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Outdoor Tobacco Smoke Exposure by Distance

실외에서 흡연으로 인한 거리에 따른 간접흡연의 노출

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Abstract

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An increasing number of cities and countries have implemented outdoor smoking restrictions at building entrances. The purpose of this study was to determine outdoor tobacco smoke (OTS) exposure as a function of distance from the smoking source. The outcomes can lead to recommendations of the appropriate distance to minimize the influence of outdoor smoking. Outdoor concentrations of ambient particulate matter smaller than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) were measured at four different distances (1, 3, 6, and 9 m) from a simulated smoking source. Wind speed and direction were measured using a wind meter. A smoking doll was used to provide tobacco smoking for approximately 3 min. One smoking experiment consisted of 13 min (5 nonsmoking min, 3 smoking min, and 5 more nonsmoking min). The difference between mean $PM_{2.5}$ concentrations during smoking versus nonsmoking conditions was taken as the OTS exposure. A novel peak analysis was used to accurately assess the acute outdoor tobacco exposure. Average peak concentration and peak frequency were used for the analysis. The OTS levels were 72.7 $\mu g/m^3$, 11.3 $\mu g/m^3$, 4.1 $\mu g/m^3$, and 2.6 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The OTS levels decreased with increasing distance from the smoking source, although detectable OTS levels were measured even at 9 m. The OTS levels were significantly higher than zero at all distances. The OTS levels were highly associated with wind direction. Although the OTS levels were higher downwind of the source, the OTS levels were not significantly different directly downwind versus at an angle to the wind direction. The OTS levels were negatively associated with wind speed. The peak frequencies and average peak concentrations during smoking conditions were significantly greater than those under nonsmoking conditions. More frequent peaks of high concentration were observed at 9 m from the smoking source. To prevent OTS exposure, the minimal distance from a smoking source should be at least 9 m.

Keywords: Outdoor tobacco smoke, Secondhand smoke exposure, $PM_{2.5}$, Distance, Wind condition, Peak

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I. Introduction

Secondhand smoke (SHS) is composed of sidestream smoke (smoke released from the burning end of a cigarette) and exhaled mainstream smoke (smoke exhaled by the smoker) (U.S. Department of Health and Human Services 2006). SHS is also called environmental tobacco smoke (ETS) or passive smoking (Kesteloot 1986). SHS is a major source of indoor air pollution containing a mixture of more than 7,000 chemical by-products of tobacco combustion (U.S. Department of Health and Human Services 2010). These compounds include 3 air pollutants that meet the National Ambient Air Quality Standard criteria, 33 hazardous air pollutants regulated under the Clean Air Act, 47 pollutants of wastes whose disposal in solid or liquid form is regulated by the Resource Conservation and Recovery Act, 67 known human or animal carcinogens, and 3 industrial chemicals regulated under the Occupational Health and Safety Act (Repace 2007). No safe level of exposure to SHS exists, and breathing even small amounts of SHS can be harmful to human health (U.S. Department of Health and Human Services 2006).

SHS has been considered as the third leading preventable health hazard after active smoking and alcohol (Glantz et al., 1991). SHS exposure can have direct adverse effects on the cardiovascular system, interfering with the normal functioning of the heart, blood, and vascular systems in ways that increase the risk of heart disease (He et al., 1999). SHS can irritate and damage the lining of the airways and cause respiratory effects such as asthma, and can trigger respiratory symptoms, including cough, wheezing, and breathlessness (Hall et al., 2009; Sturm et al., 2004). SHS is associated with an increased risk for lung cancer (Brennan et al., 2004). Exposure of infants to SHS or smoking by women during pregnancy can cause sudden infant death syndrome (SIDS) and other health consequences (Tong et al., 2005; Abbott et al., 2012).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has concluded that the health risk from SHS exposure cannot be controlled by ventilation technology (American Society of Heating Refrigerating and Air-Conditioning Engineers 2005). Tobacco smoke in indoor environments most likely cannot be decreased to low enough levels through the use of ventilation technology. Operation of a heating, ventilating, and air-conditioning system can sometimes spread SHS throughout a building. The only proven way to protect the public health from SHS is to provide completely smoke-free environments, with no exceptions.

To improve the public health by reducing the public's exposure to SHS, many national and local governments have implemented an indoor smoke-free policy (Eriksen et al., 2008). This indoor smoking restriction has been effective at reducing SHS exposure in various indoor environments. Indoor levels of particulate matter smaller than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) were reduced by 93% after implementation of a smoke-free policy in Lexington, Kentucky, USA (Lee et al., 2008). Indoor $PM_{2.5}$ levels were reduced by 92% after the smoke-free air law in Scotland (Semple et al., 2007).

Significant decreases in $PM_{2.5}$ and ultrafine particle (UFP) levels were observed after the indoor smoke-free law in Italy (Valente et al., 2007). In Georgetown, Kentucky, USA, an immediate improvement of indoor air quality was attributed to the smoke-free law (Lee et al., 2007).

In response to indoor smoking bans and restrictions, many smokers are smoking outdoors, especially near the entrances to buildings. When smokers congregate and smoke outside buildings, nonsmokers who are standing nearby or entering and exiting the building can be exposed to tobacco smoke (Kaufman et al., 2011). Fine particles from outdoor smoking also drift into buildings through doors and windows (Repace 2005). Few studies have specifically measured the actual levels of tobacco smoke exposure as a function of distance from the source in outdoor environments (Kaufman et al., 2011; Klepeis et al., 2007).

