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AN OVERVIEW OF INTERNAL DOSE ESTIMATION USING WHOLE-BODY COUNTERS IN FUKUSHIMA PREFECTURE

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Abstract : A large amount of radioactive cesium was released by the Fukushima Daiichi Nuclear Power Plant accident following the Great East Japan Earthquake. Due to the increasing concerns about internal exposure, more than 50 whole-body counters (WBCs) have been installed at various locations in Fukushima Prefecture. A study on around 10,000 subjects in the early stage after the accident revealed that very few received a committed effective dose of more than 0.3 mSv for subjects (age >13 years old). Another study on WBC results for one hospital showed that the ratio of cesium-positive was 1.0% among all the subjects. Assuming a constant daily intake, the detection limit of 300 Bq/body for a typical WBC corresponds to an effective dose of 21 μ Sv/y even for a subject of age up to 10. It was also seen out that the subjects with a significant amount of body cesium are likely to regularly eat wild products, which they harvested or caught themselves without testing for radioactive cesium. These study findings suggested that the internal exposure for most of the residents was controlled at a very low level. Future tasks regarding WBC measurements are how to personally explain the WBC results to each subject and how to disclose the statistically processed WBC data to the general public.

Key words : Great East Japan Earthquake, Fukushima Daiichi Nuclear Power Plant accident, whole-body counter, internal dose, radioactive cesium

INTRODUCTION

A large amount of radioactive cesium (^{134}Cs and ^{137}Cs) was released by the Fukushima Daiichi Nuclear Power Plant (NPP) accident that followed the Great East Japan Earthquake. Radioactive cesium was widely dispersed and deposited onto the ground¹⁾. Post-Chernobyl accident studies showed that the level of internal radiation exposure of residents from ingestion of contaminated foodstuffs was nearly proportional to the deposition density, as summarized in the UNSCEAR 1988 report on the exposures from the Chernobyl accident²⁾. Hayano *et al.*³⁾ estimated that, if this also applies to the Fukushima Daiichi case, the committed effective dose (CED, the time integral (50 y for adults and 70 y for children) of effective dose rate following an intake of radioactive

materials) would be about 2 mSv for adults living in the region where the ^{137}Cs deposition density is around 100 kBq/m² (typical of Fukushima City).

Due to the concerns about internal exposure, more than 50 whole-body counters (WBCs) have been installed at various locations in Fukushima Prefecture after the accident to estimate internal exposure for residents⁴⁾. Some of the WBC results have been reported from operating organizations or researchers. According to the results reported from Fukushima Prefecture authorities⁵⁾, the internal exposure for 156,858 subjects (as of the end of September, 2013) was much smaller than expected from the surface soil contamination. For most of the subjects (156,832), the internal exposures were estimated to be less than 1 mSv.

This paper reports the current status of WBCs

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operated in Fukushima Prefecture and discusses two published papers on WBC results. In relation to these, general procedures for internal dose estimation and future tasks are discussed.

GENERAL PROCEDURES FOR INTERNAL DOSE ESTIMATION

The general procedure for internal dose estimation can be divided into two steps: estimating total intake from monitoring data and multiplying the respective dose coefficient (CED per unit intake) by the total intake. The dose coefficients for each radionuclide are given in the ICRP Publication^{6,7)}. There are three methods to estimate the total intake: (1) direct measurement of the body, (2) measurement of bioassay samples, and (3) measurement of radionuclide concentration in food or drinking water (in the case of ingestion). The direct measurement of the body usually refers to whole-body counting, but it also includes external counting of a part of the body such as thyroid counting.

The measurement of bioassay samples (blood, urine, etc.) can be applied to the alpha or beta emitting radionuclides as well as gamma (x) emitting radionuclides, although whole-body counting can be applied only for gamma (or x) emitting radionuclides. This is because WBCs detect radiation penetrating from the inside of the body to the outside. A disadvantage of the bioassay method is that samples should be chemically processed in some cases to make them suitable for measurement. Such preparation generally includes complex procedures and takes much time. The third method may have the largest uncertainty, mainly due to the difficulty of continuous monitoring of radionuclides contained in the total diet or drinking water on a personal basis.

