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Topics: Lessons learned on public health from the Fukushima Daiichi Nuclear Power Plant accident

＜ Review ＞

External and internal dose assessments of Fukushima residents after the 2011 nuclear disaster

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Abstract

Much effort has been made by Japanese experts to assess the dose to residents of Fukushima Prefecture in the aftermath of the 2011 nuclear disaster. Residents living near the Fukushima Daiichi Nuclear Power Plant (FDNPP) were ordered to evacuate promptly after the accident to minimize radiation exposure. Many papers performing individual dose measurement and estimation of these residents have already been published. This paper provides a brief overview of these publications by dividing the evaluation into the early-phase (< 1 year) and the late-phase (≥ 1 year) studies, and compiling the lessons learnt from the 2011 nuclear disaster. One common view of the studies by the Japanese experts is that the levels of exposure are generally low. Aside from the internal thyroid dose from short-lived radionuclides (mainly ^{131}I) at the early phase, both the external and internal doses attributable to the nuclear disaster are comparable or less than those from natural radiations. A number of individual dose measurements at the late phase have provided useful information for understanding exposure situations in everyday life for people living in the affected area. One key remaining issue for the dose assessment is to evaluate the related uncertainty, in particular for the internal thyroid dose received at the early phase. Thus, there is a role for further studies to improve the certainty of dose estimations.

keywords: Fukushima Daiichi Nuclear Power Plant, dose assessment, external dose, internal dose, nuclear accident, residents

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I. Introduction

More than 7 years have passed since the natural disaster affecting the Fukushima Daiichi Nuclear Power Plant (FDNPP) run by Tokyo Electric Power Company (TEPCO) in March, 2011. The resulting accident caused contamination by radionuclides across a wide area of East Japan [1]. A large number of residents living in the municipalities near the FDNPP were ordered to evacuate promptly after the accident in order to prevent radiation exposure [2]. The total amounts of iodine-131 (^{131}I) and cesium-137 (^{137}Cs) released to the atmosphere from March 12 to May 1, 2011 were estimated to be 151 PBq and 14.5 PBq, respectively [3], which roughly correspond to one-tenth and one-fifth of the amounts in the Chernobyl accident [4]. Much effort has been made to understand the extent of radiation exposure of residents in Fukushima Prefecture. One common view of the various publications by Japanese experts is that both the external and internal doses of the residents due to the accident were generally low. Therefore, the future radiation-induced health risks are expected to be undetectable. However, there still remain problems in the dose assessment, such as the related uncertainty, in particular for the early internal dose of ^{131}I, and particularly the thyroid exposure experienced by small children. This paper provides a brief overview of the major

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dose assessment results of the residents by dividing into studies into early- (< 1 year after the accident) and late- (≥ 1 year) phase studies, and identifies important lessons learnt from the experiences in the FDNPP accident.

II. External dose assessment

1. Early phase

The residents living in the municipalities near the FDNPP were ordered to evacuate their hometowns shortly after the accident from their hometown [2]. Some residents were forced to evacuate many times because of repeated expansion of the restricted zone by the Japanese Government repeatedly. The first exploratory committee of Fukushima Health Management Survey (FHMS) was held at the end of May, 2011 and an external dose assessment for all residents in Fukushima Prefecture (~2 millions) was proposed as a part of FHMS (Basic Survey) [5]. Fukushima Prefecture commissioned Fukushima Medical University (FMU) as the organization responsible for the FHMS. For this survey, it was decided that an external dose assessment be performed based on the personal behavioral data (i.e., the whereabouts of the person after the accident) derived from self-administrative questionnaires. To facilitate this, the National Institute of Radiological Sciences (NIRS, currently, reorganized as one of the directorates of National Institutes for Quantum and Radiological Science and Technology, QST) developed an external dose estimation system and computed external doses of hypothetical persons with 18 evacuation scenarios to grasp the levels of external doses to real persons in advance of the data-gathering [6]. This system utilized both digitized personal behavioral data and the chronological data of ambient dose rate maps in Fukushima Prefecture. The latter dataset was created based on a simulation by the System for Prediction of Environmental Emergency Dose Information (SPEEDI) for the period from March 12 to 14 and the measurement data by Ministry of Education, Culture, Sports, Science and Technology (MEXT) for the period from March 15 and later. The system considered a structural shielding factor (= indoor/outdoor ambient dose rate) depending on the type of building, and a body size correction factor with age. Note that the system calculated the effective dose from external irradiation for the first four months only after the accident. As a result, the maximum dose was 19 mSv for the delayed evacuation scenario from one place in Iitate village which the Japanese Government designated as the deliberate evacuation area for relocation in April 2011. The doses for the prompt evacuation scenarios from the 20 km radius of the FDNPP were relatively low.

