Early Intake of Radiocesium by Residents Living Near the Tepco Fukushima Dai-ichi Nuclear Power Plant After the Accident. Part 2: Relationship Between Internal Dose and Evacuation Behavior in Individuals

EARLY INTAKE OF RADIOCESIUM BY RESIDENTS LIVING NEAR THE TEPCO FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANT AFTER THE ACCIDENT. PART 2: RELATIONSHIP BETWEEN INTERNAL DOSE AND EVACUATION BEHAVIOR IN INDIVIDUALS

Naoaki Kunishima,[*†‡] Osamu Kurihara,[*] Eunjoo Kim,[*] Tetsuo Ishikawa,[§] Takashi Nakano,[*] Kumiko Fukutsu,[*] Kotaro Tani,[*] Kazuo Furuyama,[*] Shozo Hashimoto,[*] Misao Hachiya,[* ††] Yutaka Naoi[‡] and Makoto Akashi[*]

[*] National Institutes for Quantum and Radiological Sciences and Technology, National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba-city, Chiba, Japan

[†] Self-Defense Forces Central Hospital, 1-2-24 Ikejiri, Setagaya-ku, Tokyo, Japan

[§] Fukushima Medical University, 1-Hikarigaoka, Fukushima-city, Fukushima, Japan

[‡] Juntendo University, 1-1 Hongo, Bunkyo-ku, Tokyo, Japan

[††] Present application: Nuclear Technology Safety Center

Co-responding author:

Osamu Kurihara,

National Institutes for Quantum and Radiological Science and Technology,

4-9-1 Anagawa, Inage-ku, Chiba-city, Chiba, Japan

Tel: +81-43-206-4734

Fax: +81-43-284-1769

E-mail: kurihara.osamu@qst.go.jp

Abstract

The Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident exposed members of the public to radiation. This study analyses the relation between personal behavior data obtained from 112 out of 174 subjects who underwent whole-body measurements by the National Institute of Radiological Sciences (NIRS) during the period from 27 June to 28 July 2011 and their committed effective doses (CEDs) from ^{134}Cs and ^{137}Cs. The whereabouts of the 112 persons living in municipalities near the FDNPP (mainly, Namie town) on several days in March, 2011 are graphed on maps. It was confirmed that most subjects started evacuation promptly and had left the 20-km-radius of the FDNPP by the end of 12 March. The individual CEDs were poorly correlated with the person's distances from the FDNPP at any day in March. Meanwhile, the percentage of persons remaining within the 20-km radius of the FDNPP was 100% at 16:00 on 12 March and 42.9% at 0:00 on 15 March for those with CEDs > 0.1 mSv, whereas the corresponding values were much lower for those with CEDs ≤ 0.1 mSv. This suggests that the time of evacuation would be one of the crucial factors for the early intake; however, more personal behavior data are needed to be analyzed to clarify the relevance to the individual internal dose.

Keywords: Fukushima Dai-ichi Nuclear Power Plant; personal behavior; committed effective dose; internal dose

INTRODUCTION

A catastrophic natural disaster triggered by the Great East Japan Earthquake on the Pacific coast of the main island of Japan on 11 March 2011 with a magnitude of 9.0 killed around 20,000 people (including missing people) (National Police Agency 2016). The main cause of death was not the earthquake itself, but the massive tsunami generated by the earthquake. The nuclear reactors at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) run by the Tokyo Electric Power Company (TEPCO) were automatically shut down at the time of the earthquake; the ensuing tsunami caused a complete loss of cooling functions of the three reactor cores, resulting in the release of radionuclides into the environment. This accident has tentatively been ranked as Level 7, the highest level on the International Nuclear Event Scale (INES), and the same level as the Chernobyl accident in 1986 (Nuclear Emergency Response Headquarters 2011). According to the recent atmospheric transport and dispersion model (ATDM) analyses by Katata *et al.* (Katata et al. 2015), the estimated discharge amounts of ^{131}I and ^{137}Cs were 151 PBq and 14.5 PBq, respectively. These amounts are much smaller than those in the Chernobyl accident: 1760 PBq for ^{131}I and 85 PBq for ^{137}Cs (UNSCEAR 2000).

Much effort has been made to estimate the doses to residents living in the areas radiologically affected by this accident, in particular, Fukushima Prefecture (Hosoda et al. 2013, Kim et al. 2016, Matsuda et al. 2013, Tsubokura et al. 2015, Nomura et al. 2016, Ishikawa et al. 2016). However, there have been only a limited number of studies focusing on the early doses to members of the public. Ishikawa *et al.* reported the estimates of early external doses received by the Fukushima Prefectural residents for the first four months after the accident based on time-series ambient dose rate maps and data on the whereabouts of each person (Ishikawa et al. 2015). The arithmetic mean and maximum values of the individual external effective doses were 0.8 mSv and 25 mSv, and 99.4% of 421,394 Fukushima residents were estimated as having an effective dose below 3 mSv. On the other hand, the information on which estimations of the early internal dose can be based has been very scarce. Only about 1,300 human measurements directly related to ^{131}I, the largest contributor to the early internal dose, were obtained (NIRS 2012, Tokonami et al. 2012, Matsuda et al. 2013, Kamata et al. 2013). Environmental measurements shortly after the accident are also limited in number, so that it has been difficult to develop reliable models for internal exposure pathways.

The present study analyzed personal behavior data obtained from 112 out of 174 subjects who underwent whole-body counter (WBC) measurements at the National Institute of Radiological Sciences (NIRS) from 27 June to 28 July 2011. Details on the results have been described in the authors' companion paper (Kim et al. 2016). Although these measurements could detect radiocesium (^{134}Cs and ^{137}Cs) only, it is hoped that the measurements convey a clue to understanding the early internal dose to the public, including that from ^{131}I and the other short-lived radionuclides. The main purpose of this study was thus to clarify the relationship, if any, between the individual internal doses from radiocesium and personal behavior data. This is important from the viewpoint of identifying the behavior patterns that could lead to significant doses.

MATERIALS AND METHODS

Personal behavior data

The NIRS performed the WBC measurements on the 174 subjects living near the FDNPP during the period from 27 June and 28 July 2011. These subjects were selected by Fukushima Prefectural Government and included 125 adults (≥18-y) and 49 children (<18-y) based on the age at the time of the accident. Ninety of the 174 subjects were residents from Namie town and the rest were from several municipalities near the FDNPP (**Fig. 1**). Namie town is one of the areas highly contaminated with radionuclides and has been designated as the difficult-to-return zone (where the annual external dose is predicted to be higher than 50 mSv) since April, 2011 (Ministry of Economy, Trade and Industry 2012).

In this study, the personal behavior data obtained from 112 out of the 174 subjects were analyzed together with their internal doses that were already evaluated in the authors' previous study (Kim et al. 2016). The composition of the 112 persons by the municipality and gender/age are displayed in **Fig. 2**. The numbers of adults and children were 78 and 34, respectively. The personal behavior data were generated from answer sheets of a self-administered questionnaire on the person's whereabouts in chronological order during the first four months after the accident, and they were stored in electric files. This questionnaire has been used in the Basic Survey to estimate individual external doses, one of the core components of the Fukushima Health Management Survey (Ishikawa et al. 2015, Yasumura et al. 2012). The personal behavior data were the same as those used in the Basic Survey and consisted of the whereabouts (the place name and its latitude and longitude), the time spent indoors/outdoors or moving, and the type of the building where the person stayed (e.g., a wooden house, a concrete building) although only the whereabouts data were analyzed in this study. These data are provided hourly until 25 March and daily (representative places to stay or commute) during the period from 26 March to 11 July 2011. The use of the personal behavior data in this study was approved by the ethics review committees of the NIRS and Fukushima Medical University. For the persons whose personal behavior data were unavailable, the exposure scenario obtained from a brief interview by the NIRS staff members at the time of the WBC measurements was used as a reference.

Internal dose calculation

The internal dose calculation of the 174 subjects has been described in the authors' companion paper (Kim et al. 2016). Briefly speaking, the internal dose from ^{134}Cs and ^{137}Cs was calculated based on the ^{134}Cs body content determined by the WBC measurements. The reason for not using the ^{137}Cs body content was that the detection rate of ^{137}Cs was much lower than that of ^{134}Cs. Minimum Detectable Activity (MDA) values for ^{134}Cs and ^{137}Cs were evaluated to be 320 Bq and 570 Bq, respectively. One reason why ^{137}Cs was higher than ^{134}Cs in terms of the MDA value was the difference in the key peak in identifying each radionuclide. In detail, the key peak for ^{137}Cs (662 keV: 85.1%) overlapped with the other peaks from ^{134}Cs (605 keV: 97.6%, 569 keV: 15.4%), whereas the key peak for ^{134}Cs (796 keV: 85.5%, 802 keV: 8.7%) did not. Instead, the ^{137}Cs body content was determined by multiplying the ^{134}Cs body content by the factor (1.1) obtained from measurement results of the subjects from whom both radionuclides were detected. These results demonstrated that the body contents of ^{134}Cs and ^{137}Cs were correlated well with each other. The age-dependent committed dose per unit intake (DPUI) values and whole-body retention rates were taken from the database published by the International Commission on Radiological Protection (ICRP) (ICRP 2012) and a software package, MONDAL, developed by the NIRS (Ishigure et al. 2004), respectively. Regarding the intake scenario, acute inhalation of Type F compounds with 1 μm in activity median aerodynamic diameter (AMAD) on 12 March, 2011 was assumed (Kim et al. 2016). From the results of the previous study, the 90th percentile of the individual internal doses to the subjects was about 0.1 mSv in committed effective dose (CED) for both the adults and the children.

Data analyses

Mann-Whitney's *U* test was performed to confirm differences between two groups using SPSS software package 22. (IBM-Japan Co., Japan). A *p*-value below 0.05 was considered significant. The distances of the subjects from the FDNPP were calculated using Hubeny's simplified formula (Ubukawa et al. 2014); the latitude and longitude of the FDNPP were set at 37.421071 and 141.032755, respectively. The whereabouts of the 112 persons were also graphed on maps using Google My Maps (Google).

