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Original Article

Application plan for radiological exposure model using virtual reality–based radiological exercise system

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ABSTRACT

New exercise technology such as the virtual reality (VR)–based exercise system is required to meet soaring demand for target participants in exercises and to alleviate the difficulties in personnel mobilization through an alternative approach to the exercise system. In a previous study, event tree methodologies were introduced in setting up an exercise scenario of a VR-based radiological exercise system. In the scenario, the locations at which major events occur are rephrased as nodes, routes as paths, and public response actions as protective actions or contents of an exercise at individual locations. In the study, a model for estimating effective doses to the participants is proposed to evaluate the exercise system, using the effective dose rates at particular times and locations derived from a computer program. The effective dose received by a student when she/he follows a successful route is about a half of the dose received when she/he does not follow the exercise guide directions. In addition, elapsed time to finish an exercise when following a successful route is less than one-third of the time spent to finish an exercise when following the guide's directions.

1. Introduction

Attempts to hold an exercise to simulate a radiological disaster, with vast personnel mobilization, have been evaluated as hardly possible because large numbers of the public residing within the emergency planning zones (EPZs), which were greatly extended according to protective actions that were recently revised and updated after the Fukushima accident, shall have to participate in the exercise. Currently, precautionary action zones (PAZs) are “identified as 3–5 km radius areas where the population within the zones is instructed to immediately take an iodine thyroid blocking (ITB) agent, reduce inadvertent ingestion, and safely evacuate to beyond the urgent protective action planning zone (UPZ).” In the meantime, “UPZs are also identified as 5–30 km where people within the zones are instructed to immediately remain indoors (shelter in place) until evacuation, take an ITB agent, and reduce inadvertent ingestion. If there is a potential for a severe airborne release, the population is instructed to safely evacuate beyond the UPZ as soon as possible without delaying evacuation of the public within the PAZ within 1 h of the declaration of a General Emergency by the shift supervisor of the nuclear power plant (NPP)” [1].

On the other hand, the status of exercises has been evaluated as at low efficiency levels, and personnel participation by the public in exercises is very poor. To overcome these issues, there have been increasing demands of a new concept such as virtual reality (VR) technology applied to a radiological exercise system. In the meantime, varieties of VR-based systems have been developed and applied to NPPs and related areas abroad [2–5].

To develop a VR-based radiological exercise system, we made an effort to study the Fukushima Daiichi Accident Technical Volume 3/5 published by the International Atomic Energy Agency (IAEA) [6]. Major events by time series that occurred during the Fukushima NPP accident have been reviewed, and issues raised in the public protection points of view have been carefully considered. We also studied the public opinions on the current exercise system and reflected emergency experts' comments as much as possible in the development of the current exercise system [7,8]. Varieties of limitations exist in applying the current radiological response system to accident situations. To overcome or alleviate these kinds of problems to a maximum extent, it is believed that varieties of scenarios must be applied to the VR-based radiological exercise system.

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The performance level of an exercise greatly depends on the components of the exercise scenario. Therefore, the components of an exercise shall be selected carefully to meet the requirements, objectives, and performance goals of the exercise when it is organized and planned.

Exercise phases, which are required to minimize exposure to radiation in cases of radioactivity release, are defined as event units, and these event units are reclassified as successes or failures. To physically realize all cases of probable occurrence of event units defined and combinations of successes and failures, event tree technology was used, as explained in detail in our previous studies [9,10]. Event tree technology is a method to represent successes and failures of varieties of events by time series prepared to mitigate an initiating event and the following accident consequences in a tree-type structure.

To enhance the exercise efficiency, we decide to conduct an evaluation of an exercise. We are planning to evaluate the exercise based on the radiation exposure doses to the exercise participants. In the estimation of radiation exposure dose, we are going to calculate the exposure dose using the dose rates at specific times and locations and information on the locations of participants or their behaviors, such as response actions according to time during an exercise.

