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Review

A Brief Review of Dose Estimation Studies Conducted after the Fukushima Daiichi Nuclear Power Plant Accident

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Since the Fukushima Daiichi Nuclear Power Plant accident began, many papers on dose estimation have been published. Generally, dose estimation needs dosimetric parameters and assumptions on personal behavior such as style of intake (in the case of internal exposure) and daily time budget (external exposure). Differences in these parameters as well as dose estimation methods result in different dose values, which sometimes leads to misunderstanding and confusion for the general public. This paper reviews articles which mention internal and external doses to residents due to the accident, together with available information on dose estimation methods and assumptions used in those studies. The reviewed articles are categorized according to their topics: (1) internal dose to thyroid, (2) internal dose to the whole-body (effective dose), and (3) external dose. In addition, dose due to natural and medical radiation is discussed.

Key words: dose estimation, Fukushima, gamma ray dose rate, thyroid, whole-body counting

1. Introduction

Since the Fukushima Daiichi Nuclear Power Plant accident began, many papers have been published related to measurement of environmental radioactivity or radiation and dose estimation. As described in typical technical documents[1-4], dose estimation needs dosimetric parameters and assumptions as well as monitoring data. For example, the general procedure for internal dose estimation can be divided into two steps: estimating total intake from monitoring data and multiplying a dose coefficient (committed effective dose per unit intake)[5-7] by the total intake. There are three methods to estimate the total intake: direct measurement of the body, measurement of bioassay samples, and measurement of radionuclide concentration in air (in the case of inhalation).

The third method may have the largest uncertainty, mainly due to the difficulty of personal monitoring of breathed air. Thus, radionuclide concentration at a nearby outdoor monitoring site is usually used instead of the concentration in inhaled air, although the assumption is unrealistic that people stay outdoors all day long. Due to this assumption, dose is probably overestimated.

A report by the WHO states that in the two most affected locations, Namie and Iitate, of Fukushima Prefecture, the preliminary estimated radiation effective doses for the first year ranged from 12 to 25 mSv[8]. These estimated doses were based on “conservative”

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assumptions. For example, it was assumed that people consumed only food produced in the area where monitoring was implemented. Moreover, it was assumed that relocation in the "deliberate evacuation area" took place at 4 months, although the inhabitants of this area were subjected to relocation at different times earlier than this. The WHO report clearly recognized that the doses were possibly overestimated due to these assumptions.

Thus, the dose estimation methods, dosimetric parameters and assumptions should be considered for comparisons and discussions on the estimated doses. In this respect, this paper reviews articles which mention internal and external doses to residents and workers due to the accident, together with available information on the assumptions and dosimetric parameters used in those studies.

2. Doses due to the Fukushima accident

2.1 Internal dose to thyroid

After the accident, relatively large numbers of direct measurements of thyroid activity for residents (thyroid screening) were done using survey meters without energy discrimination of gamma rays. Hosokawa *et al.*[9] reported that it was conceivable for thyroid equivalent doses not to have reached 50 mSv. Kim *et al.*[10] reported that among 1,080 children, there were no subjects (for the age group of 1-y-old as of March 24) who exceeded the screening level (0.2 μSv h^{-1}) corresponding to a thyroid equivalent dose of 100 mSv. Kim et al also reported that no significant signals were detected in 55.4% of these children and the maximum dose was 43 mSv. Although the method used for thyroid screening is convenient, Hosokawa *et al.*[9] pointed out that the main problem in thyroid screening is the unknown effects of other radioactive materials.

On the other hand, only limited numbers of measurements by a spectroscopic method were done. Since spectrometers can distinguish gamma rays from cesium (^{134}Cs and ^{137}Cs) and ^{131}I, the accuracy of activity estimation for gamma ray spectroscopic method might be higher than that for the screening method. Tokonami *et al.*[11] estimated thyroid doses from ^{131}I activity measured using a NaI(Tl) spectrometer and found that the highest equivalent dose was 33 mSv among 62 persons from under 1 to 83 years old. Matsuda *et al.*[12] measured internal exposure for 173 evacuees and short-term visitors to Fukushima Prefecture. They used a whole-body counter with two NaI(Tl) detectors to measure ^{131}I activity and estimated that the maximum thyroid equivalent dose was 20 mSv.

The dose from the short-lived radionuclide ^{132}I (half-life: 2.3 h) may affect thyroid dose estimation. Balonov *et al.*[13] pointed out the significance of the contribution from ^{132}I after the Chernobyl accident. Hosoda *et al.*[14] measured ^{132}I concentration in environmental samples immediately after the Fukushima accident and estimated the dose contribution due to inhalation of ^{132}I at less than 2 %. However, ^{132}I can be generated from ^{132}Te incorporated into the body, as Balonov *et al.* noted. This remains uncertain and needs further study.

