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Cancer and non-cancer risk associated with PM10-bound metals in subways

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ABSTRACT

Non-cancer and cancer health risks to humans associated with respirable particulate matter ≤10 µm (PM_{10}) in an indoor microenvironment such as a subway cabin are currently a public concern. In this study, detailed investigations of human health risks due to PM_{10}-bound metals in a subway cabin were conducted for the first time. Cancer risks (CRs) were estimated for inhalation exposure (CR_{inh}) using a Monte Carlo probability density function and were compared with incremental lifetime CRs (ILCRs). Moreover, the percentage contributions of each metal to the risk levels were calculated to identify the elements potentially responsible for human health risks. The significant (>1) for non-CRs levels as HI (hazard index) was estimated for children and adults for all types of exposure (inhalation, ingestion, and dermal). Pb, Cr, and Ni were recognized as the foremost contributors to the HQ (hazard quotient) levels for all types of exposure. For subway commuters, the CR_{inh} and ILCR levels for adults were marginally higher than the satisfactory maximum point of confinement of the lifetime carcinogenic risk level (1×10^{-5}) where as CR_{inh} for children was within the acceptable limit (1×10^{-6}–1×10^{-5}). Cr was identified as the predominant carcinogenic element, with 91% contribution to the total CR level in the subway cabin on the Seoul Metropolitan Subway.

1. Introduction

Air pollution exposure causes adverse effects such as respiratory infections, chronic bronchitis, lung cancer, and heart disease in humans (Chuang et al., 2011; Roy et al., 2017, 2019a, 2019d). The World Health Organization (WHO) has classified airborne particulate matter (PM) as a human carcinogen (International Agency for Research on Cancer, 2013). PM pollution levels and health risks in a typical indoor microenvironment such as a subway are of particular public concern. The main health hazard factors are related to PM-bound metals, which have an immediate connection with cardiovascular breakdown, carcinogenicity, respiratory diseases, depressed immunity functions, and mortality (WHO International Programme on Chemical Safety, 1998; Behear, 2008; Chuang et al., 2011; Kim et al., 2013). In more than 60 countries, citizens are using metros for affordable and rapid transportation (Xu and Hao, 2017). However, high PM concentration levels have been reported for subway system in Europe (particulate matter ≤ 10 µm (PM_{10}): 40–400 µg/m^3; particulate matter ≤ 2.5 µm ($PM_{2.5}$): 13–165 µg/m^3), America (PM_{10}: 78–126 µg/m^3; $PM_{2.5}$: 57–78 µg/m^3), and Asia (PM_{10}: 55–366 µg/m^3; $PM_{2.5}$: 10.2–287 µg/m^3) (Johansson and Johansson, 2003; Cha and Olofsson, 2018; Kam et al., 2011; Sitzmann

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et al., 1999; Seaton et al., 2005; Barmparesos et al., 2016; Salma et al., 2009; Li et al., 2007; Ye et al., 2010; Kwon et al., 2008, 2015), as reported in Table 1.

In South Korea, approximately 4 million (35% of the total commuters) people are taking advantage of the Seoul Metropolitan Subway (SMS) (Park et al., 2012). The daily ridership varies from 8984 to 34,880 people (Kwon et al., 2015). Moreover, the SMS system is the 3rd busiest metro (after Tokyo, Japan, and Beijing, China) and the longest (940 km) subway system in the world (Park et al., 2012). Commuters face poor air quality inside the subway system because of its confined underground operating space (Park et al., 2012). Numerous investigations have been conducted on air contamination levels on the SMS (Table 1). High PM levels have been found at all stations (138.2 ± 49.1 μg/m^3), concourses (120.8 ± 46.8 μg/m^3), and subway tunnels (200.75 ± 21.99 μg/m^3) with respect to outdoor levels (55.9 ± 19.9 μg/m^3) in the SMS (Park et al., 2014; Kwon et al., 2015). Among the PM categories, PM_{10} is a significant air pollutant in the metro framework in Seoul. Human exposures to PM10-bound toxic potential metals in the SMS are a health risk. Genotoxicity is associated with the presence of carcinogenic potential elements in the subway air (Roy et al., 2019b). Currently, it is common practice to assess the potential cancer risk (CR) of multiple carcinogenic elements all over the world (Tarafdar and Sinha, 2017; Tarafdar et al., 2019; Roy et al., 2019c). However, to date, there has been limited data published on the significance of non-CR and CR levels in subway passenger cabins. Human health risk levels due to continuous exposure of PM pollution levels inside subway cabins is a most important undertaking because commuters spend a great deal of time in them.

The aim of this study is to provide detailed insight into the age-specific health risk levels by monitoring data on PM_{10}-bound metals in a subway cabin in the SMS published by Park et al. (2012). The objectives were (1) to assess the age-specific (child and adult) health risk levels due to PM_{10}-bound metals in subway cabins, (2) to verify the CR data with the incremental lifetime CR (ILCR) levels for inhalation exposure, (3) to apply a Monte Carlo simulation to verify the CR via inhalation exposure (CR_{inh}), and (4) to appraise the rate contribution of each element to the risk levels to identify the most significant components.

