CEDs of the G1 subgroups were rather higher than those of the G2 subgroup for Futaba and Okuma.

Although the subjects with extremely high doses could be biased by their irregular behaviors, we speculate that one likely reason for the above contradicting results concerns the second-round temporary re-entry of evacuees into the restricted area (corresponding to the 20-km radius of the FDNPP) that was conducted for the period between 19 September and 24 December 2011 (Sato et al. 2015). A system for this temporary re-entry was organized from 10 May 2011 under radiation-protection measures for residents who needed to visit their houses in the highly radiologically contaminated area. These residents were asked to wear Tyvek suits before their entry into the restricted area and to then undergo a surface contamination check of their bodies and belongings when they left the restricted area. The screening value indicating that decontamination was necessary was initially set at 100,000 cpm; it was later revised as 13,000 cpm as a reading value of the Geiger- Mueller survey meters used for the surface contamination check. In the first-round temporary reentry conducted until 9 September, residents gathered at transfer stations outside the restricted area and then moved by buses to sites near their homes. The belongings to be retrieved from their homes were restricted to one 70 cm × 70 cm vinyl bag for each family. This restriction was abolished in the second-round temporary reentry or later. The residents were then allowed to return home by their private cars and may have retrieved many more items. As a result, the false-positive detection would increase in WBC measurements of these residents due to trivial surface contamination on their clothes or possessions. In fact, it has been reported that such cases suddenly increased after the second-round temporary re-entry started (Momose et al. 2012). The false-positive detection was confirmed by additional WBC measurements after subjects removed their outer clothing or changed into clean gowns; however, this procedure was conducted essentially for children only and not for adults until the end of January 2012. A survey of body surface contamination was performed by radiation control experts prior to the WBC measurements; however, there may have been overlooked contaminations (Kurihara et al. 2018). The present study's Namie subjects are expected to be only minimally affected by such contamination, considering that the subjects who promptly evacuated to less-contaminated places minimized their exposure doses (**Fig. 7**). It should also be noted that these subjects had almost completed their WBC measurements before the second-round temporary re-entry started in September 2012 (**Fig. 2**).

Fig. 8 compares the 90th-percentile CEDs of the Namie evacuees between the G1 and G2 subgroups for each destination excluding Areas 4 and 5 (which had n-values <15). The CEDs of the G2 subgroups are higher than those of the G1 subgroups for all of the analyzable destinations due to the difference in the magnitude of exposure on 12 March. The CEDs of the Prompt subgroups for Areas 6 and 7 are considerably low compared to those for Areas 1–3, as was the ^{137}Cs detection rate as described earlier. This again suggests that these Namie subjects were little exposed on both 12 and 15 March (and/or later). Assuming that the magnitude of exposure in Areas 1–3 on 12 March was the same as that in Areas 6 and 7, the CEDs of the G1 subgroups would be mostly affected by the exposure on 15 March in each area. The average (geometrical mean) of the 90th-percentile values over Areas 1–3 is 0.062 mSv (0.061 mSv) for the G1 subgroups and 0.13 mSv (0.12 mSv) for the G2 subgroups. This indicates that the exposure on 15 March could be significant for the G1 subgroups depending on their destinations, although the CED of the G1 group is much lower than that of the G2 group among the Namie subjects (**Fig. 2**). The magnitude of exposure on 15 March, which can currently be regarded as the CED of the G1 subgroups of Namie, would be ranked in descending order as follows: Area 3 > Area 2 > Area 1 > Areas 6 and 7.

Several limitations of this study should be mentioned. The personal behavior data available in this study were those up to 25 March 2011. It is thus not known whether or not additional intake by the subjects occurred after that day, although the restriction of food and drink consumption that was implemented shortly after the 11 March accident would minimize this possibility. A second study limitation is that the differences in the sex and age distributions among the four towns were not corrected. Special considerations may be necessary, particularly regarding the difference in the biological half-life of Cs between males and females (Uchiyama 1978). In fact, the ^{137}Cs detection rate was quite different between the males and females in this study (**Table 2**). A third study limitation is that the subjects were not necessarily representative of each town. These limitations will be addressed in our future studies.

SUMMARY AND PERSPECTIVES

The present study examined the relationship between individual Cs doses and evacuation behaviors of adult residents of four towns neighboring the FDNPP who underwent WBC measurements. The main findings are summarized as follows.

