보건학 석사 학위논문

Measurement of outdoor tobacco smoke exposure by distance up to 21 meters from smoking source

거리에 따른 실외 간접흡연 노출 평가

2023 년 8 월

서울대학교 보건대학원

환경보건학과 환경보건학 전공

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이 논문을 보건학 석사 학위논문으로 제출함

2023 년 5 월

서울대학교 보건대학원

환경보건학과 및 환경보건학 전공

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2023 년 6 월

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Abstract

Measurement of outdoor tobacco smoke exposure by distance up to 21 meters from smoking source

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As there is no safe level of secondhand smoke exposure, many countries have implemented indoor smoke-free policies and some countries have implemented outdoor non-smoking areas. But there is no clear standard about the distance of the outdoor non-smoking area. The aims of this study were to determine outdoor tobacco smoke (OTS) exposure by distance up to 21 m and to identify factors associated with OTS, such as wind direction and wind speed. To determine the OTS levels, $PM_{2.5}$ concentrations were measured at distances of 6 m, 12 m, 15 m, 18 m, and 21 m by real-time aerosol monitors. A total of 164 measurements were conducted for 5 days from August to October 2022. The measurement included background concentration for 5 minutes before smoking and OTS level for 3 minutes with smoking. The OTS levels were analyzed by calculating the difference between the average background $PM_{2.5}$ concentration and the average $PM_{2.5}$ concentration for last two minutes of smoking. One-sampled t-test was conducted to assess that each distance of OTS levels was significantly higher than 0 μg/m^3, and a multiple linear regression analysis was conducted to determine the factors that affect the OTS levels, such as wind speed, distance, and wind direction. The average OTS levels at all distances were significantly higher than 0 μg/m^3 in calm wind condition. In the regression model, the OTS levels were significantly associated with the distance. The OTS levels tended to decrease when the distance increased. This study concluded that OTS at 21 m was significantly higher than 0 μg/m^3. The finding could be used as evidence for regulating the outdoor non-smoking area.

Keywords : Secondhand smoke, Outdoor tobacco smoke, $PM_{2.5}$, Multiple regression

Student Number : 2021-22529

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1. Introduction

Secondhand smoke consists of sidestream and mainstream smoke. Sidestream smoke is the smoke released from the end of a cigarette and mainstream smoke is the smoke exhaled by a smoker (U.S. Department of Health and Human Services, 2006). Especially, sidestream smoke contains higher concentrations of the various toxins (U.S. Department of Health and Human Services, 2006). Secondhand smoke exposure could cause several health effects. Secondhand smoke exposure could cause hypertriglyceridemia and increase cardiometabolic risk (Kim et al., 2022). Secondhand smoke exposure can increase the risk of stroke and damage the body's cells (U.S. Department of Health and Human Services, 2014). Secondhand smoke exposure had association with several diseases, such as lung and stomach cancer (Zhang et al., 2022). Due to several health effects, there is no safe level of secondhand smoke exposure (U.S. Department of Health and Human Services, 2006).

Many countries have implemented indoor smoke-free policies to prevent the health effects of secondhand smoke exposure. In New South Wales, Australia, smoking is prohibited in every enclosed public place (The Office of the New South Wales Parliamentary Counsel, 2018). In Scotland, smoking is prohibited in public places except some designated rooms in residential accommodation, adult care homes (The Scottish Parliament, 2022). In Korea, smoking is prohibited in most indoor public places, such as hospital, government office, school, and restaurant (Korea Ministry of Health and Welfare, 2021). These regulations were effective in reducing the indoor $PM_{2.5}$ concentration (Semple et al., 2007; Singh et al., 2020). The World Health Organization recommended smoking-free policies as the only effective strategy to reduce the risk of secondhand smoke exposure not only indoor environments but outdoor and outdoor workplaces (World Health Organization, 2007).

Despite the indoor smoking cessation policies, people continue to smoke outdoors near the buildings. In Türkiye, smoking was observed frequently in entrances, parking lots, patios, and walkways (Kaplan et al., 2019). Smoking near the building can affect the occupants and people entering the building through doors or windows (Kaufman et al., 2011). In the USA, 14.2 million students were exposed to outdoor secondhand smoke (Puvanesarajah et al., 2022). In Georgia, USA, the biomarkers of secondhand smoke exposure from outside of restaurants and bars were detected significantly in nonsmokers, such as salivary cotinine and urinary 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (St.Helen et al, 2012). In Germany, people were highly exposed to secondhand smoke in outdoors than indoors (Mlinarić et al., 2022).