Table 1
Worldwide summary of the particulate matter levels in subway systems.

Zone	City	References	Assessment Year	Particulate Matter	Average Concentration (μg/m^3)
America	Mexico City	Gomez-Perales et al. (2004)	2002	$PM_{2.5}$	67
		Mugica-Álvarez et al. (2012)	2007	PM_{10}, $PM_{2.5}$	112.79, 67.28
	New York City	Morabia et al. (2009)	2007–2008	$PM_{2.5}$	30.6
		Vilcassim et al. (2014)	2013–2014	$PM_{2.5}$	139.3
		Wang and Gao (2011)	2008	$PM_{2.5}$	44.33
	Los Angeles	Kam et al. (2011)	2010	PM_{10}, $PM_{2.5}$	78.0, 56.7
	Santiago	Suárez et al. (2014)	2011–2012	$PM_{2.5}$	62.4
Europe	London	Sitzmann et al. (1999)	1995–1996	$PM_{2.5}$	892.8
	Prague	Braniš (2006)	2003–2004	PM_{10}	113.4
		Cusack et al. (2015)	2013	PM_{10}, $PM_{2.5}$, PM_1	193, 108, 40.9
	Helsinki	Aarnio et al. (2005)	2004	$PM_{2.5}$	53.5
	Italian Cities	Cartenì et al. (2015)	2006	PM_{10}, $PM_{2.5}$	217, 52.5
		Ripanucci et al. (2006)	2005	PM_{10}	413
	Budapest	Salma (2007)	2006	PM_{10}	155
	Istanbul	Şahin et al. (2012)	2007	PM_{10}	200
		Onat and Stakeeva (2014)	2007–2008	$PM_{2.5}$	115.5
	Milan	Ozgen et al. (2016)	2010	PM_{10}, $PM_{2.5}$, PM_1	148, 91, 36
	Athens	Barmparesos et al. (2016)	2012	PM_{10}, $PM_{2.5}$, PM_1	320.8, 88.1, 18.7
	Barcelona	Martins et al. (2016)	2013–2014	$PM_{2.5}$	58.3
	Frankfurt	Gerber et al. (2014)	2013	PM_{10}, $PM_{2.5}$, PM_1	62, 33, 18
Asia	Tokyo	Furuya et al. (2001)	1997	TSP	90
	Guangzhou	Chan et al. (2002b)	2002	PM_{10}, $PM_{2.5}$	55, 44
	Beijing	Li et al. (2007)	2004	TSP, PM_{10}, $PM_{2.5}$, PM_1	456, 324, 112, 38.2
	Shanghai	Ye et al. (2010)	2008	PM_{10}, $PM_{2.5}$, PM_1	366, 287, 231
		Qiao et al. (2015)	2013	PM_{10}, $PM_{2.5}$, PM_1	71, 61, 58
	Hing Kong	Chan et al. (2002a)	1999–2000	PM_{10}, $PM_{2.5}$	44, 33
	Taipei	Cheng (2012)	2010	PM_{10}, $PM_{2.5}$	31, 24
		Cheng and Yan (2011)	2011	PM_{10}, $PM_{2.5}$	58, 32
	Delhi	Goel et al. (2015)	2012	$PM_{2.5}$	141.5
	Seoul (line no 1–4)	Kim et al. (2008)	2004–2005	PM_{10}, $PM_{2.5}$	359, 129 (at platform)
	Seoul (line no 4)	Park et al. (2014)	2012	PM_{10}	200.75 (in subway tunnel)
	Seoul (line no 1, 2, 4, and 5)	Park and Ha (2008)	–	PM_{10}, $PM_{2.5}$	129.3, 105.4 (at platform)
	Seoul (line no 2, 3, and 4, 7)	Kwon et al. (2008, 2015), and Roy et al. (2019b)	2007, 2014–2015	PM_{10}	142, 131 (in subway tunnel, at station)
	Seoul (Jegi, Chungmuro, Yangjae, and Seouldae)	Jung et al. (2012)	2009	PM_{10}	137 (at platform)
	Seoul (line no 1–4)	Kim et al. (2010)	2008	PM_{10}, $PM_{2.5}$	130, 75 (at platform)
	Seoul (This study)	Park et al. (2012)	2010	PM_{10}	65.7 (at platform)

Note: PM, particulate matter; TSP, total suspended particles.