Whole-body counting of cesium has been conducted on a larger scale compared with the thyroid activity measurement, as described later. Hosoda *et al.*[15] suggested a method to estimate thyroid dose from whole-body counting results. They assumed a ratio of inhaled activity of ^{131}I to ^{134}Cs from some of their measurements. Using the ratio and whole-body counting data for cesium, they estimated the maximum thyroid dose for a child at 18 mSv for more than 2,000 residents of Namie town, Fukushima Prefecture.

Kamata *et al.*[16] took urine samples from residents and estimated thyroid dose. They reported that the equivalent doses to thyroid were 27–66 mSv for adults (*n*=4 among 11 subjects investigated), which indicated a significant level of ^{131}I, and 44 mSv for children (*n*=1 among 4 subjects investigated). These estimated values (obtained by thyroid screening, the gamma-ray spectroscopic method and estimation from urine samples) seem to give results of similar order.

However, WHO estimates are larger than these values probably due to their conservative assumptions. The WHO report[8] said in the most affected area of Fukushima Prefecture the estimated thyroid doses were within the dose band of 10–100 mSv, with the exception of one sample location where the estimated thyroid doses to adults were within a dose band of 1–10 mSv and another sample location where the upper bound of the estimated thyroid doses to infants was 200 mSv. In the rest of Fukushima Prefecture, the estimated thyroid doses are within a dose band of 1–10 mSv for adults and 10–100 mSv for children and infants.

Conservative assumptions were also used for the thyroid dose estimated by the computer program SPEEDI[17]. It used the assumptions that a one-year old infant stayed outdoors all day long and was not evacuated. As a result, it showed a wide area (extending over five city areas) with thyroid doses exceeding 500 mSv. The dose estimation based on such a conservative assumption is called "projected dose", which is defined as the dose that would be received if no countermeasures were to be taken[18]. If the projected dose is not accompanied by an explanation about the conservative assumptions used, it might cause confusion to the public.

Thyroid dose to residents in other prefectures was also estimated by some studies. For example, Takeyasu *et al.*[19] estimated dose to residents in Tokai village in Ibaraki Prefecture, which is located about 100 km south of the Fukushima Daiichi Nuclear Power Plant. They estimated doses to adults and 1-year children as 8 mSv and 25 mSv, respectively; however, these were based on the conservative assumption that people stayed outdoors all day long (projected dose).

Considering the uncertainty associated with the assumption (people stay outdoors all day long) used by Takeyasu *et al.*[19] and other studies, the ratio of indoor to outdoor concentration is an important factor. The Nuclear Safety Council of Japan proposed a value of 0.25 for the ratio[20], while EURANOS[21] suggested that 0.5 for 0.5 μm aerosols, 0.125 for 4 μm aerosols and 1 for non-reactive gases such as CH_3I were appropriate. Thus, the physical and chemical forms of iodine are important for dosimetry, when total intake is estimated from environmental monitoring data (not from direct measurement of the thyroid). Information on physical and chemical forms of iodine and particle size is lacking in the case of Fukushima accident. For cesium, Kaneyasu *et al.*[22] reported that the activity median aerodynamic diameter (AMAD) for cesium was 0.53 to 0.63 μm from samples taken in April and May 2011.

Another factor which may affect inhalation dose estimation from airborne activity monitoring is the protective measures taken against inhalation of airborne radioactive materials such as wearing masks[23]. Simply protecting the nose and mouth using a handkerchief is effective for reducing the inhalation dose[24, 25]. When these uncertainties related to inhaled activity are considered, it is clear that the estimation of dose from monitoring or simulation of airborne activity is not as accurate as the direct measurement of thyroid activity.

Yamaguchi reported[26] dose due to ingestion of ^{131}I through food. The 90%tile of thyroid dose to 1- to 6-y children was estimated to be 1 mSv based on food monitoring data. Kinase *et al.*[27] estimated "averted dose" as well as thyroid dose due to ingestion of ^{131}I in drinking water. The averted dose means the dose prevented by the application of a countermeasure or set of countermeasures, i.e. the difference between the projected dose and the actual projected dose. They estimated averted doses to the thyroid at 8.3 mSv for 1-year-old children in Iitate village in Fukushima Prefecture. Thus, the tap water restrictions implemented by government authorities were considered to be effective in the early phase of the emergency exposure situation.

