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Acute and Chronic Health Risk Assessment for Inhalation and Ingestion Exposure in Acrylic Acid Leak Accidents

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Abstract

We established a hypothetical acrylic acid leak accident scenario, conducted a health risk assessment of local residents, and compared an actual accident case and the hypothetical scenario. The exposed subjects were divided into four age groups, and a non-carcinogenic risk assessment was conducted for inhalation and soil ingestion. In the hypothetical scenario, 40 tons of acrylic acid were leaked in Ulsan for 1 h from 12:00 am on January 1, 2017, and in the actual accident case, 3 L of acrylic acid were leaked in Hwaseong, Gyeonggi Province, for 1 h from 11:00 am on March 5, 2020. The environmental concentration of acrylic acid was calculated using the dynamic multimedia environmental model. Non-carcinogenic assessment of the hypothetical scenario showed the hazard index exceeded 1 across all age groups, suggesting that a health risk is likely to occur due to inhalation exposure to acrylic acid resulting from a chemical accident. Hazard_{acute} exceeded 1 until 2 h after the accident under the hypothetical scenario, indicating the likelihood of a health risk. Thus, we propose a methodology that can assess changing concentrations in a hazardous chemical leak from a chemical accident based on the time, place, the chemical's behaviors in different environmental media, and the health risk posed by the exposure of the chemical to local residents in the area affected by the accident.

Keywords: Health Risk Assessment, Non-carcinogenic Assessment, Inhalation Exposure, Ingestion Exposure, Acrylic Acid, Chemical Accident, The Dynamic Multimedia Environmental Model

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1. Introduction

Chemicals are increasingly used in Korea and abroad due to the recent acceleration of industrialization, and more than 400 new types of chemicals are introduced annually. Approximately 1,000 businesses handling chemicals in Korea are located in large industrial clusters such as Sihwa, Yeosu, Ulsan, and Onsan, while 15,000 others are located in small and medium-sized industrial clusters as well as agricultural clusters across the country. Hence, a chemical accident can potentially occur anywhere in the country, and no one is safe from it (Kim et al., 2017). It is therefore necessary to review response and post-accident management options to protect people from chemical accidents.

Most chemical factories or chemical handling processes are part of the process industry where advanced tech-intensive and complex processes are interconnected, and any serious industrial accidents such as fire, explosions, and leaks can not only cause casualties and property damage, but also pollute the environment or cause harm to local residents (Lee et al., 2013). Leaks in particular can cause huge social ripple effects. Gas or steam from a hazardous chemical leak can spread across the affected area and infiltrate the human body through the skin or respiratory system, causing lethal damage to local residents and workers (Jo et al., 2017).

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50 According to statistics from the National Institute of Chemical Safety, a total of 110 chemical leak
51 accidents have occurred as of November 2020, and the accident that leaked the largest amount of
52 chemicals occurred in Nam-gu, Ulsan, at 2:00 pm on August 10, 2015, where 22 tons of hydrochloric
53 acid were leaked from a 40-ton tank in a workshop due to poor facility control (National Institute of
54 Chemical Safety's website).

55

56 Since human losses were reported from a couple of large-scale chemical accidents, including a
57 hydrofluoric acid accident in Gumi, people have been more wary of chemical accidents and hazards
58 posed by chemicals, and studies on chemical accident responses as well as national-level responses
59 have been conducted continuously. Under the Ministry of Environment(MOE), the National Institute of
60 Chemical Safety(NICS) provides the estimated areas affected by chemical accidents in the Chemical
61 Accident Response Information System(CARIS) and makes efforts to reduce damages arising from
62 chemical accidents (Kim et al., 2020). Additionally, it was reported that local residents lived within 1
63 km of some of the recent chemical accidents in Korea, and that the accidents posed a serious hazard to
64 the residents, making it necessary to develop a method that can predict and assess the impact of a
65 chemical accident on the health of local residents (Park et al., 2020).

66

67 This study was conducted as part of a study on developing technology to assess post-chemical accident
68 human body impact for five years between 2017 and 2021 with the aim of establishing response and
69 post-accident management options for chemical accidents by the Ministry of Environment to protect
70 local residents. We prepared a hypothetical chemical leak accident scenario for acrylic acid, among
71 other substances requiring preparation for accidents under the Chemical Substances Control Act,
72 conducted a health risk assessment on local residents in the area affected by the accident to analyze
73 inhalation and ingestion exposure, applied the developed health risk assessment method to an actual

accident case, compared the results obtained with those from the hypothetical scenario, and provided a reference for establishing a suitable chemical accident response and post-accident management options.