2. Materials and methods

Human health risk assessments include steps such as data collection and analysis, exposure assessment, toxicity analysis, and risk simulation (Wu et al., 2011; Megido et al., 2017). In this study, the CRs and non-CRs from PM_{10}-bound metal levels inside a subway cabin in the SMS in 2010 have been simulated using the data reported by Park et al. (2012). We made the following assumptions: 1) the potentially exposed target age groups were children (0 to ≤12 years old) and adults (13 to ≤70 years old), representing portions of the SMS commuters; 2) the exposure time was 30 min per day, five days per week, throughout the year (252 days) for a lifetime (12 years for children and 70 years for adults); 3) risk analysis parameter values such as body weight, inhalation rate, and ingestion rate were taken from the Korean standard (Supplementary Tables 1 and 3), while the Cr(VI) level was considered as one-seventh of the total Cr (United States Environmental Protection Agency (USEPA), 2011; Massey et al., 2013; Izhar et al., 2016).

2.1. Sample collection and analysis

As per Park et al. (2012), SMS Line No. 7 was considered for the evaluation of the PM_{10} concentration levels inside a passenger cabin. Sampling was conducted in January, April, July, and October 2010. PM_{10} levels were determined utilizing a light-scattering monitor (LD-3B, Sibata Co.) at intervals of 6 s. The sampling inlet was kept within the passenger breathing zone by placing a sampler in a passenger seat. In addition, PM_{10} dust samples were likewise gathered utilizing a mini-volume air sampler (PAS201, Air Metrics Co.) with an average flow rate of 5 L min^{-1} using a 0.2-μm polytetrafluoroethylene (PTFE) membrane filter of size 47 mm (Whatman). A nitric acid/hydrochloric acid method with microwaves (MARSS, CEM) was used for the elemental analysis after one-half of the sampled filter paper had been pre-processed. For pre-processing, the filter papers were dried for three days in an electronic desiccator (Oyin 09678BN, Sanplatec Co.) and the differences in weight were measured using an electronic scale (HM-202, A&DCo.) with a sensitivity of 0.01 mg. The acid-extracted solution was filtrated (No. 5B, 110 mm, Advance MFS Inc. filter paper), diluted with 50 ml of ultrapure water, and stored in a refrigerator at 4 °C. The PM_{10}-bound metals were analyzed via inductively coupled plasma-atomic emission spectroscopy (ICP-AES: DRE ICP, Lee man Labs Inc.) of the extracted solution. Detailed descriptions of the study area, sampling techniques, and analysis methods are available in Park et al. (2012).

2.2. Assessment of human health risk

The daily exposure through inhalation (EC_{inh}), dermal absorption (DAD_{derm}), and ingestion (CDI_{ing}) were calculated for PM_{10}-bound metals using Equations (1–3) in Supplementary Section S1 (USEPA, 1989, 2004, 2009). For non-CR assessment, hazard quotients (HQs) and hazard indexes (HIs) were estimated using Equations (4–7) in Supplementary Information Section S1.1 (USEPA, 1989, 2004, 2009). Moreover, HQs and His greater than 1 were considered as probable non-CRs. The CRs of the PM_{10}-bound metals (Pb, Cr (VI), and Ni) were estimated for CR_{inh}, ingestion (CR_{ing}), and dermal contact (CR_{derm}) using Equation 8 in Supplementary Information Section S1.2 (USEPA, 1989, 2004, 2009). The Monte Carlo simulation software package Crystal Ball (11.1.2.4.600; Oracle) was used to evaluate CR_{inh}. In this simulation, a random value of each variable parameter was selected from its respective distribution. After the CR assessment, the input variable most affected was determined through a sensitivity analysis. The CR_{inh} levels were verified by the CR values obtained from the Monte Carlo probabilistic uncertainty analysis, the input parameter values for which are presented in Supplementary Table 3. In addition, ILCR was calculated using Equation (9) in Supplementary Section S1.3 for PM_{10}-bound Cr(VI), Ni, and Pb to compare the CR levels with CR_{inh} values (Sarkar and Khillare, 2011;USEPA, 2011; Widziewicz et al., 2018).

2.3. Study uncertainty

Human attributes and conduct are predominate factors creating uncertainty. This is reflected to some degree in the consequences of the risk assessment. Notwithstanding, these variations might make the risk assessment increasingly sensitive, and so we were careful regarding data interpretation. The concentrations of PM_{10} and PM_{10}-bound metals were taken from Park et al. (2012), and it is assumed that they followed the standard methodology and quality control (QC)/quality assurance (QA) techniques in their assessment. Moreover, a Monte Carlo simulation with 50,000 iterations was utilized to limit the degree of vulnerability. The IR (Inhalation Rate), SA (Skin Surface Area), and AF (Adherence Factor) were acquired from the suggested values for Korea. Be that as it may, there is still a chance of uncertainty in the CR evaluation process. The actual exposure levels depend on the type of location, duration of stay in the train, pollution level, commuter age type, and the physiology and morphology of the respiratory system.

