Investigation on Decision-Making Criteria for Public Protective Actions in Nuclear Emergencies

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Abstract
Background: The Fukushima Daiichi nuclear accident gave us a lesson on the importance of effective and timely implementation of public protective actions. National protection strategies, including decision-making process of public protective actions, should be developed at the preparedness stage of nuclear accidents. In particular, dose criteria for the decision-making of public protective actions should be predetermined.

Materials and Methods: The dose criteria adopted in 24 countries and those provided by international standards were investigated for urgent protective actions (sheltering, evacuation, and iodine thyroid blocking [ITB]) and early protective actions (temporary relocation and restriction on food consumption). Other important factors such as exposure duration, dose quantities, and dose concept were also reviewed in this study.

Results and Discussion: Most countries have applied different dose criteria ranging from 10 mSv to 100 mSv and exposure duration for dose estimation. An effective dose has been used for decision-making of all protective actions except for ITB, whereas thyroid dose (equivalent dose or absorbed dose) has been applied for ITB. Projected dose as the concept of radiation dose was found to be more appropriate than avertable dose due to conservative and practical reasons. The general range of dose criteria, which is in accordance with reference levels of 20–100 mSv, and exposure duration were obtained from the statistical data analysis.

Conclusion: The dose criteria as a single value suggested in this study will be utilized for updating the dose criteria for decision-making of public protective actions in Republic of Korea. The revised dose criteria will be reflected in the emergency response plans of government authorities and nuclear licensees in the future.

Keywords: Nuclear Emergency, Public Protective Actions, Intervention Levels, Reference Levels, Dose Criteria

Introduction

In March 2011, the Fukushima Daiichi nuclear accident was caused by the Great East Japan Earthquake and tsunami, which resulted in the release of radioactive materials into the environment. People within a radius of 20 km of the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before being recently advised to voluntarily evacuate. The accident and the protective actions introduced in both the emergency response and recovery phase impacted the way of life of populations in the areas affected. In June 2012, the number of evacuees peaked at approximately 164,000, and the number was around 119,000 by January 2015 [1]. Public protective actions such as evacuation, relocation, and restric-
tions on food consumption were very difficult due to an unclear decision-making process, bad weather conditions, and a lack of relevant emergency response resources [1, 2].

From the perspective of public protective actions, one of the key lessons learned from the Fukushima Daiichi nuclear accident was that arrangements need to be in place to allow timely decisions to be made on the implementation of predetermined protective actions. Therefore, national protection strategies should be developed at the preparedness stage of nuclear accidents not only to avoid severe deterministic effects but also to reduce the risk of stochastic effects. For effective and timely implementation of the protective actions, decision-making criteria should be predetermined by national authorities. The International Atomic Energy Agency (IAEA) published safety standards reports on the safety requirements and safety guides dealing with the dose criteria for decision-making called ‘generic criteria’ for public protective actions in nuclear or radiological emergencies [3, 4]. Some countries have directly used these criteria as the IAEA suggested; however, some other countries have adopted the revised dose criteria or operational criteria such as operational intervention levels (OILs) through their own reviews. The OILs are measurable quantities such as dose rates or radioactivity concentrations that correspond to the dose criteria for decision-making. In Republic of Korea, the dose criteria and OILs provided by the past IAEA requirement [5] and technical document [6] have been applied, respectively, in the national regulation or the relevant response procedure. In this context, the research project for updating the dose criteria and the operational criteria for decision-making of public protective actions was initiated in 2022. As a part of the research project, the dose criteria adopted in foreign countries were investigated, and the distribution of the criteria was analyzed in the present work.

### Materials and Methods

The International Commission on Radiological Protection (ICRP) and the IAEA have provided the dose criteria for the decision-making of public protective actions. In this work, the dose criteria provided by the ICRP [7, 8] and IAEA [3–5] were investigated as references. The criteria applied in 24 different countries [9–15] were investigated for statistical analysis. The countries surveyed in this study were Australia, Austria, Belgium, Bulgaria, Canada, China, Croatia, Czechia, Denmark, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Japan, Norway, Poland, Spain, Sweden, Switzerland, the United States, and the United Kingdom.

Public protective actions are mainly divided into urgent protective actions and early protective actions. The urgent protective actions include sheltering, evacuation, and iodine thyroid blocking (ITB), whereas the early protective actions include temporary relocation, restrictions on the consumption of foods, milk, and drinking water, etc. These protective actions should be implemented depending on the response phase as well as the radiological impacts at the on- and off-sites. In this study, the dose criteria for the decision-making of urgent and early protective actions were mainly investigated. In addition, we reviewed exposure duration for dose estimation using prediction models, specific dose quantities (effective dose, equivalent dose, or absorbed dose), and the concept of the radiation dose (projected dose or avertable dose) applied in 24 countries.