Since ^{134}Cs and ^{137}Cs emit gamma rays, whole-body counting is the most suitable method for estimating the total intake. The estimation of total intake from whole-body counting is affected by an intake scenario (when the intake occurs or occurred) assumed for dose estimation. That is, whole-body counting gives an amount of radionuclide(s) present in the body at the time of measurement. The total intake should be estimated by extrapolating from the amount of cesium in the body at the time of measurement to that at the time of intake(s), considering excretion of cesium from the body. The excretion (biological) half-life highly depends on age. For example, it is around 100 days for adults, but 13 days for 1 year old infants⁷⁾. First, either a single or

multiple intakes should be assumed on the basis of circumstances such as dietary habit, behavior of the person, etc. Then, time of the intake(s) should also be assumed from circumstances. In the case of the Fukushima NPP accident, a single (acute) intake just after the accident or chronic (daily) intake since the accident are common scenarios.

Even if the total body content of cesium is accurately measured, the estimation of total intake has uncertainty depending on these assumptions. Once the assumptions for intake(s) are fixed, however, it is relatively easy to estimate internal exposure due to radioactive cesium by using the software program Mondal-3, which was developed by the National Institute of Radiological Sciences⁸⁾. It includes a data library for fractions of inhaled or ingested radioactivity retained in the whole body or a specific organ or excreted daily into urine or feces and a user interface program for data input/output and dose calculation.

AN OVERVIEW OF WHOLE-BODY COUNTING IN FUKUSHIMA PREFECTURE

The number of WBCs in Fukushima Prefecture has been drastically increased after the Fukushima NPP accident from three to more than 50⁴⁾. Fukushima Prefecture authorities installed eight WBCs and some local governments or hospitals independently acquired their own WBCs.

As mentioned before, an intake scenario should be assumed to estimate CED from monitoring data. According to the website of the Fukushima Prefecture authorities⁹⁾, the scenario was changed from acute intake on March 12, 2011 to chronic intake from March 12, 2011 to the day of the WBC measurement. The former scenario had been used until January 31, 2012 and the latter has been used after that. Other organizations operating WBCs seem to follow the same scenarios.

The WBC data from each organization in Fukushima Prefecture are not collected into a common database. Each organization seems to report the WBC results to each subject. In some cases the results are statistically analyzed and reported on the organization's website. In the case of Fukushima Prefecture authorities, the distribution of CED is reported on their website. As of the end of September 2013, a total of 156,858 subjects had been measured from June 2011. For these subjects, the dose distribution is not given for units smaller than 1 mSv: 156,832, less than 1 mSv; 1 to 2 mSv, 14; 2 to 3 mSv, 10; and more than 3 mSv, 2. A more de-

tailed distribution of dose such as 0.1 mSv steps is not disclosed on the website. Subjects with cesium-negative are also categorized as “less than 1 mSv”.

Other local governments tend to report their WBC results in a similar style of dose distribution. At present, almost no one has cesium body content corresponding to more than 1 mSv per year. According to the calculation by Mondal-3, the annual dose of 1 mSv for an adult corresponds to 30,000 Bq of cesium of total body (a chronic intake scenario), or chronic daily intake of 210 Bq.

On the other hand, Soma City and Hirata Central Hospital authorities report more detailed information such as cesium content per body weight. Tsubokura *et al.*¹⁰⁾ also reported more detailed information for Minami-Soma City residents. Iwaki City reports the number ratio of subjects with cesium-negative to all the subjects¹¹⁾. The ratio was 98.0% for the data in 2011 and 2012¹²⁾ and it was 99.5% in the first half of 2013.

WBC RESULTS OBTAINED USING THE ACUTE INTAKE SCENARIO

The WBC measurements of residents of Fukushima Prefecture started on June 27, 2011 as a pilot

study as measurements of 122 subjects at the National Institute of Radiological Sciences. After that, Japan Atomic Energy Agency (JAEA) measured a large number of subjects with two WBCs.