In this study, the CR was calculated by considering the PM exposure levels in a Seoul Metro passenger cabin. Furthermore, it has been identified that $PM_{2.5}$ is more potentially detrimental to the pulmonary system than other types of PM owing to the small particle size and toxin-absorption ability (Dockery et al., 1993; Cascio et al., 2009). Carcinogenic elements have more affinity to small-sized PM (Zhang et al., 2008; Sarigiannis et al., 2015). A human health risk assessment for fine-sized PM in subway passenger cabins could provide the basis for future work based on this study.

3. Results and discussion

3.1. Status of PM_{10} and PM_{10}-bound metals in the subway passenger cabin

The PM_{10} concentration in the subway cabin was observed to be highest in winter, followed by spring, summer, and autumn. The

PM_{10} concentration levels were higher during the rush-hour periods than at other times (the number of commuters and frequency of trains is higher in the rush-hour periods). In winter, PM_{10} concentration levels were 1.53E+2 and 9.0E+1 μg/m^3during the rush and non-rush periods, respectively. In winter, the air ventilation duration is generally reduced to maintain the passenger cabin temperature (Park and Ha, 2008; Park et al., 2012), and this may have caused the higher PM_{10} levels in the passenger cabin. The yearly average of the 24 h concentration level of PM_{10} is 6.57E+1 μg/m^3, which is below the Korean standard for subway platforms (1.5E+2 μg/m^3) (Park et al. 2012; Ministry of the Environment). In Korea, the average PM_{10} concentrations were reported as 3.59E+2 and 1.37E+2 in subway station and train cabin, respectively in 2004 (Kim et al., 2008; Park and Ha, 2008). Moreover, in Seoul subway tunnel PM_{10} levels were recorded as 2.00E+2 μg/m^3 by Jung et al. (2012) and Park and Ha (2008). Globally, it has been found that the PM concentration is comparatively higher in subway systems (Table 1) than the other mode of transportation. In North America, it has been reported that PM_{10} levels are 1.13E+2 and 7.80E+1 μg/m^3 in Mexico City and Los Angeles, respectively (Mugica-Álvarez et al., 2012; Kam et al., 2011). In Europe, PM_{10} concentrations are in the range 1.93E+2 to 4.13E+2 μg/m^3 in Prague, Budapest, Istanbul, Milan, Athens, and Frankfurt subway systems (Cusack et al., 2015; Salma 2007; Şahin et al., 2012; Ozgen et al., 2016; Barmparesos et al., 2016; Gerber et al., 2014; Ripanucci et al., 2006). In Asia, significant PM_{10} levels are in the range of 3.66E+2 to 4.40E+1 μg/m^3 in Guangzhou, Beijing, Shanghai, Hong Kong, and Taipei subways (Chan et al., 2002b; Li et al., 2007; Ye et al., 2010; Chan et al., 2002a; Cheng and Yan, 2011).

Subway PM has more harmful components than surface PM. It has been reported that subway PM is 8–4 times more genotoxic than PM in outdoor air (Karlsson et al., 2005). Moreover, PM_{10}-bound elements are responsible for both non-CR and CR levels in a particular area. The average concentrations of Mn, Fe, Cr, V, Cu, Ni, Pb, and Zn were 2.40E−1, 2.93E+1, 1.47E−1, 5.00E−2, 2.00E−1, 6.40E−1, 9.70E−1, and 2.29E+0 μg/m^3, respectively (Supplementary Table 2). Among these, the average concentration was highest for Fe, followed by Zn and Pb. Fe, which is a principal component in metro PM, can be sourced from rails, wheels, sparkles from the brakes, and electric lodge tracks (Johansson and Johansson, 2003; Park et al., 2012). Furthermore, the presence of Fe along with Mn, Cr, and Cu indicates railroad track and draft line abrasion sources (Gehrig et al., 2007). Pb, which is a signature element for industrial emission sources, can be generated from the abrasion of construction materials on the platforms and outdoor dust infiltration through the passengers (Roy et al., 2019a). Moreover, Pb and Ni are commonly found in industrial and vehicular exhaust emission sources, respectively, while the presence of Al indicates crustal erosion (Jena and Singh, 2017; Roy et al., 2019b; Roy et al., 2016). PM from outdoor sources could have infiltrated through the ventilation system and commuter movements. Metal-enriched PM in the subway system not only produces secondary pollutants through movement and transformation but is also responsible for metal poisoning of subway commuters through long-term exposure (Wang et al., 1998). The endurance and perception of environmental pollution are different for individuals. Globally, significant levels of PM_{10}-bound Fe, Cu, Ni, Cr, and Mn concentrations have been reported in American, European, and Asian subway systems (Mugica-Álvarez et al. 2012; Cheng and Yan 2011; Zhang et al. 2019; Barmparesos et al. 2016).