2. Methods

2.1 The dynamic multimedia environmental model

To calculate the concentration of acrylic acid remaining in the environment after an acrylic acid leak accident, we used the dynamic multimedia environmental model developed by Lee et al. (2019) in a study on developing technology to assess post-chemical accident human body impact. A dynamic multimedia environmental model was established to identify the environmental behaviors of hazardous pollutants in the air, soil, and water, depending on the changing climate, by assuming abnormal conditions. This study reflected the movement of a hazardous pollutant via the air and established a model for soil and water, considering various conditions, including the impact of sedimentation (Park et al., 2020). The area for modeling was set as 15 km x 12 km, and the nested grid in the area was set as 0.1 km x 0.1 km. Meteorological information from the beginning of the accident to its end was collected from the Korea Meteorological Administration and used as meteorological data required to operate the dynamic multimedia environmental model under the hypothetical scenario and the actual accident case.

2.2 Exposure scenario

2.2.1 Hypothetical acrylic acid accident

To conduct a health risk assessment of local residents in the area affected by an acrylic acid leak accident, we referenced a 40-ton hydrochloric acid tank leak accident in 2015, which involved the largest ever leakage of chemicals in Korea, and developed a hypothetical acrylic acid leak accident scenario. The accident location under this hypothetical scenario was selected as Ulsan, where a chemical accident is considered to be likely to occur due to its large industrial clusters, and it was assumed that

40 tons of acrylic acid leaked from a random factory at the center of Ulsan for 1 h from 12:00 am on January 1, 2017. The time when the concentration of acrylic acid was below 0.01 ppb in the environment after the accident was considered to be the clearance time point. The endpoint concentration of acrylic acid was assumed to be 0.01 ppb at the author's discretion due to a lack of previous data.

2.2.2 Actual acrylic acid accident

To compare the difference after applying the above method to the actual accident case and to the hypothetical scenario, a health risk assessment was conducted with respect to acrylic acid exposure in an actual accident case. The actual acrylic acid leak accident, which is similar to the hypothetical scenario, occurred at 10:55 am on March 5, 2020, at a factory in Hwaseong, Gyeonggi Province, where 3 L (3.153 kg) of acrylic acid was leaked for 1 h. The end of the accident was assumed when the endpoint concentration of acrylic acid was achieved (below 0.01 ppb (25 °C, 1 atm), as in the hypothetical scenario (Table 1).

2.3 Health risk assessment

2.3.1 Chronic exposure

A chronic health risk assessment was conducted based on a 4-step method suggested by the US National Research Council(NRC) and the US National Academy of Sciences(NAS) to reflect the characteristics of a chemical accident where the concentration of a hazardous chemical changes over time (Park et al., 2019).

We found that acrylic acid can cause non-carcinogenic toxicity from inhalation exposure through air and oral ingestion exposure through the soil. The Integrated Risk Information System(IRIS) in the US Environmental Protection Agency(US EPA) was used to obtain dose-response information on non-

carcinogenic toxicity depending on the exposure pathway to determine the reference dose(RfD) and reference concentration(RfC) (Table 2).

The subjects for exposure assessment were divided by age into those the following groups: 0 – 9 years, 10 – 18 years, 19 – 64 years, and > 65 years. Exposure factors, referenced from the Korean Exposure Factor Handbook and Korean Child Exposure Factor Handbook by the Ministry of Environment, were applied to these age groups. The amount of soil ingestion in adults, which is not available from such data by the Ministry of Environment, was referenced from data obtained from the US EPA (Table 3).