- The individual evacuation behaviors were quite diverse, and more than half of the study population evacuated outside Fukushima Prefecture on a voluntary basis as of ~20 March (data is not presented here)

- The ^{137}Cs detection rate was significantly different between the two groups (G1 and G2) which were divided based on the distances between their whereabouts and the FDNPP just before the first major release on 12 March. This significant difference was due mostly to the subjects of Namie and Futaba, and not those of Okuma and Tomioka. This result corresponds to the plume passage on 12 March and supports our previous study (Igarashi et al. 2020).
- The upper-percentile CEDs of the G2 groups were higher than those of the G1 groups for all four towns, although the difference in CEDs between these two groups varied with the town. The highest and lowest CEDs were found in the G2 group of Futaba and the G1 group of Namie (0.16 mSv and 0.04 mSv at the 90th percentile, respectively). The CEDs of both the G1 and G2 groups of Okuma and Tomioka were relatively high, although these subjects were expected to be less exposed on both 12 and 15 March, as was the G1 group of Namie. It was also found that the CEDs of the G1 group of Futaba were comparable to those of the G2 group of Namie.
- The ^{137}Cs detection rate of the G1 subgroup that evacuated outside Fukushima Prefecture after the major release on 15 March was considerably higher in the residents of Futaba (30.4%) and Okuma (30.8%) compared to that of Namie (10.5%) even though the WBC measurements for the former two towns were conducted in the later period. The CEDs of the same G1 subgroup were rather higher than those of the corresponding G2 subgroup of residents of Futaba and Okuma.
- Although the data of the subjects with extremely high doses could be biased due to the subjects' irregular behaviors, the WBC measurements were likely to be influenced by contamination that could be occasionally overlooked in the second-round temporary re-entry (except for the Namie residents).
- The results of the analyses of the Namie residents, most of whom underwent the WBC

measurements before the second-round temporary re-entry, indicate that the area including the middle part of Fukushima Prefecture (Area 3) was relatively more affected by the major release event on 15 March.

In conclusion, our analyses revealed that the early Cs intake due to the FDNPP accident remained detectable in the WBC measurements of certain present subjects; however, at the same time, the possible artificial contamination and/or other causes may have significantly interfered with the intake values. Further investigations are necessary to minimize such interference from the WBC data and address the limitations of the present study. More detailed and comprehensive analyses of the available data will help resolve these problems.

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Footnotes

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Figure captions

Fig. 1 The locations of Fukushima Prefecture in Japan (*left*) and Namie, Futaba, Okuma, and Tomioka towns in Fukushima Prefecture (*right*; the municipalities are in gray).

Fig. 2 The monthly composition of subjects from each town in the WBC measurements.

Fig. 3 Seven areas divided for the purpose of the second analysis. Areas 1–6 are municipalities in Fukushima Prefecture excluding Futaba, Okuma, Tomioka, and Naraha. *Area 1* includes Namie (Tsushima district), Kawamata-town, Iitate-village, and Minamisoma-city. *Area 2:* Fukushima-city, Date-city, Kuwaori-town, and Kunimi-town. *Area 3:* Nihonmatsu-city, Motomiya-city, Koriyama-city, Sukagawa-city, Kagamiishi-town, and Otama-village. *Area 4:* Tamura-city, Kawauchi-village, Miharu-town, Ono-town, Hirata-village, and Katsurao-village. *Area 5:* Iwaki-city. *Area 6:* the rest of the municipalities in Fukushima Prefecture. *Area 7:* places outside Fukushima Prefecture.

Fig. 4 The CEDs of the G1 and G2 groups for each town analyzed.

Fig. 5 The n-values of the subgroups divided by the destinations as of 0:00 on 16 March 2011. **A:** the G1 subgroups. **B:** the G2 subgroups.

Fig. 6 The CEDs of the subgroups divided by the destinations as of 0:00 on 16 March 2011. **A:** the G1 subgroups. **B:** the G2 subgroups.

Fig. 7 The CEDs of the subgroups of Area 7 for each town. **A:** the G1 subgroups. **B:** the G2 subgroups.

Fig. 8 The 90th-percentile CEDs of the subgroups of Namie for each destination (excluding Areas 4 and 5).

Table1

Table 1. Age and sex data of the study population in the four towns affected by the March 11, 2011 FDNPP accident

Town:	**Namie**		**Futaba**		**Okuma**		**Tomioka**	
Age, yrs	Male	Female	Male	Female	Male	Female	Male	Female
18–30	22	92	6	42	9	79	31	96
31–40	53	117	19	77	15	140	20	140
41–50	12	12	14	20	5	27	5	36
51–60	3	2	6	9	0	5	1	3
61–70	1	1	5	7	2	0	3	2
≥71	0	0	1	4	0	0	0	1
Subtotal	91	224	51	159	31	251	60	278
Total	315 (28.9%)		210 (24.3%)		282 (11.0%)		338 (17.8%)	

The numbers in parentheses are the percentages of males.

Table2

Table 2. The Cs (^{134}Cs and ^{137}Cs) detection rates for the subjects from each town

	Namie		Futaba		Okuma		Tomioka	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
^{134}Cs	47/91 † (51.6%) ‡	49/224 (21.9%)	34/51 (66.7%)	40/159 (25.2%)	19/31 (61.3%)	57/251 (22.7%)	30/60 (50.0%)	23/278 (8.3%)
	96/315 (30.5%)		74/210 (35.2%)		76/282 (27.0%)		53/338 (15.7%)	
^{137}Cs	51/91 (56.0%)	64/224 (28.6%)	35/51 (68.6%)	44/159 (27.7%)	19/31 (61.3%)	59/251 (23.5%)	35/60 (58.3%)	44/278 (15.8%)
	115/315 (36.5%)		79/210 (37.6%)		78/282 (27.7%)		79/338 (23.4%)	

† Detected/All (see Table 1).