3.2. *Human health risks in the subway passenger cabin*

3.2.1. *Non-CRs*

The HQs for the child and adult age groups in subway passenger cabins are listed in Table 2. For children, HQ_{ing} was highest for Pb (1.27E+1), followed by Cr (2.24E+0), Fe (1.91E+0), and Ni (1.46E+0) with significant (>1) levels, while HQ_{derm} was found to be significant for Cr (3.51E+1), Ni (7.44E+0), and Pb (2.58E+0). For adults, a significant HQ_{ing} level was obtained for Pb (4.97E+0) and HQ_{derm} levels for Ni (3.99E+0), Cr (1.88E+0), and Pb (1.38E+0). Conversely, HQ_{inh} levels were not significant in either children or adults. HIs were significant for all types of exposure and age groups (4.52E+1 and 2.43E+1 for children and adults, respectively). The results indicate that the Seoul subway passengers suffered from significant non-CRs (ingestion and dermal absorption) inside the subway cabins. In Seoul, the outdoor pollution level is comparatively better than inside metro cabins. Roy et al. (2019b) previously reported significant outdoor non-CR levels in Seoul through ingestion. However, Lovett et al. (2018) and Wang et al. (2016) reported insignificant levels of non-CR in the subway transit routes in Los Angeles and Tianjin ((HI: 4.10E−2 and 1.08E−3, respectively).

The elemental percentage contribution results for the non-CR level are shown in Fig. 1. For HQ_{ing}, the maximum contribution was

Table 2
Non-cancer risks via exposure to PM_{10}-bound metals in children and adults inside a subway passenger cabin.

Element	RfC_i (mg/m^3)	RfD_0 (mg/kg/day)	GIABS	Children			Adult		
				HQ_{ing}	HQ_{derm}	HQ_{inh}	HQ_{ing}	HQ_{derm}	HQ_{inh}
Mn	5.00E−05	1.40E−01		7.83E−02	0.00E+00	1.38E−01	3.07E−02	0.00E+00	1.38E−01
Fe		7.00E−01		**1.91E+00**	0.00E+00	0.00E+00	7.50E−01	0.00E+00	0.00E+00
Cr(VI)	1.00E−04	3.00E−03	1.30E−02	**2.24E+00**	**3.51E+01**	4.23E−02	8.76E−01	**1.88E+01**	4.23E−02
V	1.00E−04	5.00E−03		4.57E−01	0.00E+00	1.44E−02	1.79E−01	0.00E+00	1.44E−02
Cu		4.00E−02		2.28E−01	4.65E−02	0.00E+00	8.96E−02	2.49E−02	0.00E+00
Ni	2.00E+05	2.00E−02	4.00E−02	**1.46E+00**	**7.44E+00**	9.21E−01	5.73E−01	**3.99E+00**	9.21E−01
Pb		3.50E−03	1.00E+00	**1.27E+01**	**2.58E+00**	0.00E+00	**4.97E+00**	**1.38E+00**	0.00E+00
Zn		3.00E−01		3.49E−01	7.10E-02	0.00E+00	1.37E−01	3.81E−02	2.19E−04
HI				**1.94E+01**	**4.52E+01**	**1.12E+00**	**7.60E+00**	**2.43E+01**	**1.12E+00**

Note: Significant non-cancer risk values are in bold. PM, particulate matter; RfC, reference concentration; RfD, reference dose; GIABS, gastrointestinal absorption factor; HQ, hazard quotient (ing, ingestion; derm, dermal; inh, inhalation).

for Pb (65%), followed by Cr (12%), Fe (10%), and Ni (8%). Approximately 78% of the total HQ_{derm} level came from Cr, followed by Ni (16%) and Pb (6%). Ni contributed 83% of the HQ_{inh} value, followed by Mn (12%) and Cr (4%). The percentage contribution results show that Pb, Cr, and Ni are the elements presenting the highest non-CR levels inside subway cabins. Hence, for children, HQ_{derm} showed 69% of the total HI, followed by HQ_{ing} (29%) and HQ_{inh} (2%) (as shown in Fig. 2). For adult, HQ_{derm} had the maximum contribution (74%), followed by HQ_{ing} (23%) and HQ_{inh}(3%). HQ_{derm} made the highest contribution to the total HI levels for both age groups, as shown in Fig. 2. Maximum HQ_{derm} levels were obtained by the selection of values for exposure parameters such as SA, GIABS (gastrointestinal absorption factor), and AF and the reference dose (RfD) and concentration (RfC) levels (in mg/kg) of each metal considered in this study.