Using this system, the external dose estimation of the residents has been continued to the present. The number of the residents whose external doses were estimated reached 552,298 as of 30 June 2017. As the intermediate result, it was reported that the individual external doses for the first 4 months were below 3 mSv for 99.4% of 421,394 residents (excluding radiation workers). The arithmetic mean and maximum of the doses of the residents from the Soso region covering the municipalities within the restricted zone (within the 20 km radius of the FDNPP) were 0.8 mSv and 25 mSv, respectively [7]. Regarding the mean dose, the doses of the Kenpoku and Kenchuo regions where no evacuation orders were issued were higher than that for the Soso region. This suggested that the prompt evacuation may have significantly reduced exposure doses of the residents living near the FDNPP.

Several municipalities in Fukushima Prefecture initiated external dose measurements of the residents using passive-type personal dosimeters [8]. According to the results of Fukushima city, the individual external dose from September 1 to November 30, 2011 (3 month) was less than 1 for 99.7% of the 36,767 examined subjects including infants, elementary and junior school students and pregnant women. The first-year average dose estimates of Fukushima city, Date city, Ninonmatsu city, Tamura city and Koriyama city were 2.1 mSv, 1.9-3.3 mSv, 2.4-2.5 mSv, 1.2-1.4 mSv and 1.7 mSv, respectively, by adding the results of the Basic Survey [9]. These estimates are smaller than those from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2013 report [10].

2. Late phase

In April 2012, the Japanese Government reorganized the contaminated areas in the eastern part of Fukushima Prefecture in accordance with the levels of the projected annual external dose (excluding the dose from natural radiation) [11]. The newly designated areas were categorized into the followings: (1) difficult-to-return areas (> 50 mSv), (2) restricted habitation areas (20-50 mSv) and (3) evacuation-directive-lift prepared areas (< 20 mSv). The projected annual external dose was calculated from the airborne survey in conjunction with a simple assumption, namely 16 h for the time spent indoors and 8 h for the time spent outdoors. A structural shielding factor (0.4) was applied to the time spent indoors. For example, the projected annual external dose of 20 mSv corresponds to the ambient dose rate outdoors of 3.8 μSv h^{-1} excluding the contribution from natural radiation.

However, a considerable discrepancy is often found between the projected dose and the individual dose directly measured with personal dosimeters (PDs). To clarify this gap, many studies have been performed by recruiting volunteers who wore PDs and recorded their time spent at each place in daily life [12-17]. As a result, it was found that the main cause for the discrepancy lay in the fact that the time spent outdoors was much shorter than 8 h for most of the volunteers. The measured individual dose was often smaller by several times the projected dose. Other studies focused on the structural shielding factor of inhabitant places [18] and the time variation of the dose rate in daily life using electric PDs (e.g., D-shuttle) [12,13]. The estimated annual external doses in the late phase were generally lower than 1 m Sv y^{-1} in the non-evacuation areas [19,20] and were lower than the projected annual external dose in the other areas [21,22].

III. Internal dose assessment

1. Early phase

Regarding internal exposure, the most concerning radionuclide in the early phase is ^{131}I with a physical half-life of about 8 days. Based on Chernobyl studies, radioiodine contributes a significantly higher dose to the thyroid than to the whole-body (effective dose) due to its biokinetic behavior, which is of great concern in particular for small children [23]. The Japanese Government regulated the distribution and consumption of food and drink that exceeded provisional regulation values for the radioactivity concentration shortly after the accident [24]. In addition, a collapse in the food supply chain due to damage to distribution facilities, lack of transportation vehicles or electricity, and the closure of retail stores should have significantly reduced consumption of contaminated foodstuff by people even before the implementation of restriction orders [25]. However, there were still possible pathways for internal exposure, such as inhalation of radioactive plumes and ingestion of water very early after the accident, which have not been fully investigated.

