보건학석사 학위논문

Indoor Levels and Emission Rate of Ultrafine Particles from Resurfacer in Ice Rink

실내 아이스링크장의 정빙기 사용으로 인한 초극미세입자(UFP)의 농도수준과 방출률

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이 논문을 보건학석사학위 논문으로 제출함

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Abstract

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Hazardous pollutants from fuel-powered resurfacers can be accumulated in indoor ice skating rinks. The purpose of this study was to determine indoor ultrafine particle (UFP) levels in ice rinks and to characterize UFP decay and emission rates. All fifteen public ice rinks in the Seoul metropolitan area were investigated for UFP and carbon monoxide (CO) concentrations from January to March, 2012. UFP concentrations were simultaneously measured by P-Trak and DiSCmini monitors, and CO concentration was measured by an electrochemical monitor. Three ice rinks did not show peaks in UFP concentrations, and one ice rink used two resurfacers simultaneously. The data from the 11 ice rinks were further analyzed. High peaks of UFP and CO concentrations were observed when the resurfacer was operated. The average air change rate in ice rinks was 0.21 ± 0.13 h^{-1}. Decay rates of UFP number concentrations by the P-Trak and DiSCmini in the 11 ice rinks were 0.54 ± 0.21 h^{-1} and 0.85 ± 0.34 h^{-1}, respectively. The decay rate of UFP surface area concentration was 0.33 ± 0.15 h^{-1}. The average emission rates of UFP number concentrations by P-Trak and DiSCmini were $1.2 \times 10^{14} \pm 6.5 \times 10^{13}$ particles min^{-1} and $3.3 \times 10^{14} \pm 2.4 \times 10^{14}$ particles min^{-1}, respectively. The average emission rate of UFP surface area concentration was $3.1 \times 10^{11} \pm 2.0 \times 10^{11}$ μm^2 min^{-1}. High UFP and CO concentrations were associated with resurfacing process. DiSCmini measured higher decay and emission rates than P-Trak due to their different measuring mechanisms and size ranges. The estimated decay and emission rates may be useful to determine the appropriate ventilation levels and establish a source reduction plan.

Keywords: ice rinks, ventilation rate, ultrafine particle, decay rate, emission rate

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Ⅰ. Introduction

Ice skating rinks have become popular recreational locations. Their indoor air quality is a growing concern due to emission of hazardous pollutants from resurfacers in enclosed indoor environments (Guo et al., 2004). The resurfacer is periodically used to maintain a smooth ice surface and is often powered by propane or gasoline with an internal combustion engine. While resurfacing ice rinks, the resurfacers generate combustion by-products, which differ based on the fuel and engine types of the resurfacer.

Carbon monoxide (CO) poisoning was first identified in 1971 (Anderson, 1971). Malfunctioning indoor ice resurfacers increased the CO concentration up to 250 ppm. Furthermore, several indoor ice rinks were found to have high CO levels in the Boston area (Spengler et al., 1978); 82% of the hourly concentrations exceeded the 1-h National Ambient Air Quality Standard of 35 ppm.

When resurfacer fuel was replaced with propane, the incidence of CO poisoning decreased. However, propane-fueled resurfacers generated high levels of nitrogen dioxide (NO_2) due to their increased combustion temperatures. Enclosed ice rinks in several countries have been monitored and found to have high levels of NO_2 due to propane-fueled resurfacers. Most ice rinks had indoor levels of NO_2 at more than 100 ppb (Levy et al., 1998).

Other emission pollutants from resurfacers were total volatile organic compounds (TVOC) and particulate matter less than 2.5 μm of aerodynamic diameter ($PM_{2.5}$). The 3-h level of TVOC concentrations in five ice arenas in Finland ranged from 150 to 1200 μg m^{-3} (Pennanen et al., 1997). Recently, TVOC and $PM_{2.5}$ levels in ice rinks in Hong Kong ranged from 550 to 765 μg m^{-3} and 28 to 62 μg m^{-3}, respectively (Guo et al., 2004).

Ultrafine particles (UFP) with an aerodynamic diameter of less than 100 nm are one of pollutants of indoor ice rinks due to the combustion process of ice resurfacers (Rundell, 2003). Ultrafine particle is growing interest for their roles in respiratory health effects (Donaldson et al., 2002; Donaldson et al., 2001; Peters et al., 1997). Several animal studies demonstrated adverse effects toward the lung, heart, and vascular tissue (Harder et al., 2005; Nemmar et al., 2003; Oberdorster et al., 1992; Oberdorster et al., 1996). Furthermore, due to quantum dot penetrating stratum corneum and localization within the epidermal layers, the skin is a potential pathway for UFP exposure (Ryman-Rasmussen et al., 2006).

The UFP levels in ice rinks have not been well characterized, although fuel-powered resurfacers generated hazardous small particles. To date, only one study has investigated UFP levels in ice rinks (Rundell, 2003). That study was conducted in 10 indoor ice arenas in New York, USA. Four ice arenas used propane-fueled resurfacers and the other used gasoline-fueled resurfacers including a gasoline-powered edging machine. A gasoline-powered ice edger was used to shave down the edges of the rink, which ice resurfacers cannot access. This study indicated that the primary indoor source of PM_1 in the ice arenas was the internal combustion engines of fuel-powered resurfacers and ice edgers.

Indoor UFP levels can be affected by the decay and generation of UFP and by ventilation. However, information on the decay and emission rates of UFP from fueled-powered resurfacers in ice rinks is minimal. Most studies have evaluated the decay and emission rate of particles from cooking activities in residential locations (He et al., 2004; Olson and Burke, 2006; Wallace et al., 2004).