It was assumed that the exposed subjects performed normal activities without much change after the chemical accident. The inhalation exposure concentration was used depending on the exposure pathway, outdoor exposure concentration, and indoor exposure concentration. The outdoor exposure concentration was calculated using a dynamic multimedia environmental model. The indoor exposure concentration was calculated using the indoor concentration prediction model (Eq. 1) developed by Park et al. (2018), considering that the leaked acrylic acid entered indoors. The average daily dose (ADD) was determined using the calculated indoor and outdoor exposure concentrations (Eq. 2).

$$C_{indoor} = 0.33C_{outdoor} \dots\dots\dots (Eq. 1)$$

where

C_{indoor} : Indoor toxic pollutant concentration (mg/m³)

$C_{outdoor}$: Outdoor toxic pollutant concentration (mg/m³)

$$ADD(mg/kg/day) = \frac{\sum_{n=1}^{CLT} (C_{n \text{ outdoor}} \times IHR \times OET) + (C_{n \text{ indoor}} \times IHR \times IET)}{BW(kg) \times AT(day)} \dots\dots\dots (Eq. 2)$$

where

CLT: Period until the extinction of the target chemical in the environment (day)

$C_{n \text{ outdoor}}$: Concentration of the outdoor target chemical n days after accident occurrence (mg/m^3)

IHR: Inhalation rate (m^3/day)

OET: Outdoor exposure time (day)

$C_{n \text{ indoor}}$: Concentration of the indoor target chemical n days after accident occurrence (mg/m^3)

IET: Indoor exposure time (day)

BW: Body weight (kg)

AT: Average exposure time (day)

Regarding ingestion exposure in the soil, the ADD was calculated assuming that the acrylic acid in the soil was fully absorbed into the body during ingestion (Eq. 3).

$$\text{ADD}(\text{mg}/\text{kg}/\text{day}) = \frac{\sum_{n=1}^{\text{CLT}} (C_{n \text{ soil}} \times \text{ITR}_{\text{Soil}})}{\text{BW}(\text{kg}) \times \text{AT}(\text{day})} \dots \dots \dots (\text{Eq. 3})$$

where

CLT: Period until the extinction of the target chemical in the environment (day)

$C_{n \text{ soil}}$: Concentration of the target chemical in soil n days after accident occurrence (mg/kg)

ITR_{Soil} : Soil intake rate (kg/day)

BW: Body weight (kg)

AT: Average exposure time (day)

Finally, the risk of acrylic acid, a non-carcinogenic toxic substance, was calculated using the hazard Index(HI) based on the reference dose and ADD from the exposure assessment (Eq. 4). When the calculated HI exceeded 1, a health risk due to acrylic acid exposure was considered likely.

$$HI = \frac{ADD(mg/kg/day)}{RfD(mg/kg/day)} \dots\dots\dots (Eq. 4)$$

where

HI: hazard index

ADD: average daily dose (mg/(kg·day))

RfD: reference dose (mg/(kg·day))

2.3.2 Acute exposure

To perform an acute health risk assessment, we used the Acute Exposure Guideline Level (AEGL) developed by the National Advisory Committee(NAC) under the US EPA to monitor ordinary citizens' exposure to air during a chemical leak or disaster (Table 4). The exposure concentration of acrylic acid in the air was calculated for hourly assessments using the dynamic multimedia environmental model, and the assessment ended when no part of the assessed area exceeded the AEGL. The exposure concentration in the air and hourly levels for AEGL-2, which predicts a concentration in the air whereby the general population may experience serious and sustained adverse effects or disabilities in their ability to evacuate, were compared to determine Hazard_{acute}.

Regarding Hazard_{acute}, the value converting the AEGL represented in ppm, which serves as the threshold for acute exposure, into mg/m³ was compared; when the exposure concentration exceeded the threshold, a health risk arising from acrylic acid in the chemical accident was considered to occur (Eq. 5).

$$Risk_{acute} = \frac{C_{n\ Air}(mg/m^3)}{AEGL(mg/m^3)} \dots\dots\dots (Eq. 5)$$

where

$Risk_{acute}$: Risk of Acute

$C_{n\ Air}$: Hazardous pollutant concentration in the air over time after the accident (mg/m^3)

AEGL: AEGL-2 for hazardous pollutant (1 h) (mg/m^3)

2.3.3 Risk map

To represent the results of risk assessment more easily so that they can be understood intuitively, the open-source Geographic Information System(GIS) program Quantum Geographic Information System(QGIS) V.3.10.10 was used to produce a risk map. Similar to the dynamic multimedia environmental model, the risk map had a $0.1\text{ km} \times 0.1\text{ km}$ grid in a $15\text{ km} \times 12\text{ km}$ area. It was represented in red for the hazard index and $\text{Hazard}_{acute} > 1$ as determined from the risk assessment, orange for $0.5 - 1$, yellow for $0.1 - 0.5$, light green for $0.1 - 0.05$, and green for $0 - 0.05$.