RESULTS

Individual internal dose

The CEDs of the 112 persons were not significantly different from those of the other 62 persons whose personal behavior data were not obtained (p=0.618). **Fig. 3** shows the CED distributions of the 78 adults (Panel A) and the 34 children (Panel B) included in the study. The 78 adults consisted of 34 males and 44 females. The lowest CED bars included persons in whom ^{134}Cs was not detected (ND); their CEDs were regarded as zero in that case. As shown in the figure, the CED distributions of the adults and the children are similar to each other (p=0.363). The 90th percentile CED values were also similar to each other: 0.10 mSv for the adults and 0.11 mSv for the children. However, this result indicates the possibility of overestimations of the internal doses to the children as described in the authors' previous paper. In short, the CED should be higher in the adults than the children, taking into account the fact that the DPUIs are relatively comparable among the different age groups (5 y, 3.6×10^{-9} Sv Bq^{-1}; 10 y, 3.7×10^{-9} Sv Bq^{-1}; 15 y, 4.4×10^{-9} Sv Bq^{-1}; Adult, 4.6×10^{-9} Sv Bq^{-1} for inhalation of Type F compounds of ^{134}Cs), and the intake is likely to be larger in adults than children. On the other hand, the difference in the CED between the adult males and the adult females was found to be significant (p<0.001). **Table 1** summarizes gender, ^{134}Cs content, CED and the exposure scenario for 30 of the 125 adult subjects in order of decreasing the CED. The exposure scenarios were obtained from the interview by the NIRS staff members. All of those ranked in the top ten CEDs were male. The highest CED (0.63 mSv) was found in a 69-y-old male from Futaba town. According to his scenario, he saw hydrogen explosion at the Reactor 1 building on March 12 and received decontamination. His personal behavior data was, however, unavailable. The male with the second highest CED (0.24 mSv) was supposedly a cattle farmer. He stayed at his pasture until March 17 to feed his cows.

Displacement of the persons after the accident

Figs. 4 and **5** show the whereabouts of the 78 adults and the 34 children on the map of Fukushima Prefecture at 0:00 on 12, 13, 15, 20 and 25 March (not displaying the persons who evacuated outside the prefecture). The symbols in these figures denote the groups categorized by the level of CED as follows: Group 1 (CED > 0.1 mSv), Group 2 (0.05 mSv < CED ≤ 0.1 mSv), Group 3 (0 mSv < CED ≤ 0.05 mSv), and Group 4 (0 mSv) for the adults; Group 1 (CED > 0.1 mSv), Group 2 (0 mSv < CED ≤ 0.1 mSv), and Group 3 (0 mSv) for the children. The persons whose ^{134}Cs contents were ND were regarded to have zero CED as described earlier. As shown in the figures, almost all persons had evacuated from the area within a 30-km radius of the FDNPP as of 20 March. **Fig. 6** shows the representative evacuation scenarios for residents of Namie town. This scenario was considered as one of the 18 representative evacuation scenarios for municipalities located near the FDNPP (Akahane et al. 2013) and consists of the following two passages: (1) Namie town office (departure at 12:00) to Tsushima district (the northwest part of the town) on 12 March (arrival at 15:00) and (2) Tsushima district (departure at 10:00) to Adachi gymnasium in Nihonmatsu city (arrival at 14:00) on 16 March. As shown in **Figs. 4** and **5**, the displacement of persons living in the coastal areas of Namie town generally agreed with the representative evacuation scenario; however, the actual evacuations had a wide variety of destinations as time proceeded. It was also confirmed that a significant number of the study subjects evacuated outside Fukushima Prefecture after the accident.

Fig. 7 shows the time-trend of the numbers of persons staying the following distances from the FDNPP: ≤ 5 km, 5–10 km, 10–20 km, 20–30 km and > 30 km. The distance of the person during a displacement was calculated as the average of the distances from the departure and destination places. The Japanese Government issued evacuation orders for residents within the 3-km radius at 21:23 on 11 March, within the 10-km radius at 5:44 and within the 20-km radius at 18:25 on 12 March, and also issued an indoor evacuation order for residents in the 20- to 30-km radius at 11:01 on 15 March (Nuclear Emergency Response Headquarters 2011). Our results show that most of the persons living near the FDNPP had left the 20-km radius before the third evacuation order.

Factors influencing the internal dose

Figs. 8 and **9** show the relationship between the CED and the distance from the FDNPP at 0:00 and 16:00 on 12 March and at 0:00 on 13, 15, 20 and 25 March for the 78 adults and the 34 children, respectively. The groups in the figures are the same as those in **Figs. 4** and **5**. Each circle marker on each plot represents a single person. Note that only the x-values of the plots change with time. The results demonstrate a poor correlation between the CED and the distance on any date for both the adults and the children. However, a closer look at the adult results shows that the persons with higher CEDs (Group 1) tended to delay their evacuations compared to those with lower CEDs. This becomes more obvious in **Table 2**, which provides the percentage of the 78 adults staying within the 20-km radius of the FDNPP (the gray-colored areas in **Figs. 8** and **9**) for each group at different times. The percentage of Group 1 (CED > 0.1 mSv) is 100% at 16:00 on 12 March and 42.9% at 0:00 on 15 March, whereas the corresponding ratios of the other group are ≤ 20% and 0%. That difference was not, however, seen in the 34 children as shown in **Table 3**.

DISCUSSION

This is the first study on the early intake of radionuclides by Fukushima residents involved in the FDNPP accident using the personal behavior data obtained through the Fukushima Health Management Survey. In this study, the personal behavior data obtained from 112 of the 174 subjects of the WBC measurements at the NIRS were analyzed together with their internal doses due to intake of ^{134}Cs and ^{137}Cs. Sixty-six of the 112 persons were residents of Namie town. The data were also graphed on a map of Fukushima Prefecture to realize the displacement of persons after the accident.

Fig. 10 demonstrates the time trend of percentages of those who evacuated from each municipality (Nuclear Emergency Response Headquarters 2011). These data were obtained from 9,070 responders to a postal survey by the National Diet of Japan Fukushima Accident Independent Investigation Commission. According to the Commission’s report, the majority of residents of Futaba town, Okuma town and Tomioka town started evacuation in the morning on March 12 shortly after evacuation orders by each municipality. Such was the case with those living within the 10-km radius in Namie town. On the other hand, evacuation was delayed in Iitate village and Kawamata village, which were designated as deliberate evacuation areas (where the annual cumulative external dose is expected to be higher than 20 mSv) in April, 2011.

The displacements of the residents of these municipalities were confirmed in this study. As seen in **Figs. 4** and **5**, most of the subjects who lived in the coastal areas of Namie town evacuated to the northwest part of the town by the end of 12 March, and stayed there for a couple of days. As mentioned earlier, this displacement is similar to one evacuation scenario for Namie town's residents although the time of evacuation was slightly different. The route of this scenario is overlapped by the highest contamination area (**Fig. 11**), which is supposed to give relatively high internal doses to evacuees from Namie town. This was also suggested by the internal dose estimation obtained by coupling the 18 evacuation scenarios with the ATDM simulations based on WSPEEDI-II (Worldwide version of System for Prediction of Environmental Emergency Dose Information version 2) (Kim et al. 2016). The latest ATDM analyses also predicted that the above area was generated by wet deposition of radionuclides during the period from late 15 March to early 16 March (Nuclear Emergency Response Headquarters 2011). Thereby, from the viewpoint of intake via inhalation, it is of great importance to identify the whereabouts of persons on these days and on 12 March, when a hydrogen explosion occurred at the Reactor 1 building (15:36). This may be true as demonstrated by the result of **Table 2**, which suggests that the whereabouts on 12 and 15 March are a key factor for the resulting internal dose. Of particular concern is intake on 12 March, when most residents living near the FDNPP were undergoing evacuation. Intake on 12 March is also important because the internal doses from short-lived radionuclides other than ^{131}I are expected to have been relatively high (Shinkarev et al. 2015). It is noted that all the adults categorized into Group 1 remained within a 20-km radius of the FDNPP as of the end of 12 March.

Regarding the children analyzed, there was no relationship between the CEDs and personal behaviors. This can be caused by overestimations of the internal doses to the children as described earlier. Actual intake is likely to continue intermittently for a certain period of time depending on the individual exposure environment, although ingestion would be minimized because of the Japanese government's prompt restrictions on distribution and consumption of food and drink items contaminated with radionuclides (Hamada et al. 2012). Accordingly, the assumed intake scenario (namely, acute inhalation on 12 March) could result in significant overestimations, especially for younger children whose whole-body retention rates are much lower. It is supposed that the times of inhalation could be estimated by superimposing the personal behavior data on the radionuclide air concentration maps generated by ATDM simulations at the same time. This issue will be addressed in the next study.

Limitations of the personal behavior data should be mentioned. These data have been produced based on answers to the self-administered questionnaire. Accordingly, the accuracy of the data depends on the answerer's memory. Late answerers may have forgotten or confused details after the accident. In this regard, the personal behavior data used in this study generally fit with the exposure scenarios obtained at relatively early times after the accident although the exact time of each person's evacuation was mostly missing from the exposure scenarios. This may indicate that the data were reasonably accurate for most of the persons analyzed. There are also other limitations on the personal behavior data. For instance, the whereabouts of a person during the periods recorded as his or her moving are unknown in the data, which could introduce a large error for those who moved far from the place of departure over time. The building type, which is needed for external dose estimation (Akahane et al. 2013), is also difficult to use in the internal dose estimation because the dose reduction factor for shelter from inhalation cannot be determined only by building type. This factor is also affected by the duration of plume exposure (United States Environmental Protection Agency 2012).

In conclusion, the present study demonstrated that the personal behavior data were potentially useful for the estimation of the early internal doses to Fukushima residents. As demonstrated, the time of evacuation would be one of the crucial factors for estimations of the early intake by residents living near the FDNPP. In other words, this result may suggest that the dominant pathway of intake was inhalation during exposure to radioactive plumes. However, it is still necessary to analyze more personal behavior data of the persons who were directly measured in order to obtain more concrete results. Finally, it is noted that the exposure scenarios of the persons examined were informative for understanding their exposure situations. It seems that adult persons with relatively high internal doses have fairly plausible reasons such as direct contamination, witnessing the explosion, outdoor occupations, etc.