3.2.2. CRs in the subway passenger cabin

CR_{inh} values were estimated for PM_{10}-bound Cr(VI), Ni, and Pd (Table 3). The total CR_{inh} level was compared to the ILCR value calculated for the same PM_{10}-bound elements (Table 3). For children, the CR_{inh} value was found to be significant ($>10^{-6}$) for Cr(VI) (7.98E−6), while for adults, Cr(VI) and Ni showed significant CR_{inh} levels (3.77E−5 and 2.56E−6, respectively). Cr(VI) showed a five-fold higher CR for adults than children. Similarly, Wang et al. (2016) reported significant CR_{inh} levels for $PM_{2.5}$-bound Cr (2.33E−06) at the Tianjin subway in China. The total CR_{inh} levels were also found to be approximately five times higher for adult (4.15E−5) than for children (8.79E−6), as shown in Fig. 3. Hence, the ILCR level for Cr(VI) was estimated as 1.46E−5 for the adult group, which was 1.8 times higher than for the children group (7.89E−6). A comparative study of the total CR using CR_{inh} and ILCR for inhalation exposure for children and adult is shown in Fig. 3. Total CR_{inh} and ILCR were at the same level for the children group where as for adults, CR_{inh} was slightly higher than ILCR. However, the CR_{inh} and ILCR levels for the individual groups showed the same range of risks. The CR_{inh} levels were justified using the ILCR values for both age groups, with a slight deviation for the adults. The CR_{inh} and ILCR levels were less than the acceptable lifetime carcinogenic risk levels (1×10^{-6} to1 $\times 10^{-5}$) for children (Xu and Hao, 2017)but slightly higher than the upper limit of the acceptable lifetime carcinogenic risk levels in subways for adults (1×10^{-6} to 1×10^{-4}), although still within the acceptable range of CR for regulatory purposes set out by USEPA (Widziewicz and Loska, 2016), as shown in Fig. 3. CR was significantly higher for the adult group than the children group. Jung et al. (2012) reported a significant CR at the subway tunnel in Korea, while Lovett et al. (2018) reported similar CR (4.20E−5) in a subway transit route in Los Angeles; this also exceeded the acceptable range (1×10^{-6} to 1×10^{-5}) of the WHO lifetime carcinogenic risk for commuters. CR is categorized as very low ($\leq 10^{-6}$), low (10^{-6} to 10^{-4}), moderate (10^{-4} to 10^{-3}), high (10^{-3} to 10^{-1}), and very high ($\geq 10^{-1}$) by the New York State Department of Health (2012). In their study, low CR levels were found for both age groups of subway commuters.

CR_{inh} calculated by the Monte Carlo probability density function showed similar risk levels to actual CR_{inh}. The Monte Carlo simulation predicted mean CR_{inh} levels of 2.07E−5 and 8.97E−06 for adults and children, respectively (Fig. 4). Exposure duration had a strong influence on the CR levels for both age groups.

The percentage contribution of each element was calculated to recognize their potential CR element in the study area. The percentage contributions of the metals to the total CR_{inh} and ILCR showed the same results for both age groups. Cr(VI) showed the highest level, with a contribution of 91%, followed by Ni (8%) and Pb (1%), as shown in Fig. 3. Hence, Cr(VI) was identified as the highest potential carcinogen inside the subway passenger cabin. Past reports have revealed Cr and Ni as marker components of oil ignition sources (Song et al., 2001; Morawska and Zhang, 2002; Lee et al., 2002), thus indoor/outdoor combustion process could be the possible source of Cr in the metro (Chillrud et al., 2004). In addition, Ni and Pb are markers for vehicular emission sources (Lim et al., 2010). These components could originate from diesel vehicles stuck in traffic jams around evening time. Park et al. (2014) found that oil burning sources contributed 17% of the total PM_{10} level in a metro tunnel, while Park et al. (2012) identified 52.5% inorganic components, 37.3% other material, and 10.2% anions as the predominant sources in subway passenger cabins. In addition, the significant CR and non-CR risk levels were due to the PM_{10}-bound Cr, Ni, and Pb in the subway passenger cabins in the SMS. These components could be markers for both inward contamination (e.g. oil ignition and brake, rail, and wheel wear) and outer

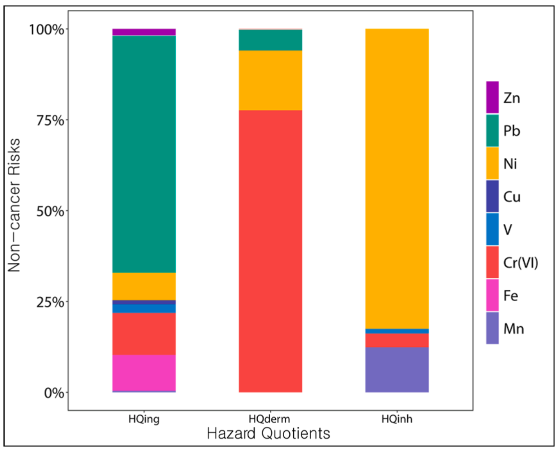

Fig. 1. Percentage contributions of PM_{10}-bound metals to non-cancer risks.