An increasing number of cities and local governments have implemented outdoor smoking restrictions at building entrances (Klein et al., 2007; Thomson et al., 2009; Lee et al., 2010). In Ontario, Canada, the Smoke-free Ontario Act prohibits smoking within 9 m of any entrance of a public or private hospital, nursing home, approved home, or independent health facility (Smoking and Health Action Foundation 2010). In Australia, Queensland's Tobacco and Other Smoking Products Act of 1998 prohibits smoking outdoors within 4 m of a nonresidential building entrance (The Office of the Queensland Parliamentary Counsel 1998). In the United States, more than 850 communities and many states have enacted smoke-free entryway provisions that help keep tobacco smoke from drifting indoors (American Nonsmokers' Rights Foundation 2012). The smoke-free entryway laws require that no smoking occur within a certain distance (usually 15–25 feet) of doorways, operable windows, and air intake vents of smoke-free buildings (American Nonsmokers' Rights Foundation 2012). However, insufficient scientific evidence exists to determine the appropriate distance from which to restrict smoking from the entrance of a building. Therefore, a study on the movement and dispersion of outdoor tobacco smoke (OTS) is necessary.

Air pollutants emitted at a certain point are dispersed, transported, or concentrated depending on source characteristics, the surrounding environment, and meteorological conditions (Wark et al., 1998). To predict the concentration of air pollutants at a particular receptor point downwind from the source, dispersion models are commonly used (Alharbi 2011). The Gaussian plume model is a simple model for atmospheric dispersion over a short range (within 10 km from the source) (Curtiss et al., 1996). However, such a dispersion model was not applicable to the experimental conditions of this study.

The purpose of this study was to determine OTS exposure by distance from a smoking source. The findings can lead to recommendations of the minimum distance for outdoor smoking restrictions and provide scientific evidence to support the restriction of smoking near building entrances.

II. Methods

1. Study site

The outdoor experiment was conducted on the rooftop of the Graduate School of Public Health building at Seoul National University in Seoul, Korea. The rooftop area is a relatively open space without any blocking walls near the experimental site. The seven-story building was located away from any major road. The experimental site itself did not contain any significant PM sources. The outdoor experiments were conducted on 5 different days in May 2012. No experiment was conducted on rainy days or days with dust storms.

2. Monitoring procedures

A smoking simulation was conducted using a smoking doll, which was designed to actually smoke a cigarette and inhale and exhale cigarette smoke through the squeezing of a pump. The doll was 15 cm × 45 cm × 13 cm. One inhalation volume was approximately 30 ml. During one experiment for 3 min, the pump was squeezed 90 times at 2-s intervals. The smoking doll and monitor inlets were placed at respiratory height (approximately 1.5 m).

The smoking doll was used to provide tobacco smoke for approximately 3 min. One smoking experiment consisted of 13 min (10 min nonsmoking and 3 min smoking). For each experiment, the $PM_{2.5}$ concentration was measured continuously for 5 min under nonsmoking conditions, then for 3 min while one cigarette was smoked by the smoking doll, and then for an additional 5 min after cessation of the cigarette smoking. In total, 98 experiments were conducted.

Figure 1. Smoking doll.

The $PM_{2.5}$ concentration was measured using a real-time aerosol monitor (SidePak, Model AM510; TSI, Shoreview, MN, USA). Four SidePak monitors were placed at 1, 3, 6, and 9 m in a line from the smoking doll and set to record $PM_{2.5}$ concentrations at 1-s intervals. During the experiments, the wind speed and direction were measured every 2 s at the smoking point using a wind meter (Kestrel, Model 4500; Nielsen-Kellerman, Boothwyn, PA, USA). The reported precision for the angle of wind direction was 1°, and the direction of wind was denoted by compass angle (0° = north; 90° = east; 180°

= south; 270° = west). The precision for wind speed was 0.1 m/s. The ambient temperature and relative humidity were also measured using a thermo-hygrometer (HOBO, Model U10; Onset, Bourne, MA, USA) at the smoking point. The data were recorded by the HOBO at 10-min intervals.

The SidePak was factory-calibrated to the reparable fraction of standard ISO 12103, A1 Test Dust (Arizona road dust). Prior to the experiments, the SidePak was charged, and the $PM_{2.5}$ inlets were cleaned and zero-calibrated with a high-efficiency particulate air (HEPA) filter, according to the manufacturer's specifications. The monitor was fitted with a 2.5-μm impactor, and the airflow rate was set at 1.7 l/min to measure the $PM_{2.5}$ concentration.

A correction factor was applied to the raw data from each SidePak monitor to account for inherent differences between the monitors. The correction factor for each monitor was determined by placing the four SidePak monitors together at the experimental site and conducting a series of side-by-side experiments comparing the monitors. The comparison tests were conducted under smoking conditions. The data were recorded at 3-min intervals, as a running average.

3. Analytical methods

Following the experiments, the data were downloaded to a computer for data management and analysis using TrakPro Software V.4.5.1.0 (TSI). The device displays the real-time $PM_{2.5}$ concentration in mg/m^3. For data analysis, this unit was changed to μg/m^3 (i.e., multiplied by 1000). A standard calibration factor of 0.295, obtained by calibration against a gravimetric measurement, was applied to the raw data to correct for the properties of SHS (Lee et al., 2008).

The $PM_{2.5}$ data collected during each experiment were divided into two measures: "smoking exposure," referring to the average $PM_{2.5}$ exposure during smoking, and "no-smoking exposure," referring to the average $PM_{2.5}$ exposure before and after the cigarette was smoked. To minimize the influence of smoking ignition, the first 30 s of data obtained during smoking were excluded from the data analysis. The difference in mean $PM_{2.5}$ concentration between smoking and no-smoking (C_s–C_b) indicated the OTS level.

The wind data included the compass angle of wind direction and was classified as downwind or upwind. Downwind data were further sub-classified as "main angle" and "side angle", as shown in Figure 2.