The Nuclear Emergency Response Local Headquarters of the Japanese Government conducted screening campaigns for thyroid exposure of children (aged ≤ 15 y) at Kawamata town, Iwaki city and Iitate village at the end of March, 2011 [26]. The subjects totaled 1,080. The results showed that no subjects exceeded the screening level corresponding to 100 mSv for hypothetical 1-y-old children with chronic intake via inhalation of ^{131}I from March 12 to 23 (12 days). Revised dose estimations of the screening campaigns have been published, demonstrating that the 90th percentile values of the thyroid equivalent dose for Kawamata town, Iwaki city and Iitate village were 7.3, 15.9 and 14.7 mSv, respectively [27]. Regarding the other direct human measurements to identify ^{131}I, Tokonami S, et al. have reported the results of their measurements of residents and evacuees from Namie town and Minamisoma city during the period from April 12 to 16 [28]. Significant ^{131}I radioactivity in the thyroid was found in 46 out of 62 subjects and the maximum thyroid doses of children and adults were 23 mSv and 33 mSv, respectively. Matsuda N, et al. have also reported their results from evacuees and responders who visited to Fukushima Prefecture for a short period of time [29]. The number of the subjects totaled 173. The measurements were performed within one month after the accident using a whole-body counter (WBC). ^{131}I, cesium-134 (^{134}Cs) and ^{137}Cs were significantly detected from more than 30% of the examined subjects. The maximum thyroid equivalent dose was 20 mSv. Meanwhile, Kamada N, et al. estimated thyroid doses of 15 residents of Kawamata town and Iitate village based on the urine samples taken on May 5 and from May 29 to June 6, 2011 [30]. In 5 of the 15 subjects tested, ^{131}I was detected in the urine samples; the thyroid equivalent doses were 27–66 mSv.

Afterwards, Fukushima Prefecture decided to perform further individual monitoring using WBC units to respond to a growing concern about internal exposure among the residents. This task was initially commissioned to NIRS and Japan Atomic Energy Agency (JAEA) at the beginning. NIRS performed WBC measurements of 174 subjects mainly from Namie town, Kawamata town and Iitate village during the period from June 27 and July 28, 2011 [31]. At this time, only ^{134}Cs and ^{137}Cs were the only targeted radionuclides because ^{131}I had completely decayed out by this time. As a result, the number of the subjects with significant detection of both ^{134}Cs and ^{137}Cs were relatively small: 28.8% for adults and 4.1% for children. The 90th percentile and maximum committed effective dose (CED) for the adults from ^{134}Cs and ^{137}Cs were 0.1 mSv and 0.63 mSv, respectively. JAEA reported the results of the first-year WBC measurements of the 9,927 residents from the areas where evacuation orders were issued [32]. The major findings are as follows: (1) 22 subjects (including 21 children aged ≤ 12 y) exceeded 1 mSv (the maximum CED: 3 mSv); (2) the (extrapolated) median CED values of the two age groups of 13–17 y and > 17 y were 0.02 mSv and 0.025 mSv, respectively; (3) the 95th percentile CED value of all the subjects was ~0.1 mSv; (4) the CEDs of the children (< 8 y) from whom Cs was significantly detected were much higher than those of their parents or elderly family members. Note that a common intake scenario, namely acute inhalation on March 12, 2011, was applied to the WBC measurements by the two institutes. This might lead to an overestimations of the internal dose of residents because of possible incidents of intake at a later time period than the assumed intake day.