A mass balance model can be applied to estimate the emission rates of UFP. To determine emission rates, the model requires information on factors such as the air change rate (ACH), decay rate of pollutants, and volume of the indoor space.

The purposes of this study were to determine the indoor levels of UFP and characterize their decay and emission rates from resurfacers. CO and UFP concentrations were continuously monitored to estimate the air change rate (ACH) as well as UFP decay and emission rates.

Ⅱ. Methods

2.1 Subjects and measurement methods

Fifteen of all seventeen indoor ice rinks located in the Seoul metropolitan area were investigated from January to March, 2012. Two rinks were excluded since one was not open to the general public, and another was a part of an amusement park. The 15 ice rinks were monitored over 2 days. Each day, the sampling was completed in approximately 4 h, which included one to two resurfacing periods. Outdoor measurements (15 min each) were conducted before and after the indoor measurements. For indoor measurements, instruments were placed on the first or second step of the spectators' benches. For outdoor measurements, instruments were located adjacent to the facility with a height of 1.5 m above the ground. The inlets of instruments were placed away from any direct emission sources.

Real-time monitors were applied to obtain continuous UFP and CO concentrations. UFP number concentrations were measured by P-Trak (model 8525; TSI, Shoreview, MN, USA) and DiSCmini (Matter Aerosol, Wohlen, Switzerland) monitors. CO was measured with an electrochemical monitor (model 435; Testo AG, Lenzkirch, Germany). Temperature was measured by a HOBO U10 data logger (Onset, Bourne, MA, USA). The indoor volume of ice rinks was estimated by a field technician.

A P-Trak monitor, condensation particle counter (CPC), have been used in other studies to estimate UFP number concentration (Chao et al., 2003; Matson, 2005; Zhu et al., 2005). The instrument includes a condensation section in which particles are drawn through a saturator tube and mixed with *iso*-propanol vapor. This section allows particles to grow into larger droplets, which can be counted using a laser beam and photo-detector with particle sizes ranging from 0.02 to 1 μm. Zero calibration was performed prior to each measurement, as recommended by the manufacturer.

DiSCmini is a miniature diffusion size classifier. This instrument is based on the electrical charging mechanism of the aerosols (Fierz et al., 2008); generated positive air ions from a corona discharge are mixed with the aerosol. The particles were then detected in two stages. During the first stage, small particle deposits form by diffusion, while in the second stage, all other particles are captured by a high-efficiency particle filter. The average particle size (mode diameter) ranged from 10 to 300 nm, which was estimated by the ratio of the filter current to the diffusion current. Furthermore, the number of particles and alveolar lung-deposited surface area were also determined based on the total current.

The CO monitor used an electrochemical method, which limited current density measured at the electrode surface.

All instruments (excluding the HOBO U10) were set to log-in intervals of 30 s or applied averages of 30 s of data from shorter logging intervals to match each data point. The HOBO U10 was set to a logging interval of 5 min.

2.2 Calculation of the air change rate

Indoor ventilation rates play an important role in indoor pollutant levels. Since fuel-powered resurfacers generated CO, the continuous CO concentration profiles after resurfacing could be applied to estimate ACH (Lee et al., 1994b). Assuming complete mixing inside the rink, no chemical reaction with CO, and negligible penetration of outdoor CO concentration, the ACH (h^{-1}) could be calculated by the following equation,

$$\ln\left[\frac{C_{in\_CO}\,(t)}{C_{in\_CO}\,(0)}\right] = -\,\mathrm{ACH}\cdot t \qquad (1),$$

where

$C_{in\_CO}\,(t)$: Indoor concentration of CO at time t (ppm)

$C_{in\_CO}\,(0)$: Indoor concentration of CO at time 0 (ppm)

ACH : Air change rate (h^{-1})

t : Elapsed time (h)

2.3 Estimation of the UFP decay rate

The continuous UFP concentration profiles after resurfacing were applied to estimate decay rate of UFP (K) (Abt et al., 2000; He et al., 2005). Assuming well-mixed condition, the constant ACH and K, zero penetration coefficient of outdoor UFP concentration, and no indoor emission sources (G = 0), the K could be calcuated by the following time-dependent equation,

$$\ln\left[\frac{C_{in\_UFP}(t)}{C_{in\_UFP}(0)}\right] = -(K + \text{ACH}) \cdot t \qquad (2),$$

where

$C_{in\_UFP}(t)$: Indoor concentration of UFP at time t (particles cm^{-3} or $\mu m^2 cm^{-3}$)

$C_{in\_UFP}(0)$: Indoor concentration of UFP at time 0 (particles cm^{-3} or $\mu m^2 cm^{-3}$)

K : Decay rate of UFP (h^{-1})

By plotting t over ln[$C_{in\_UFP}(t)/C_{in\_UFP}(0)$], slope of decay could be determined. Since the slope included ACH and UFP decay rate, the estimated ACH by CO was subtracted.The ACH and decay rate of UFP were calcuated when continous decaease of CO and UFP concentraion were maintined for 30 min. The ACH and decay rate of UFP were accepted when the R^2 value of regression was >

0.5. If the ACH was not available for a specific decay period, the average ACH of other ice rinks was applied to calculate the decay rate.