‡ Percentages.

Table3

Table 3. The residual Cs body contents (Bq) for the subjects from each town

Rank:	**Namie**		**Futaba**		**Okuma**		**Tomioka**	
	^{134}Cs	**^{137}Cs**	**^{134}Cs**	**^{137}Cs**	**^{134}Cs**	**^{137}Cs**	**^{134}Cs**	**^{137}Cs**
Maximum	4.6×10^3	5.9×10^3	6.1×10^3	7.9×10^3	1.3×10^3	1.5×10^3	1.1×10^3	1.4×10^3
95th percentile	1.1×10^3	1.5×10^3	1.2×10^3	1.3×10^3	7.9×10^2	1.1×10^3	4.9×10^2	6.1×10^2
90th percentile	7.7×10^2	1.1×10^3	7.9×10^2	9.7×10^2	5.2×10^2	7.0×10^2	3.5×10^2	5.1×10^2
75th percentile	4.2×10^2	5.3×10^2	4.0×10^2	5.1×10^2	2.6×10^2	3.5×10^2	n.d.	n.d.

n.d.: not detected.

Table4

Table 4. The numbers of G1 and G2 groups for each town, with their ^{137}Cs detection rates

	G1	**G2**	**p-value [c]**
Namie	35/151 [a] (18.8%) [b]	80/49 (62.0%)	**
Futaba	33/87 (27.5%)	46/44 (51.1%)	**
Okuma	45/124 (26.6%)	33/80 (29.2%)	
Tomioka	28/111 (20.1%)	15/148 (25.6%)	
Total	141/473 (23.0%)	210/321 (39.5%)	**

[a] Detected/Not detected for ^{137}Cs. [b] ^{137}Cs detection rate. [c] **$p<0.01$.

Table5

Table 5. Compositions of the numbers of subjects with/without the positive ^{137}Cs detection for each subgroup with the ^{137}Cs detection rates.

	Namie		**Futaba**		**Okuma**		**Tomioka**		**Total of four towns**		
	G1	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**p-value [c]**
Area 1	5/14 [a] (26.3%) [b]	10/7 (58.5%)	11/22 (33.3%)	11/10 (52.4%)	0/0	2/1	0/0	1/1	16/36 (30.8%)	24/19 (55.8%)	**
Area 2	9/31 (22.5%)	12/11 (52.2%)	2/7	4/4	6/3	4/8	4/10	3/15 (16.7%)	21/51 (29.2%)	23/38 (37.7%)	
Area 3	10/24 (29.4%)	26/8 (76.5%)	3/11	12/5 (70.6%)	4/12 (25.0%)	5/16 (23.8%)	5/13 (27.8%)	5/17 (22.7%)	22/60 (26.8%)	48/46 (51.1%)	**
Area 4	1/4	3/4	0/2	2/4	8/43 (15.7%)	6/21 (22.2%)	4/19 (17.4%)	16/35 (31.4%)	13/68 (16.0%)	27/64 (29.7%)	*
Area 5	2/3	4/0	2/1	2/2	4/3	5/3	4/9	7/7	12/16 (42.9%)	18/12 (60.0%)	
Area 6	2/24 (7.7%)	8/10 (44.4%)	1/12	4/6	4/22 (15.4%)	6/8	2/15 (11.8%)	4/16 (20.0%)	9/73 (11.0%)	22/40 (35.5%)	**
Area 7	6/51 (10.5%)	17/9 (65.4%)	14/32 (30.4%)	11/13 (45.8%)	18/41 (30.5%)	4/23 (14.8%)	8/45 (15.1%)	15/57 (20.8%)	46/169 (21.4%)	47/102 (31.5%)	*
Sum	35/151 (18.8%)	80/49 (62.0%)	33/87 (27.5%)	46/44 (51.1%)	44/124 (26.6%)	32/80 (28.6%)	27/111 (19.6%)	51/148 (25.6%)	139/473 (22.7%)	209/321 (39.4%)	**

[a] Detected/Not detected for ^{137}Cs. [b] ^{137}Cs detection rate. The data are provided in the case of the number of subjects ≥15. [c] *p<0.05, **p<0.01. Note: The number of subjects in the table totals 1,142 (see the text).