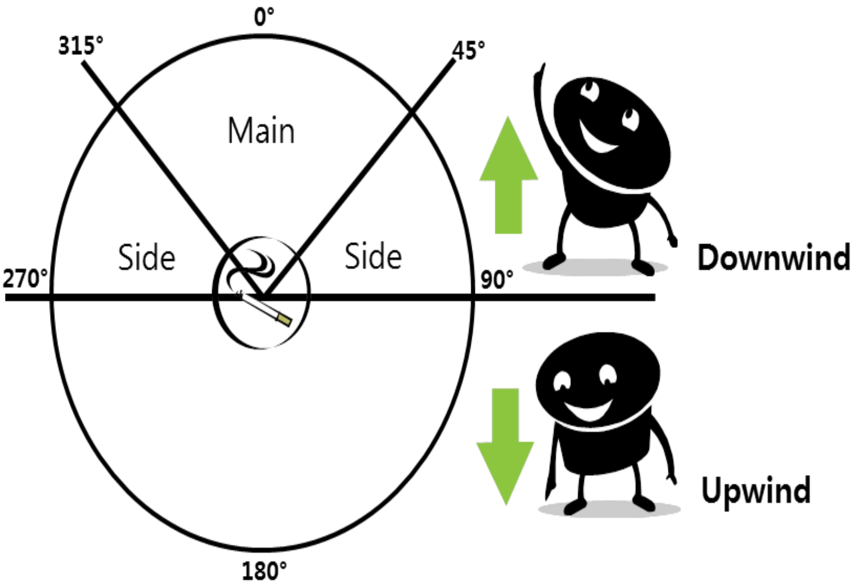

Figure 2. Classification of wind direction.

(1) Statistical analysis

Descriptive statistics were used to describe the characteristics of the OTS data. Student's *t*-test was used to compare $PM_{2.5}$ levels by distance. A multiple linear regression analysis was used to examine the relationship between $PM_{2.5}$ concentrations downwind and variables that influence exposure (i.e., wind direction, wind speed) by distance. All statistical analyses were conducted using Predictive Analytics Software (PASW) Statistics version 18.0 (SPSS Inc., Chicago, IL, USA). Sigma Plot 10.0 (Systat Software Inc., Chicago, IL, USA) and Office Excel 2010 (Microsoft Corp., Redmond, WA, USA) were used to plot the data.

(2) Peak analysis

The data obtained during smoking conditions exhibited a highly fluctuating pattern. For this study, a peak was defined as an increase of at least 35 $\mu g/m^3$ in 1 s (C_i–C_{i-1}). From the distributions of C_i–C_{i-1}, the level at 99.5% was 33 $\mu g/m^3$. However, we chose 35 $\mu g/m^3$ as the discriminator because it is the threshold level set by the U.S. National Ambient Quality Standards for $PM_{2.5}$, averaged over a 24-h period. In the event of more than one peak within a 9-s interval (C_{i-4}–C_{i+4}), the maximum concentration within that interval was selected as the peak. Peak frequency was calculated as number of peaks per time. The average peak concentration and peak frequency were used for further analysis.

III. Results

1. Assurance of measurement quality

The four SidePak monitors were compared in 10 different experiments. Figure 3 shows the association between $PM_{2.5}$ concentrations from the four SidePak monitors. Strong linear correlations were observed between the four SidePak monitors, with all coefficients of determination (R^2) values above 0.95. The R^2 of SidePak No. 1 and No. 2 was 0.9796, that of SidePak No. 1 and No. 3 was 0.9779, and the R^2 of SidePak No. 1 and No. 4 was 0.9699. Slopes of the linear regression without intercept were 0.9763 between No. 1 and No. 2, 0.9491 between No. 1 and No. 3 and 0.9464 between No. 1 and No. 4. Since all slopes were not significantly different from a unity (p>0.05), all data from the four Sidepak monitors were not adjusted.

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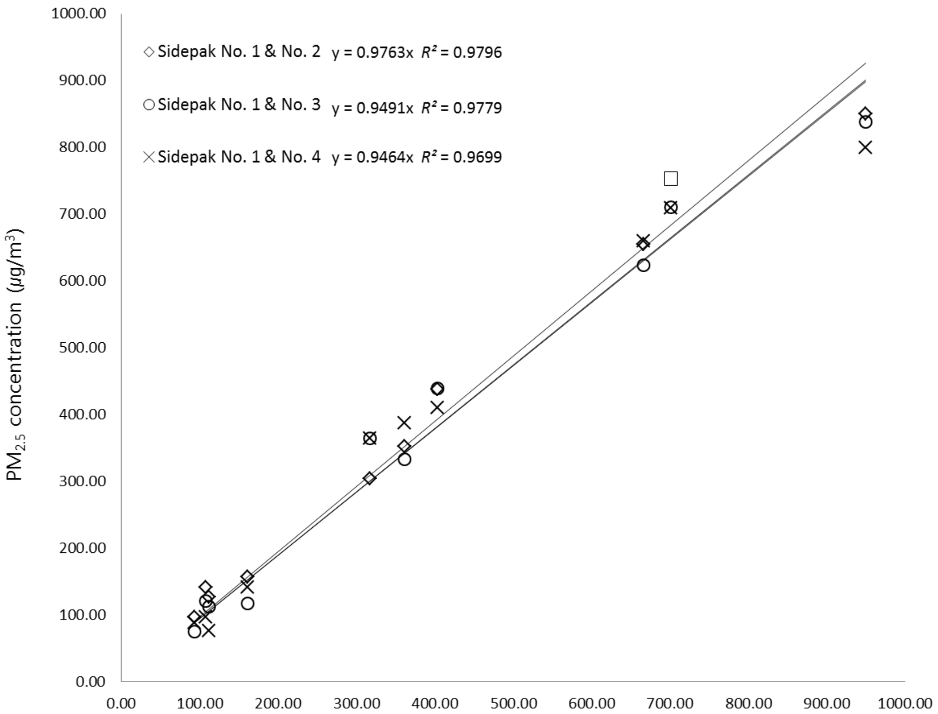

Figure 3. Comparisons between pairs of four SidePak monitors.

2. Descriptive analyses

In total, 98 smoking simulation tests were conducted outdoors. The average temperature over the 5 days of tests was 27.1℃ ± 3.4℃, and the average relative humidity for the 5 days was 32.7% ± 6.3%. The average wind speed for the 5 days was 0.8 ± 0.6 m/s. During the smoking simulation tests, 70% of the data were classified as downwind, and 30% were classified as upwind.