2.4 Estimation of the UFP emission rate

The mass-balance model could be described as the following equation

$$\frac{dC_{in\_UFP}}{dt} = P\cdot \text{ACH}\cdot C_{out\_UFP} + \frac{G}{V} - (\text{ACH}+K)\cdot C_{in\_UFP} \qquad (3),$$

where

dC_{in_UFP}/dt : UFP concentration change with time (particles cm^{-3} min^{-1} or μm^2 cm^{-3} min^{-1})

P : Penetration coefficient across the envelope of ice rinks

C_{out_UFP} : Outdoor concentration of UFP (particles cm^{-3} or μm^2 cm^{-3})

G : Emission rate of UFP from resurfacers (particles min^{-1} or μm^2 min^{-1})

V : Volume of the indoor ice rinks (cm^3)

C_{in_UFP} : Indoor concentration of UFP (particles cm^{-3} or μm^2 cm^{-3})

Assuming negligible penetration coefficient of UFP (P = 0), G could be estimated by the equation (4) by rearranging the equation (3)

$$G = \left[(\text{ACH} + K) \cdot C_{in\_UFP} + \frac{dC_{in\_UFP}}{dt}\right] \cdot V \qquad (4).$$

The episode of UFP generation was selected when indoor UFP levels increased by more than 5% after resurfacing for 30 s. The endpoint of emission rates was determined as when the UFP concentration peaked after resurfacing. Similar criteria were used in a previous report (Wallace et al., 2004). Average values of the decay and emission rates of UFP from emission episodes in each ice rink were applied.

2.5 Statistical analysis

The Kolmogorov–Smirnov test was applied to test the normality of UFP and CO concentrations. Since the distribution was not completely regular, a nonparametric test was employed. The Wilcoxon signed-ranks test was used for paired comparisons of the 2 days, as well as indoor and outdoor concentrations of UFP and CO. Linear regression was used to assess the relationship of the UFP number concentrations between P-Trak and DiSCmini as well as to estimate the ACH and decay rate of UFP. Spearman correlation coefficient was used to determine association between decay and emission rate of UFP and age of resurfacers. The resurfacer ages were divided into two groups (gruop1: age < 7 and group2: age ≥ 7) based of median value of resurfacer ages. SAS 9.2 (SAS Institute Inc., Cary, NC, USA) was used for all statistical analyses. For all tests, a *P*-value of 0.05 was regarded as significant. SigmaPlot 9.0 (Systat Software, Inc., Chicago, IL, USA) and Microsoft Office Excel 2010 (Microsoft Corp., Redmond, WA, USA) were used to draw graphs.

Ⅲ. Results

3.1 Characteristics of indoor ice rinks and resurfacers

The average indoor volume of 15 ice rinks was 39,186 ± 79,114 m^3 and ranged from 6440 to 324,000 m^3. Table 1 shows the brand names and operating fuels of each ice resurfacer. One of the ice rinks used two gasoline-fueled resurfacers during the resurfacing period. Overall, three brands of resurfacers were used to maintain ice rinks. The Zamboni resurfacer was used in 11 ice rinks (69%), Olympia resurfacers were used in three (19%), and Dupon in two (13%). Twelve of the 16 ice resurfacers (75%) were powered by propane. Three gasoline-fueled (19%) and one electric battery-powered (6%) resurfacers were used in the ice rinks.

Table 1. Brand names and operating fuels of resurfacers in 15 ice rinks

Brand name	Operating fuel			Total
	Propane	Gasoline	Electricity	
Zamboni	9	2	-	11 (69 %)
Olympia	2	1	-	3 (19 %)
Dupon	1	-	1	2 (13 %)
Total	12 (75 %)	3 (19 %)	1 (6 %)	16 (100 %)

3.2 UFP and CO concentrations in the ice rinks

Of the 15 ice rinks, results of four rinks were not included in further analysis. Three of the four ice rinks did not show peaks in UFP concentrations. One of the three ice rinks used a battery-powered resurfacer and another one operated full ventilation. Third one did not use a resurfacer during the measurement period due to small number of ice skating rink users. One of the four ice rinks used two gasoline-fueled resurfacers simultaneously.

Overall, indoor and outdoor concentrations of UFP and CO between two repeated measurements in 11 ice rinks are shown in Table 2. Both indoor and outdoor UFP number concentrations by P-Trak and DiSCmini and UFP surface area concentrations did not differ significantly between the 2 days. While the indoor CO concentrations did not differ significantly between the 2 days, the outdoor CO concentrations showed a significant difference ($P < 0.05$). UFP number concentrations by P-Trak and DiSCmini and UFP surface area concentrations did not differ significantly between indoor and outdoor environments. However, indoor CO concentrations were significantly higher than outdoor CO concentrations ($P < 0.05$).

Table 2. Indoor and outdoor concentrations of UFP and CO between two repeated measurements