Momose *et al.*¹³⁾ reported internal doses due to radioactive cesium for a total of 9,927 subjects measured by JAEA from July 11, 2011 to January 31, 2012. For 80% of the subjects, radioactive cesium was not detected. For the subjects with cesium-positive, radionuclides other than radioactive cesium were not detected.

Fig. 1 shows the amount of radioactive cesium detected for each age group. The maximum amount for the age group of less than 8 years old was 2,700 Bq and that for the age group of more than 18 was 14,000 Bq. The activity ratio of ^{137}Cs to ^{134}Cs was 1.12 to 1.26, which agreed well with the ratio (1.1 to 1.3) calculated theoretically according to their physical decay.

Fig. 2 shows distribution of CED for the subjects with cesium-positive for four age groups. The acute intake scenario was assumed for these subjects. For lower age groups, the percent of persons with a higher dose seems to be increased. For the age group of more than 13, however, the CEDs for most of the subjects were less than 0.3 mSv. According to a procedure used by JAEA, if a significant

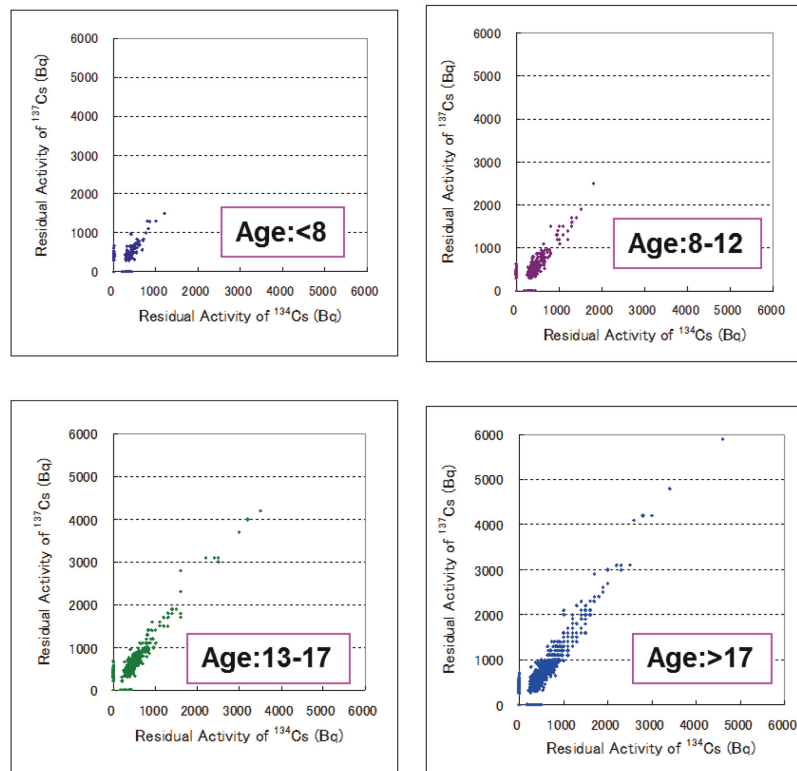


Fig.1. Distribution of radioactive cesium for subjects with cesium-positive (reproduced from Ref 13).