Due to the risk of outdoor secondhand smoke exposure, several countries prohibit outdoor smoking within a certain distance from indoors, but there is no clear standard about the distance of the non-smoking area (Klein et al., 2007; Thomson et al., 2009; Lee et al., 2010). In Korea, according to the Enforcement Regulations of the National Health Promotion Act, smoking rooms should be located 10 m or more from the entrance of non-smoking facilities to prevent damage from secondhand smoke (Korea Ministry of Health and Welfare, 2022; Seoul Metropolitan Government, 2022). In British Columbia, Canada, smoking is prohibited within 6 m of doorways, windows, or air intakes in public places and workplaces (Ministry of Health, 2020). In Singapore, smoking is prohibited within 5 m from the outer edge of any part of the entrance or any external window or other openings (National

Environment Agency, 2020). Therefore, it is necessary to determine whether secondhand smoke can affect people by distance.

Several previous studies conducted the measurements outdoor by distance, but the distance was mostly near-field which was less than 10 m. Hwang et al measured $PM_{2.5}$ concentration at 1, 3, 6, and 9 m away from cigarettes, and $PM_{2.5}$ concentration at 9 m was higher than the background concentration (Hwang et al., 2014). Klepeis et al measured secondhand smoke levels in 10 outdoor public places at 0.25 m, 0.5 m, 1 m, and 2 m from sources and indicated that secondhand smoke exposure level could be affected by wind conditions and smoker proximity (Klepeis et al, 2007). Ott et al measured $PM_{2.5}$ personal exposure of nonsmokers at 0.5 m, 1 m, and 1.5 m from smoker in sidewalk bus stops and indicated that $PM_{2.5}$ concentrations by secondhand smoke were significantly higher than the background concentrations (Ott et al, 2014). Torretta et al measured PM_{10} exposure of outdoor secondhand smoke in campus by measuring PM_{10} concentration at various location within 5 m near the entrance (Torretta at al., 2020). Kungskulniti et al measured $PM_{2.5}$ concentration in beach which 1 and 2 m from the smokers in Thailand (Kungskulniti et al., 2018).

The aim of this study was to determine the outdoor tobacco smoke (OTS) exposure by distance up to 21 m and to determine factors associated with outdoor secondhand smoke, such as wind direction and wind speed. To determine OTS exposure, the $PM_{2.5}$ concentration was measured by tobacco smoke. This study analyzed exposure to secondhand smoke at various distances and it could provide evidence to determine the non-smoking area.

2. Materials and methods

2.1 Study site

The measurements were conducted in the outdoor space in Seoul National University campus. The sampling site was located at least 6 m away from the buildings where not many people pass by. The measurements were conducted on 5 different days from August to October 2022. The measurement was performed except on rainy and windy days, which was over 3 m/s, and the days when outdoor $PM_{2.5}$ concentration was higher than 35 μg/m^3 which was the 24 hours threshold of US National Ambient Air Quality Standards. The measurements were conducted after 9 pm to be not affected by smokers.

2.2 Measurements

To determine OTS levels, the $PM_{2.5}$ concentration was measured. OTS was generated by using a smoking doll. Before smoking the cigarette, the background concentration was measured for 5 minutes. After 5 minutes, a cigarette was smoked using a smoking doll for 3 minutes as a smoking period by measuring $PM_{2.5}$ concentration. While smoking, the smoking doll was pumped once every 2 seconds and smoked 1 cigarette for 3 minutes. After smoking for 3 minutes, more than 2 minutes for a break until measuring the background concentration. These processes were repeated 164 times.

To measure the $PM_{2.5}$ concentration, the real-time aerosol monitors (SidePak AM520, TSI) were used, which were located at 6 m, 12 m, 15 m, 18 m, and 21 m simultaneously from the smoking doll. At 6 m away from the smoking doll, the wind speed and direction were measured using a wind meter (Kestrel 4500, Nielsen-Kellerman) with a real-time aerosol monitor, and outdoor temperature and humidity were measured using a thermo-hygrometer (HOBO UX100-003, Onset). All measuring instruments were fixed at 140 cm height from the ground using a tripod which was near the respiratory height.

The measurement interval of the real-time aerosol monitors was set to 1 second, the windmeter was set to 2 seconds, and the thermo-hygrometer was set to 1 minute. Before starting the measurement, all instruments were set the time setting at the same time. The real-time aerosol monitors were set a flow rate to 1.7 L/min and conducted calibration using a HEPA filter before the measurement.