The average $PM_{2.5}$ concentrations during the pre-smoking periods were 34.4 ± 19.0 $\mu g/m^3$, 37.2 ± 19.6 $\mu g/m^3$, 38.3 ± 20.7 $\mu g/m^3$, and 39.6 ± 21.7 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The average $PM_{2.5}$ concentrations during the post-smoking periods were 34.9 ± 19.1 $\mu g/m^3$, 37.6 ± 19.6 $\mu g/m^3$, 38.7 ± 20.8 $\mu g/m^3$, and 39.9 ± 21.8 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The average $PM_{2.5}$ concentrations were not significantly different during the pre-smoking and post-smoking periods. Therefore, the data obtained during both nonsmoking periods were combined for the analyses.

The average $PM_{2.5}$ concentrations during the smoking periods were 107.3 ± 74.5 $\mu g/m^3$, 48.6 ± 21.7 $\mu g/m^3$, 42.5 ± 20.0 $\mu g/m^3$, and 42.2 ± 20.2 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The average $PM_{2.5}$ concentrations during the combined nonsmoking conditions were 34.7 ± 19.1 $\mu g/m^3$, 37.4 ± 19.6 $\mu g/m^3$, 38.5 ± 20.8 $\mu g/m^3$ and 39.8 ± 21.8 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. Thus, the $PM_{2.5}$ concentrations were significantly greater during the smoking periods than during the nonsmoking periods at comparable distances ($p < 0.05$).

Table 1. Average $PM_{2.5}$ concentrations during smoking and nonsmoking periods at various distances from the source

Distance (m)	Mean ± SD ($\mu g/m^3$)		
	Smoking	Nonsmoking (pre-smoking)	Nonsmoking (post-smoking)
1	107.3 ± 74.5	34.4 ± 19.0	34.9 ± 19.1
3	48.6 ± 21.7	37.2 ± 19.6	37.6 ± 19.6
6	42.5 ± 20.0	38.3 ± 20.7	38.7 ± 20.8
9	42.2 ± 20.2	39.6 ± 21.7	39.9 ± 21.8

3. Differences between mean $PM_{2.5}$ concentrations during smoking and nonsmoking periods by distance

The differences between mean $PM_{2.5}$ concentrations during the smoking and nonsmoking periods were 72.7 ± 70.9 μg/m^3 at 1 m, 11.3 ± 11.1 μg/m^3 at 3 m, 4.1 ± 4.2 μg/m^3 at 6 m, and 2.6 ± 3.5 μg/m^3 at 9 m. These average differences, which represent the OTS levels, were significantly greater than 0 μg/m^3 at all distances ($p < 0.05$).

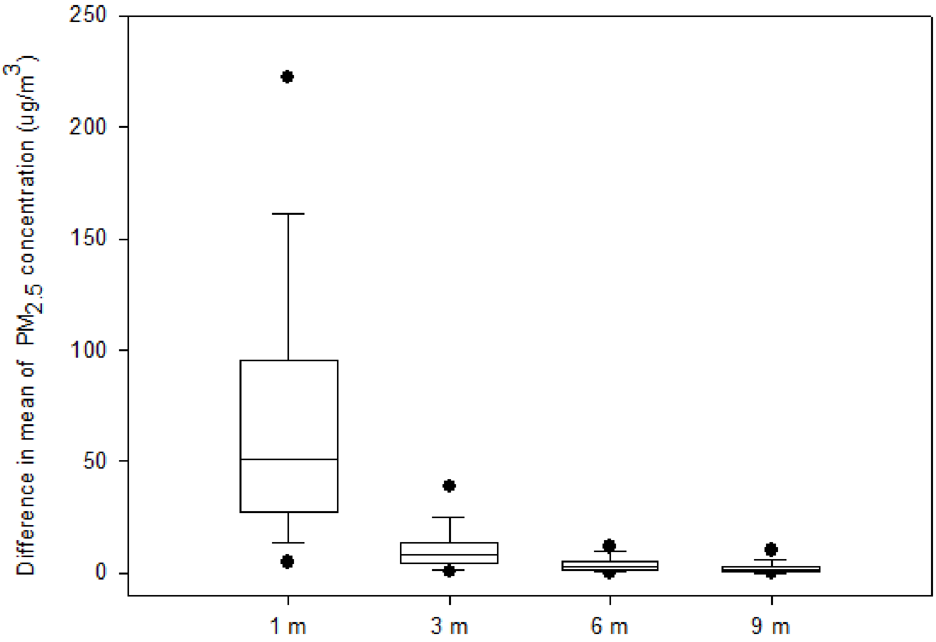

Figure 4. Differences between mean $PM_{2.5}$ concentrations during smoking and nonsmoking periods at various distances from the source (N = 98).

Note: * $p < 0.05$, statistically significant for Student's *t*-test. Median is represented by the line in the box. Box limits represent the 25^{th} and 75^{th} percentiles. The whiskers extend to the 10^{th} and 90^{th} percentiles. Circles above the 90^{th} percentile represent the 95^{th} percentile, and circles below the 10^{th} percentile represent the 5^{th} percentile.

4. OTS level by wind condition

When the wind direction was classified as downwind, the differences between mean $PM_{2.5}$ concentrations during the smoking and nonsmoking periods were greater than when the wind direction was classified as upwind. The differences under downwind conditions were 86.4 ± 90.1 $\mu g/m^3$, 13.1 ± 12.9 $\mu g/m^3$, 4.7 ± 4.7 $\mu g/m^3$, and 3.2 ± 3.8 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The differences under upwind conditions were 32.4 ± 61.8 $\mu g/m^3$, 6.1 ± 10.6 $\mu g/m^3$, 3.1 ± 9.4 $\mu g/m^3$, and 1.3 ± 3.4 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The differences between the differences under downwind conditions versus upwind conditions were statistically significant ($p < 0.05$) at 1 m, 3 m, and 9 m, but not at 6 m ($p = 0.14$).