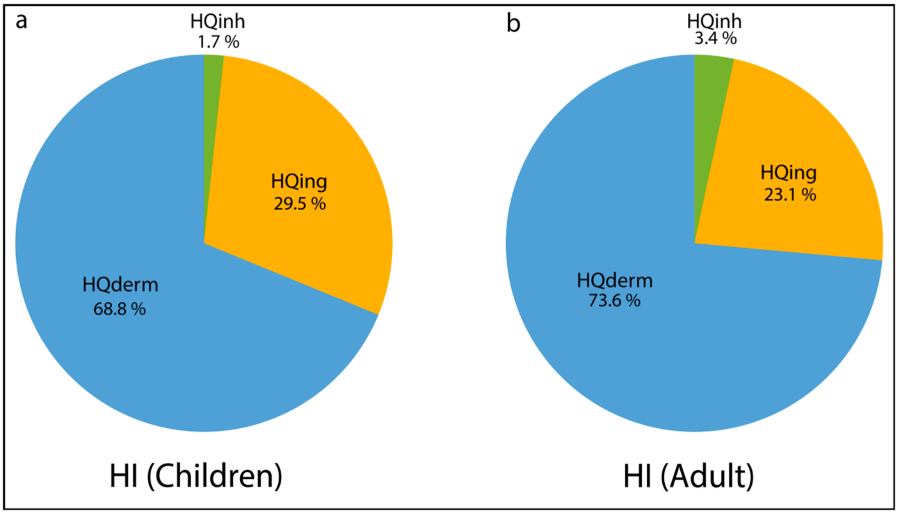

Fig. 2. Percentage contribution of hazard quotients (HQs) to the hazard indexes (HIs) for children and adults inside the subway cabin. Note: ing, ingestion; derm, dermal; inh, inhalation.

Table 3
Cancer risks for inhalation exposure to PM_{10}-bound carcinogenic metals for children and adult inside a subway passenger cabin in the SMS.

Element	IUR (μg/m^3)	CSF$_i$ (mg/kg day)	Children		Adult	
			CR$_{inh}$	ILCR	CR$_{inh}$	ILCR
Cr(VI)	1.20E−02	4.10E+01	**7.98E−06**	**7.89E−06**	**3.77E−05**	**1.46E−05**
Ni	2.60E−04	9.10E−01	7.52E−07	7.61E−07	**3.56E−06**	**1.41E−06**
Pb	1.20E−05	4.20E−02	5.26E−08	5.32E−08	2.49E−07	9.88E−08

Note: Significant cancer risk values are in bold. IUR, inhalation unit risk; CSF, contaminant specific factor; CR$_{inh}$, cancer risk (inhalation); ILCR, incremental lifetime cancer risk.

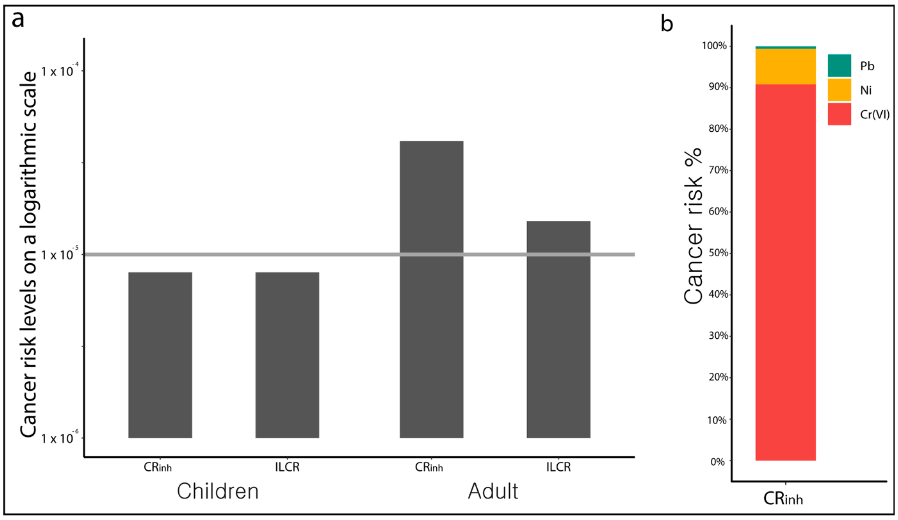

Fig. 3. Total cancer risks via inhalation exposure and percentage contribution of PM_{10}-bound metals in children and adults inside the subway cabin. Note: CR$_{inh}$, cancer risk (inhalation); ILCR, incremental lifetime cancer risk. The value Zero (0) on Y axis is indicating the risk level value > 10^{-6}; 1 × 10^{-5} is acceptable life time carcinogenic risk level, WHO (Xu and Hao, 2017).