Figure1 Fig. 1

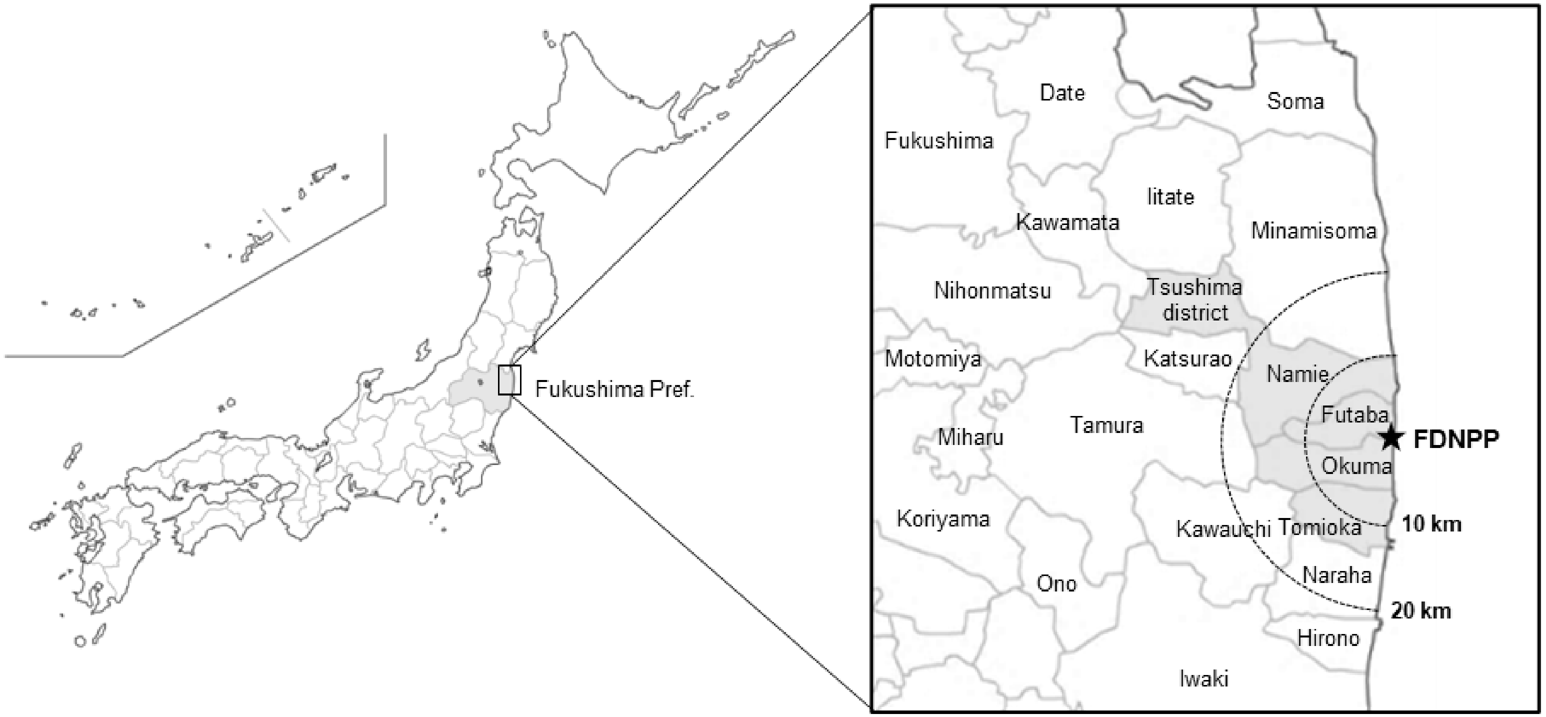

Figure2
Fig. 2