To determine the national decision-making criteria, the national reference levels to be applied in emergency exposure situations should be predetermined. In general, reference levels of 20–100 mSv, as a residual dose, are recommended to be applied in emergency exposure situations. Table 1 shows the dose criteria for public protective actions provided by the ICRP and IAEA. The ICRP recommendations [4, 5] and IAEA GS-R-2 [6] suggested applying the avertable dose for

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<tbody>
<tr>
<td>Sheltering</td>
<td>5–50 mSv in 2 days</td>
<td>-10 mSv in 2 days</td>
<td>10 mSv in 2 days</td>
<td>100 mSv in 7 days</td>
</tr>
<tr>
<td>Evacuation</td>
<td>50–500 mSv in 7 days</td>
<td>-50 mSv in 7 days</td>
<td>50 mSv in 7 days</td>
<td>100 mSv in 7 days</td>
</tr>
<tr>
<td>Iodine thyroid blocking</td>
<td>50–500 mSv</td>
<td>-100 mSv</td>
<td>100 mSv</td>
<td>50 mSv in 7 days</td>
</tr>
<tr>
<td>Temporary relocation</td>
<td>5–15 mSv in 1 month or 1,000 mSv</td>
<td>-100 mSv in 1 year or -1,000 mSv</td>
<td>30 mSv in 1 month</td>
<td>100 mSv in 1 year</td>
</tr>
<tr>
<td>Restriction on food consumption</td>
<td>10 mSv in 1 year</td>
<td>-</td>
<td>Applying activity concentrations</td>
<td>10 mSv in 1 year</td>
</tr>
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decision-making. However, the IAEA GSR Part 7 [3], which is the recent standard requirements on preparedness and response for a nuclear or radiological emergency, reported that the dose criteria as protection quantities can be applied with a projected dose or received dose derived from the national reference levels. For decision-making of public protective actions, the projected dose is preferred in most cases, except for taking longer-term medical actions. Remarkably, in emergency exposure situations, ICRP 103 recommended reference levels between 20 mSv/yr and 100 mSv/yr for all countermeasures combined in an overall protection strategy [16]. Since the publication of ICRP 103, no specific decision-making criteria have been provided by the ICRP.

The criteria for decision-making of sheltering and evacuation were separately provided in the ICRP recommendations [7, 8] and the IAEA GS-R-2 [5], in which the lower criterion was applied for sheltering even though the period considered as the exposure duration is shorter. However, the recent IAEA standards [3, 4] showed a single dose value for sheltering or evacuation, which can be determined by considering the situations. The criteria for decision-making of ITB decreased in the recent IAEA reports [3, 4]. The committed absorbed dose to the thyroid was suggested to be applied for ITB in the IAEA GS-R-2 [5], whereas the committed equivalent dose to the thyroid was suggested to be applied in the ICRP recommendations [7, 8] and the recent IAEA reports [3, 4]. The exposure durations for thyroid dose estimation were not provided in the ICRP recommendations [7, 8] and the IAEA GS-R-2 [5]. However, the exposure duration of 7 days was provided as one of the urgent protective actions in the recent IAEA reports [3, 4].

The criteria for decision-making of temporary relocation were provided as a monthly dose or annual dose since the temporary relocation is one of the early protective actions that will be generally implemented following urgent protective actions. As the criteria for decision-making of restriction on food consumption, the IAEA GS-R-2 [5] provided activity concentrations depending on the radionuclides. On the other hand, an annual dose of 10 mSv, which resulted from the ingestion of foods, milk, and drinking water, was provided in the ICRP 63 [7] and the recent IAEA reports [3, 4].

Results and Discussion

1. Criteria for Urgent Protective Actions

The dose criteria for urgent protective actions were investigated in 24 countries [9–15]. Figs. 1 and 2 show the distribution of effective doses adopted for sheltering and evacuation, respectively. For decision-making of sheltering, 13 countries (54.2%) have adopted an effective dose of 10 mSv. Three countries (12.5%) have applied OILs instead of dose criteria, and five countries (20.8%) have adopted the dose range or different single values depending on the age group. For decision-making of evacuation, most countries have adopted higher criteria than those for sheltering. Among 24 countries, an effective dose of 50 mSv and 100 mSv accounted for 29.2% (seven countries each), respectively. Three countries (12.5%) have also applied OILs, and four countries (16.7%) have adopted the dose range instead of a single dose value.