Thyroid dose estimation for workers was also done. Kurihara *et al.*[28] surveyed a total of 560 workers involved in controlling the accident in the early stage. The largest and second-largest ^{131}I contents were 9760 Bq and 7690 Bq, which corresponded to effective doses of 590 mSv and 470 mSv. Thyroid dose would be roughly 20 times as large as these two largest effective doses.

2.2 Internal dose to the whole body

Internal dose to the whole body mainly due to radioactive cesium (^{134}Cs and ^{137}Cs) has been estimated by whole-body counting. Fukushima Prefecture authorities are operating some whole-body counters with the cooperation of JAEA (Japan Atomic Energy Agency) workers[29]. According to a report by Fukushima Prefecture, more than 140,000 residents (as of July 2013) had been measured by whole-body counting[30]. The number did not include residents who were measured at hospitals independent from the program operated by Fukushima Prefecture. Thus, the total number of subjects already measured will be much larger than 140,000. According to the prefectural report, most of the estimated doses (99.98%) were less than 1 mSv (committed effective dose).

As for the results which were not included in the report by Fukushima Prefecture, the situation seems to be similar. Tsubokura *et al.*[31] reported measurement results of 9,498 residents in Minamisoma city, Fukushima Prefecture. A total of 3,286 individuals had detectable levels of cesium, but the maximum committed effective dose was estimated at 1.07 mSv. Hayano *et al.*[32] reported that the cesium detection frequency between 12 to 20 months after the accident was 1.0% (0.09% for children). In this case, the detection limit corresponded to 21 μSv/y (age: up to 10 years) and 13 μSv/y (age: up to 15 years) assuming a constant daily intake[33].

At present, Fukushima Prefecture has more than 50 whole-body counters[34]. In the early stage after the accident, surface contamination and high background radiation level were problems in appropriate dose estimation[35]. However, collaboration and discussions among researchers and operators of whole-body counters have led to improved measurement accuracy[36]. Although it was reported that high activity was observed for mushrooms locally grown in contaminated areas[37], dietary intake of ^{134}Cs and ^{137}Cs is generally low[38] due to safety regulations of food and water[39].

Internal exposures (effective doses) in other prefectures than Fukushima are much lower. Amano *et al.*[40] estimated effective dose to adults (in Chiba Prefecture, inhalation and ingestion of tap water) at 81.5 μSv for two months after the accident. That for children (2-7y) was 152 μSv. A similar estimation was done by Nakagawa *et al.*[41], who estimated effective dose due to inhalation at 25 μSv in Tokyo. Priest[42] reported effective doses due to inhalation and external gamma ray exposure in various places in Japan. However, the dose estimation by these three studies was based on conservative assumptions (projected dose). The actual dose may be lower than these values.

2.3 External dose

The most comprehensive estimation of external dose to the residents in Fukushima Prefecture has been done by the Fukushima Health Management Survey[43, 44]. The doses (for the first four months after the accident) were obtained by superimposing the behavior data (daily time-budget and record of movement) of the residents on the gamma ray dose rate maps[45]. This survey has estimated doses for about 445,015 persons, as of the end of July 2013[46]. The dose distributions were: less than 1 mSv, 65.9%; less than 2 mSv, 94.8%; less than 3 mSv, 99.3%; and the maximum was 25 mSv (excluding radiation workers). This estimation took the behavior data of residents into consideration, so accuracy could be higher than the estimation from measurement of radioactivity in soil[47-49] or measurement of ambient gamma ray dose rate.

The estimation from measurement of radioactivity in soil usually uses coefficients to convert deposition density of radionuclides on the surface soil to ambient gamma ray dose rate[50, 51]. The coefficients are given for each radionuclide. This method has an advantage that soil samples can be measured in laboratories with low-background and high-accuracy detectors such as high purity germanium (HPGe) detectors. It enables accurately estimation of each radionuclide concentration. However, non-uniform deposition of radionuclides onto the soil and the behavior of the residents may be sources of dose estimation uncertainty. The studies[47-49] cited above noted that the estimated dose could be overestimated, because it was assumed that people stayed outdoors all day long.

The dose estimation from measurement of ambient gamma ray dose rate (i.e. in-situ measurement) was also conducted with the gamma ray spectroscopic method[52, 53]. Hosoda *et al.*[52] estimated one-year cumulative external doses for evacuees to Fukushima city, Koriyama city and Nihonmatsu city from the residential area where the maximum dose was measured in Namie town. The doses were 57–68 mSv, 57–59 mSv and 59–64 mSv, respectively, including consideration of a shielding factor of 0.4[24, 25] for wooden houses and a daily time-budget (outdoors: 8 h and indoors: 16 h). The estimation by Hosoda *et al.* included the assumption that evacuees were living at the maximum dose rate point for two months after the accident. This assumption may have led to their values being higher than the maximum dose estimated by the Fukushima Health Management Survey (25 mSv).