In this article, we introduce how to calculate the dose rates at specific times and locations and approximate the participant locations according to the exercise scenario. We are planning to judge the possibility of application through example calculations.

2. Methods and materials

2.1. Evaluation of a VR-based exercise system

The phases of a radiological emergency exercise are divided into major event units during an exercise, and the implementing objects of VR are determined by the exercise topics of the major events. In addition, relevant variables of the implementation are itemized to make virtualization easy.

Most emergency exercises generally proceed with response actions according to a preplanned major scenario event list. Similarly, a VR-based radiological emergency exercise system must be prepared according to the specific major scenario event list. Thus, major events that occur by time series during a radiological emergency are defined.

To determine major event units, radiological emergency–related acts, enforcement decrees, enforcement regulations, and notifications from the Nuclear Safety and Security Commission are reviewed, and roles of emergency response agencies and organizations under the national radiological emergency response system are studied and analyzed. In addition, exercise scenarios of personnel mobilization of emergency response agencies and organizations and major issues in the individual exercise phases are carefully reviewed.

A radiological emergency is classified into three phases: an alert, site area emergency, and general emergency. When an emergency occurs at an NPP, it is normal to proceed with the emergency sequences described previously. However, only a site area and general emergency require response actions by the public. At this point of time, physical conditions (i.e., traffic, communications, and roads), meteorological conditions (i.e., wind speed and direction), measures for public relations and communications, and environmental situations and conditions of the public (i.e., current position, health status, and patient's probable mobility) should be carefully considered. In addition, an exercise scenario prepared by the nuclear licensee should be displayed by time series to review the response actions to be taken by the individual emergency response agencies, organizations, and the public.

According to the main issues discussed previously, major events in individual phases during an emergency are determined. In the case of a site area emergency, the steps are 1) notification of a site area emergency as an initiating event, 2) recognition of the announced emergency, 3) conduction of indoor sheltering, and 4) taking of protective actions as defined by major event time series. In the case of a general emergency, the major time series steps are 1) notification of a general emergency as an initiating event, 2) recognition of the announced emergency, 3) conduction of evacuation action, 4) moving to assembly posts, 5) transport to shelter, 6) contamination monitoring, and 7) triage. However, activities after arriving at a shelter (i.e., contamination monitoring, decontamination, registration, receiving daily necessities, and so on) are not directly related to the public exercise items, and they have low priority in major event units. The public response actions were derived from an actual exercise scenario prepared for a national unified exercise conducted by the Korean nuclear regulatory authority jointly with central government ministries and local governments for the Wolseong NPPs. Major event units are listed in Table 1.

In the meantime, it is almost impossible to implement all possible kinds of probable scenarios in the VR-based emergency exercise system. Therefore, we used the event tree structure mainly applied in the Probabilistic Safety Analysis to understand the scenario spectrum, as explained in detail in our previous studies [9,10]. By using the Probabilistic Safety Analysis technology, we can consider almost all possible scenarios that may occur in a radioactive material release accident.

Exercise phases that minimize the exposure to radiation in cases of radioactivity release are defined as event units, and these event units are reclassified as successes or failures. To physically realize all cases of probable occurrence of event units defined and combinations of successes and failures, event tree technology is used. Event tree technology is a method to represent successes and failures of varieties of events in a time series prepared for mitigating an initiating event and following accident consequences in a tree-type structure.

2.1.1. Determination of movement route and movement time

Movement route approximates the exercise participant's location while movement time is an approximation of the time taken to arrive at a particular location according to the exercise scenario.

In this study, we choose a student group as a subject group for the exposure dose evaluation and decide to calculate the projected effective doses according to possible student actions during an exercise. We believe that the student group is normally very enthusiastic about participation in electronic game–like programs such as VR-based exercise systems. It is strongly believed that this

Table 1
Major event units during a site area and general emergency.