Fig. 3 shows the exposure duration for dose estimation using prediction models for sheltering and evacuation, respectively. For decision-making of sheltering, seven countries (29.2%) have applied exposure duration of 2 days, and six countries (25%) have applied 7 days. And nine countries (37.5%) did not provide data on the exposure duration. For the decision-making of evacuation, 14 countries (58.3%) have

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**Fig. 1.** Effective dose distribution for decision-making of sheltering. OIL, operational intervention levels.

**Fig. 2.** Effective dose distribution for decision-making of evacuation. OIL, operational intervention levels.
applied the exposure duration of 7 days, and nine countries (37.5%) did not also provide the exposure duration. All 24 countries applied the effective dose for decision-making of sheltering and evacuation. The projected dose accounted for 41.7% (10 countries), and the avertable dose accounted for 29.2% (seven countries) as the concept of radiation dose adopted in the dose criteria.

For decision-making of ITB, 12 countries (50%) have applied dose criteria regardless of age. On the other hand, seven countries (29.2%) have applied different dose criteria for ITB between adults and children group. The dose criteria applied for ITB in 12 countries are shown in Fig. 4. Thyroid dose of 50 mSv accounted for 41.7% (five countries), while 100 mSv accounted for 33.3% (four countries) for decision-making of ITB. Two countries (16.7%) have applied the dose range. In the other seven countries applying different dose criteria depending on the age, a thyroid dose between 10 mSv and 50 mSv was applied for child group, whereas thyroid dose between 50 mSv and 250 mSv was applied for adults. Fig. 5 shows the thyroid dose quantities applied for ITB in 24 countries. Fourteen countries (58.3%) have applied the committed equivalent dose to the thyroid, and five countries (20.8%) have applied the committed absorbed dose to the thyroid. The other five countries (20.8%) have applied OILs or provided no data on the thyroid dose quantities. It was found that only five countries (20.8%) have applied exposure duration of 7 days, whereas most countries did not provide data on the exposure duration. As the thyroid dose for decision-making of ITB, the projected dose accounted for 41.7% (10 countries), and the avertable dose accounted for 29.2% (seven countries).

2. Criteria for Early Protective Actions

Among 24 countries, only 11 (45.8%) have provided dose criteria for decision-making of temporary relocation. The dose criteria applied for temporary relocation in 11 countries are shown in Fig. 6. Four countries (36.3%) have applied 30 mSv in 1 month, 20 mSv in 1 year, and 100 mSv in 1 year accounted for 18.2%, respectively. The other two countries (18.2%) have applied dose rage or OILs. Most of them have
applied the effective dose, except for some countries that apply OILs instead of single dose values or dose ranges.

For decision-making of restrictions on the consumption of foods, milk, and drinking water, only 10 countries (41.7%) provided dose criteria. Among 10 countries, five have applied the effective dose by ingestion of foodstuffs, and the other five countries have applied activity concentrations or OILs. Fig. 7 shows the distribution of the effective dose for decision-making regarding restrictions on the consumption of foodstuffs in five countries. Among countries applying effective doses, 1 mSv/yr accounted for 40%, and each of 3, 6, and 10 mSv/yr accounted for 20%, respectively. Among countries applying operational quantities, 40% have applied activity concentrations and 60% have applied OILs.

3. Discussion on Decision-Making Criteria

Dose criteria for decision-making have been provided with protection quantities such as effective dose or equivalent dose. An effective dose has been used for decision-making of all protective actions except for ITB. The effective dose is generally used for the purpose of radiation protection in all exposure situations, including emergency exposure situations. The recent IAEA reports [3, 4] have suggested additionally considering the equivalent dose to fetus and relative biological effectiveness-weighted absorbed dose to the bone marrow. However, we suggested that effective dose can be used as a representative value for decision-making of public protective actions except for the case of ITB, in which an equivalent dose to the thyroid is preferred to be applied. In the real case of nuclear emergencies, estimation of projected doses would be unlikely to be easy to perform immediately after the accident occurred since the source term information is necessary to estimate the projected doses using prediction models. Therefore, alternative ways such as using operational criteria such as emergency action levels (EALs) and OILs, which are immediately achievable, should be prepared in advance.

As the concept of radiation dose, projected dose is more appropriate for decision-making than avertable dose. The projected dose is the radiation dose expected to be received if the protective actions were not taken, whereas the avertable dose means the radiation dose that would be expected to be averted if the protective actions were properly taken. For a more conservative and practical approach, the projected dose should be used for decision-making of public protective actions.