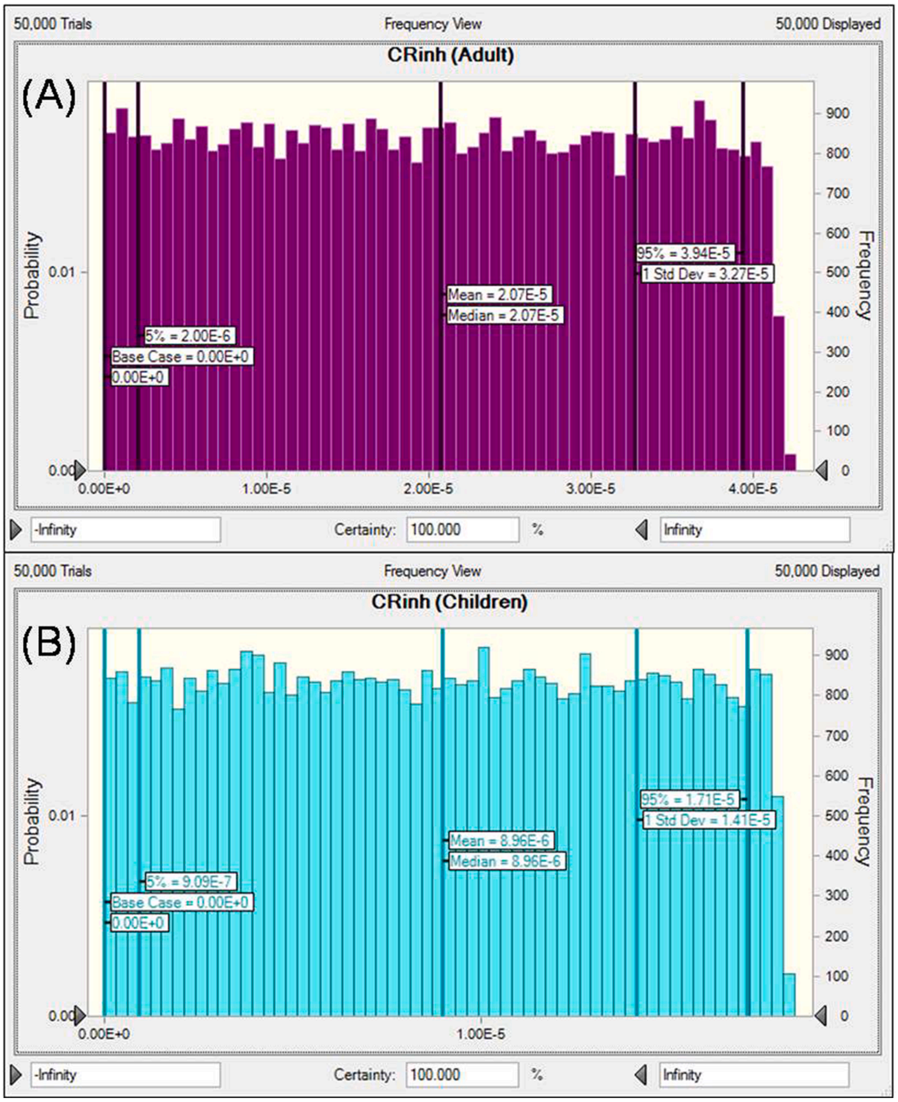

Fig. 4. Probability density functions of the inhalation cancer risks predicted for (A) adult and (B) children inside a subway cabin. Note: CR_{inh}, cancer risk (inhalation).

contamination (e.g. street and soil dust) sources.

4. Conclusions

Subways, which are comfortable and rapid transport systems and the most preferred transportation method for commuters in 60 countries, have been identified as a potential health risk zone for commuters. The assessment of human health risks in an indoor microenvironment for PM10-bound trace metals in a subway passenger cabin is a unique and important area of study in developed and developing countries. In this study, the SMS passenger cabin had lower PM_{10} concentration levels compared to the indoor air quality standard set by the Korean Ministry of the Environment, although the human health risks (CR and non-CR) associated with PM_{10}-bound metals was found to be significant for both children and adults. The CRs were estimated to be within the acceptable limit of the lifetime carcinogenic risk level for subways for the children group (1×10^{-6} to 1×10^{-5}). The adult group showed a slightly higher risk level than the acceptable limit of lifetime carcinogenic risk ($>1 \times 10^{-5}$). Overall, low CR_{inh} levels were found for both age groups of subway commuters in the SMS. PM_{10}-bound Cr, Ni, and Pb, potential elements for non-CR and CR, were at high levels. Among all the elements, Cr(VI) showed the highest contribution (91%). Both internal and outdoor pollution sources could be responsible for the risk levels inside the passenger cabins. These elements can enter subway systems through vents and be transported to passenger cabins through the clothing and shoes of passengers. Moreover, source control and the ability of air-cleaning technology can be useful to control the pollution levels in the subway. In spite of the fact that this investigation is centered on a specific city tram framework in

Korea but it could be a good model for global subway air pollution and it health risk level related research. In addition, the outcomes of this research can be useful for subway commuters, scholars, and policymakers to bring about a pollution-free healthy under ground transportation system.

5. Capsule

Cancer risk levels for adult were found slightly higher than the acceptable upper limit of the lifetime carcinogenic risk level for subway commuters.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2020.102618.

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