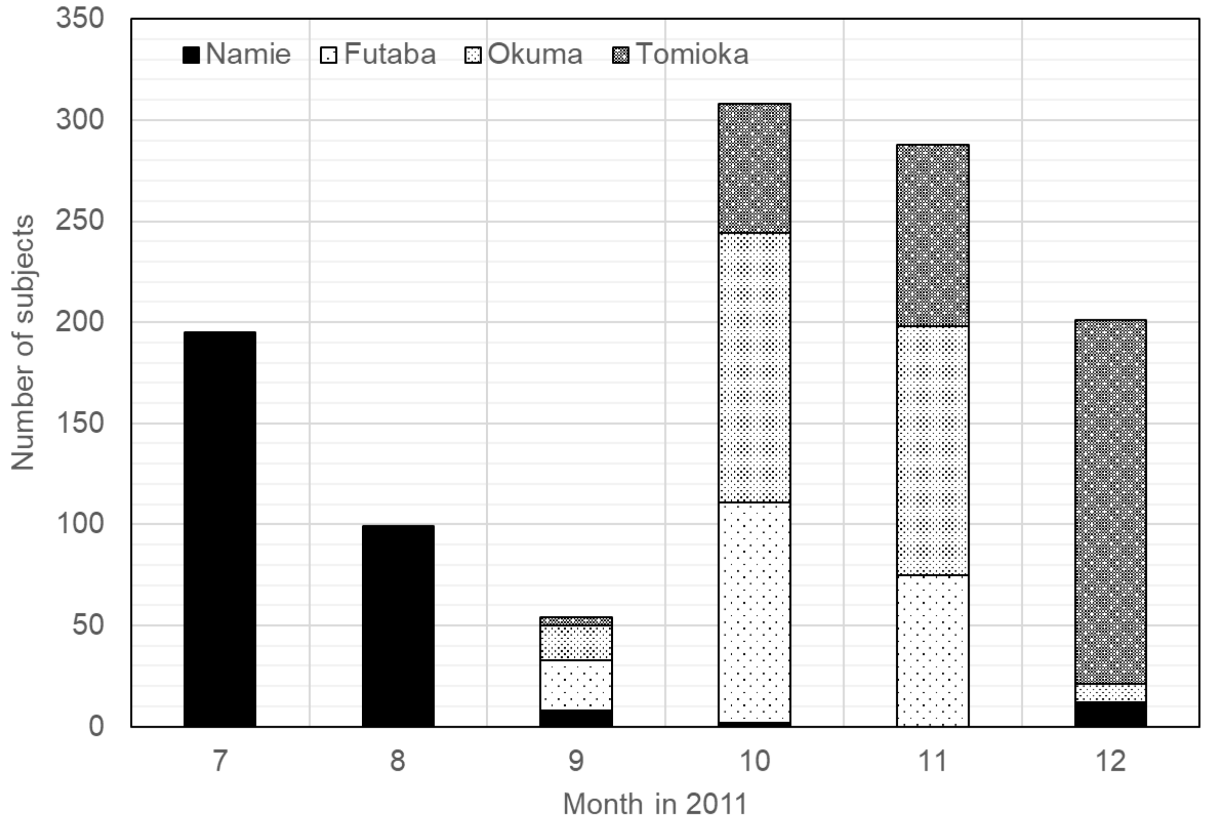

Figure3

Fig. 3

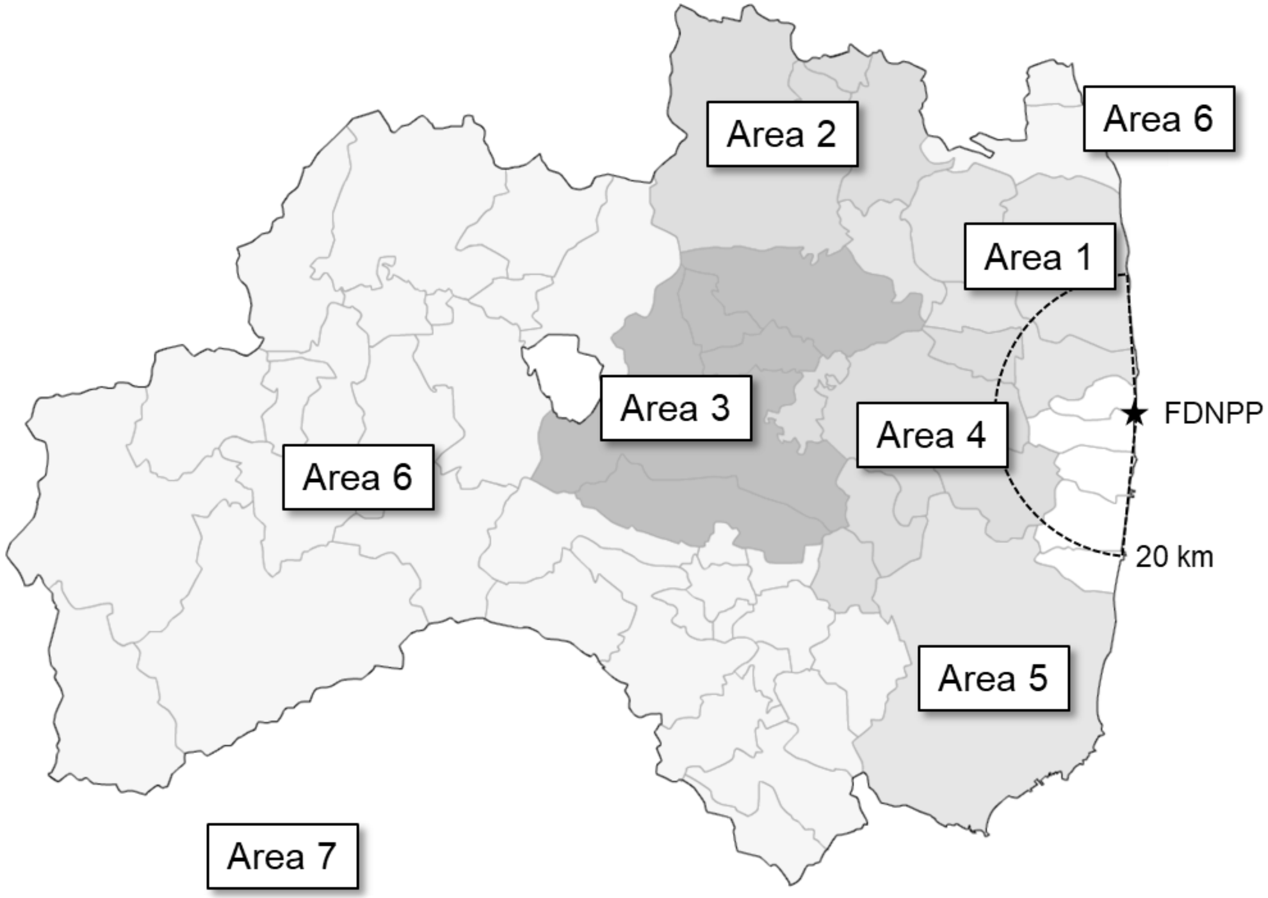