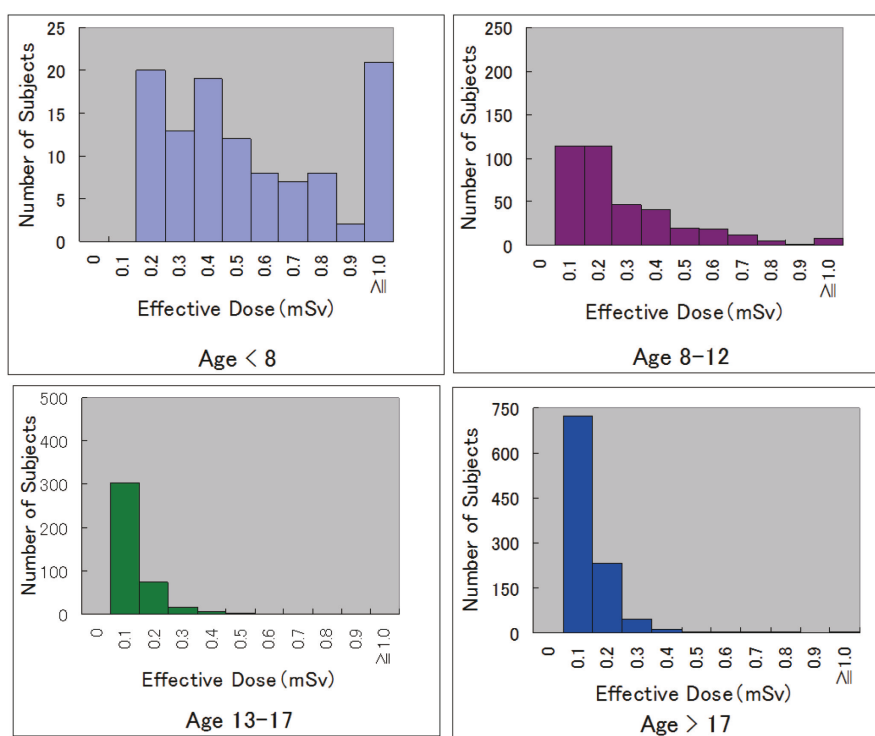


Fig. 2. Distribution of CEDs for subjects with cesium-positive. CEDs were calculated assuming the acute intake scenario (reproduced from Ref 13).

body content (exceeding the detection limit) is observed for a child of less than 8 years old, an additional whole-body counting was performed on the child's parents or other adult family members who were evacuated in the same manner as the child to allow a better assessment of the child's result. As a result, those parents and children showed a big difference in body content of cesium.

Two possible reasons were considered: effects of surface contamination and difference in the intake scenario. For the former reason, some of the subjects with a remarkable amount of cesium were measured again after changing their clothes. The amount of cesium measured was considerably decreased or not detected after changing their clothes. Later, JAEA decided to ask subjects to change clothes for measurements (after January 2012).

For the latter reason, the assumption of a single uptake on March 12, 2011 was not always valid for children, who have a shorter cesium retention half-time than that of adults. Application of the acute intake scenario to the measured body content gave a higher CED than that of chronic intake scenario. From these two reasons, although the subjects whose dose was estimated to be more than 1 mSv were almost all children, their actual doses were highly likely to have been smaller than the estimated CEDs.

JAEA also checked the amount of body ^{40}K , which is necessarily present in the human body, mainly to check calibration of the WBCs. For most of the subjects, measured ^{40}K was similar to reference values suggested in the UNSCEAR report, although there were some subjects for which body ^{40}K was not detected.

WBC RESULTS OBTAINED USING CHRONIC INTAKE SCENARIO

The Hirata Central Hospital located 45 km southwest of Fukushima Daiichi NPP acquired a FASTSCAN (Canberra Inc.) WBC in October 2011 and started measurements of residents. The detection limits for the FASTSCAN were 300 Bq per body for both cesium (^{134}Cs and ^{137}Cs). Hayano *et al.*³⁾ reported the WBC results for 32,811 subjects measured from October 2011 to November 2012.

The percentage of cesium-positive subjects to all the subjects was 12.1% for measurements before February 2012. However, the subjects did not change their clothes for these measurements. The policy was changed from March 2012 and all the subjects were asked to change their clothes. The ratio after that was 1.0%. Even in the case of cesium-positive, the amount was almost less than 10 Bq per body weight. In particular, the ratio for children

(less than 15) was zero.

However, total body cesium of more than 4,000 Bq was observed for four subjects. It was found that they regularly ate items for which contamination advisories have been issued such as wild mushrooms, wild boar, fresh-water fish, etc., which they harvested or caught themselves, or received from neighbors, but which were not tested for radioactive cesium. These subjects were advised again to avoid consuming such foodstuffs, whereupon their body burdens decreased at rates consistent with the biological half-life of cesium.