	Location	Visit 1						Visit 2						* *P*-value
		N	Mean	SD	Median	Min	Max	N	Mean	SD	Median	Min	Max	
PNP (particlescm^{-3})	Ice rink	11	2.7×10^4	1.5×10^4	2.5×10^4	1.0×10^4	6.3×10^4	11	3.2×10^4	2.8×10^4	2.0×10^4	9.4×10^3	9.6×10^4	0.83
	Outdoor	11	2.9×10^4	1.4×10^4	2.7×10^4	1.2×10^{14}	6.0×10^4	11	2.6×10^4	1.2×10^4	2.5×10^4	9.0×10^3	4.8×10^4	0.52
	** *P-value*		0.70						0.58					
PND (particlescm^{-3})	Ice rink	10	4.3×10^4	2.7×10^4	4.2×10^4	1.3×10^4	1.0×10^5	11	4.8×10^4	4.5×10^4	3.0×10^4	1.3×10^4	1.5×10^5	0.28
	Outdoor	11	4.2×10^4	2.1×10^4	3.7×10^4	1.6×10^4	8.9×10^4	11	3.8×10^4	2.0×10^4	3.4×10^4	1.2×10^4	8.4×10^3	0.52
	P -value		0.92						0.64					
SA (μm^{2}cm^{-3})	Ice rink	10	97.0	49.2	91.7	34.7	201.1	11	110.6	97.5	84.8	27.8	347.5	0.16
	Outdoor	11	123.6	53.8	115.4	66.6	235.0	11	98.1	55.8	90.9	37.1	234.1	0.12
	P -value		0.13						0.52					
CO (ppm)	Ice rink	11	33.9	34.9	18.1	1.6	90.4	11	33.2	32.1	22.2	4.0	91.3	0.21
	Outdoor	11	1.9	2.9	0.8	0.0	8.9	11	3.5	4.8	1.0	0.0	13.1	< 0.05
	P -value		< 0.05						< 0.05					

**P-value* between two visiting days, Wilcoxon's signed rank test
***P-value* between indoor and outdoor, Wilcoxon's signed rank test
PNP: particle number concentration of P-Trak
PND: particle number concentration of DiSCmini
SA: alveolar lung-deposited surface area concentration of DiSCmini

Indoor UFP and CO levels of ice rinks varied due to resurfacing. Figure 1 shows the typical temporal profiles of indoor UFP and CO concentrations. When the resurfacers were operated, UFP and CO concentrations increased during the resurfacing period, and then gradually decreased after resurfacing.

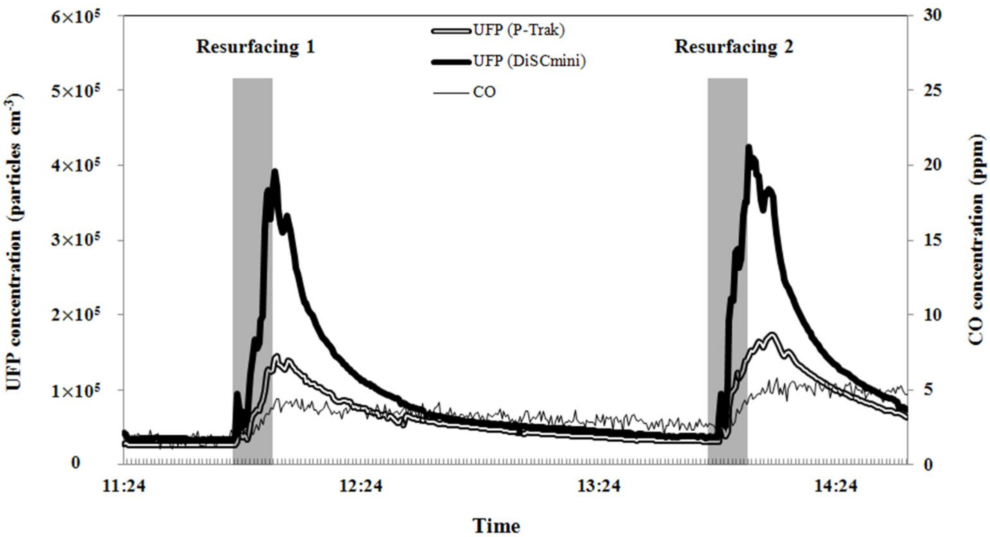

Figure 1. Typical temporal profiles of indoor levels of UFP and CO concentrations.

A 1-h average of CO concentrations, subtracted from the indoor measurement, was compared with the 1-h WHO guidelines for CO concentrations (25 ppm) (WHO., 2005). The 1-h average CO concentrations of 11 ice rinks were 35.7 ± 35.6 ppm. Four indoor ice rinks exceeded the 1-h WHO guidelines of CO concentrations (77.5 ± 20.3 ppm), while seven ice rinks complied with the guidelines (11.8 ± 8.5 ppm).

3.3 Comparison of two different particle number counters

Two different instruments were used to estimate UFP number concentrations. Figure 2 shows correlations of UFP number concentrations between P-Trak and DiSCmini for indoor (4-h measurements) and outdoor (15-min measurements) of the 11 ice rinks in two separated days. The concentrations by DiSCmini were 1.53 times higher than those by P-Trak. The correlation coefficients (R^2) were 0.94 between two instruments. The correlation between two instruments was not different by indoor and outdoor.

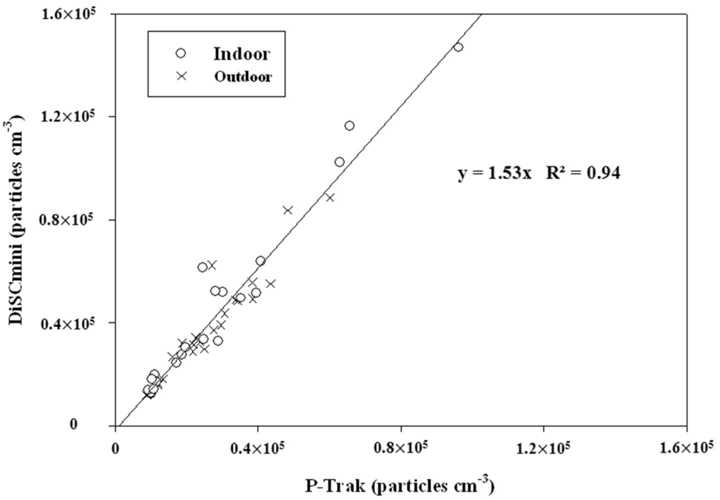

Figure 2. Correlations of UFP number concentrations between P-Trak and DiSCmini for the indoor and outdoor environment

3.4 Average particle size (mode diameter) during resurfacing

The average particle size (APS) was measured by DiSCmini in 11 ice rinks. Figure 3 shows typical temporal profiles of the average particle size during the indoor sampling period. The APS rapidly decreased when the resurfacer was operated, and it gradually increased after resurfacing.