Initial event	Event unit
Notification of a site area emergency	Recognizing a site area emergency, indoor sheltering, and protective action
Notification of a general emergency	Recognizing a general emergency, evacuation action, moving to assembly posts, and transport to a shelter

Table 2
Effective whole body doses after 2 days of radioactive material release from the nuclear power plant calculated by the K-REDAP program [mSv].

	1 km	2 km	5 km	8 km	10 km	20 km	30 km	40 km
N	5330.00	6070.00	339.00	130.00	122.00	31.10	8.51	2.91
NNE	5330.00	6070.00	388.00	257.00	164.00	10.80	2.47	1.59
NE	5330.00	1160.00	236.00	31.60	30.60	0.55	0.22	0.13
ENE	5330.00	1160.00	20.10	1.04	0.09	0.00	0.00	0.00
E	5330.00	969.00	2.64	0.01	0.00	0.00	0.00	0.00
ESE	5330.00	969.00	0.00	0.00	0.00	0.00	0.00	0.00
SE	5330.00	121.00	0.00	0.00	0.00	0.00	0.00	0.00
SSE	5330.00	121.00	0.00	0.00	0.00	0.00	0.00	0.00
S	5330.00	609.00	0.00	0.00	0.00	0.00	0.00	0.00
SSW	5330.00	609.00	0.00	0.00	0.00	0.00	0.00	0.00
SW	5330.00	79.70	0.00	0.00	0.00	0.00	0.00	0.00
WSW	5330.00	79.70	0.00	0.00	0.00	0.00	0.00	0.00
W	5330.00	720.00	0.00	0.00	0.00	0.00	0.00	0.00
WNW	5330.00	720.00	0.08	0.00	0.00	0.00	0.00	0.00
NW	5330.00	933.00	6.39	0.23	0.04	0.00	0.00	0.00
NNW	5330.00	933.00	121.00	19.70	13.70	1.87	0.13	0.00

K-REDAP, Korea Hydro and Nuclear Power-Radiological Emergency Dose Assessment Program

group will also be very effective in training. Thus, we select this group as a representative group in developing VR-based radiological emergency exercise scenarios, and a VR gear exercise system that targets student use for the trial basis is developed.

2.1.1.1. Determination of nodes for the student group. During normal schooling hours, students' outdoor activities usually take place on the school playground. A playground at a school, a classroom, a student's individual home, and an assembly post are selected as possible locations on route to the final refuge shelter in this exercise process. These locations are called nodes and are the most probable places at which protective actions or contents of an exercise should be undertaken by students.

2.1.1.2. Determination of routes for the student group. Routes consist of series of nodes that eventually reach a refuge shelter. We determined five possible routes for the student group as follows:

Route 1: playground—classroom—refuge shelter
Route 2: playground—classroom—home—assembly post—refuge shelter
Route 3: playground—classroom—home—stay at home—refuge shelter
Route 4: playground—home—assembly post—refuge shelter
Route 5: playground—home—stay at home—refuge shelter

2.1.1.3. Protective actions or exercise contents at individual locations (nodes) by scenario. **Playground:** After recognizing an emergency, either enter a classroom or go home to find family members.

Classroom: After entering a classroom, wash hands and face to remove any possible contamination and follow teachers' instructions such as closing windows, shutting off the heating, ventilation and air conditioning (HVAC) system, and watching the news for the next instructions on mass media.

Home: After getting into a house, wash hands and face to remove any possible contamination, change clothes and seal up worn clothes outdoors in a waste bag, and follow instructions such as closing windows, shutting off the HVAC system, and listening to radio or television or checking online for further instructions. Alternatively, stay at home until either voluntarily going to an assembly post or being required to go to a refuge shelter. However, if a student enters a classroom first and goes home, protective actions are assumed to already be done by other family member(s).

Assembly post: After arriving at an assembly post, follow the emergency guide's instructions, listen carefully to nurses' or physicians' instructions on administering iodine prophylaxis, and wait for the guide's next instructions.