3. Results

3.1 Identifying the clearance time point for acrylic acid in the environment

3.1.1 Acrylic acid clearance time point in the hypothetical accident

When 40 tons of acrylic acid were leaked under the hypothetical scenario, the dynamic multimedia environmental model showed that the exposure concentration went below 0.01 ppb 21 days after the chemical accident. The clearance time point of acrylic acid leakage in the hypothetical accident was determined to be 21 days, which was used as the exposure period to conduct the risk assessment on chronic exposure.

3.1.2 Acrylic acid clearance time point in the actual accident

When 1 ton of acrylic acid was leaked during the actual accident, the dynamic multimedia environmental model showed that the exposure concentration went below 0.01 ppb 1 day after the chemical accident. The clearance time point of acrylic acid leakage in the actual accident was determined to be 1, which was used as the exposure period to conduct the risk assessment on acute exposure.

3.2 Chronic risk assessment results

3.2.1 Non-carcinogenic inhalation exposure (air)

The chronic health risk assessment conducted on inhalation exposure in the air under the hypothetical accident scenario showed that the average hazard index exceeded 1 across all age groups and a health risk for local accidents in the affected area was considered likely (Table 5). The risk map representing the results for the hypothetical scenario showed the highest hazard index southeast of the accident location across all age groups (Figure 1).

The chronic health risk assessment conducted on inhalation exposure in the air for the actual accident case showed an average hazard index of 6.29×10^{-2} in those aged 0 – 9, 2.22×10^{-2} in those aged 65 and older, 2.02×10^{-2} in those aged 10 – 18 years, and 1.95×10^{-2} – in those aged 19 – 64 years. As the hazard index did not exceed 1 in any age group, a health risk for local residents in the affected area was found unlikely; however, since it exceeded 1 in some parts of the area, the health risk was considered likely to occur locally (Table 5). The risk map representing the results for the actual accident showed the risk at the center and northeast of the accident location, and the highest hazard index was detected from the center to the southeast (Figure 2). When comparing the age groups on the risk map, those aged 0 – 9 years showed the widest area with the hazard index exceeding 1.

3.2.2 Non-carcinogenic ingestion exposure (soil)

The hazard indices for all age groups calculated from the chronic health risk assessment conducted on ingestion exposure under the hypothetical accident scenario are given in Table 6. The average hazard index was 1.71×10^{-7} in those aged 0 – 9 years, 1.18×10^{-8} in those aged 10 – 18 years, 1.10×10^{-8} in those aged > 65 years, and 9.89×10^{-9} in those aged 19 – 64 years. The hazard index did not exceed 1 in any age group, and a health risk for local residents was considered unlikely due to acrylic acid ingestion exposure in the soil under the hypothetical scenario (Table 6). The risk map representing the results under the hypothetical scenario did not exceed 1 across the area, which was green (Figure 3).

The chronic health risk assessment conducted to analyze ingestion exposure during the actual accident revealed the average hazard index to be 1.68×10^{-9} in those aged 0 – 9 years, 1.17×10^{-10} in those aged 10^{-18} years, 1.08×10^{-10} for those aged > 65 years, and 9.74×10^{-11} for those aged 19 – 64 years. The hazard index did not exceed 1 in any age group, and a health risk for local residents was considered unlikely due to acrylic acid ingestion exposure in the soil regarding the actual accident (Table 6). The risk map representing the results under the hypothetical scenario did not exceed 1 across the area, which was green (Figure 4).

3.3 Acute risk assessment results

The acute health risk assessment under the hypothetical accident scenario found that the risk persisted for likely up to 2 h after the accident, and it was unlikely to be present after 3 h as the $\text{Hazard}_{\text{acute}}$ did not exceed 1 (Table 7). The risk map representing the results under the hypothetical scenario showed that the $\text{Hazard}_{\text{acute}}$ was most widely distributed 2 h after the accident, and it vanished rapidly after 3 h and all the areas turned green (Figure 5).

The acute health risk assessment in the actual accident case found that the risk was unlikely, as the $\text{Hazard}_{\text{acute}}$ did not exceed 1 after the accident (Table 7). The risk map representing the results under the

hypothetical scenario showed that all the areas were green after the accident, indicating no risk (Figure 6).

4. Discussion

We used the dynamic multimedia environmental model to assess the exposure of local residents to a chemical leaked in a hazardous chemical accident and the likelihood of an acute and chronic health risk. A risk map was prepared so that the health impact can be understood intuitively.