Figure4
Fig. 4

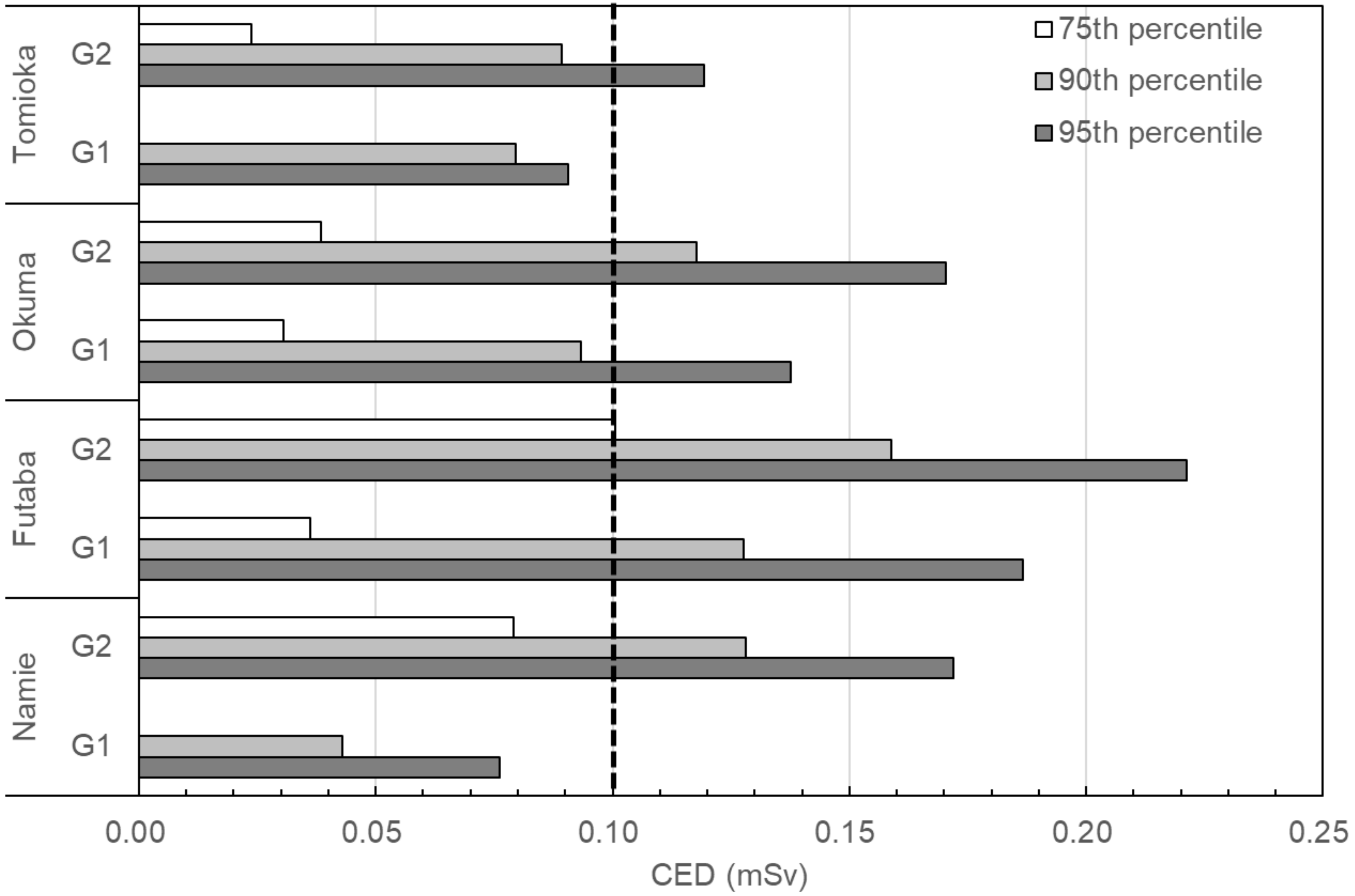

Figure5
Fig. 5