Hayano *et al.*³⁾ mentioned a sampling-bias-free dataset among the WBC results. The dataset was for school children of Miharu Town. The first screening for the children was conducted between November 24, 2011 and February 29, 2012, and included 1,494 children among 1,585 children enrolled in the study; the second was conducted between September 3, 2012 and November 8, 2012, and included 1,383 children. Coverages were 94.3% and 95.0%, respectively. The results of the second screening showed that in the fall of 2012, none of the 1,383 children had a detectable level of radioactive cesium. In view of the high coverage of 95%, it was safe to conclude that the low level of internal exposure in Miharu Town was not due to sampling bias.

The first screening, in the winter of 2011-2012, found that 54 of the 1,494 children were cesium-positive. As discussed above, some of the detections in the first measurements may have been caused by surface contamination (clothing).

DISCUSSION AND FUTURE TASKS

As mentioned above, the internal exposures for residents in Fukushima Prefecture were much smaller than expected from the surface soil contamination.

Momose *et al.*¹³⁾ found that very few subjects received a CED of more than 0.3 mSv for subjects of the age groups of more than 13, even if the conservative scenario (acute intake just after the accident) was assumed. Hayano *et al.*³⁾ reported that the percentage of cesium-positive was 1.0%. Assuming a constant daily intake and the detection limit of 300 Bq/body for typical WBCs used in Fukushima Prefecture, Hayano *et al.* calculated the daily intake of ¹³⁷Cs was 2.4 Bq/day. This suggested that recently daily intake of cesium for most people did not exceed 2 Bq/day. They also pointed out that the subjects with a significant amount of body cesium were

likely to regularly eat wild products, which they harvested or caught themselves without testing for radioactive cesium. In other words, the amount of cesium for residents who ate commercially available food was too small to detect with the WBCs used in Fukushima Prefecture.

A study on daily intake of radioactive cesium by the food-duplicate method also showed a low level of daily intake¹⁴⁾. In this study, radioactive cesium was detected in 25 of 26 samples from Fukushima in December 2011. The median dietary intake of radioactive cesium was 4.0 Bq/day (range <0.26-17 Bq/day). The median of estimated annual effective dose from radioactive cesium calculated assuming that the daily intake was constant throughout the year was 23 μ Sv/year (range <2.6-99 μ Sv/year), which was much lower than 1 mSv.

Another study¹⁵⁾ by the food-duplicate method was conducted from November 2011 to March 2012 and from June 2012 to September 2012; each period covered 100 families throughout Fukushima Prefecture. Among the 200 meals thus analyzed, 12 were found to have ¹³⁴Cs and/or ¹³⁷Cs concentrations exceeding 1 Bq/kg. Even with the largest radioactive cesium value in this survey, daily consumption of such meals throughout a year gave an annual effective dose that did not exceed 0.1 mSv.

However, there still remain two issues related to WBCs. The first one is how to explain the findings to the subject. The results (body content of radioactive cesium and CED) are usually sent to each subject by mail without any detailed explanation. Most of the public do not have an opportunity to ask someone about their WBC results. In this respect, face-to-face communication is desirable.

The second one is that only the one-digit CED such as less than 1 mSv is open to the public; more detailed values are not disclosed. Each person is supposed to receive his or her own WBC result, but it is not possible to locate its value in the total distribution of cesium body content or CED. The detection limit of 300 Bq/body for typical WBCs corresponds to annual effective doses of 21 μ Sv/y (age up to 10) and 13 μ Sv/y (age up to 15), as Hayano *et al.*³⁾ calculated. Also, the category of "less than 1 mSv" includes subjects with cesium-negative. Disclosing the detailed distribution of CED could be helpful for the general public to understand the current status of internal exposure in Fukushima Prefecture. Also, gathering data from WBCs operated in Fukushima Prefecture and analyzing the cesium-positive ratio and the distribution of CED values in more detail may be important for deciding the policy

of operation of WBCs in the future.

By solving these two issues, residents in Fukushima Prefecture will be able to understand that for most, their internal exposure is low enough and that the internal exposure is controllable by avoiding some wild products with high cesium concentrations.

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