CONCLUSION

Personal behavior data obtained from 112 of 174 subjects who underwent whole-body measurements by the NIRS during the period from 27 June to 28 July 2011 were analyzed in the present study. In addition, the whereabouts of the 112 persons were graphed on a map of Fukushima Prefecture. As a result, it was confirmed that most of the persons started evacuation promptly and had left the 20-km radius of the Fukushima Daiichi Nuclear Power Plant (FDNPP) by the end of 12 March in accordance with evacuation orders by the Japanese government and local municipal authorities. The representative evacuation scenario for residents of Namie town, which was expected to yield the high internal dose, was also identified. The individual committed effective doses (CEDs) from ^{134}Cs and ^{137}Cs were poorly correlated with the person's distance from the FDNPP on several days in March. Meanwhile, among the adults analyzed, the time of evacuation for persons with relatively high CEDs tended to be delayed compared to that for the others. However, it is still necessary to analyze more personal behavior data to clarify the relevance to the individual internal dose for estimating the early internal dose mainly due to ^{131}I.

Acknowledgements

We wish to express thanks to all members of the research center of radiation emergency medicine of the NIRS in fiscal year 2011 for their assistance. We also thank Mr. Masanori Yuuki of Tokyo Nuclear Service Co., Ltd. for his assistance.

This study was conducted as part of the comprehensive study on the dose estimation of residents in the Fukushima Daiichi Nuclear Power Plant accident funded by the Ministry of the Environment, Japan (2014-2016) and also as a collaborative study between the NIRS and Fukushima Medical University.

REFERENCES

Akahane K, Yonai S, Fukuda S, Miyahara N, Yasuda H, Iwaoka K, Matsumoto M, Fukumura A and Akashi M. NIRS external dose estimation system for Fukushima residents after the Fukushima Dai-ichi NPP accident. Sci. Rep. 3: 1670; 2013.

Google My Maps. Available at ***https://www.google.com/mymaps.*** Accessed on 21 March 2016.

Hamada N, Ogino H and Fujimichi Y. Safety regulations of food and water implemented in the first year following the Fukushima nuclear accident: J. Radiat. Res. 53: 641-671; 2012.

Hubeny K. Weiterentwicklung der Gauss'schen Mittelbreitenformeln. Z. Vermess. 84: 159-163; 1959. (http://tancro.e-central.tv/grandmaster/excel/hubenystandard.html)

Hosoda M, Tokonami S, Akiba S, Kurihara O, Sorimachi A, Ishikawa T, Momose T, Nakano T, Mariya Y and Kashiwakura I. Estimation of internal exposure of the thyroid to ^{131}I on the basis of ^{134}Cs accumulated in the body among evacuees of the Fukushima Daiichi nuclear power station accident. Environ. Inter. 61: 73-76; 2013.

International Commission on Radiological Protection. Compendium of dose coefficients based on ICRP Publication 60. ICRP Publication 119. Ann. ICRP 41 (Suppl.); 2012.

Ishigure N, Matsumoto M, Nakano T and Enomoto H. Development of software for internal dose calculation from bioassay measurements. Radiat. Prot. Dosim. 109: 235-242; 2004. MONDAL3 (updated version) available at ***http://www.nirs.go.jp/db/anzendb/RPD/mondal3.php***. Accessed on 21 March 2016.

Ishikawa T, Yasumura S, Ohtsuru A, Sakai A, Akahane K, Yonai Sh, Sakata R, Ozasa K, Hayashi M, Ohira T, Kamiya K and Abe M. An influential factor for external radiation dose estimation for residents after the Fukushima Daiichi nuclear power plant accident-time spent outdoors for residents in Lite Village. J. Radiol. Prot. 36: 255-268; 2016.

Ishikawa T, Yasumura S, Ozasa K, Kobashi K, Yasuda H, Miyazaki M, Akahane K, Yonai Sh, Ohtsuru A, Sakai A, Sakata R, Kamiya K and Abe M. The Fukushima health management survey: estimation of external doses to residents in Fukushima prefecture. Sci. Rep. 5: 12712; 2015.

Kamata N., Saito O, Endo S, Kimura A and Shizuma K. Radiation doses among residents 37km northwest of the Fukushima Dai-ichi nuclear power plant. J. Environ. Radioact. 110: 89-89; 2012.

Katata G, Chino M, Kobayashi T, Terada H, Ota M, Nagai H, Kajino M, Draxler R, Hort M C, Malo A, Torii T and Sanada Y. Detailed source term estimation of the atmospheric release for the Fukushima Daiichi nuclear power station accident by coupling simulations of atmospheric dispersion model with improved deposition scheme and oceanic dispersion model. Atoms. Chem. Phys. 15: 1029-1070; 2015.

Kim E, Kurihara O, Kunishima N, Nakano T, Tani K, Hachiya M, Momose T, Ishikawa T, Tokonami Sh, Hosoda M, and A kasha M. Early intake of radiocesium by residents living near the Tepco Fukushima Dai-ichi nuclear power plant after the accident Part 1: internal doses based on whole-body measurements by NIRS. Health Phys (Accepted: 24 June 2016)

Kim E, Kurihara O, Tani K, Ohmachi Y, Fukutsu K, Sakai K and Akashi M. Intake ratio of ^{131}I to ^{137}Cs derived from thyroid and whole-body doses to Fukushima residents. Radiat. Prot. Dosim. 168: 408-418; 2016.

Matsuda N, Kumagai A, Ohtsuru A, Morita N, Miura M, Yoshida M, Kudo T, Takamura N and Yamashita S. Assessment of internal exposure doses in Fukushima by a whole body counter within one month after the nuclear power plant accident. Radiat. Res. 179: 663-668; 2013.

Ministry of Health, Labour and Welfare (MHLW). Handbook of Health and Welfare Statistics 2014. Available at ***http://www.mhlw.go.jp/english/database/db-hh/2-1.html***. Accessed on 21 March 2016.

Ministry of Internal Affairs and Communications (MIC). Results of examinations on internal exposure by radioactive materials. 2011 (in Japanese). Available at ***http://www.soumu.go.jp/menu_news/s-news/52460.html***. Accessed on 21 March 2016.

Ministry of Economy, Trade and Industry. About the radiation dose in the evacuation directive areas and the evacuation directive lifted areas (in Japanese). 2014. Available at www.meti.go.jp/earthquake/nuclear/radioactivity/index.html. Accessed 24 December 2014.

Nagano M, Kawamura H, Yamamoto M, and Ohuchi A. Acquisition of personal tourism activity information based on GPS log mining method. Proceedings of the Fifth Asia Pacific Industrial Engineering and Management Systems Conference 2004. Fifth APIEMS, Gold Coast, Australia. Available at ***http://www.apiems.org/***. Accessed on 21 March 2016.

Nation Police Agency of Japan. Damage situation and police countermeasures associated with 2011 Tohoku district – off the Pacific Ocean Earthquake, 2016. Available at ***https://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf.*** Accessed on 21 March 2016.

National Institute of Radiological Sciences. Proceedings of the first NIRS symposium on reconstruction of early internal dose in the TEPCO Fukushima Daiichi nuclear power station accident. Chiba: National Institute of Radiological Sciences; NIRS-M-252; 2012

Available at ***http://www.nirs.go.jp/publication/ irregular/pdf/nirs_m_252.pdf***. Accessed on 21 March 2016.

Nuclear Emergency Response Headquarters Government of Japan. Report of Japan Government to the IAEA Ministerial Conference on Nuclear Safety − The accident at TEPCO's Fukushima Nuclear Power Stations June 2011. Available at ***http:// japan.kantei.go.jp/kan/topics/201106/iaea_houkokusho_e.html***. Accessed on 21 March 2016.

Nomura Sh, Tsubokura M, Furutani T, Hayano R, Kami M, Kanazawa Y, and Oikawa T. Dependence of radiation dose on the behavioral patterns among school children: a retrospective analysis 18 to 20 months following the 2011 Fukushima nuclear incident in Japan. J. Radiat Res. 57(1): 1-8; 2016.

Shinkarev S M, Kotenko K V, Granovskaya E O, Yatsenko V N, Imanaka T and Hoshi M. Estimation of the contribution of short-lived radioiodines to the thyroid dose for the public in case of inhalation intake following the Fukushima accident. Radiat. Prot. Dosim. 164: 51-56; 2015.

The National Diet of Japan. The official report of the Fukushima Nuclear Accident Independent Investigation Commission. 2012. Available at ***http://warp.da.ndl.go.jp/ info:ndljp/pid/3856371/naiic.go.jp/en***. Accessed on 21 March 2016.

Tokonami S, Hosoda M, Akiba S, Sorimachi A, Kashiwakura I and Balonov M. Thyroid doses for evacuees from the Fukushima nuclear accident. Sci. Rep. 2: 507; 2012.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation: UNSCEAR 2000 REPORT Vol. II. Annex J; 2000.

United States Environmental Protection Agency. Manual of protective action guides and protection actions for nuclear incidents: 1992.

Tsubokura M, Kato S, Morita T, Nomura Sh, Kami M, Sakaihara K, Hanai T, Oikawa T and Kanazawa Y. Assessment of the annual additional effective doses amongst Minamisoma children during the second year after Fukushima daiichi nuclear power plant disaster. PLoS One. 10(6):e0129114. doi:10.1371/journal.pone.0129114;2015.

Yasumura S, Hosoya M. Yamashita S, Kamiya K, Abe M, Akashi M, Kodama K and Ozasa K. Study protocol for the Fukushima Health Management Survey. J. Epidemiol, 22(5): 375-383; 2012.

Footnotes

[*] National Institutes for Quantum and Radiological Sciences and Technology, National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba-city, Chiba, Japan

[†] Self-Defense Forces Central Hospital, 1-2-24 Ikejiri, Setagaya-ku, Tokyo, Japan

[§] Fukushima Medical University, 1-Hikarigaoka, Fukushima-city, Fukushima, Japan

[‡] Juntendo University, 1-1 Hongo, Bunkyo-ku, Tokyo, Japan

[††] Present application: Nuclear Technology Safety Center

List of Figure captions

Fig. 1 Geometrical locations of Fukushima Prefecture and municipalities located near the FDNPP. The gray-colored area (the right of the figure) indicates the municipalities where the 174 subjects lived at the time of the accident.