2.3 Statistical analysis

Before data analysis, unit conversion of mg/m^3 to µg/m^3 and a calibration factor of 0.295 was applied to $PM_{2.5}$ concentration by real-time aerosol monitors (Lee et al., 2008). OTS levels were analyzed by calculating the difference between the average of the $PM_{2.5}$ concentration for 5 minutes of the background concentration (C_0) and the average of the $PM_{2.5}$ concentration while smoking, excluding the first minute from 3 minutes (C_n). The equation of OTS level (C_k) was calculated as follows.

$$C_k = C_n - C_0$$

To compare the OTS levels by distance whether OTS levels were significantly higher than 0 µg/m^3, one-sampled t-test was conducted. For the wind direction, the winds blowing in the 0~45˚ and 315~360˚ directions were classified as main angle, and the wind blowing in the 45~315˚ were classified as other angle.

Multiple linear regression analysis was conducted to determine the factors affecting OTS exposure, such as wind speed, distance from cigarettes, and wind direction. To determine the association except for wind conditions, multiple linear regression was also analyzed when wind speed was 0 m/s. All statistical analysis was conducted using Office Excel (Microsoft Corp., 2016), R version 4.2.1 (R Foundation for Statistical Computing, 2022), and Sigma Plot 10.0 program (Systat Software Inc., 2006).

3. Results

3.1 OTS levels

A total of 164 measurements were conducted, in which $PM_{2.5}$ concentration was measured simultaneously at each distance. The range of wind speed during the measurements was 0~2.1 m/s. OTS levels were calculated by $C_n - C_0$, which C_n is for the average of 2 minutes of $PM_{2.5}$ concentration while smoking, and C_0 is for the average of 5 minutes of background $PM_{2.5}$ concentration. Figure 1 shows the distribution of OTS levels by distance. The average OTS levels at all distances were lower than the US National Ambient Air Quality Standards and tended to decrease by distance. The OTS levels were significantly higher than 0 μg/m^3 at all distances ($p<0.001$). The number of OTS levels which were higher than 0 μg/m^3 were 142 (86.6%) in 6 m, 127 (77.4%) in 12 m, 122 (74.4%) in 15 m, 112 (68.3%) in 18 m, and 109 (66.5%) in 21 m.

Table 1. OTS levels (μg/m^3) by distance (n=164)

	OTS levels (Mean ± SD)	p-value*
6 m	12.9 ± 20.18	<0.001
12 m	4.86 ± 9.99	<0.001
15 m	2.78 ± 6.6	<0.001
18 m	2.09 ± 5.95	<0.001
21 m	1.57 ± 5.45	<0.001

*p-value of one-sampled t-test

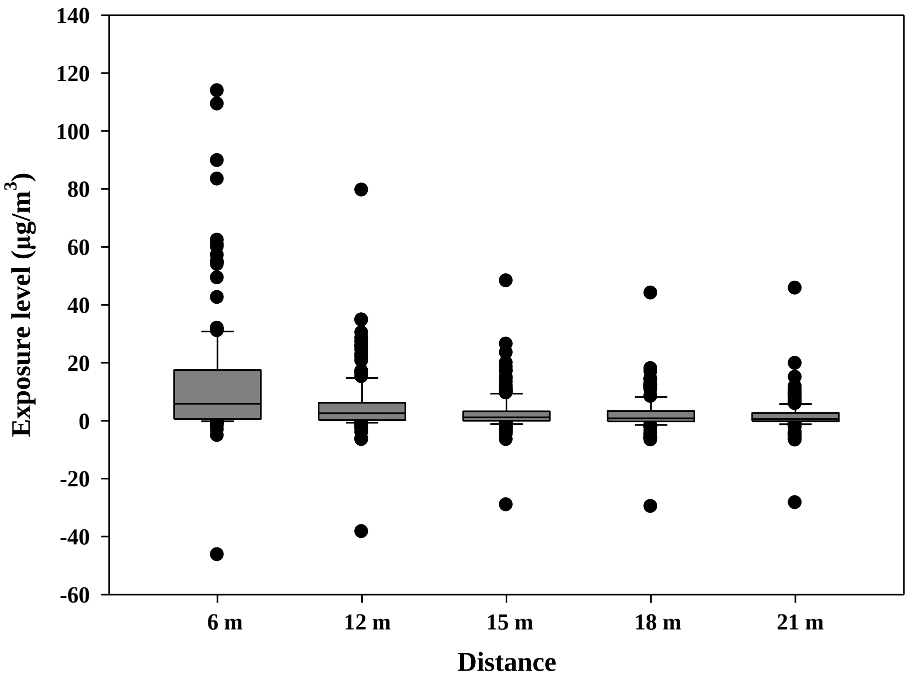

Figure 1. Distribution of the OTS levels by distance

Excluding the outliers of OTS levels, 129 measurements were analyzed. Table 2 and figure 2 show the distribution of OTS levels by distance. The OTS levels were significantly higher than 0 μg/m^3 at all distances ($p<0.001$). The number of OTS levels which were higher than 0 μg/m^3 were 110 (85.3%) in 6 m, 99 (76.7%) in 12 m, 94 (72.9%) in 15 m, 85 (65.9%) in 18 m, and 83 (64.3%) in 21 m.