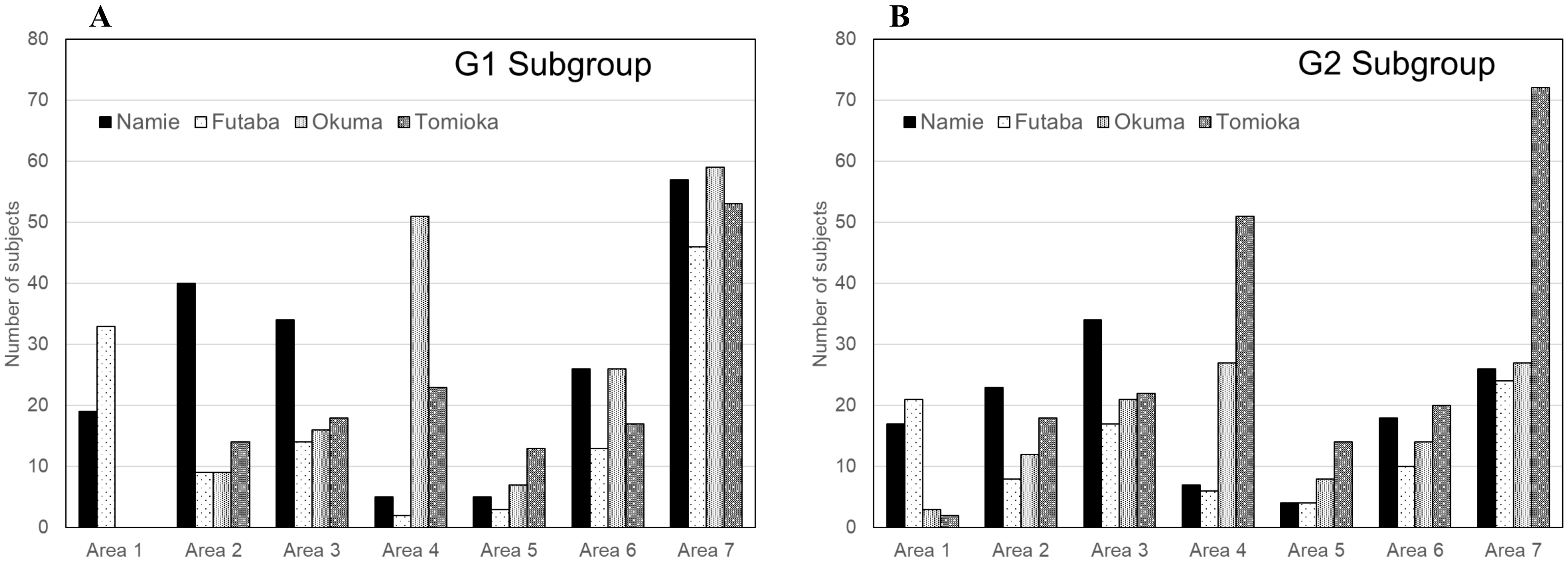

Figure6

Fig.6

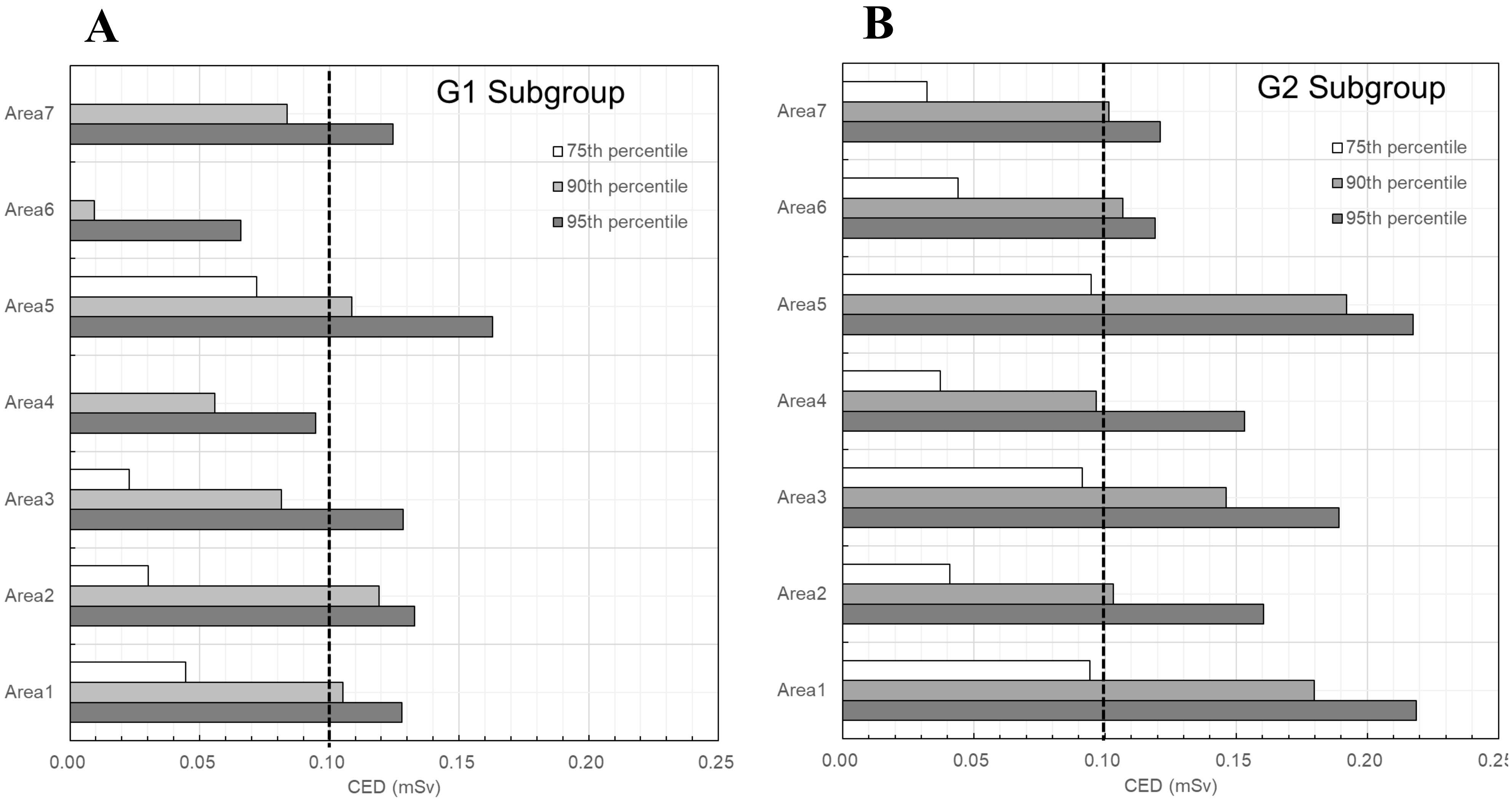