Fig. 2 Compositions of the 112 persons by the municipality (left) and gender/age group (right). The values displayed in the figure are the numbers of the persons. In the right circle, M and F denote male and female, respectively. 5y, 10y, 15y and Adult denote the age groups defined in the ICRP Publication 71.

Fig. 3 CED distributions of the 78 adults (left) and the 34 children (right).

Fig. 4 Whereabouts of the 78 adults at 0:00 on 12, 13, 15, 20 and 25 March. The persons who evacuated outside Fukushima Prefecture are not displayed. The symbols denote the groups divided by the level of the CED (see the text).

Fig. 5 Whereabouts of the 34 children at 0:00 on 12, 13, 15, 20 and 25 March. The persons who evacuated outside Fukushima Prefecture are not displayed. The symbols denote the groups divided by the level of the CEDs (see the text).

Fig. 6 Representative evacuation scenarios for residents of Namie town.

Fig. 7 Time-trend of the distances between whereabouts of the persons and the FDNPP on 12 March (hourly, the upper panel) and 13-31 March (daily, the lower panel)

Fig. 8 Relationship between the distances of the 78 adults from the FDNPP and their CEDs for each time and date displayed.

Fig. 9 Relationship between the distances of the 34 children from the FDNPP and their CEDs on each time and date displayed.

Fig. 10 Time trend of percentages of those who evacuated from each municipality. The original figure is slightly modified.

Fig. 11 Deposition density map of the total of ^{134}Cs and ^{137}Cs by airborne monitoring (corrected as of 28 August, 2011).

Table lists

Table 1 Summary of the information on the 30 adults in descending order according to the CED.

Table 2 Percentage of the 78 adults staying within a 20-km radius of the FDNPP.

Table 3 Percentage of the 34 children staying within a 20-km radius of the FDNPP.

Table1

Table 1 Summary of the information on the 30 adults in descending order according to the CED (1/2).

Rank	Gender†	Data*	^{134}Cs (Bq)	CED (mSv)	Exposure scenario obtained from an interview by the NIRS staff members at the time of the WBC measurements
1	M	N	7.15×10^3	0.63	He saw the hydrogen explosion outdoors on 12 March and evacuated to Futaba high school. He moved to Nihonmatsu city on 13 March. He reported that he received decontamination.
2	M	N	2.81×10^3	0.24	He was working in his pasture on 12 March and continued to stay in the area until 17 March to feed his cows. He temporarily evacuated to Tokyo from 17 March to 23 March, and then moved to Nihonmatsu city on 24 March. He visited his pasture once a week thereafter.
3	M	Y	2.70×10^3	0.22	He evacuated to a hall on March 12 and then evacuated to a gymnasium in Kawamata town.
4	M	Y	2.54×10^3	0.21	He stayed at his house until 15 March, and then evacuated to Nihonmatsu city.
5	M	N	2.40×10^3	0.20	He continued to stay in Iitate village and spent most of his time outdoors. He let his family evacuate.
6	M	N	2.00×10^3	0.17	He spent most of his time indoors at his house from 12 March to 15 March. He evacuated to Tsushima district (the central area of Namie town) on March 15 and then to Nihonmatsu elementary school on 17 March.
7	M	N	1.70×10^3	0.15	He stayed at the city hall and evacuated to Kawamata town at 17:00 on 12 March. He stayed there until 29 March. He was in charge of the rescue of people remaining in Futaba town.
8	M	N	1.69×10^3	0.15	He evacuated by car after the hydrogen explosion on 12 March. His car ran out of fuel at Tsushima district. He hitchhiked to Kawamata town and stayed there for three days. Afterwards, he moved to Date city and then to Fukushima city.
9	M	N	1.78×10^3	0.15	He was a local government officer. He was in charge of operating a shelter starting 12 March, and was also engaged in persuading reluctant residents to evacuate during March.
10	M	Y	1.67×10^3	0.14	He continued to work at Tsushima branch office until the end of March.
11	F	Y	1.52×10^3	0.12	She spent most of her time outdoors until she reached a shelter. She was concerned that she had waited for food outdoors for about two hours on 12 March.
12	F	Y	1.33×10^3	0.11	She evacuated to Tsushima district from her house on 12 March. She moved to Kawamata town at 6:00 on 13 March and then to Koriyama city on 15 March. She stayed in Nihonmatsu city from 25 March onward.
13	M	Y	1.40×10^3	0.11	He stayed in Namie town until 17 March. He took a daily walk as usual.
14	F	Y	1.21×10^3	0.11	She worked outdoors at the playing field of Futaba high school until 20:30 on 12 March to assist with the transport of people requiring care by helicopter. Afterwards, she stayed in Kawamata town and then moved to Nasushiobara city (Tochigi Prefecture).
15	F	Y	1.23×10^3	0.10	She evacuated to a shelter. She was concerned about her evacuation to Kawamata town.

† M, Male; F, Female; * Personal behavior data

Table 1 Continued (2/2).

Rank	Gender†	Data*	^{134}Cs (Bq)	CED (mSv)	Exposure scenario obtained from an interview by the NIRS staff members at the time of the WBC measurements
16	M	Y	9.82×10^2	0.10	His nursing-care facility became a shelter on 12 March. He evacuated to Iwaki city with people requiring care for two days.
17	M	Y	1.04×10^3	0.09	He worked outdoors to assist with the transport of people requiring care on 12 March. He evacuated indoors when the hydrogen explosion occurred and then evacuated at 16:20 by bus. He underwent decontamination on 13 March. He moved to Saitama Prefecture on 19 March.
18	M	Y	1.12×10^3	0.09	He is a driver. He worked until 12 March.
19	M	N	1.02×10^3	0.09	He worked outdoors to help transport people requiring care by helicopter when the hydrogen explosion occurred on 12 March. He noticed the falling dust at that time. He stayed overnight at the gymnasium of Futaba high school and moved to Nihonmatsu city on 13 March by helicopter. He received decontamination and then evacuated to Koriyama city.
20	M	Y	9.10×10^2	0.09	He commuted to his office on foot or by bicycle from 12 to 15 March. He evacuated to Iwaki city on 15 March and then moved to Chiba city on the same day.
21	M	Y	1.04×10^3	0.09	He remained in Iitate village. He was in charge of voluntary work preparing food outdoors for several hours from 12 to 15 March.
22	M	N	8.67×10^2	0.08	He was in charge of operations outdoors on 11 March and supporting evacuees at noon on 12 March. He heard the sound of the explosion when he was working near the seashore in Tomioka town. He evacuated to Kawauchi village at 16:00 and then moved to Koriyama city on 16 March.
23	F	Y	7.42×10^2	0.07	She evacuated to Iwaki city from 20:00 on 12 March to 8:00 on 13 March. She then stayed at her house in Hirono town. She remained sheltered indoors as requested.
24	M	Y	8.34×10^2	0.07	He stayed in Tsushima district until 17 March. He stayed in Koriyama city from 17 to 20 March, then Tsushima district from 20 to 27 Match, and Aizuwakamatsu city (the central part of Fukushima Prefecture) from 27 to 30 March.
25	M	N	7.30×10^2	0.07	He stayed at his house until 19 March. He then moved to Koriyama city and stayed there for the next two weeks. In April, he returned to his house and continued his ordinary activities.
26	M	Y	7.11×10^2	0.07	He stayed at his house until 14 March. He evacuated to Fukushima city at night on 14 March. He returned to his house a few days later because of his backache. He again returned to Fukushima city as requested.
27	M	Y	8.41×10^2	0.07	He worked as usual until 14 March (mostly, outdoors) and evacuated on 15 March.
28	M	Y	7.94×10^2	0.06	He evacuated to his relative's house on 15 March. He stayed indoors until then.
29	M	N	6.61×10^2	0.06	He evacuated to Tokyo at noon on 12 March. He returned to his house once a week a few weeks later.
30	M	Y	7.52×10^2	0.06	He evacuated to Tsushima district on 12 March. He was concerned with high ambient dose levels in this area.

† M, Male; F, Female; * Personal behavior data

Table2

Table 2 Percentage of the 78 adults staying within a 20-km radius of the FDNPP.

	Number of subjects	12:00 on 12 March	16:00 on 12 March	0:00 on 13 March	0:00 on 15 March	0:00 on 20 March	0:00 on 25 March
Group 1	7	100.0%	100.0%	42.9%	42.9%	14.3%	14.3%
Group 2	15	20.0%	13.3%	6.7%	0.0%	0.0%	0.0%
Group 3	20	30.0%	20.0%	0.0%	0.0%	0.0%	0.0%
Group 4	36	27.8%	13.9%	8.3%	0.0%	0.0%	0.0%

Table3

Table 3 Percentage of the 34 children staying within a 20-km radius of the FDNPP.