WBC measurements were also started by several hospitals where WBCs were independently installed at an early phase. Tsubokura M, et al. measured 9,498 residents (1,432 children and 8,066 adults) of Minamisoma city for the period between September 26, 2011 and March 31, 2012 [33]. A detectable amount of Cs was found in 3,268 of the subjects (235 children and 3501 adults), with only one person exceeding a dose of 1 mSv (1.07 mSv). Hayano RS, et al. also reported the results of the WBC measurements of 32,811 subjects at Hirata Central Hospital for the period from October 17, 2011 to November 30, 2012 [34]. The Cs detection rate was lower in children than in adults, and decreased with time. High Cs body contents were detected in a small part of the subjects who evidently consumed contaminated foodstuff, such as wild mushroom. The maximum CED was found to be 1.06 mSv.

Other than the direct human measurements, the monitoring results of radioactivity in food and water were used to estimate the ingestion dose [35-38]. It was pointed out that the ingestion dose evaluated by World Health Organization (WHO) and UNSCEAR was overestimated because of conservative assumptions, such as continuing consumption of contaminated items for a certain period of time [10,39]. By contrast, Murakami and Oki took into account the effect of countermeasures implemented after the accident in their estimation of the ingestion doses of citizens of Fukushima city, Tokyo and Osaka [40]. The average thyroid equivalent doses of citizens (adults) of Fukushima city, Tokyo and Osaka from ^{131}I were 2.7 mSv (Case 2), 0.37 mSv, 0.016 mSv, respectively. The average effective doses from ^{134}Cs and ^{137}Cs of the same groups from were 0.12 mSv (Case 2), 6.1 μSv, 1.9 μSv, respectively. Several studies by Japanese experts also conducted food-duplicate surveys at an early phase, demonstrating that the ingestion dose from ^{134}Cs and ^{137}Cs was much lower than 1 mSv per year [41,42]. As the most recent publication related to ingestion from tap water, Kawai M, et al. reported the estimated ingestion dose from ^{131}I at the early phase with a consideration of realistic intake scenarios based on their survey [43]. The maximum thyroid equivalent doses of 1-year-olds, 10-year-olds and adults of the evacuation areas were estimated as 22, 11 and 4.7 mSv, respectively. Those of the same groups from the non-evacuation areas were 9.5, 4.7 and 2.0 mSv, respectively. Another recent publication by Ohba T, et al. focused on the body surface contamination levels of evacuees from the areas near the FDNPP, demonstrating a difference in the levels depending on the route of evacuation [44]. This study also evaluated the contribution of the short-lived radionuclides other than ^{131}I (^{132}Te/^{132}I, ^{133}I and ^{135}I). These radionuclides may give a significant internal dose if the intake event is limited to March 12, 2011 [45].

2. Late phase

The number of WBCs available for measurements of the residents has increased in the past years. More than 50 WBCs (including mobile units) currently exist in Fukushima Prefecture [46]. Fukushima Prefecture has continued the WBC measurements of the residents (including voluntary evacuees to places outside Fukushima), and the number of the subjects has reached 327,434 as of October, 2017 [47]. The number of persons whose CED is greater than or equal to 1 mSv is 26, which has increases by only 4 persons compared to the results in 2012 (see above). This result suggests that a risk of internal exposure has been very limited in the late phase. Several other studies have also demonstrated an extremely low detection rate in the other WBC measurements thanks to detailed and comprehensive food inspections [48-50]. Meanwhile, it has been found that there are a small proportion of persons with significantly high body contents of radiocesium [51]. This was identified as being caused by ingestion of non-inspection food items and tends to be seen in elderly persons [52].

IV. Discussion

The main objective of the dose assessment in radiation accidents is to provide information for evaluating the degree of radiation-induced health risk and/or judging the necessity of radiation protection measures. It is also recognized through the experiences of the FDNPP that the information from the dose assessment should be used not only for decisions by authorities or experts, but also for support of the residents through the related communications. The importance of paying attention to social, ethical, and physiological issues is emphasized in the recent EU recommendations for preparedness and heath surveillance of the populations affected by a radiation accident [53]. However, the discussion here is mainly focused on technical issues in the external and internal dose assessments of the residents.