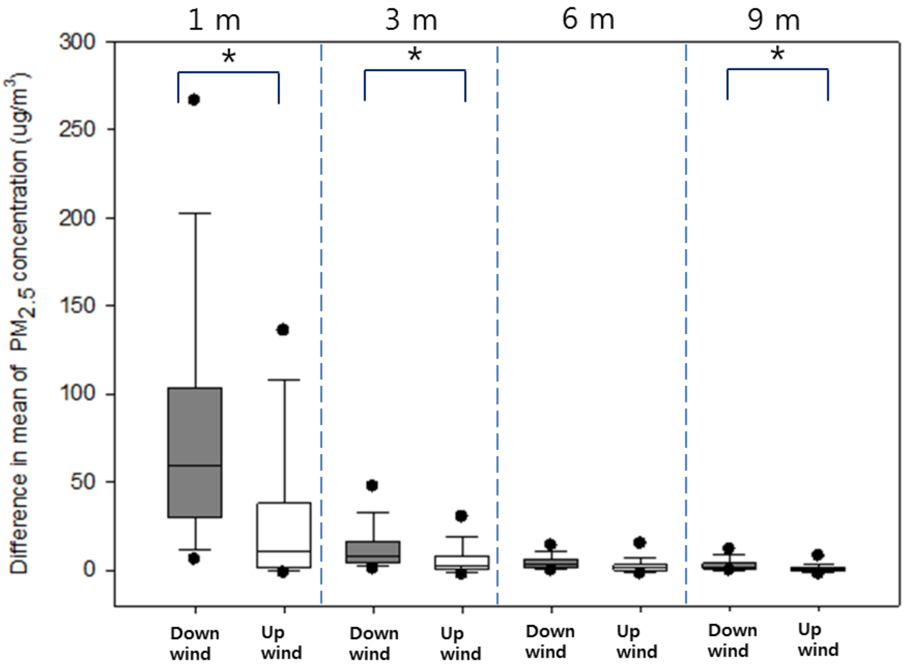

Figure 5. Differences between mean $PM_{2.5}$ concentrations during smoking and nonsmoking periods under downwind and upwind conditions (*N* = 98).

Note: * $p < 0.05$, statistically significant for Student's *t*-test. Median is represented by the line in the box. Box limits represent the 25th and 75th percentiles. The whiskers extend to the 10th and 90th percentiles. Circles above the 90th percentile represent the 95th percentile, and circles below the 10th percentile represent the 5th percentile.

When the downwind data were further classified as “main angle” and “side angle,” the differences between mean $PM_{2.5}$ concentrations during smoking and nonsmoking periods were found to be greater when the classification was “main angle” than when it was “side angle.” The differences when the downwind data were “main angle” were 94.1 ± 346.4 $\mu g/m^3$, 14.1 ± 42.0 $\mu g/m^3$, 4.7 ± 12.1 $\mu g/m^3$, and 4.1 ± 13.8 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The differences when the downwind data were “side angle” were 78.9 ± 311.4 $\mu g/m^3$, 13.6 ± 46.1 $\mu g/m^3$, 5.3 ± 16.3 $\mu g/m^3$ and 2.9 ± 9.4 $\mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The differences between the differences under “main angle” versus “side angle” downwind conditions were statistically significant only at 1 m and 9 m ($p < 0.05$).

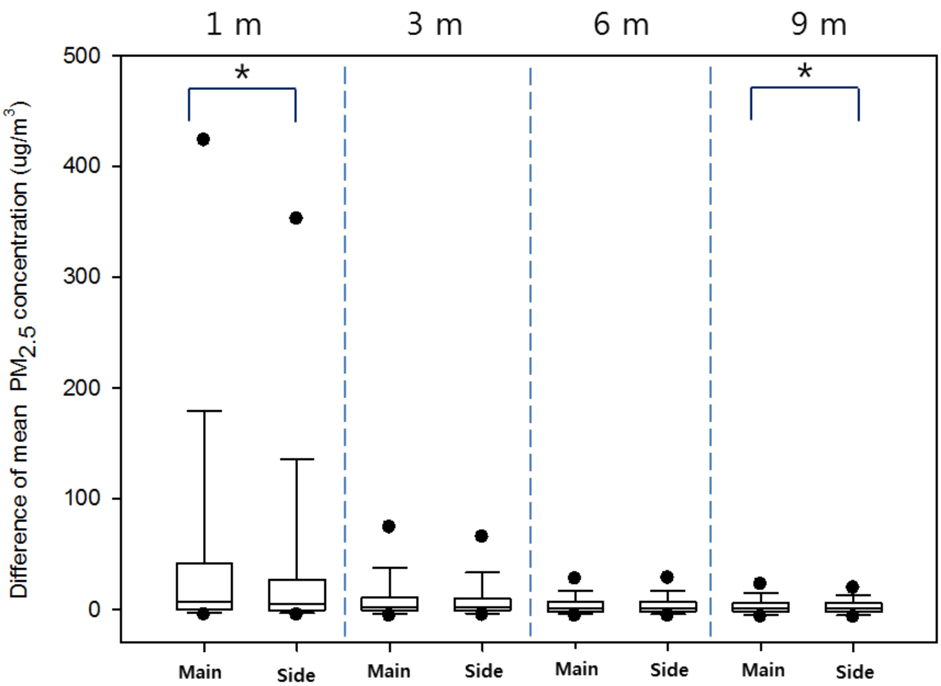

Figure 6. Differences between mean $PM_{2.5}$ concentrations during smoking and nonsmoking periods when downwind conditions were classified as "main angle" versus "side angle" by distance.

Note: * $p < 0.05$, statistically significant for Student's *t*-test. Median is represented by the line in the box. Box limits represent the 25th and 75th percentiles. The whiskers extend to the 10th and 90th percentiles. Circles above the 90th percentile represent the 95th percentile, and circles below the 10th percentile represent the 5th percentile.