The exposure factors used to conduct the health risk assessment in this study should have reflected activities over time, such as evacuation and return to normal after the chemical accident; however, there have been no standardized study on such activities. Hence, activities by the general public over time reported by the National Institute of Environmental Research (2019) were included in this study. Thus, a decrease in exposure due to evacuation after the accident was not reflected, which may have exaggerated the results of the risk assessment. However, considering the purpose of this study, which is to provide a reference for establishing response and post-accident management options to protect local residents during a chemical accident, preparing these options based on the results of the exposure and health risk assessment by considering the potential maximum exposure is essential. Future studies should also consider the potential maximum exposure during analysis.

A literature review was conducted on previous studies in Korea regarding hazardous chemical background concentrations to identify the clearance time point of acrylic acid in the environment, and it was found that there were not enough data regarding the background concentrations of acrylic acid. Hence, the endpoint concentration was assumed to be 0.01 ppb, which is the detection limit of most measuring instruments, at the author's discretion. In the future, it is necessary to designate the background concentrations of substances requiring preparation for accidents under the Chemical

Substances Control Act, including acrylic acid, and conduct studies that can determine their endpoint concentration based on the dynamic multimedia environmental model so that the clearance time point of the chemicals in the environment can be identified accurately.

The risk posed to those aged 0–9 years was the highest among all groups, which can be attributable to the low body weight of children. This finding suggests that accident response and post-accident management options must be prioritized for vulnerable groups, including children, in the case of a chemical accident.

The chronic health risk assessment of soil ingestion exposure revealed no health impact on local residents across all age groups under any scenario. Soil ingestion exposure seemed to rarely occur in adults as they were less likely to touch the soil, unlike children. Although the exposure to soil ingestion was not high in children, they were more likely to touch the soil owing to a lack of artificial green spaces in Korea and use of urethane to make playgrounds for children in Korea (National Institute of Environmental Research, 2019).

The acute risk assessment showed that local residents were exposed to high concentrations of acrylic acid in large numbers shortly after the accident under the hypothetical scenario, indicating that an accident response to acute exposure must be implemented rapidly. No acute health impact was found in the actual accident case; while this does not mean that there was no health impact, it seems to suggest that the exposure was underestimated due to the advection and diffusion of the hazardous chemical leaked continuously for 1 h in the air, as the dynamic multimedia environmental model assessed exposure on an hourly basis. Thus, it would be better to assess the resolution of the predicted exposure concentration in the model on a minute-by-minute basis. Furthermore, the minimum unit of time in the AEGL, which was used as the threshold for acute exposure in this study, was 10 min. Calculation on a

minute-by-minute basis would make it possible to build a more systematic assessment of health impact and accident response for acute exposure (Figure 7).

The risk map representing the results of the chronic health risk assessment due to inhalation exposure in the air showed that the risk was distributed southeast of the accident location under the hypothetical scenario, while the wind rose based on weather conditions in Ulsan showed that it was consistent with the actual wind direction in the city. The wind mostly blew in a northeasterly direction in Hwaseong during the actual accident case, but the wind speed in Hwaseong was lower than that in Ulsan; consequently, the chemical moved northeast or southwest, not center or northeast, as it was affected by the wind from other directions (Figure 8). This implies that not only the wind direction but also the wind speed is greatly involved in the movement of a chemical during a leak accident, and in the future, it would be necessary to consider the wind speed in addition to the main wind direction to predict the movement of a chemical in an accident.

This study identified the concentration of acrylic acid in a chemical accident by using a dynamic multimedia environmental model that considered a hazardous chemical's behaviors in the environment and its changing concentrations over time, found the clearance time point in the environment, conducted an appropriate health risk assessment, and reflected the characteristics of exposure in a chemical accident. Furthermore, we also compared the results of the health risk assessment between the hypothetical scenario and the actual accident case and provide a reference for developing health risk assessment techniques for chemical accidents.

5. Conclusions

This study focused on acrylic acid, one of the substances requiring preparation for accidents, in a hypothetical accident scenario and an actual accident case using the dynamic multimedia environmental

model developed by our team, and compared the results of acrylic acid exposure and health risk assessment of local residents in the area affected by the accident in an effort to provide a reference for establishing chemical accident response and post-accident management options.