Refuge shelter: After arriving at a shelter, follow the guide's instruction for personnel monitoring and decontamination procedure; if needed, perform registration for an evacuee, wait in the reception area, receive daily necessities, and wait for the guide's next instructions.

2.1.2. Information on dose rates at specific times and locations

There are several computer programs that can estimate the effective dose to the whole body or to an individual organ due to radioactive material release from an NPP; these are used to recommend emergency intervention actions such as indoor sheltering (10 mSv/no more than 2 days), evacuation of the general public (50 mSv/no more than 7 days), or thyroid protection (100 mGy) according to “Standards for Determining Urgent Public Protective Actions in Korean Nuclear Laws [11]”. However, owing to the licensing availabilities of the programs, we have decided to use a program called Korea Hydro and Nuclear Power-Radiological Emergency Dose Assessment Program (K-REDAP) developed by Samchang Enterprise Company & the Korea Power Engineering Company (SEC & KOPEC) to recommend emergency actions to corresponding emergency organizations outside the NPP site during an emergency [12].

Using the K-REDAP program first, we calculate the effective doses in the 16 sectors within radii of 1, 2, 5, 8, 10, 20, 30, and 40 km to whole body after 2 days and 7 days of radioactive material released. After we obtain the effective doses in each sector, we divide the effective dose values either by 48 hours for indoor sheltering (average dose rate limit of 0.208 mSv h^{-1}) or by 168 hours for evacuation case (average dose rate limit of 0.297 mSv h^{-1}), according to the Korean standards for determining urgent public protective actions [11], to obtain an effective dose rate in each individual sector. Because this program also calculates effective doses to the thyroid in the 16 individual sectors with the same radii, thyroid protection is recommended when a projected effective dose to the thyroid in a specific sector approaches the intervention level of 100 mGy. However, one should note that the method of calculating effective dose rate values for the specific locations and times used in this study essentially differs from either that of obtaining dose rate values derived from the Korean standards for determining urgent public protective actions [11] or that of using dose rate values for “monitoring and comparison with

Table 3
Effective dose rates in individual sectors within the radii from 1 km to 40 km [mSv h^{-1}].

	1 km	2 km	5 km	8 km	10 km	20 km	30 km	40 km
N	111.04	126.46	7.06	2.71	2.54	0.65	0.18	0.06
NNE	111.04	126.46	8.08	5.35	3.42	0.23	0.05	0.03
NE	111.04	24.17	4.92	0.66	0.64	0.01	0.00	0.00
ENE	111.04	24.17	0.42	0.02	0.00	0.00	0.00	0.00
E	111.04	20.19	0.06	0.00	0.00	0.00	0.00	0.00
ESE	111.04	20.19	0.00	0.00	0.00	0.00	0.00	0.00
SE	111.04	2.52	0.00	0.00	0.00	0.00	0.00	0.00
SSE	111.04	2.52	0.00	0.00	0.00	0.00	0.00	0.00
S	111.04	12.69	0.00	0.00	0.00	0.00	0.00	0.00
SSW	111.04	12.69	0.00	0.00	0.00	0.00	0.00	0.00
SW	111.04	1.66	0.00	0.00	0.00	0.00	0.00	0.00
WSW	111.04	1.66	0.00	0.00	0.00	0.00	0.00	0.00
W	111.04	15.00	0.00	0.00	0.00	0.00	0.00	0.00
WNW	111.04	15.00	0.00	0.00	0.00	0.00	0.00	0.00
NW	111.04	19.44	0.13	0.00	0.00	0.00	0.00	0.00
NNW	111.04	19.44	2.52	0.41	0.285	0.04	0.00	0.00