Table 2 shows a multiple regression model for the OTS level with wind direction (divided into downwind and upwind) and wind speed. Distance, wind direction, and wind speed were all significantly associated with the $PM_{2.5}$ concentrations. When the distance increased, $PM_{2.5}$ concentrations decreased. $PM_{2.5}$ concentrations were greater when the wind direction was downwind than when it was upwind. When the wind speed increased, $PM_{2.5}$ concentrations decreased.

Table 2. Multiple regression model for OTS level* with wind direction (divided into downwind and upwind) and wind speed

Variable	Coefficient (95% CI)	SE	*p* value
Constant	110.46 (106.58 to 114.35)	1.98	<0.0001
Distance	–6.95 (–7.48 to –6.43)	0.27	<0.0001
Wind direction			
Downwind	reference		
Upwind	–20.13 (–23.65 to –16.60)	1.80	<0.0001
Wind speed	–13.48 (–16.08 to –10.88)	1.33	<0.0001

SE: standard error.

* OTS was adjusted by the average $PM_{2.5}$ concentrations during the nonsmoking period.

Since the $PM_{2.5}$ concentrations were greater when the wind direction was downwind, as opposed to upwind, another multiple linear regression was conducted using only data from under the downwind condition. Table 3 shows the multiple regression model for the OTS level with wind direction and speed. Both distance and wind speed were significantly associated with the $PM_{2.5}$ concentrations. When the distance increased, the $PM_{2.5}$ concentrations decreased. Similarly, when wind speed increased, the $PM_{2.5}$ concentrations decreased. However, the wind direction (“main angle” versus “side angle”) was not significantly associated with the $PM_{2.5}$ concentrations.

Table 3. Multiple regression model for OTS level* with wind direction (downwind divided into “main angle” and “side angle”) and wind speed

Variable	Coefficient (95% CI)	SE	*p* value
Constant	115.41 (110.22 to 120.60)	2.65	<0.0001
Distance	–8.12 (–8.76 to –7.49)	0.33	<0.0001
Wind direction			
Main angle	reference		
Side angle	–3.20 (–7.18 to 0.79)	2.03	0.116
Wind speed	–10.58 (–13.77 to –7.39)	1.63	<0.0001

SE: standard error.

* OTS was adjusted by the average $PM_{2.5}$ concentrations during the nonsmoking period.

5. Peak analysis

Figure 7 shows the peak frequencies as a function of distance. The peak frequencies during the nonsmoking periods were 17.5 peaks/h, 11.9 peaks/h, 16.8 peaks/h, and 25.5 peaks/h at 1 m, 3 m, 6 m, and 9 m, respectively. The peak frequencies during the smoking periods were 181.9 peaks/h, 104.9 peaks/h, 50.8 peaks/h, and 46.5 peaks/h at 1 m, 3 m, 6 m, and 9 m, respectively. The peak frequencies were significantly higher during the smoking periods than during the nonsmoking periods at all distances ($p < 0.05$).

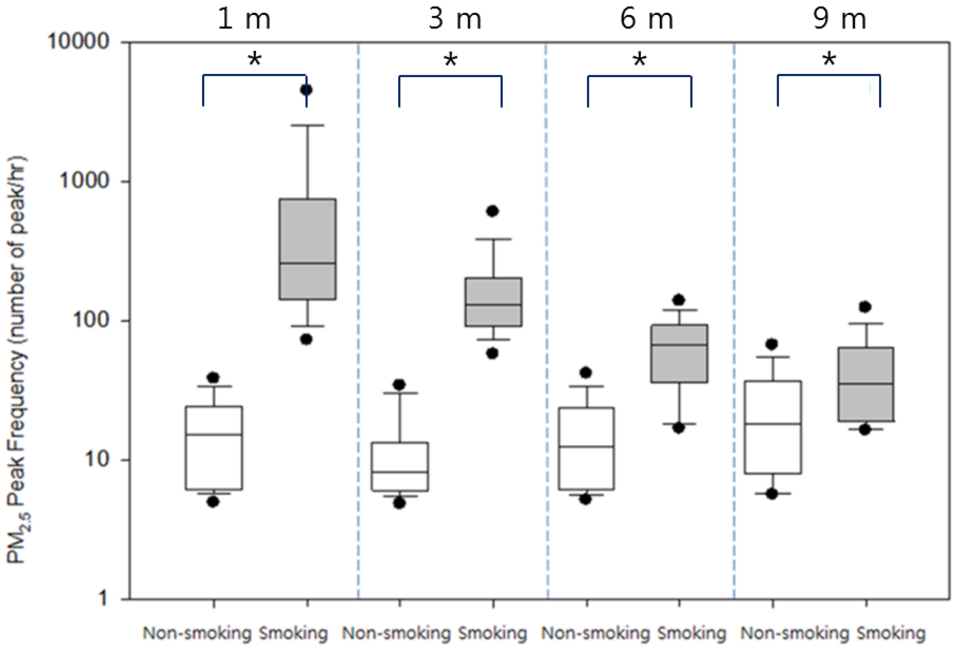

Figure 7. Distribution of $PM_{2.5}$ peak frequencies by distance.

Note: * $p < 0.05$, statistically significant for Student's *t*-test. Median is represented by the line in the box. Box limits represent the 25th and 75th percentiles. The whiskers extend to the 10th and 90th percentiles. Circles above the 90th percentile represent the 95th percentile, and circles below the 10th percentile represent the 5th percentile.

Figure 8 shows the average peak concentrations as a function of distance. The peak $PM_{2.5}$ concentrations during the nonsmoking periods were $98.7 \pm 38.0\ \mu g/m^3$, $123.3 \pm 210.2\ \mu g/m^3$, $107.6 \pm 86.5\ \mu g/m^3$ and $102.0 \pm 37.0\ \mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The peak $PM_{2.5}$ concentrations during the smoking periods were $887.4 \pm 1386.7\ \mu g/m^3$, $207.8 \pm 201.9\ \mu g/m^3$, $119.0 \pm 56.9\ \mu g/m^3$, and $103.6 \pm 41.0\ \mu g/m^3$ at 1 m, 3 m, 6 m, and 9 m, respectively. The average peak concentrations were significantly higher during the smoking periods than during the nonsmoking periods at 1 m, 3 m, and 6 m ($p < 0.05$) but not at 9 m ($p = 0.64$).