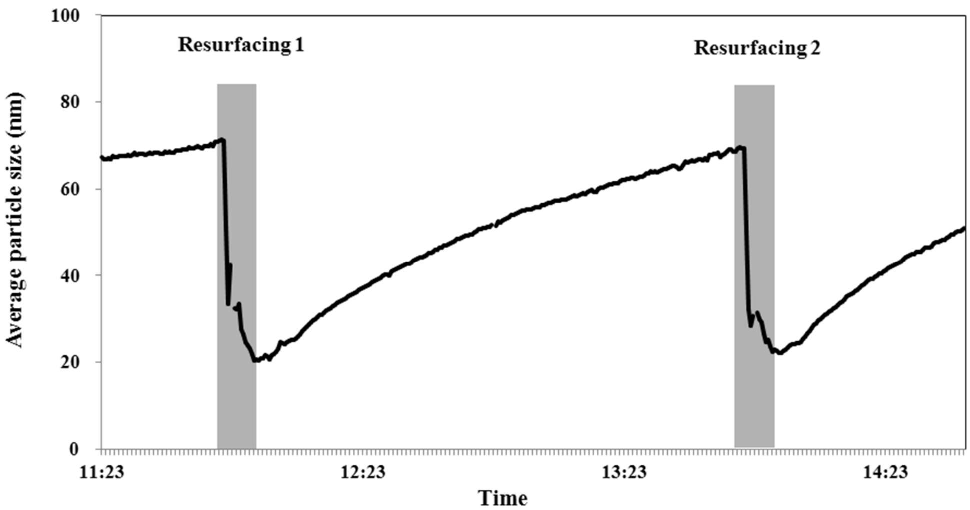

Figure 3. Typical temporal profiles of average particle size in ice rinks.

3.5 Air change rate

By continuously monitoring the CO concentration in the ice rinks, the ACH after resurfacing were estimated by equation (1). The ACH was determined in eight of eleven ice rinks, since the R^2 of CO decay from the linear regression model was less than 0.5 in three ice rinks. The average ACH in the eight ice rinks was 0.21 ± 0.13 h^{-1} and ranged from 0.06 to 0.48 h^{-1}.

3.6 UFP decay rate

CO and UFP concentrations after resurfacing were used to estimate the UFP decay rate. An example CO and UFP decay curve is shown in Figure 4.

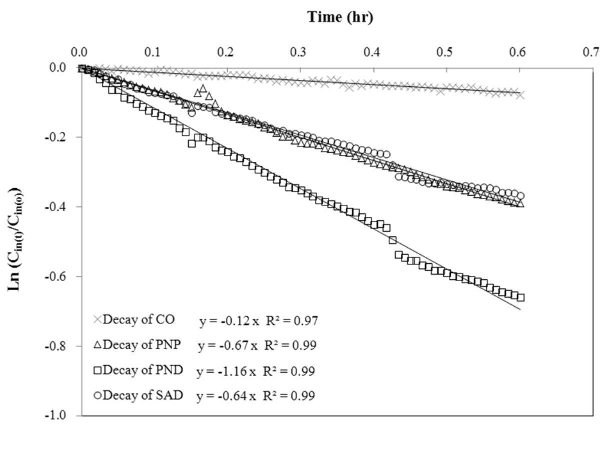

Figure 4. An example CO and UFP decay curve

UFP decay rates were estimated by equation (2). Figure 5 shows the UFP decay rates in the 11 ice rinks. The average decay rates of UFP number concentrations by P-Trak and DiSCmini were $0.54 \pm 0.21\ h^{-1}$ and $0.85 \pm 0.34\ h^{-1}$, respectively. The average decay rate of UFP surface area concentration was $0.33 \pm 0.15\ h^{-1}$. The UFP decay rates were not associated with other variables.