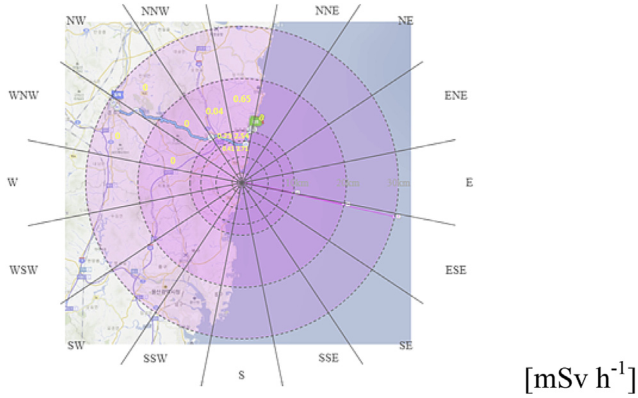

Fig. 1. Effective dose rates in the sectors with radii of 8, 10, 20, and 30 km along an evacuation route of the study.

operational intervention levels or measured operational quantities in perspective," recommended by the IAEA [1].

In the 16 sectors with radius range of 1–80 km in the Cartesian coordinate system, for the dispersion of radioactive material released in the air, the K-REDAP program uses a puff model with a releasing time of over 24 hours and dose assessment.

In the study, the following things are assumed: the radioactive sources are radioactive material released from the containment building, with release rates of 40%/day for 24 hours and 120 hours to the atmosphere and core melting of 70% damage. In addition, wind blowing directions of 230–240 degrees with wind speeds of 1.5–1.8 m/sec and atmospheric stabilities of A's are assumed.

Effective doses to whole body in the 16 sectors within radii of 1, 2, 5, 8, 10, 20, 30, and 40 km after 2 days of radioactive material release are listed in Table 2.

We calculate the effective dose rates over 2 days by dividing the effective whole body dose values listed previously by 48 hours. In Table 3, effective dose rates in the 16 sectors with different radii are listed. Even though this is not the case in a real situation, for the calculation, we assumed a constant dose rate in each individual sector for 2 days.

In Fig. 1, effective dose rates in sectors with radii of 8, 10, 20, and 30 km along the evacuation route of the study are depicted.

2.1.3. Calculation of exposure dose according to scenario

Exposure dose to a student when taking Route 2, where nodes of concern are located as follows:

School: Gampo High School (10 km–20 km N)
Home: Woosuk Villa (10 km–20 km N)
Assembly post: G Town Office (10 km–20 km N)
Shelter: Gyungju Gymnasium (20 km–30 km WNW)

In Table 4, nodes with descriptions of residence times inside nodes and outside nodes with descriptions of moving times along Route 2 are listed.

Doses received at the nodes depending on taking protective action or not:

Table 4
Nodes (stay time) and outside the nodes (moving time) on Route 2.

Node	Node		
Playground (5 min)			
Classroom (20 min)	On foot (10 min)	Home (10 min)	On foot (10 min)
Assembly post (20 min)	By bus (48 min)	Shelter	

Playground: 0.65 mSv/h * 5/60 h = 0.054 mSv.
Classroom: 0.65 mSv/h * 20/60 h * 0.05 (shielding factor) = 0.0108 mSv.
Home: 0.65 mSv/h * 10/60 h * 0.2 (shielding factor) = 0.0217 mSv.
Assembly post: 0.65 mSv/h * 20/60 h * 0.2 (shielding factor) = 0.0433 mSv.
Subtotal: 0.13 mSv.

We assumed shielding factors of 0.2 for the student's home and assembly post [one- and two-story block and brick house (without basement)] and 0.05 for the first and second floor of three- or four-story structures (500–1,000 m^2 per floor) for interior to exterior doses in the calculation [13].

In Fig. 2, effective dose rates in the individual sectors of N and NNW with radii of 8, 10, and 20 km from the reactor are listed. The school, home, and assembly post of concern are located in sector N with radii between 10 km and 20 km.

We define the following total dose to be received while a student is moving outside the nodes on Route 2:

Doses received while moving on foot outside the nodes:

School–home: 0.65 mSv/h * 10/60 h = 0.1083 mSv.
Home–assembly post: 0.65 mSv/h * 11/60 h = 0.1192 mSv
Subtotal = 0.2275 mSv.