	Number of subjects	12:00 on 12 March	16:00 on 12 March	0:00 on 13 March	0:00 on 15 March	0:00 on 20 March	0:00 on 25 March
Group 1	5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Group 2	7	57.1%	42.9%	0.0%	0.0%	0.0%	0.0%
Group 3	22	13.6%	4.5%	4.5%	0.0%	0.0%	0.0%

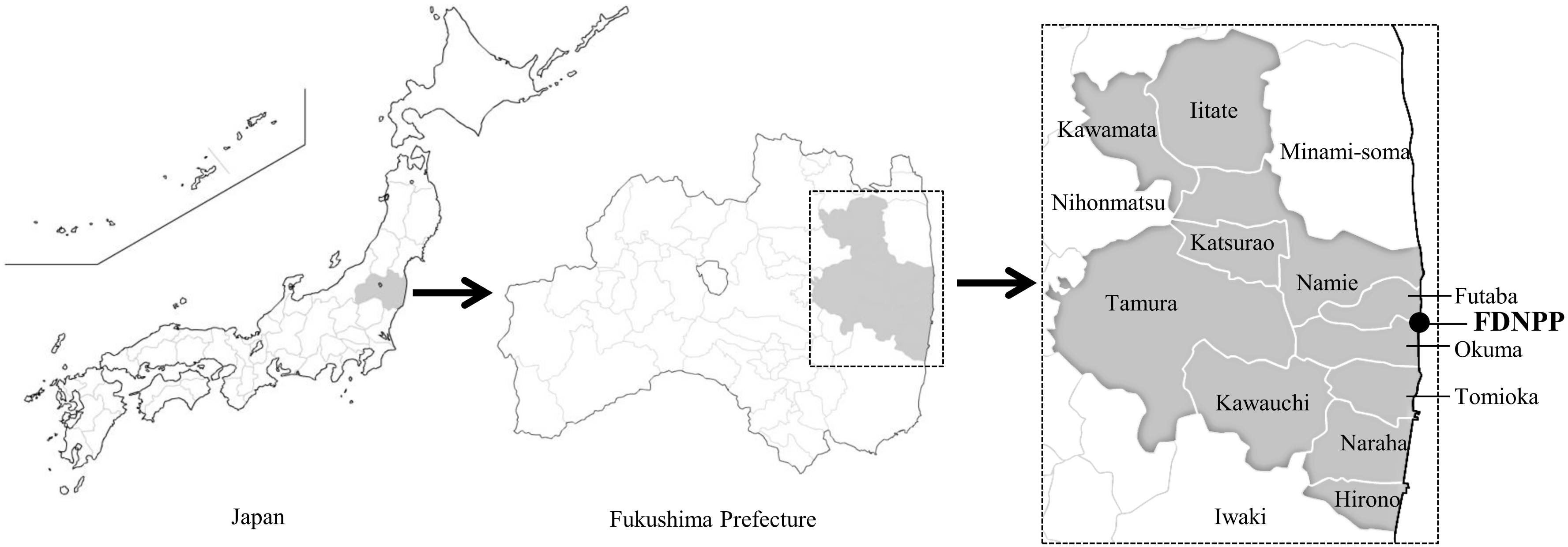

Fig. 1 Geometrical locations of Fukushima Prefecture and municipalities located near the FDNPP. The gray-colored area (the right of the figure) indicates the municipalities where the 174 subjects lived at the time of the accident.

Figure2 Fig. 2

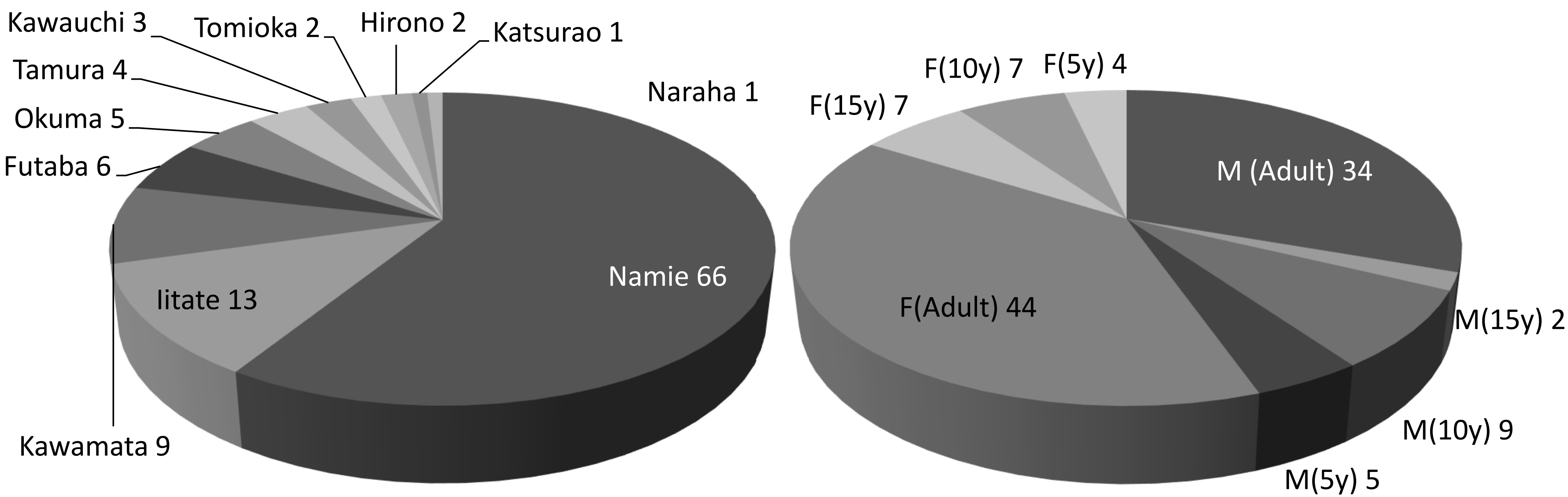

Fig. 2 Compositions of the 112 persons by the municipality (left) and gender/age group (right). The values displayed in the figure are the numbers of the persons. In the right circle, M and F denote male and female, respectively. 5y, 10y, 15y and Adult denote the age groups defined in the ICRP Publication 71.

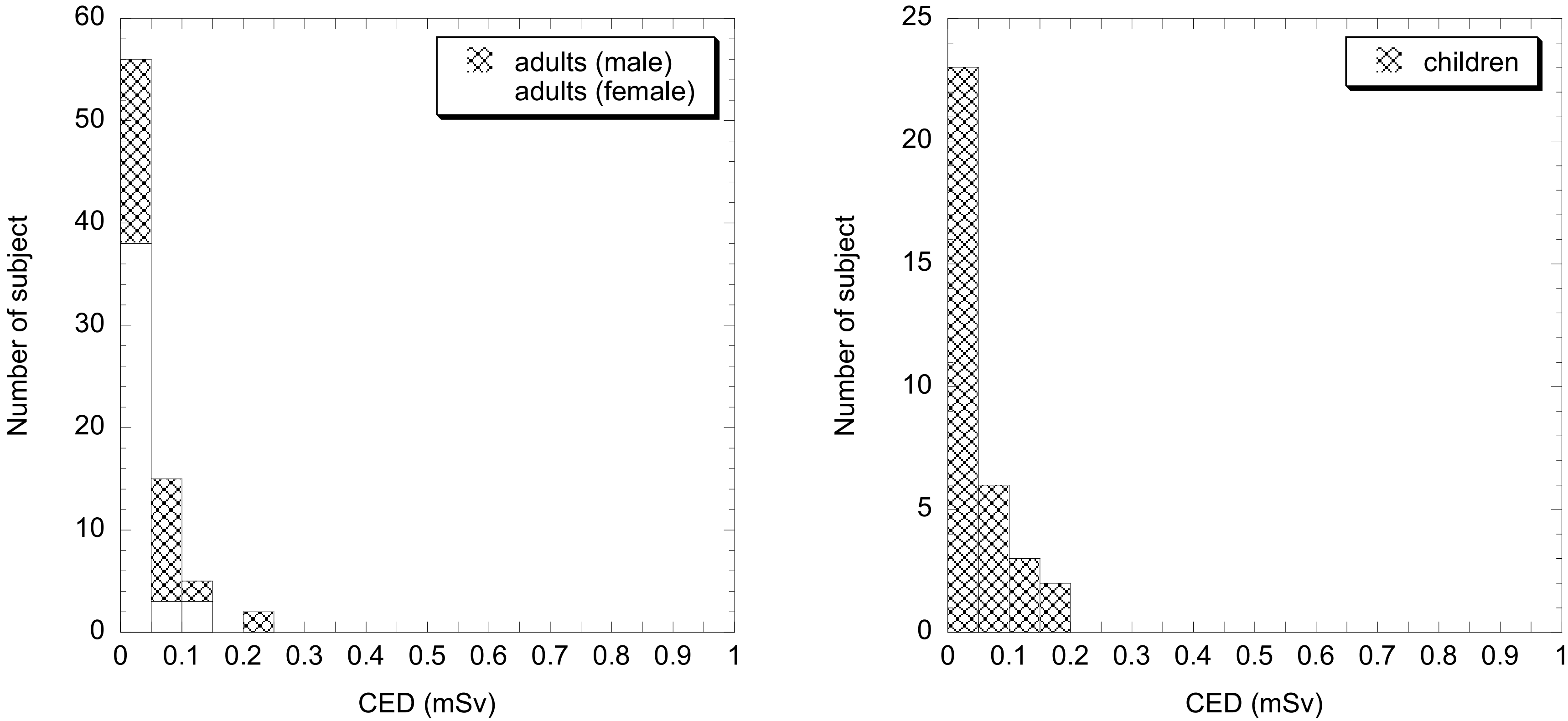

Fig. 3 CED distributions of the 78 adults (left) and the 34 children (right).