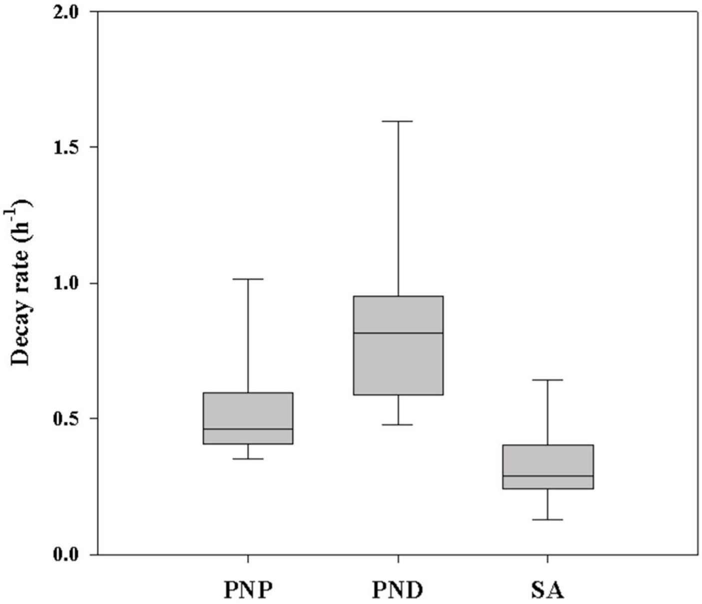

Figure 5. UFP decay rates in ice rinks

3.7 UFP emission rates from the resurfacers

Based on the estimated ACH and UFP decay rate, UFP emission rates were determined by equation (4). Figure 6 shows UFP emission rates at the 11 ice rinks. The average emission rates by P-Trak and DiSCmini were $1.2 \times 10^{14} \pm 6.5 \times 10^{13}$ particles min^{-1} and $3.3 \times 10^{14} \pm 2.4 \times 10^{14}$ particles min^{-1}, respectively. The average emission rate of UFP surface area concentration was $3.1 \times 10^{11} \pm 2.0 \times 10^{11}$ μm^2 min^{-1}.

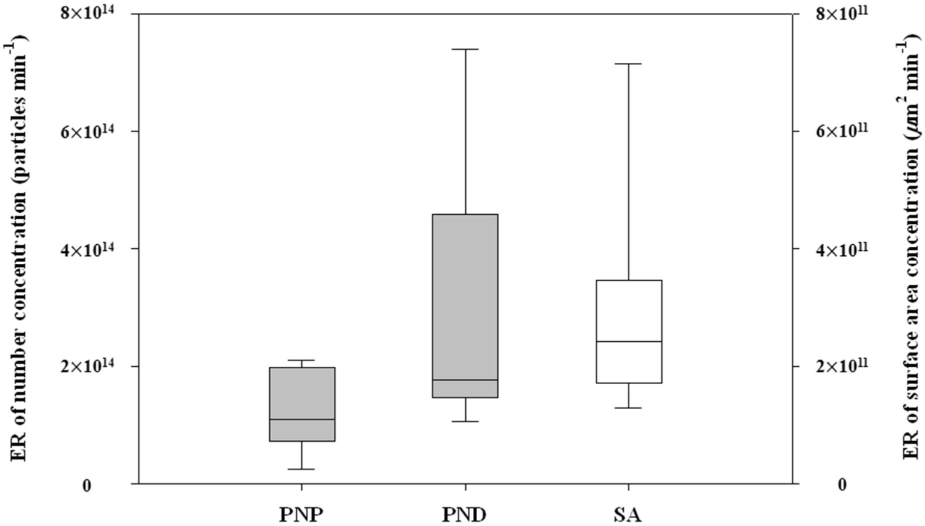

Figure 6. UFP emission rates of number concentrations (gray boxes) and surface area concentration (white box) in ice rinks. ER, emission rate.

Significant correlation was observed between the UFP emission rate and resurfacer age. The Spearman correlation coefficient (R) between emission rates of UFP number concentrations by P-Trak and DiSCmini and resurfacer ages were 0.87 and 0.75, respectively ($P < 0.05$). The Spearman correlation coefficient between emission rates of UFP surface area concentrations and resurfacer age was 0.87 ($P < 0.05$). No other variable were significant.

Ⅳ. Discussion

4.1 Indoor UFP and CO concentrations in the ice rinks

The 4-h average indoor UFP levels in the ice rinks were similar to the outdoor levels. Indoor UFP levels in locations without UFP sources were generally lower than outdoors. A lower indoor UFP levels were observed in three offices in Sweden (Matson, 2005). The I/O ratios of the three offices ranged from 0.42 to 0.52, 0.62 to 0.73, and 0.54 to 0.86. Lower indoor UFP concentrations were also observed in four apartments without smoking, cooking, or cleaning activities in Los Angeles, USA (Zhu et al., 2005). The I/O ratios ranged from 0.6 to 0.9 for larger UFP (70–100 nm). The I/O ratios ranged from 0.1 to 0.4 for smaller UFP (10–20 nm).

The presence of significant and intermittent indoor sources was demonstrated by temporal UFP and CO profiles. During the resurfacing period, peaks in UFP and CO concentrations were observed in the ice rinks. High levels of UFP ice arenas were identified in New York, USA (Rundell, 2003). The average UFP concentration in 10 ice arena were 104,175 ± 11,208 particles cm^{-3} (range: 42,273–255,400) for indoor and 3820 ± 481 particles cm^{-3} (range: 1535–11,833) for outdoor. The indoor UFP concentrations were higher than results in this study. The differences may be due to the use of two different fuel-powered resurfacers, including a gasoline-powered edging machine in one ice arena. Different ventilation rates and amounts of resurfacing could affect the results. Since the 11 ice rinks in the Seoul metropolitan area were adjacent to the main road, outdoor UFP levels were higher than the results from the study in New York. Similar outdoor UFP levels were reported in a study in Athens, Greece. Average outdoor levels of UFP during 15-min measurements were 27.1×10^3 particles cm^{-3} in a school area (N = 29) and 26.3×10^3 particles cm^{-3} in a residential area (N = 225) (Diapouli et al., 2007).