In Table 5, times taken by bus from one point to another, dose rates in the individual sectors while passing through certain points, and doses received while passing from one point to the next by bus on Route 2 are listed.

On board bus, no shielding is assumed.

In Fig. 3, effective dose rates in the individual sectors with radii of 8, 10, 20, and 30 km on Route 2 starting from the school to the shelter are listed.

Doses received at the nodes: 0.13 mSv.

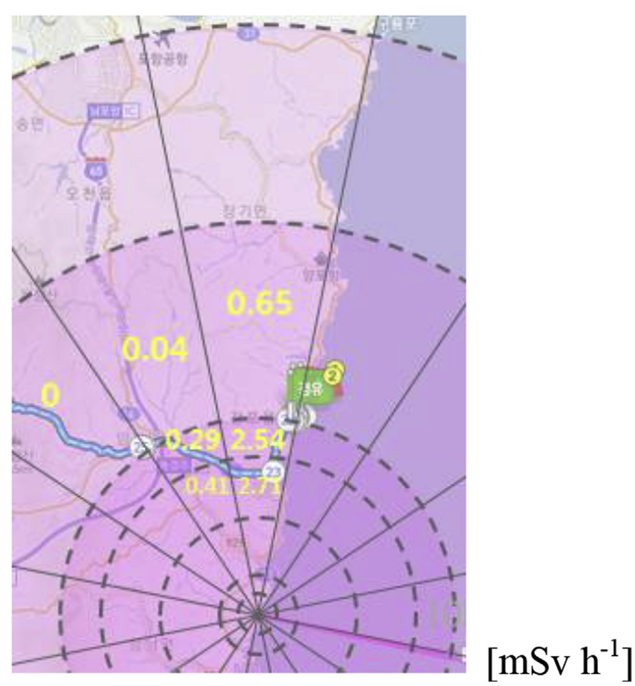

Fig. 2. Effective dose rates in the individual sectors of N and NNW with radii of 8, 10, and 20 km.

Table 5
Times taken, dose rates in the individual sectors, and dose received during passing from a point to the next by bus on Route 2.

From	To	Time taken (min)	Dose rate [mSv/h]	Dose received [mSv]
G. town office	Grandma fish store	5	2.54	0.2117
Grandma fish store	643-1 Paljori	3	2.71	0.1355
643-1 Paljori	952 Paljori	1	0.41	0.0068
952 Paljori	362-1 Ipchunri	2	0.29	0.0097
362-1 Ipchunri	472–34 Ahndongri	1	0.04	0.0007
472–34 Ahndongri	Gyungju Gym	36	0	0
Total		48		0.3643

Doses received outside the nodes: 0.2275 mSv (on foot) + 0.3643 mSv (on bus) = 0.5918 mSv.
Total = 0.72 mSv.
Elapsed time: 124 min (~2 h)
Route 1: School [playground (5 min) + classroom (20 min)] – on bus (48 min) – shelter = (0.054 + 0.0108 + 0.3643) mSv = 0.43 mSv/73 min.
Route 2: School [playground (5 min) + classroom (20 min)] – on foot (10 min) – home (10 min) – on foot (11 min) – assembly post (20 min) – on bus (48 min) – shelter = (0.054 + 0.0108 + 0.1083 + 0.0217 + 0.1192 + 0.0433 + 0.3643) mSv = 0.72 mSv/124 min.
Route 3: School [playground (5 min) + classroom (20 min)] – on foot (10 min) – home (3 h) – on bus (48 min) – shelter = [0.054 + 0.0108 + 0.1083 + (0.65 mSv/h*3 h*0.2) + 0.3643] mSv = 0.93 mSv/263 min.
Route 4: Playground (5 min) – on foot (10 min) – home (30 min) – on foot (11 min) – assembly post (20 min) – on bus (48 min) – shelter = (0.054 + 0.1083 + 0.065 + 0.1192 + 0.0433 + 0.3643) mSv = 0.75 mSv/124 min.
Route 5: Playground (5 min) – on foot (10 min) – home (3 h) – on bus (48 min) – shelter = [0.054 + 0.1083 + (0.65 mSv/h*3h*0.2) + 0.3643] mSv = 0.92 mSv/243 min.