1. External dose assessment

The internal dose estimation performed as a part of FHMS has been completed for about one-quarter of the target subjects (∼ 2 million residents in Fukushima Prefecture). The number of answerers for the questionnaires about personal evacuation behaviors has almost reached a plateau. An additional survey has confirmed that the external doses of the one-quarter subjects are representative of those of the entirety of the target subjects [54]. Further studies would be thus desired on the tendency of the dose distributions for each representative evacuation group that is extracted from actual personal behaviors data and the uncertainty in the current dose estimation, and so on.

One important issue in the late phase was the earlier mentioned discrepancy between the projected dose and the individual external dose directly measured with PDs. The Japanese Government stressed the importance of continuous monitoring for individual doses as accurately as possible and stated that the decision to return home should be made on the measured individual external doses (e.g., reading of the PDs) rather than the estimations based on the ambient dose rate [11]. In this context, NIRS and JAEA investigated the relationship between the two doses at several places in Fukushima Prefecture [55,56]. As a result, it was found that the readings of the PDs worn by adult males of average body size were about 0.7 times as large as the ambient dose at the same places and that the two doses were well proportional to each other [57]. The ratio is somewhat increased for subjects with small body sizes (e.g., children) because of the lesser shielding effect by the body against radiation coming from the back. Although this finding often gave the impression that the PDs underestimated individual external doses, Monte Carlo simulations suggested that the readings of the PDs would offer a good approximation of the effective dose of the subject under an environment where radiocesium is widely distributed in the ground [58,59]. This is important knowledge for ensuring the validity of the current individual external dose measurements in the affected areas.

Recent individual external dose measurements have been performed by utilizing the latest technologies (e.g, the combination of a D-shuttle and a GPS system) [12,13,60]. These devices provide an individual information on when and where he or she faces the most exposure to radiations in daily life. Such information would be useful for considering a method to reduce exposure effectively or as one of the risk communication tools to understand radiation sources encountered in everyday life together with explanations by experts. The importance of this kind of support to the affected population is also emphasized in the recommendations [53].

2. Internal dose assessment

The most important issue in the internal dose assessment is the difficulty in estimating the early internal doses of the residents from short-lived radionuclides mainly ^{131}I. This is because of the lack of direct human measurement data related to ^{131}I, which totals only ~1,300 data. Most of these data were obtained from a screening campaign based on a simplified measurement technique [26]. The number of the subsequent WBC measurements was relatively large; however, these measurements could not detect ^{131}I. Thus, various methods have been proposed for estimating the early internal dose, in particular, the thyroid dose due to the potential intake of ^{131}I and other short-lived radionuclides [27]. According to the dose estimations published up to the present, the upper levels of the CEDs from ^{134}Cs and ^{137}Cs and the thyroid equivalent doses from ^{131}I are ~0.1 mSv and 20~30 mSv for the residents of Fukushima Prefecture, respectively. The estimation of the thyroid equivalent doses needs to be further improved, taking into account the intervention dose level to reduce the stochastic effect on the thyroid, 50 mSv [61]. The representativeness of those subjects who underwent the screening campaign among the populations in the areas of concern should also be examined.

One method of evaluating the thyroid equivalent doses from the WBC measurements targeting radiocesium is to determine the intake ratio of ^{131}I to ^{137}Cs (or ^{134}Cs). Several studies have derived this intake ratio from the direct human measurements at the early phase [62-64]. The values of these studies were largely different from each other and tended to be smaller than the activity ratios of the two radionuclides in environmental samples. These results seem to be natural because of differences in the conditions of each study and the relatively low thyroid iodine uptake (TIU) factor in the Japanese compared to that in the biokinetic model for iodine [62,63]. However, this crucial factor used for the dose reconstruction should be further evaluated.

It is also important to recognize the uncertainty in the internal dose estimation. The intake amount can be calculated based on a combination of parameters, including breathing volume and amount of food and water intake paired with time-series of the radioactivity in drinking water, foodstuff and air. However, precise values of these parameters are often difficult to obtain in the case of emergency situations as a nuclear accident. Food and water intake can be significantly different from that in normal situations. Thus, detailed interviews of personal behaviors for the persons of concern are necessary. The time of evacuation and the occupation of the individual are also important [65].