As a result of this work, it was found that many countries have applied different dose criteria and exposure durations for dose estimation. The general range of dose criteria and exposure duration were obtained from the statistical data analysis, as shown in Table 2. The dose values accounting for less than 10% were removed in the range of dose criteria suggested in this work. According to the recent IAEA standards [3, 4], exposure durations of 7 days and 1 year were suggested for estimation of projected dose to implement urgent and
As the national criteria for decision-making of public protective actions, we believe that a single dose value is more appropriate to avoid confusion among decision-makers in the practical application process. In the initial phase of emergency response, upper values should be applied, taking account of the effectiveness of public protective actions, which should always be justified if the projected dose is expected to be higher than the upper criteria. However, it has to be noted that these dose criteria could be adjusted for the optimization of radiation protection depending on several factors such as health issues for affected populations, including special groups who need medical care, weather conditions, and emergency response resources for implementing protective actions. Accordingly, an effective dose of 100 mSv as the single dose value can be applied for decision-making of sheltering, evacuation, and temporary relocation in the urgent and early response phases. An equivalent dose to the thyroid of 100 mSv can be applied for the decision-making of ITB. The World Health Organization [17], however, reported that an increase in thyroid cancer risk was found starting from thyroid dose of 50 mSv among children between the ages of 0 and 18 years at the time of exposure. Therefore, an equivalent dose to the thyroid of 50 mSv can also be applied for decision-making of ITB considering the child group. In this process, thyroid dose for 1-year-old child should be applied for the conservative approach. For decision-making of restrictions on food consumption, an effective dose of 10 mSv can be applied only to populations living in the affected areas. This criterion is less than the reference levels of 20 to 100 mSv since the effective dose will be estimated taking into account only the ingestion of foodstuffs. However, this value could be adjusted depending on the situations in the same manner as decision-making of sheltering, evacuation, and temporary relocation.

Table 3 summarizes comparison of the dose criteria between the present Korean regulation [18] and this study. As explained earlier, these criteria as the upper values could be adjusted for the optimization of radiation protection depending on the several factors. It is expected that flexible decision-making will be available from a single dose value of 100 mSv for sheltering or evacuation in the real case of nuclear accidents. Consistent application of projected dose for all protective actions and exposure duration depending on the response phase (urgent or early) is also obtained from the revision of the dose criteria. As a complimentary tool for decision-making, operational criteria such as OILs should be derived based on the revised dose criteria to immediately implement public protective actions.

Table 3. Dose Criteria Suggested for Decision-Making of Public Protective Actions

<table>
<thead>
<tr>
<th>Protective actions</th>
<th>Dose criteria</th>
<th>Present value (Korean regulation [18])</th>
<th>Revised value (this study)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urgent protective actions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheltering</td>
<td>10 mSv in 2 days</td>
<td>50 mSv in 7 days</td>
<td>100 mSv in 7 days</td>
</tr>
<tr>
<td>Evacuation</td>
<td>100 mGy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodine thyroid blocking</td>
<td>100 mSv</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Early protective actions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporary relocation</td>
<td>30 mSv in 1 month</td>
<td></td>
<td>100 mSv in 1 year</td>
</tr>
<tr>
<td>Restriction on food</td>
<td>Activity concentrations</td>
<td></td>
<td>10 mSv in 1 year</td>
</tr>
</tbody>
</table>

Conclusion

In the present work, the dose criteria adopted in the 24 foreign countries were investigated for decision-making of public protective actions. In particular, the criteria for decision-making of sheltering, evaluation, ITB, temporary relocation, and restrictions on food consumption were investigated as urgent and early protective actions. It was confirmed that the effective dose has been used for decision-making except for ITB, and the committed equivalent dose to the thyroid has been applied in many countries rather than the committed absorbed dose for ITB. We also found that many countries have applied the projected dose as the concept of radiation dose for decision-making in nuclear emergencies.

The dose criteria suggested in this study, as well as the international standards or recommendations from the IAEA and ICRP, will be utilized for updating the dose criteria for decision-making of public protective actions in Republic of Korea. The dose criteria as a single dose value will be reviewed and revised by the relevant regulatory body based on the findings of this study. The revised dose criteria will be reflected in the emergency response plans of government authorities and nuclear licensees in the future. In addition, operational criteria such as EALs and OILs will be derived based on these dose criteria.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.
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Ethical Statement

This article does not contain any studies with human participants or animals performed by any of the authors.

Author Contribution

Conceptualization: Kim HK. Methodology: Cho I, Hwang WT. Formal analysis: Ha WH. Funding acquisition: Kim HK. Project administration: Lee C. Visualization: Lee C. Writing - original draft: Ha WH, Lee C. Writing - review & editing: Cho I, Hwang WT, Kim HK. Approval of final manuscript: all authors.

References