Figure4

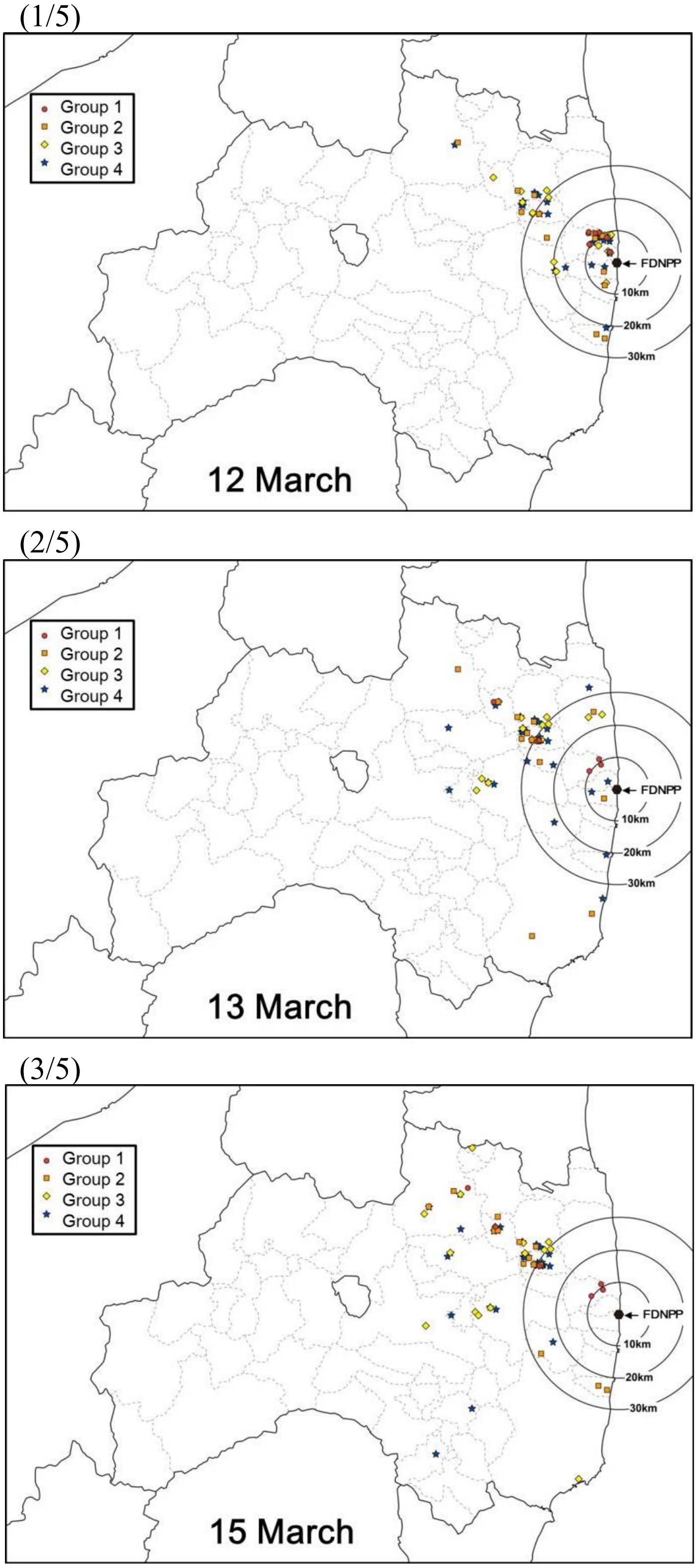

Fig. 4 Whereabouts of the 78 adults at 0:00 on 12, 13, 15, 20 and 25 March. The persons who evacuated outside Fukushima Prefecture are not displayed. The symbols denote the groups divided by the level of the CED (see the text).

Figure5

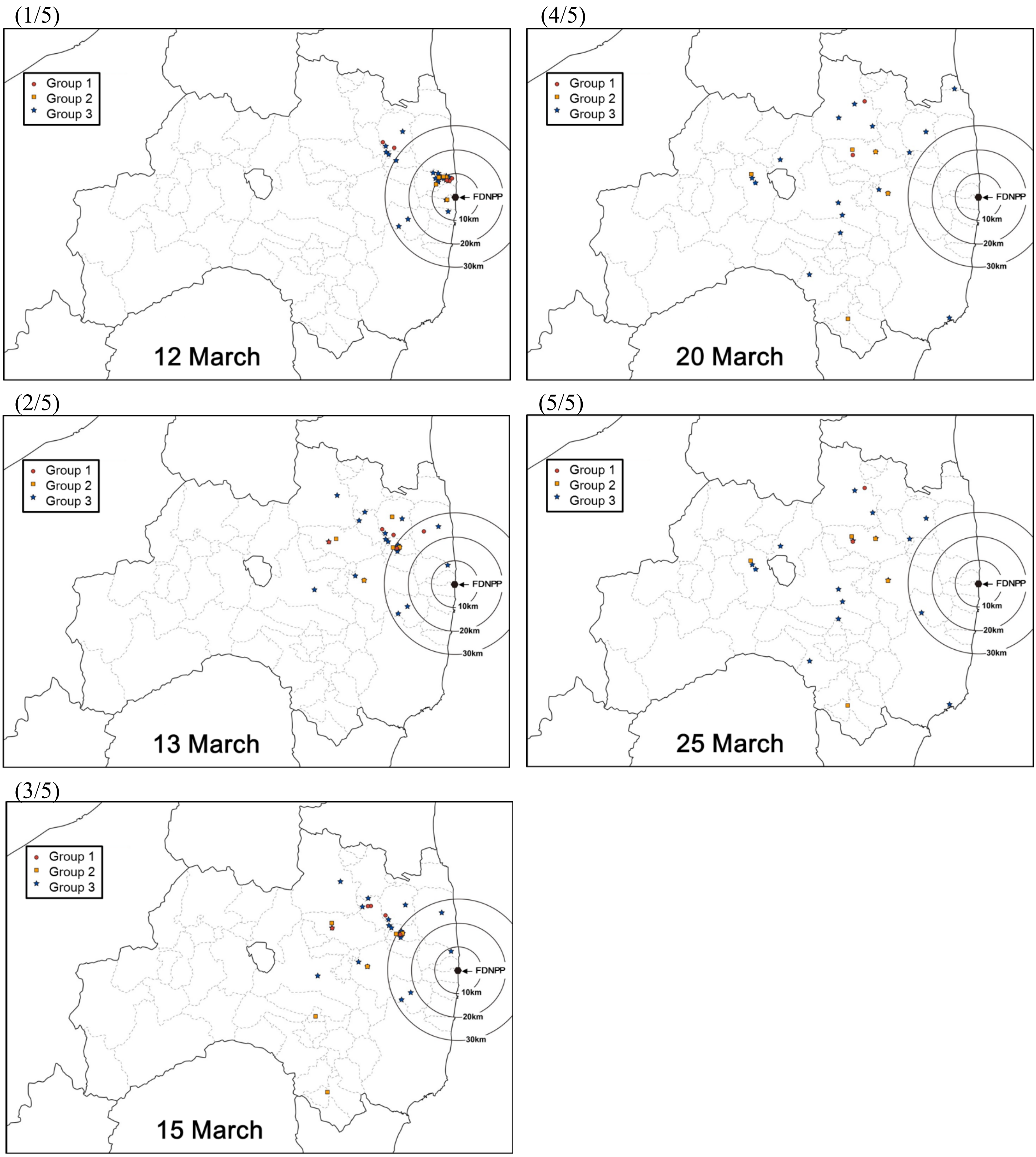

Fig. 5 Whereabouts of the 34 children at 0:00 on 12, 13, 15, 20 and 25 March. The persons who evacuated outside Fukushima Prefecture are not displayed. The symbols denote the groups divided by the level of the CEDs (see the text).

Figure6 Fig. 6

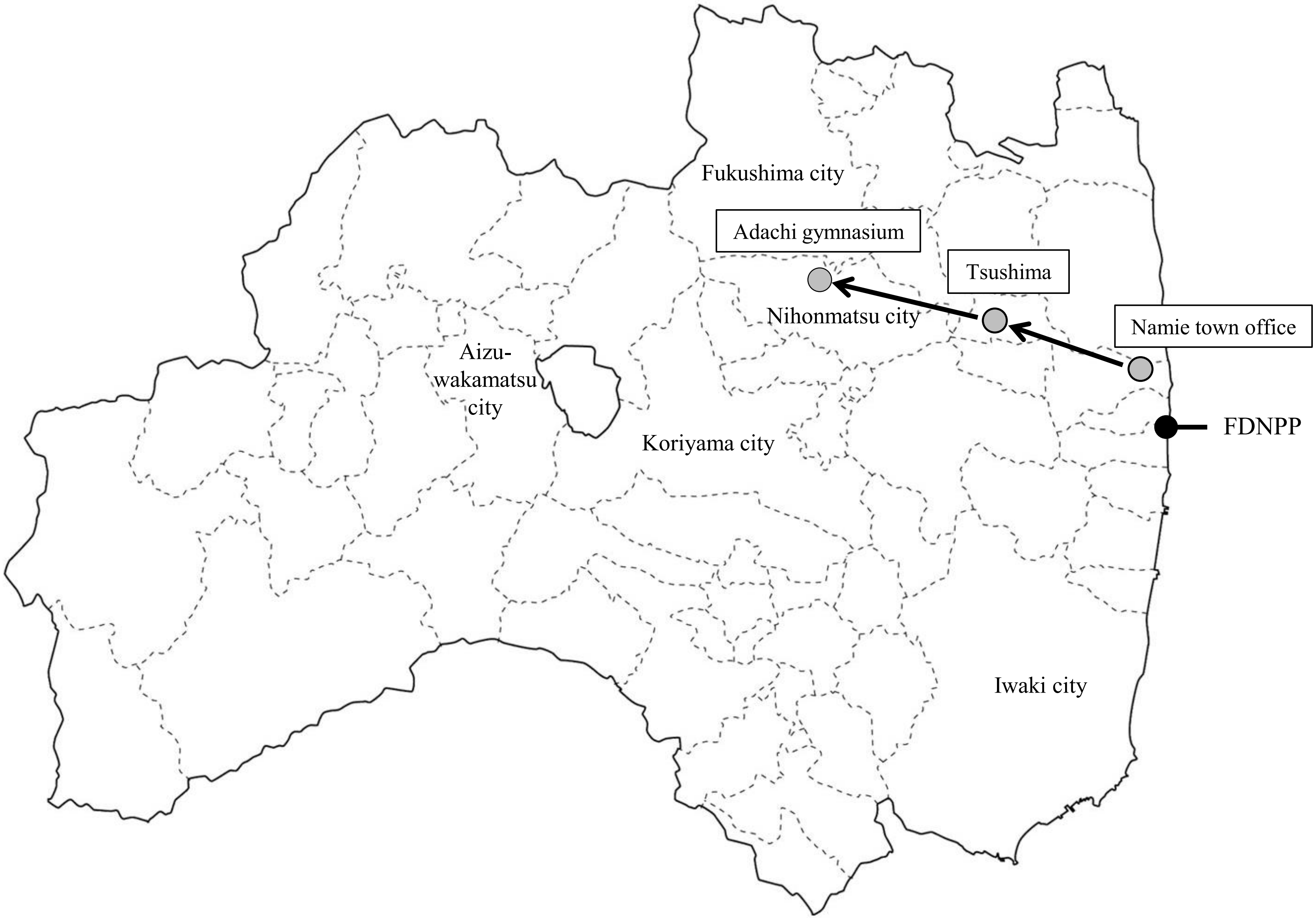

Fig. 6 Representative evacuation scenarios for residents of Namie town.