Figure7

Fig. 7

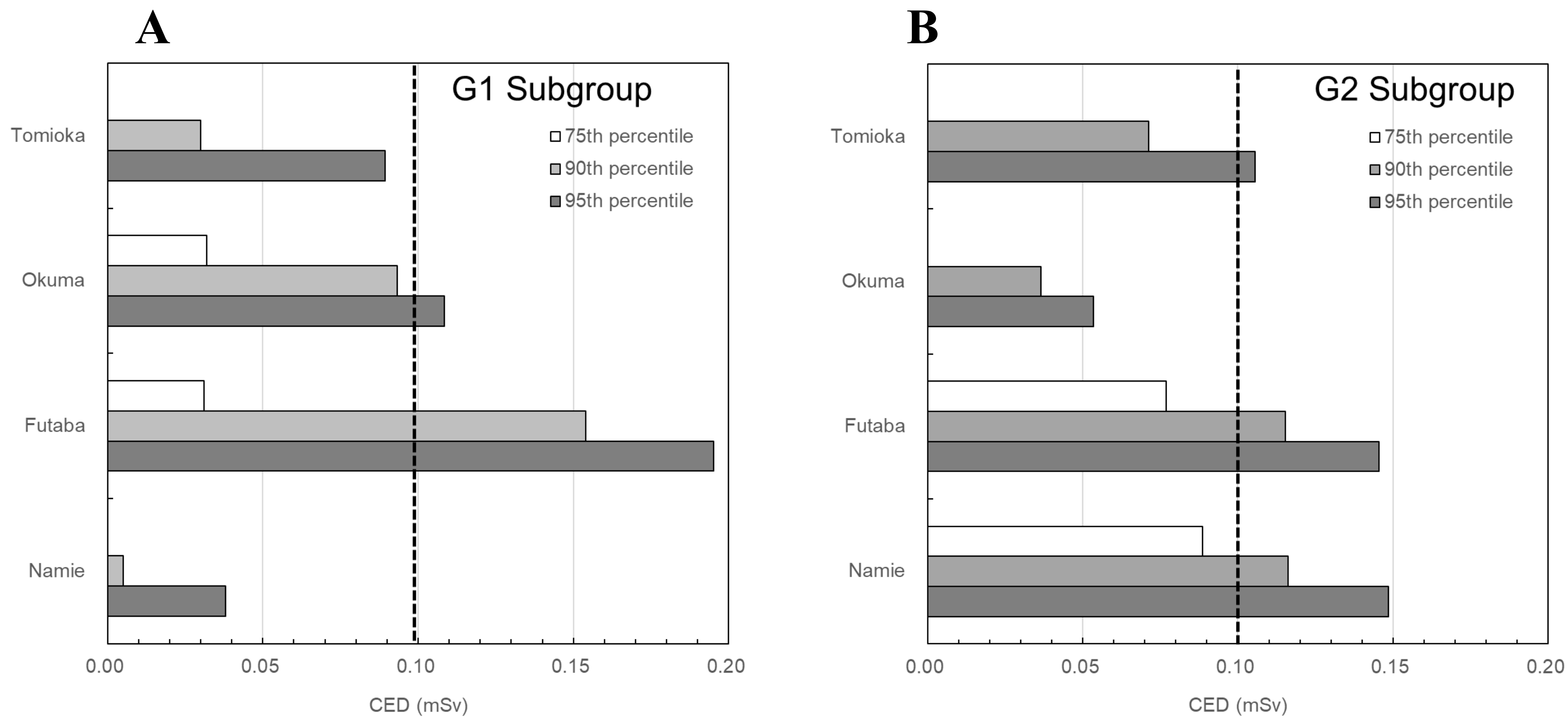

Figure8
Fig. 8