However, the uncertainty should be taken into account even in the internal dose estimation from the direct human measurements. The assumptions made in the intake scenario (the time of intake and the route of intake) greatly influence the internal dose estimate. In the WBC measurements by Fukushima Prefecture, two common intake scenarios have been used: an acute intake scenario by inhalation on March 12, 2011 (for subjects measured between June 27, 2011 and January 31, 2012) and a chronic intake scenario by ingestion from March 12, 2011 to one day before the measurement day (for subjects measured from February 1, 2012 to the present) [32]. The acute intake scenario was used to avoid underestimation of the internal dose; however, it was found that this scenario could not be accurately applied to younger age groups as the measurements came too late. This was because of the rapid decrease of whole-body retention rates of radiocesium (^{134}Cs, ^{137}Cs) for these groups over time. As a result, the small amount of the body content occasionally detected was converted to an extremely large amount of intake. Momose reported a large discrepancy in the CEDs between the children with detection of radiocesium in their WBC measurements and their parents; the CEDs of the children were considerably higher than those of the parents [32]. However, this is unlikely to occur in real situations because the intake amount should be larger in the adults than in the children, whereas the internal dose coefficients (dose per unit intake: Sv Bq^{-1}) of the adults and the children are similar to each other. The detection in the WBC measurements may be partly related to slight contamination on the subject's clothes brought back from houses in the affected areas during temporal visits. To avoid the false-positive detection, the subjects were asked to change into contamination-free gowns before their WBC measurements. From the viewpoint of the dose reconstruction, it is important to clarify how long the evidence of the early intake remains in the WBC measurements.

At the late phase, the number of WBCs available has been increasing. To the present, more than 50 WBCs exist in Fukushima Prefecture alone [46]. A periodical check on the accuracy of these WBCs has been performed by NIRS, demonstrating that the WBC measurements in Fukushima Prefecture are of sufficient quality [66]. As described earlier, the WBC measurements at the late phase have suggested that the levels of internal exposure are minimal. However, the experts have stressed that it is of great importance to continue the WBC measurements of the residents in Fukushima Prefecture.

V. Conclusion and Perspective

Much effort has been made to obtain external and internal dose assessments of residents of Fukushima Prefecture. One common view of the related publications by Japanese experts is that the exposure dose related to the 2011 nuclear disaster in Fukushima is minimal. It is thus expected that radiation-induced health effects would be undetectable. This should be largely attributed to prompt radiation protection measures for the residents. A number of individual dose measurements at the late phase provide not only information on the levels of exposure received in everyday life, but also data useful for understanding the radiation. One remaining issue in the dose assessment is to evaluate the related uncertainty, in particular for the early internal dose, mainly from ^{131}I. Additionally, it is necessary to use the lessons learnt from the 2011 nuclear disaster to establish a feasible and effective population monitoring procedure in case of a future nuclear accident.

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Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this article.

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2011 原子力災害後における福島住民の外部及び内部被ばく線量評価

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抄録

2011年３月11日に発生した東京電力福島第一発電所事故（福島原発事故）から既に７年間が経過し，これまでの間，主として福島県住民を対象とした個人線量測定及び評価が数多く行われてきた．言うまでもなく，住民に対する個人線量評価は，今後の放射線被ばくに起因する健康影響の評価を行う上で重要である．本稿では，これまでに報告された関連する日本人研究者による主要論文の概観を行うともに，福島原発事故に係る個人線量測定及び評価に係る経験や課題について記述した．福島県住民が同事故によって受けた全身の被ばく線量の推計値は総じて低く，自然放射線から受ける年間の被ばく線量と同等またはそれ以下とする論文が大半であった．現存被ばく状況下にある近年のきめ細かい個人線量測定は，追加被ばく線量を低減するための方策を検討する上で有用であり，また，放射線リテラシーの醸成に貢献している．個人線量評価における残された大きな課題としては，特に事故初期の被ばく線量の不確かさの評価であり，さらなる研究が望まれる．

キーワード：福島第一原発，線量評価，外部被ばく，内部被ばく，原発事故，住民