Figure7

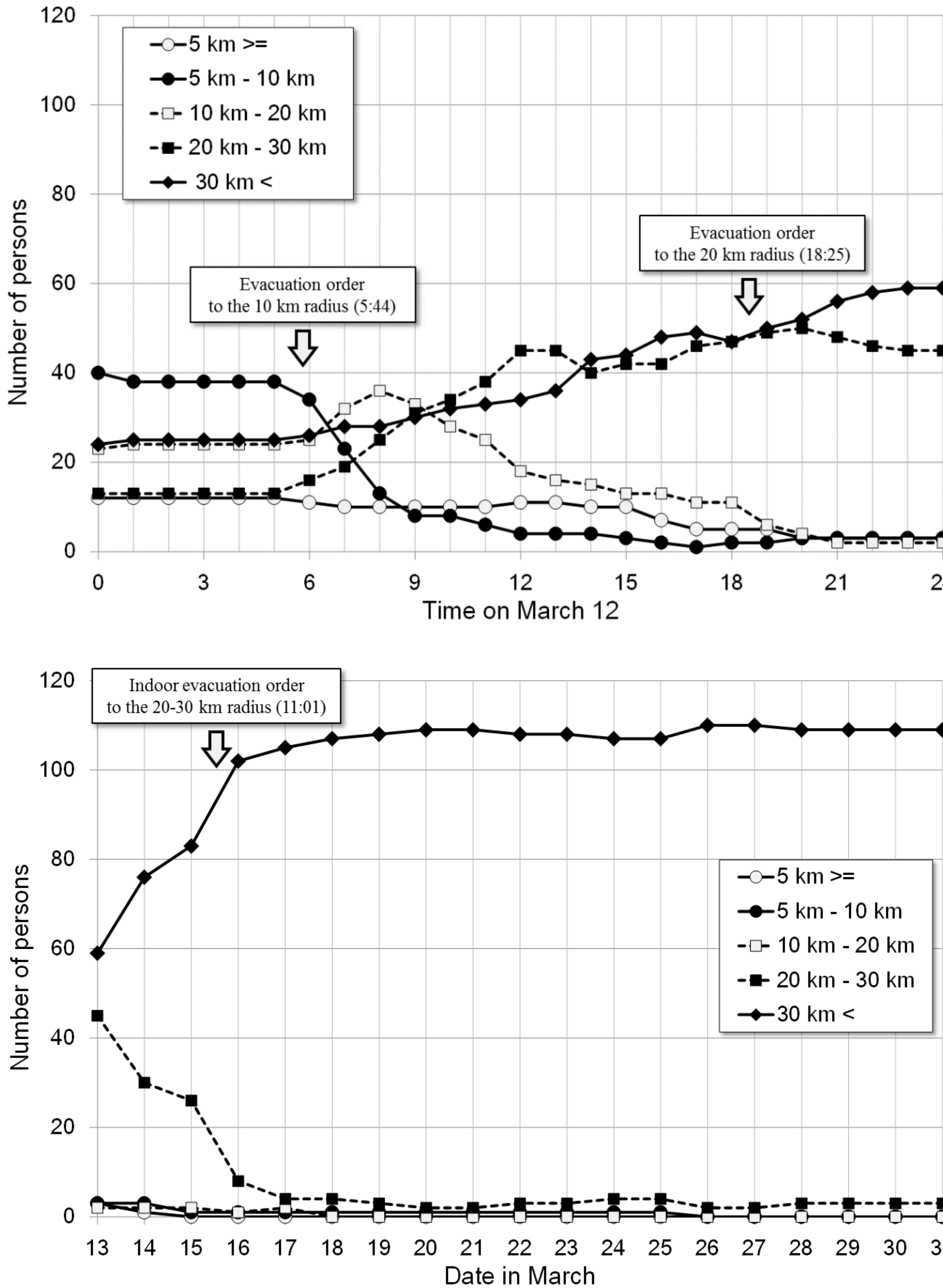

Fig. 7 Time-trend of the distances between whereabouts of the persons and the FDNPP on 12 March (hourly, the upper panel) and 13-31 March (daily, the lower panel)

Figure8

Fig. 8

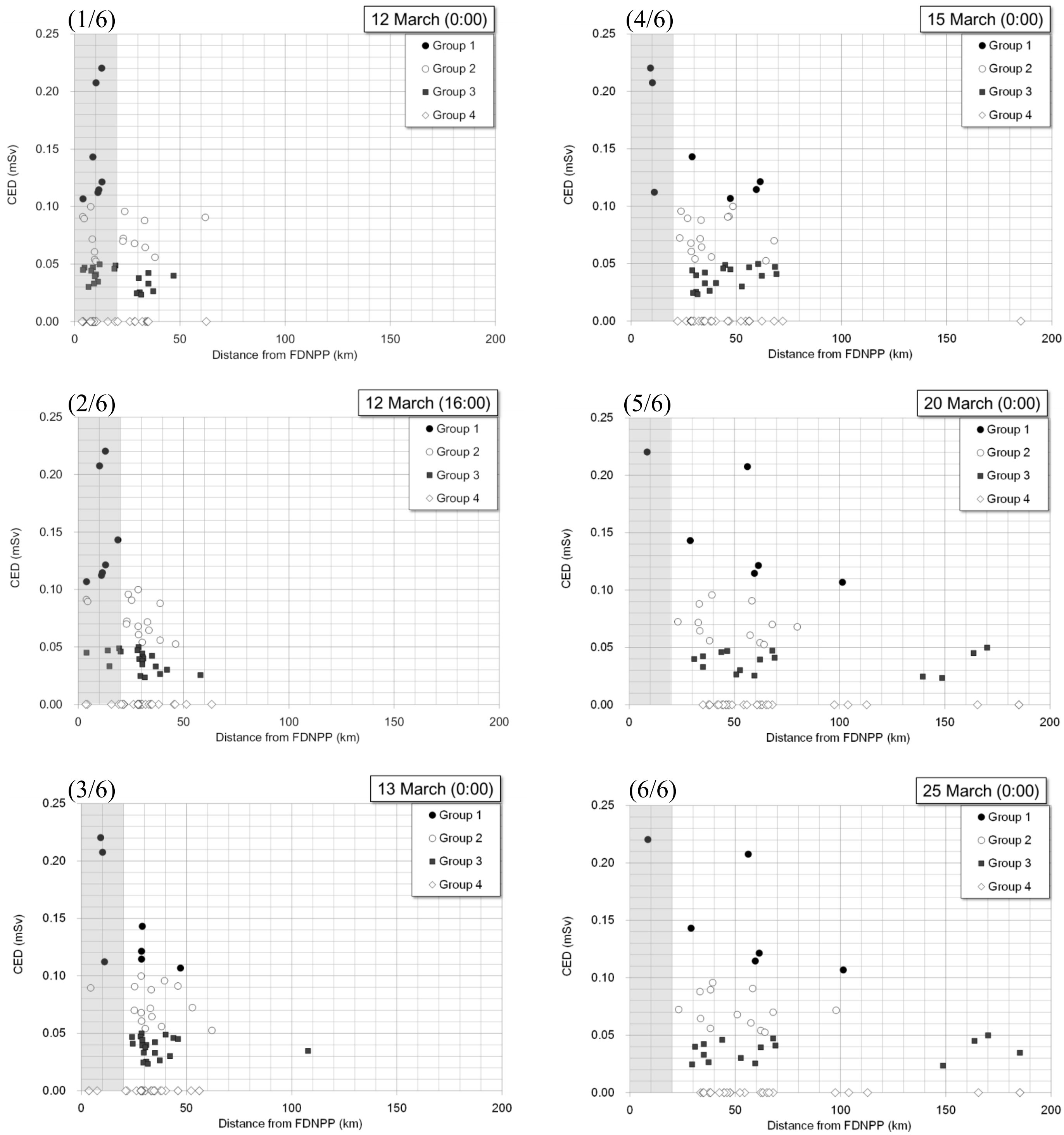

Fig. 8 Relationship between the distances of the 78 adults from the FDNPP and their CEDs for each time and date displayed.