The indoor air quality of CO in specific ice rinks was not acceptable. Four of 11 indoor ice rinks did not comply with the 1-h WHO limit of 25 ppm. The CO concentrations in the ice rinks was noncomplied with the WHO guideline were approximately 460% higher than the WHO limit. High levels of indoor CO were reported in other countries. The indoor CO concentrations ranged from 4 to 117 ppm in ice rinks powered by propane fuel (Lee et al., 1994a). Four of six ice rinks had higher CO levels than the reference limit of 25 ppm. The indoor levels of CO were investigated in Finnish ice arenas (Pennanen et al., 1997). The highest 1-h average CO level ranged from 17 to 29 ppm in five ice arenas. Two of five ice arenas used propane-fueled powered resurfacers and were in compliance with the 1-h WHO guidelines.

4.2 Different particle concentrations between P-Trak and DiSCmini

UFP can be measured by various methods. This study used two different instruments to measure indoor and outdoor levels of UFP number concentrations, i.e., P-Trak and DiSCmini. P-Trak measures particles ranging in size from 0.02 to 0.1 μm, utilizing a light scattering principle. DiSCmini measures particles ranging from 10 to 300 nm using an electrical charge mechanism. Each instrument has different measuring mechanisms and particle size ranges. Therefore, the outcomes may differ between the two instruments. The concentrations measured by DiSCmini were approximately 53% higher than those measured by P-Trak. The two instruments were well correlated.

The use of P-Trak near combustion sources has been shown to affect the reliability of the results. P-Trak showed good correlations (R^2 = 0.94) with a CPC (model 3022a; TSI) in an apartment located away from the freeway (Zhu et al., 2006). However, particles of approximately 25–30-nm in size that were freshly emitted from vehicles were underestimated. The performance of DiSCmini was tested by a CPC (model 3775; TSI) on a high-traffic highway (Fierz et al., 2011). The average particle concentration measured by DiSCmini was 18%, which was overestimated compared to the CPC with an R^2 of 0.90 on Switzerland's main east–west highway.

4.3 Estimation of average particle size of UFP in ice rinks

DiSCmini provided the average particle size (mode diameter). Average particle sizes significantly decreased during the resurfacing period. When resurfacing was complete, the APS increased gradually. This indicated that propane-fueled resurfacers generated a significant amount of small-sized UFP. The decrease in APS in ice rinks during resurfacing periods associated with the resurfacer combustion process.

The generation of small particles from combustion processes of vehicle engines was previously reported. The count median diameter (CMD) of 19.2-nm particles was identified when a liquefied petroleum gas (LPG)-powered vehicle was running at a speed rate of 100 km h–1 (Ristovski et al., 2005).

To characterize the size distribution of particles in ice rinks, the portable aerosol spectrometer (PAS, model 1.109; Grimm Technologies, Douglasville, GA, USA) was used during preliminary testing. This instrument had 31 size channels ranging from 250 nm to 3200 nm. However, no peaks or signals were detected for the indoor ice rinks. Although the operational temperature range of the instrument was 0–40ºC based on the manufacturer's manual, the instrument may be affected by low-temperature conditions. The indoor and outdoor temperature of 10 of the 11 ice rinks was 5.7 ± 2.2ºC (range: 3.0–9.2) and 6.3 ± 2.0ºC (range: 3.7–9.4), respectively.

4.4 ACH in ice rinks

The ACH in the 11 ice rinks were very low since most of the ice rinks were airtight and full ventilation was not used. This result was similar to an indoor ice rink study in Massachusetts in 1994. The average ACH of the indoor ice rinks was 0.21 h^{-1} under normal operating conditions (Lee et al., 1994b). However, the average ACH reached 1.82 h^{-1} when full mechanical ventilation was operated. A survey of 10 ice arenas in the Greater Boston and Nova Scotia area found that the ACH ranged from 0.1 to 3.5 h^{-1} (Demokritou et al., 2000).

4.5 UFP decay rate

No comparable studies of decay rates of UFP in ice rink have been published. Although no variables were significantly associated with the decay rates, one ice rink had high decay rate of UFP number and surface area concentrations. Decay rates can be associated with indoor volume, types of surface material, and air mixing status during decay period (Abadie et al., 2001; Abt et al., 2000; Nazaroff et al., 1993). The higher decay rate in the ice rink may be due to a different surface material on ceiling. The ceilings of most ice rinks were smooth and constructed of steel, plastic, or concrete. However, the ceiling of the ice rink with high decay rate was covered with a glass fiber film for acoustic isolation.

4.6 UFP emission rates from resurfacers

No comparable studies of emission rates of UFP from resurfacers have been published. The UFP emission rates were positively correlated with the resurfacer age. Emission rate of pollutants from machinery equipment can be affected by other factors such as engine temperature, maintenance and age of the equipment. Higher CO emission rate was observed in cooler engine of resurfacers (Lee et al., 1994b). Another study indicated that emission factors of particulate matter (PM) from light-duty gasoline vehicles (LDGV) increased with age of vehicles (Kuhns et al., 2004). Since most resurfacers in the rinks had periodical maintenance for a half year and similar engine temperature due to 2-hour regular resurfacings, resurfacer age might be only significant factor for UFP emission rate.

4.7. Limitations

Although the 15 public indoor ice skating rinks were investigated, data from 11 rinks were available for further analysis. The 11 ice rinks may be a limited to characterize indoor UFP levels, and decay and emission rates. However, the present study investigated all indoor ice rinks in the Seoul metropolitan area. Another limitation of this study was lack of size distribution of UFP. During preliminary testing, the portable aerosol spectrometer (PAS, model 1.109; Grimm Technologies, Douglasville, GA, USA) was used to characterize the size distribution of aerosol particles in indoor ice rinks. This instrument had 31 size channels ranging from 250 nm to 3200 nm. However, no peaks or signals were detected for the indoor ice rinks, while the monitor provided signal at outdoor location. The possible reason was that the monitor could not measure at the low temperature of ice rinks.