In a relatively low contamination area, it may be important to estimate the dose contribution from natural radiation, separately from artificial radiation due to the accident. Minato developed a software program for this[54]. A gamma ray spectrum (pulse height spectrum) can be unfolded by this software and primary gamma ray fluxes can be obtained. Then, dose rate due to each radionuclide is estimated using conversion coefficients.

After the accident, many types of portable survey meters (Geiger-Mueller counters and CsI(Tl) detectors were widely used, without energy discrimination of gamma rays. Their response to a radiation field could be different. Furuta and Kusama[55] made a performance test for several types of survey meters and found that measurement values in μSv/h could differ between the survey meters.

External dose estimation with personal dosimeters has been done for residents by researchers[56, 57] as well as local government authorities (cities and villages). The former studies suggested that the dose estimated from the outdoor gamma ray dose rate is generally larger than the dose measured by personal dosimeters. Specifically, Yoshida-Ohuchi *et al.*[56] pointed out that the relationship for dose rates outdoors and indoors for 17 wooden detached houses was linear with a slope of 0.5. Many personal dose estimations using passive dosimeters have been done by local governments which distributed passive dosimeters to residents upon their request. Two types of passive dosimeters have been used for this purpose: radio-photoluminescence (RPL) glass dosimeters and optically stimulated luminescence (OSL) dosimeters[58]. The dosimeters were usually retrieved after being used for a few months and each resident was notified of the individual dose. Also, the results have been statistically processed and released on several web pages[59, 60]. These will be helpful for the general public to see the level of exposure for periods which were not covered by the Fukushima Health Management Survey (after July 11, 2011).

Personal dosimetry measurements were also done by Monzen *et al.*[61] for support staff members during the early stage of the accidents. They reported that the maximum cumulative dose for a single participation (after March 15, 2011) for support activities was around 100 μSv.

On the other hand, some of the TEPCO (Tokyo Electric Power Company) workers received high doses. It was reported that six TEPCO workers received effective doses above the 250 mSv allowed by Japanese law for front-line emergency workers[62, 63]. The largest part of those doses resulted from intakes of ^{131}I, ^{134}Cs and ^{137}Cs. Most of the workers who received high doses were exposed in the early days of the accident.

The doses due to the accident mentioned above are the “past” doses which were estimated to be already received by these people. On the other hand, prediction of doses which will be received in the future (lifetime doses) would be useful for planning the return of evacuees to their hometowns, assuming several conditions[64]. It will be necessary to understand the assumptions to interpret the prediction results.

3. Doses due to natural radiation and medical radiation

The main purpose of the present paper is to review internal and external doses due to the Fukushima nuclear accident. However, it is useful for understanding these doses to compare them with the doses due to natural and medical radiation. The sources of natural radiation can be categorized as: (1) radon, thoron and their progenies; (2) cosmic rays; (3) terrestrial radiation; and (4) ingestion from food. Annual average doses from these sources in Japan have been well summarized by Hosoda *et al*[65]. According to the literature[66], in Japan, the average value for dose due to natural radiation is around 2.1 mSv per year and the average value for dose due to medical exposure is 3.87 mSv per year. It should be noted that the real dose due to medical radiation is quite different from person to person.

Even for natural radiation, the dose can differ from place to place. For example, according to a nation-wide survey of indoor radon concentration in Japan[67], the arithmetic mean was 15.5 Bq/m^3 (corresponding to 0.45 mSv/y), although the maximum was 208 Bq/m^3 (corresponding to 6.0 mSv/y, if the same estimation method is applied). Also, 0.73 mSv from the 2.1 mSv (average in Japan) is estimated to come from ingestion of the naturally occurring radionuclide, ^{210}Po[68]. Because the greatest contributors to the dose (0.73 mSv) are marine products, dietary habit may affect dose due to natural radiation.

4. Summary

Many dose estimation studies have been conducted since the Fukushima Daiichi Nuclear Power Plant accident began. Some of the studies published so far were reviewed in the present paper. Differences in dose estimation methods and dosimetric parameters resulted in different dose values. In some cases, the dose tended to be overestimated on the basis of conservative assumptions. On the other hand, more realistic doses based on actual situations were also estimated in some studies. In the future, the doses should be discussed and explained together with the assumptions and parameters used in their estimations to avoid confusion and misunderstanding, especially for the general public.

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