Figure9

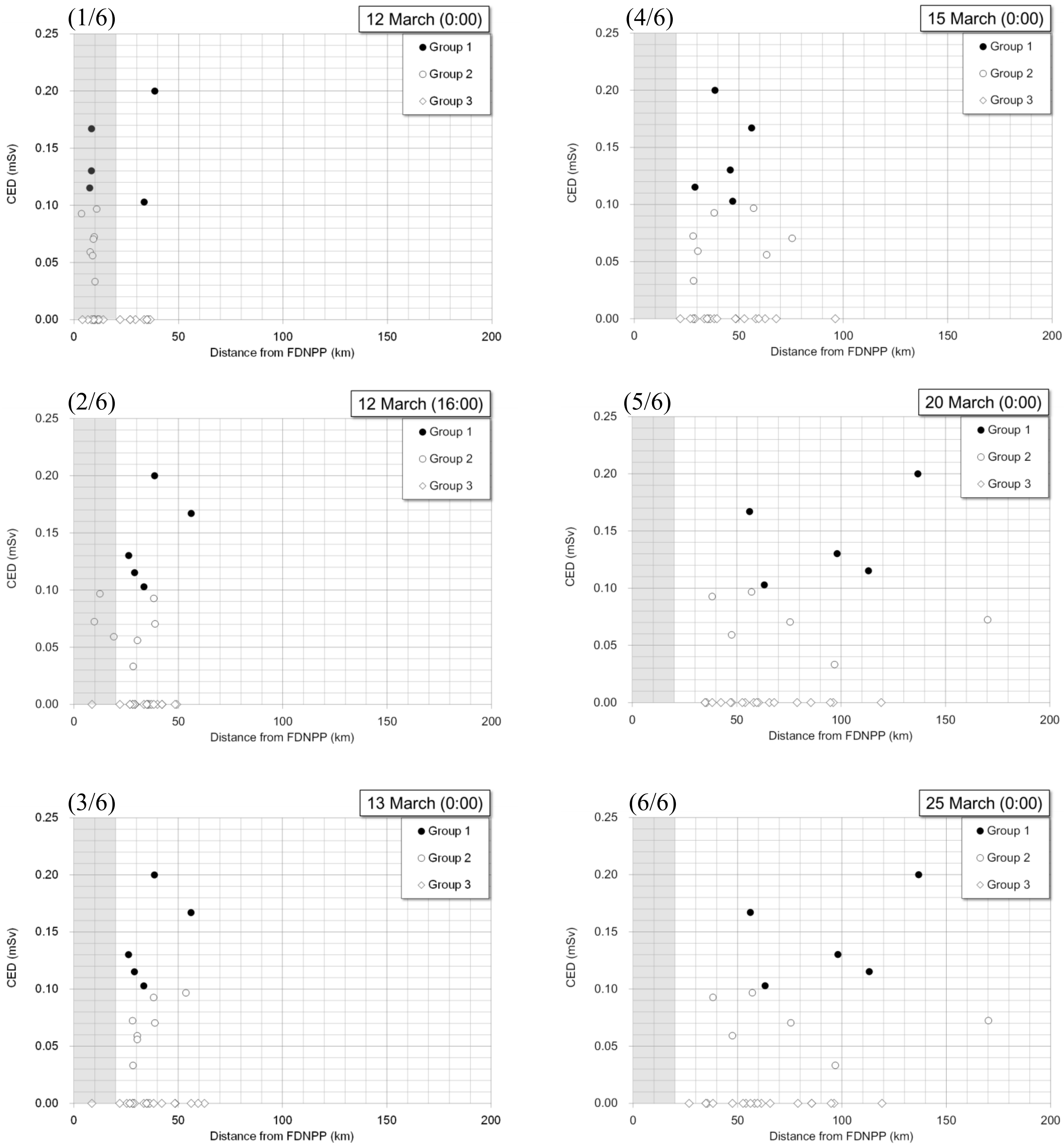

Fig. 9 Relationship between the distances of the 34 children from the FDNPP and their CEDs on each time and date displayed.

Figure 10

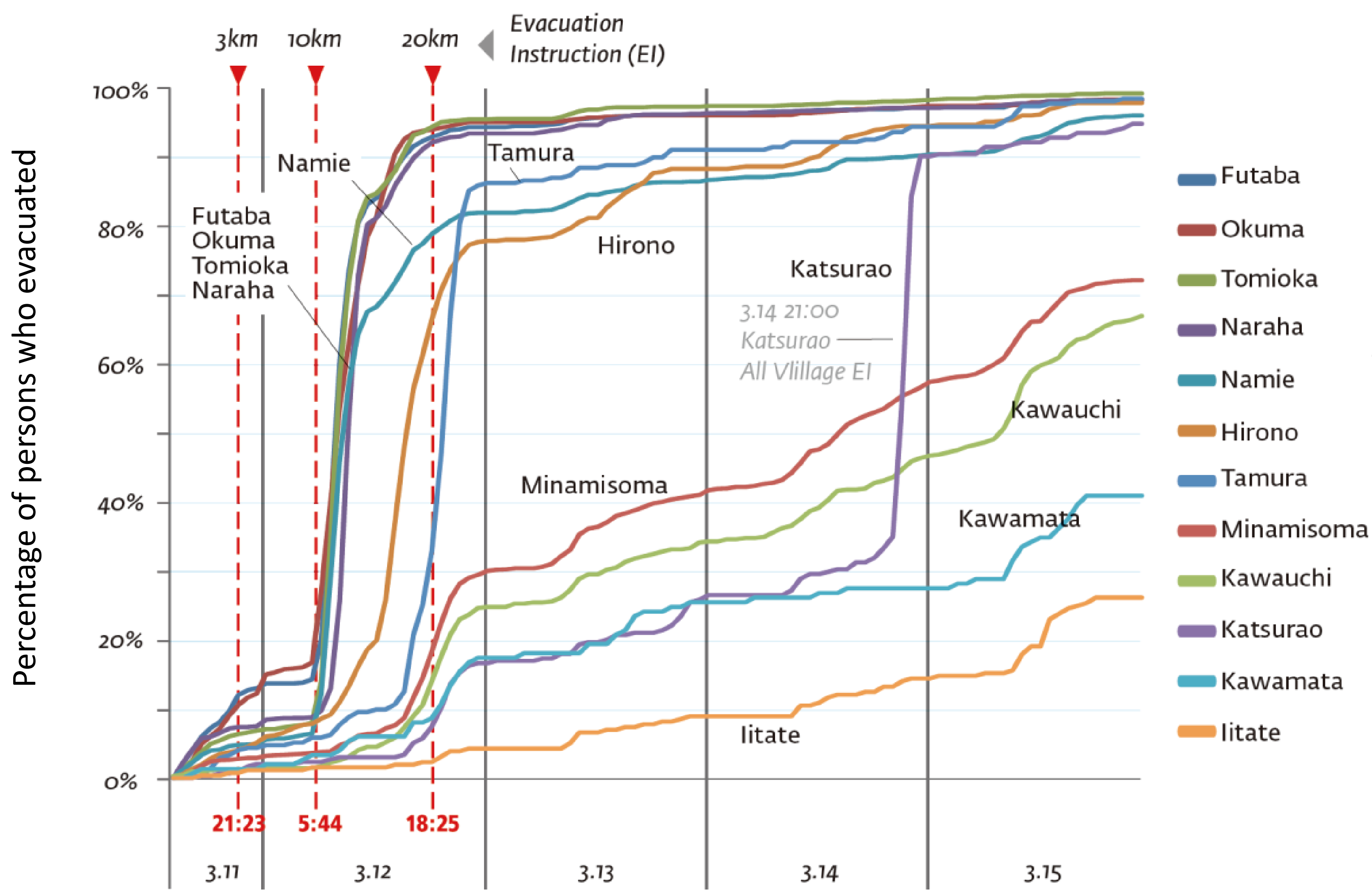

Fig. 10 Time trend of percentages of those who evacuated from each municipality. The original figure is slightly modified.

Figure 11

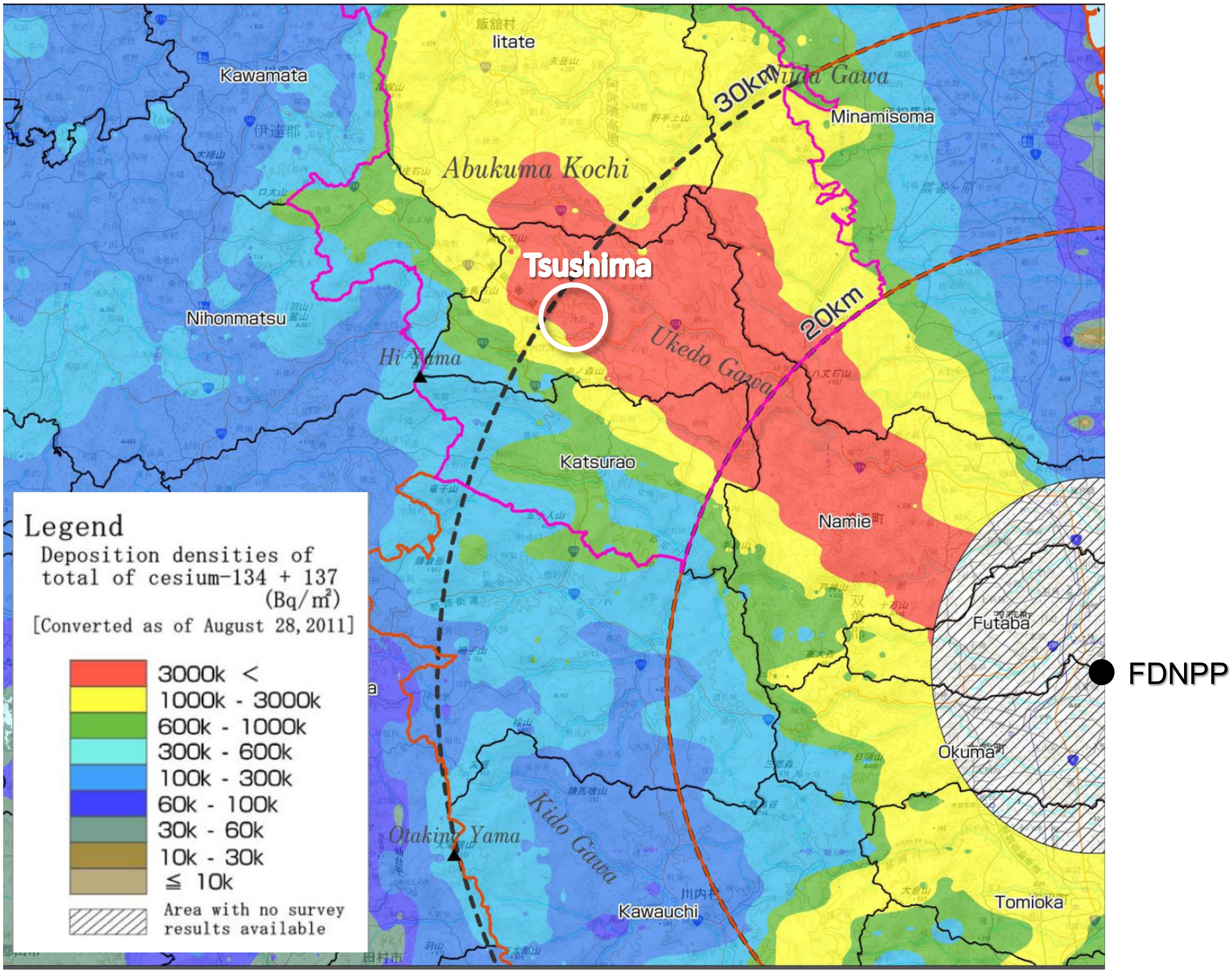

Fig. 11 Deposition density map of the total of ^{134}Cs and ^{137}Cs by airborne monitoring (corrected as of 28 August, 2011).