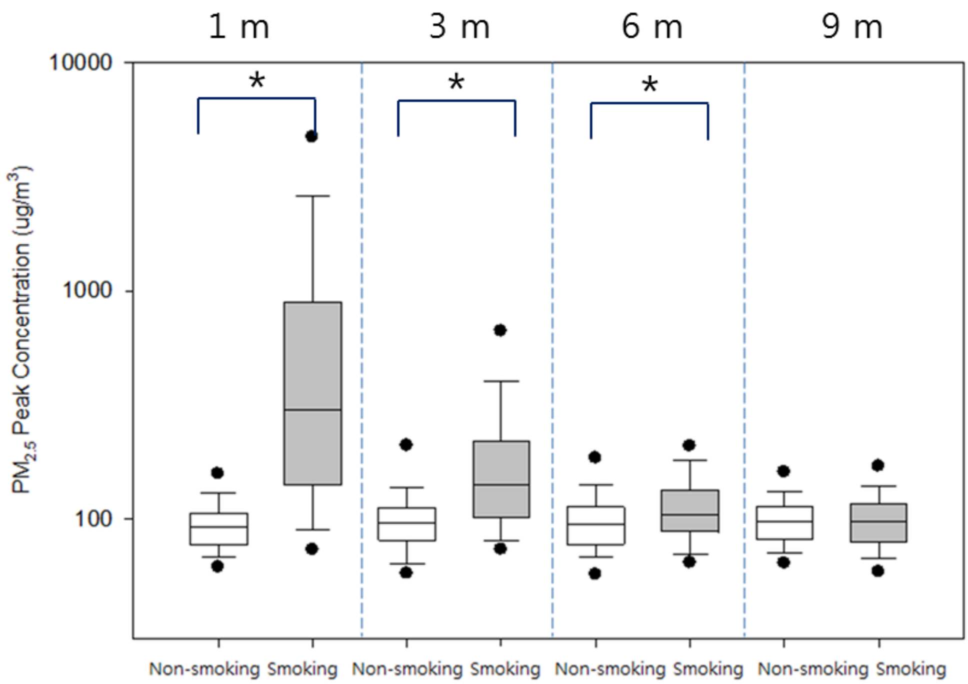

Figure 8. Distribution of $PM_{2.5}$ peak concentrations by distance.

Note: * $p < 0.05$, statistically significant for Student's *t*-test. Median is represented by the line in the box. Box limits represent the 25th and 75th percentiles. The whiskers extend to the 10th and 90th percentiles. Circles above the 90th percentile represent the 95th percentile, and circles below the 10th percentile represent the 5th percentile.

IV. Discussion

The OTS levels were defined as the difference in $PM_{2.5}$ concentrations during the smoking versus nonsmoking periods. Although the experimental site was deliberately chosen to be away from any major road or other potential $PM_{2.5}$ source, the $PM_{2.5}$ concentrations during nonsmoking periods were not zero. This background $PM_{2.5}$ concentration was assumed to relatively constant throughout both smoking and nonsmoking periods. Therefore, the $PM_{2.5}$ concentrations measured during the smoking periods were corrected for this background by subtracting the concentrations measured during the nonsmoking periods. No significant difference was observed in the $PM_{2.5}$ concentrations before and after the smoking sessions.

The OTS level decreased with increasing distance from the smoking source. The average OTS level at a distance of 1 m from the source was 72.7 $\mu g/m^3$, which is twice the U.S. National Ambient Air Quality Standard threshold of 35 $\mu g/m^3$ for 24 h. The OTS level was reduced to 11.3 $\mu g/m^3$, 4.1 $\mu g/m^3$ and 2.6 $\mu g/m^3$ at 3 m, 6 m, and 9 m, respectively. This decrease in $PM_{2.5}$ concentration with distance was probably due to dispersion of the smoke plume. This result is in agreement with other studies demonstrating a reduction in $PM_{2.5}$ concentration with increasing distance from a source of tobacco smoke (Kaufman et al., 2011; Klepeis et al., 2007). However, the earlier studies were conducted on patios with an overhead cover, whereas our study measured the OTS in a relatively open area.

The OTS levels were significantly impacted by wind direction. The OTS levels were greater when the direction was downwind than when it was upwind. This result is consistent with another study that reported outdoor tobacco smoke was highly dependent on wind direction, with upwind concentrations likely to be very low and downwind concentrations likely to be high (Klepeis et al., 2007). However, the OTS levels were not significantly different whether the downwind direction was “main angle” or “side angle,” when the distance was greater than 3 m, probably due to rapid changes in wind conditions.

Wind speed was negatively associated with the OTS level. The OTS level decreased with increasing wind speed. The smoke plume may be dispersed quickly and widely at higher wind speeds. This result is consistent with a study showing that the concentration of air pollutants around a source was inversely related to wind speed (Klepeis et al., 2009).

To prevent OTS exposure, the recommended distance from a smoking source should be at least 9 m. Although the OTS level decreased with distance, detectable OTS levels were measured even at a distance of 9 m outdoors. The average OTS level at 9 m was 2.6 $\mu g/m^3$. When the wind direction was downwind, the average OTS level at 9 m was 3.2 $\mu g/m^3$. Although there are no data on the health implications of this level of OTS exposure, we should note that detectable levels of OTS occurred even at 9 m. Most legislation aimed at providing smoke-free outdoor areas prohibit smoking within 3–6 m of an entrance or air intake of any public building (Smoking and Health Action Foundation 2010). However, this distance may not be sufficient to prevent OTS exposure, and it may be necessary to increase this distance to at least 9 m.