Penetration coefficient could not be estimated since the study did not measure indoor and outdoor UFP concentrations simultaneously. Assuming the zero penetration coefficient of UFP from outdoor to indoor may cause uncertainties. Previous studies have assumed penetration coefficient close to 1 for fine and coarse particles (Wallace, 1996). However, other studies have indicated that the penetration coefficient of UFP is less than 1 (Zhu et al., 2005). Penetration coefficients of 0.64 for particle sizes of 0.02–1 μm were estimated in six residences in Hong Kong (Chao et al., 2003). Zero penetration coefficient may overestimate UFP emission rates in this study. However, contribution of outdoor UFP to indoor UFP levels may be minimal with very low ventilation rates in ice rinks. Similarly, negligible outdoor particle (range: 0.015–6 μm) sources has also been used in another study (He et al., 2005).

In future studies, indoor ice rinks should be more investigated for indoor UFP levels, including the UFP decay and emission rates, since ice rinks use various resurfacer brands and operate fuels under different ventilation conditions. Furthermore, the size distribution of aerosol particles in ice rinks should be identified. To reduce the uncertainty of the model, infiltration of UFP in ice rinks should be estimated in future studies.

4.8 Suggestions

High UFP and CO concentrations have been found when ice resurfacers were operated. Therefore, the risk of UFP, CO exposure, and adverse health effects may be high to athletes and susceptible people, such as children who use ice rinks. To reduce hazardous combustion due to by-products generated from resurfacers, general recommendations are required. The replacement of fossil-fueled resurfacers with battery-powered machines is recommended. Also, the ventilation of the ice rinks could be increased. The replacement of battery-powered resurfacers may be expensive, and therefore, increasing the ventilation rates and reducing the number of resurfacers may be more practical.

V. Conclusion

Fifteen ice rinks in the Seoul metropolitan area were investigated. The 11 ice rinks were further analyzed for indoor levels of UFP and CO and decay and emission rates of UFP. The 11 ice rinks used propane-fueled resurfacers. High UFP and CO concentrations were associated with the resurfacing process. Indoor CO levels in several ice rinks were not acceptable. Most ice rinks had low ventilation rate. DiSCmini measured higher UFP decay and emission rates than P-Trak, since the two instruments have different measuring mechanisms and size ranges. The estimated decay and emission rates may be useful in determining appropriate ventilation rates and establishing UFP source reduction plans.

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국문초록

Indoor Levels and Emission Rate of Ultrafine Particles from Resurfacer in Ice Rink

실내 아이스링크장의 정빙기 사용으로 인한 초극미세입자(UFP)의 농도수준과 방출률

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연료를 사용하는 정빙 작업으로 인해 발생하는 유해 오염물질은 실내아이스링크 장에서 축적될 수 있다. 본 연구의 목적은 실내 아이스링크 장의 초극미세입자(UFP)의 농도수준을 파악하고, 정빙기

사용으로 인해 발생되는 UFP 의 감소율과 방출률을 정량화하고자 하였다.

2012 년 1 월부터 3 월까지 대한민국 수도권 지역에 있는 전체 15 개 실내 아이스링크 장에서 UFP 와 CO 농도를 측정하였다.
UFP 측정은 실시간 입자 수 농도 측정기인 P−Trak (model 8525, TSI, USA)과 DiSCmini (matter aerosol, Swiss) 모니터를 이용하였다. CO 측정은 전기화학 모니터 (model 435, Testo, Germany)를 이용하였다.

3 곳의 아이스링크 장에서 UFP 피크 값이 없었고 다른 한 곳은 정빙 시 두 대의 정빙기가 동시에 사용되었다. 11 곳의 실내아이스링크 장의 데이터를 추가 분석 하였다. 실내에서 정빙 작업 동안 UFP 와 CO 의 피크 값이 확인되었다. 아이스링크 장의 평균 환기율은 0.21 ± 0.13 h^{-1} 이었다. P−Trak 과 DiSCmini 로 측정된 11 개 아이스링크 장에서 평균 UFP 입자 수 농도의 감소율은 각각 0.54 ± 0.21 h^{-1} 그리고 0.85 ± 0.34 h^{-1} 이었다. 평균 UFP 표면적 농도의 감소율은 0.33 ± 0.15 h^{-1} 이었다. P−Trak 과 DiSCmini 로 측정된 평균 UFP 의 입자 수 농도 방출률은 각각 $1.2 \times 10^{14} \pm 6.5 \times 10^{13}$ particles min^{-1} 그리고 $3.3 \times 10^{14} \pm 2.4 \times 10^{14}$ particles min^{-1} 이었다. 평균 UFP 표면적 농도의 방출률은 $3.1 \times 10^{11} \pm 2.0 \times 10^{11}$ μm^2 min^{-1} 이었다.

UFP 와 CO 농도의 높은 피크 값은 정빙 작업과 매우 연관이 있었다. DiSCmini 로 측정된 UFP 감소율은 P−Trak 의 측정값 보다 더

높았는데 두 기기가 다른 측정 메커니즘과 범위를 가지고 있기 때문이었다. 산출된 UFP의 감소율과 방출률은 적절한 환기와 발생원 저감계획에 유용이 이용될 수 있을 것이다.

주요어: 아이스링크, 환기율, 극초미세입자, 감소율, 방출률

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