The hypothetical accident scenario assumed that 40 tons of acrylic acid leaked from a random factory located in a national chemical industrial cluster in Ulsan for 1 h at 12:00 am on January 1, 2017, while in the actual accident case, 3 L (3.153 kg) of acrylic acid were leaked for 1 h from 11:00 am on March 5, 2020, in a factory in Hwaseong, Gyeonggi Province. We ran a dynamic multimedia environmental model developed based on the above conditions until the background concentration of acrylic acid (0.01 ppb) was reached in the environment. Acrylic acid concentrations over time by environmental medium by the time obtained in the model and the exposure factor across age groups were used to determine the non-carcinogenic hazard index and Hazard_{acute} over time in all age groups, and the GIS program was used to represent the obtained results on a risk map.

The dynamic multimedia environmental model determined the clearance time point of acrylic acid in the environment to be 21 days under the hypothetical scenario and 1 day for the actual case.

According to the chronic health risk assessment conducted on the inhalation exposure of acrylic acid remaining in the air, the average hazard index suggested that a health risk was likely for local residents in the accident-affected area under the hypothetical scenario. Under the actual accident case, the average hazard index was 6.29×10^{-2} in those aged 0 – 9 years, 2.02×10^{-2} in those aged 10 – 18 years, 1.95×10^{-2} in those aged 19 – 64 years, and 2.22×10^{-2} in those aged > 65 years, suggesting that the health risk was unlikely for local residents across all age groups in the accident-affected area. It exceeded 1 in some parts of the area, indicating that health risks may occur locally.

The chronic health risk assessment of ingestion exposure in the soil revealed that the average hazard index under the hypothetical scenario was 1.71×10^{-7} in those aged 0 – 9 years, 1.18×10^{-8} in those aged 10 – 18 years, 9.89×10^{-9} in those aged 19 – 64 years, and 1.10×10^{-8} in those aged > 65 years, suggesting that a health risk was unlikely for local residents across all age groups in the accident-affected area. Regarding the actual accident case, the average hazard index was 1.68×10^{-9} in those aged 0 – 9 years, 1.17×10^{-10} in those aged 10 to 18 years, 9.74×10^{-11} in those aged 19 – 64 years, and 1.08×10^{-10} in those aged > 65 years, indicating that the health risk was unlikely for local residents across all age groups in the accident-affected area.

Regarding the acute health risk assessment, Hazard_{acute} exceeded 1 just 2 hours after the accident under the hypothetical scenario, suggesting that a health risk was likely for local residents in the area affected by the accident. The risk map representing these results showed the widest hazard 2 h after the accident. In the actual case, Hazard_{acute} did not exceed 1 after the accident, suggesting that the health risk was unlikely for local residents in the accident-affected area.

The results of this study are expected to be useful in developing chemical accident response and post-accident management options as it suggests a methodology that can assess changing concentrations of a hazardous chemical leaked during a chemical accident based on time, place, movement, advection, diffusion, and clearance in different environmental media, as well as the health risk posed by the exposure of local residents to the chemical.

Ethical Approval and consent to participate

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Consent to Publication

Not applicable

Availability of data and materials

Not applicable

Competing of Interests

The authors declare that they have no competing interests

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Author Contribution

Conceptualization, C.M.Lee., H.B.Lim.; Data analysis, H.B.Lim., S.H.Park., H.J.Hong., J.Y.Jeong.; Modeling data calculation, H.S.Kim.; Health risk calculation, H.B.Lim., S.H.Park., H.J.Hong., J.Y.Jeong.; Writing-original draft, H.B.Lim.; Writing-review & editing, H.B.Lim, S.H.Park.; Project administration, C.M.Lee.; All authors read and approved the final manuscript.

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Figures

Figure 1

Hazard index of inhalation exposure risk map by age (Virtual scenario)

Figure 2

Hazard index of inhalation exposure risk map by age (Real scenario)

Figure 3

Hazard index of intake exposure risk map by age (Virtual scenario)

Figure 4

Hazard index of intake exposure risk map by age (Real scenario)

Figure 5

Riskacute risk map by Time (Virtual scenario)

a. 1 hour

b. 2 hour

Figure 6

Riskacute risk map by Time (Real scenario)

Figure 7

Wind rose of Ulsan-Si Metropolitan City during the Risk assessment period (KMA 2020)

Figure 8

Wind rose of Hwasung-Si Metropolitan City during the Risk assessment period (KMA 2020)