We used a novel method of peak analysis in this study to compensate for quickly fluctuating wind conditions. Unlike indoor concentrations, outdoor concentrations can rapidly change in a few seconds. The peak analysis used here was appropriate for our 1-s measurement intervals. Our peak analysis demonstrated a greater chance of exposure to peak $PM_{2.5}$ concentrations when smoking was occurring outdoors, as the peak frequencies and average peak concentrations were greater during smoking periods than during nonsmoking periods. Although the difference in peak frequencies was significant at all distances, the differences in average peak concentrations were significant only at distances up to 6 m. These findings imply that smoking may cause frequent and high, acute OTS exposure at 6 m. Considering the irritating effect of tobacco smoke, such acute, high exposure should be avoided.

This study has several limitations. First, a smoking doll was used for smoking simulation in this study. Although smoking by the doll was simulated with consistent interval, it could be different from real smoking behavior by people. Second, the experiment measured OTS levels only at distances up to 9 m, and OTS exposures were still detectable at 9 m. Although smoking probably causes OTS exposure at distances greater than 9 m, we are not able to extrapolate the minimum distance needed to prevent OTS exposure from our results. Further study is needed to determine this minimum distance. Third, the study measured the OTS in a relatively open area to mimic the environment around a building entrance. However, the experimental site may not be typical in terms of air movement near a building entrance. Fourth, the study used only one smoking source. In reality, smokers often congregate near building entrances and in smoking areas. As the number of smokers increases, the OTS level is also likely to increase. Therefore, the OTS level at 9 m may be much greater when more than one smoker is present.

V. Conclusions

$PM_{2.5}$ exposures from tobacco smoke in an outdoor environment were measured at various distances from the smoking source. The OTS level decreased with increasing distance from the smoking source. The OTS level was significantly greater downwind of the source than upwind. Wind speed was negatively correlated with the OTS level. However, OTS was detectable at 9 m, regardless of the wind condition. Therefore, to prevent OTS exposure, the minimum distance from a smoking source should be at least 9 m.

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국문초록

Outdoor Tobacco Smoke Exposure by Distance

실외에서 흡연으로 인한 거리에 따른 간접흡연의 노출

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간접흡연으로 인한 피해 방지를 위해, 많은 나라에서 실내 금연법을 시행하고 있으며, 시행 이후 다양한 실내 환경에서 간접흡연에 의한 노출이 감소하였음을 여러 가지 연구를 통해 증명된 바 있다. 실내 금연에 따르기 위해 흡연자들은 실외공간이나 건물입구에서 흡연이 증가하였고 이로 인해 건물을 출입하는 이용객이나. 건물 근처를 지나가는 보행자들에게 간접흡연 영향을 미칠 수 있다. 그리하여, 많은 나라의 지방자치단체에서 건물입구에서 제한된 거리에서의 흡연을 금지하여 실

외 금연 규제를 실시 하고 있다. 그러나, 건물 출입구로부터 제한된 거리에서 금연을 위한 법을 제정할 때 그 거리를 고려하는데 있어 과학적 증거는 불충분한 실정이다. 따라서, 본 연구의 목적은 바람의 영향을 고려하여, 실외에서 흡연의 영향이 미치지 않는 거리를 찾는 것이다.

본 연구는 2012년 5월 서울대학교 관악 캠퍼스 내 다른 오염원으로부터 $PM_{2.5}$ 노출이 최소인 곳에서 실외 흡연을 진행하였다. 실시간 직독식 에어로졸 모니터를 이용하여 인형으로부터 1.3.6.9 미터 떨어진 곳에서 $PM_{2.5}$ 농도를 측정하고, 풍향풍속계를 이용하여 바람상태 측정하였다. 하나의 실험은 비흡연 5분, 흡연시간 3분, 비흡연 5분으로 구성되어 총 13분으로 이루어졌다.

각 거리 별 농도 분석을 통하여 거리에 따른 비흡연시와 흡연시의 농도 차이를 비교하였고, 또한 다중선형회귀분석을 통하여 $PM_{2.5}$ 농도와 바람의 영향에 의한 관계를 보고자 하였다. 실외에서 간접흡연으로 발생한 오염물질은 바람과 같은 환경적 요인에 의해 순간적으로 농도가 변할 수 있기 때문에, 이러한 고농도 패턴의 분석을 위해 새로운 컨셉의 peak 분석을 실시하였다.

실험 결과, 모든 거리에서 비흡연시에 비해 흡연 시 $PM_{2.5}$ peak 농도 수준이 높았으며 ($p<0.05$), 이를 통해 1,3,6,9 미

터 모두 흡연의 영향을 받음을 알 수 있었다. 또한 비흡연시와 흡연시의 평균 농도차이를 바람의 방향에 따라 나누어 분석한 결과, 바람의 방향이 역풍일 때가 순풍 일 때보다 6미터를 제외한 1,3,9미터에서 통계적으로 유의하게 높았다($p<0.05$). Peak 분석을 실시한 결과, 피크 밀도는 1,3,6,9 미터에서 모두 비흡연시보다 흡연시의 시간당 피크 밀도가 높았으며, 또한 $PM_{2.5}$ 평균피크농도 수준은 9 미터를 제외한 1,3,6미터에서 비흡연시보다 흡연시의 평균피크농도 수준이 통계적으로 유의하게 높았다.

본 연구를 통해 흡연원으로부터 거리가 증가함에 따라 야외에서의 $PM_{2.5}$ 농도 수준이 감소함을 파악 할 수 있었다. 실험을 통해 9 미터에서도 $PM_{2.5}$ 의한 영향을 받는 것을 알 수 있었으며, 이를 통해 실외 금연법을 정하는데 있어서 건물입구에서 최소한 9 미터까지는 흡연 제한 구역으로 정해야 한다는 결론을 내릴 수 있었다. 본 연구는 흡연 제한구역의 거리를 정하는데 있어 과학적인 근거를 제공하여 법규를 제정하는데 있어 기초 자료로 활용 할 수 있을 것이다.

주요어 : 실외흡연, 간접흡연, 미세먼지($PM_{2.5}$), 거리, 바람 상태, peak

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