3. Results

As can be seen, the dose received by a student when she/he follows a successful route that an exercise system aims at (Route 1) is about half of the dose received when she/he does not follow the exercise guide directions, stays at home (Route 3 or Route 5) for a long period of time (3 hours), and finally is forced to go to a shelter. In addition, elapsed time to finish an exercise when following a successful route is less than one-third of the time spent to finish an exercise when the student does not follow the directions given by the exercise guides. Therefore, with this hard fact, we can fully convince student participants that they should follow the directions given by the exercise guides to receive a minimum dose and to successfully finish the exercise within the time constraint.

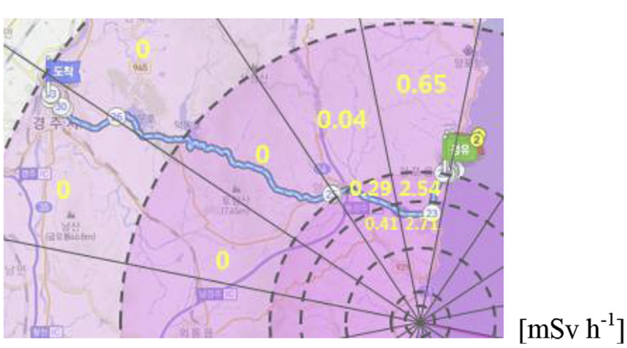

Fig. 3. Effective dose rates in the individual sectors with radii of 8, 10, 20, and 30 km on Route 2 to the shelter.

4. Discussion

We propose to apply the radiological exposure dose calculation method to evaluate a VR-based radiological exercise system. However, as discussed earlier, there is a rudimentary assumption that contradicts the real situation. First, effective dose rate in each individual sector with a specific radius is not constant over the period of time, whereas we assumed it was. Because we do not have other information available on the effective dose rates in real time at specific locations and times, we assume average values of effective dose rates in the individual sectors with radius range of 1–40 km over the time period of concern. In a real situation, the effective dose gradually increases with time when a release of radioactive material starts and then slowly decreases with time when the release of radioactive material stops. However, we assume an average constant value for the effective dose during the time of concern. Therefore, this assumption might lead to overestimation of doses in the individual sectors in the long range.

In the future, if we can calculate more realistic values for the effective doses, such as values of function of the movement times and routes according to scenarios consisting of combinations of successes and failures of major events by time series or as functions of degree of protective actions taken, then the dose received by the exercise participant would be more realistic.

According to the Homeland Security Exercise Evaluation Program [14], exercise evaluation guides (EEGs) are designed to accomplish several goals. Among those goals, EEGs help organizations map exercise results to exercise objectives, core capabilities, capability targets, and critical tasks for further analysis and assessment.

As explained, EEGs are measures to assess core capability, capability target, and critical task of participant organization, but there is a great gap between those measures and the assessment goals for public exercise proficiency and enhancement of and improvement in the preparedness capability. In the meantime, in this study, we decided to select exposure dose calculation for the evaluation of an exercise system. Therefore, core capability, capability target, and critical task are not selected as exercise assessment elements, and no ground rule was set to assess the exercise on the basis of these elements.

During the initial development of the dose calculation in the system, a simple prototype VR gear–based exercise system with a series of successful and failure events was developed and tested to identify possible difficulties that would occur in the future and to reduce the trial and error in the final phase of the study. From this attempt, the weak points of the emergency arrangements and strategy we now have are expected to be identified and deduced.

Because the VR exercise system introduced here is intended for the public, other VR exercise systems customized for personnel in various response organizations under the national emergency preparedness and response system are expected to be developed in the near future.

Conflicts of interest

All authors have no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2018.03.009.

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