Table 2. OTS levels (μg/m^3) by distance, excluding outliers of the OTS levels (n=129)

	OTS levels (Mean ± SD)	p-value*
6 m	7.72 ± 8.98	<0.001
12 m	2.35 ± 2.91	<0.001
15 m	1.18 ± 1.88	<0.001
18 m	1.04 ± 2.17	<0.001
21 m	0.89 ± 1.80	<0.001

*p-value of one-sampled t-test

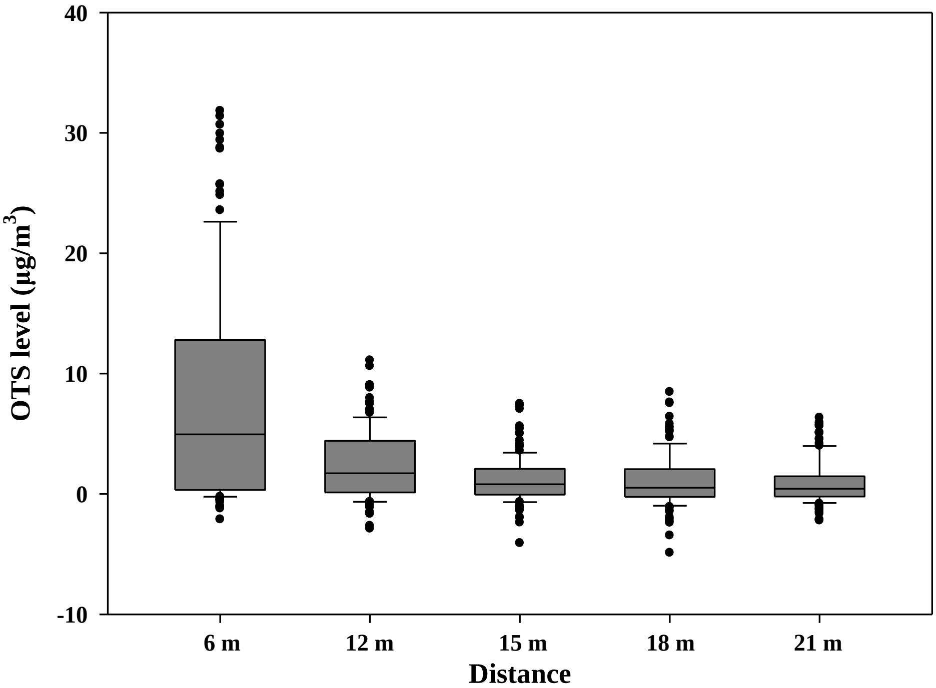

Figure 2. Distribution of the OTS levels by distance excluding outliers

3.2 Multiple regression by wind conditions

Table 3 shows the multiple regression model of the OTS levels by distance, wind speed, and wind direction. Figure 3 shows the distribution of OTS levels by main and other angle at each distance. Wind direction was classified as main angle (0~45˚ and 315~360˚) and other angle (45~315˚). In multiple regression model, the OTS levels were significantly associated with distance. The OTS levels tended to decrease when the distance increased. The OTS levels were also significantly associated with the wind direction, wind speed and interaction of wind direction and wind speed. The OTS levels tended to increase when the wind speed increased, and the wind direction was other angle. The difference of main and other angle was not significantly difference at all distance (6 m; $p=0.051$, 12 m; $p=0.470$, 15 m; $p=0.940$, 18 m; $p=0.615$; 21 m; $p=0.386$) (Figure 3).

Table 3. Multiple regression model of the OTS levels by distance and wind conditions (n=164)

Variable	Coefficient (95% CI)	Standard error	p-value
Intercept	14.66 (12.07 ~ 17.25)	1.32	<0.001
Distance	-0.75 (-0.90 ~ -0.61)	0.08	<0.001
Wind direction			
Main angle	Reference		
Other angle	1.25 (-0.42 ~ 2.93)	0.85	0.143
Wind speed	2.21 (-1.69 ~ 6.11)	1.99	0.266

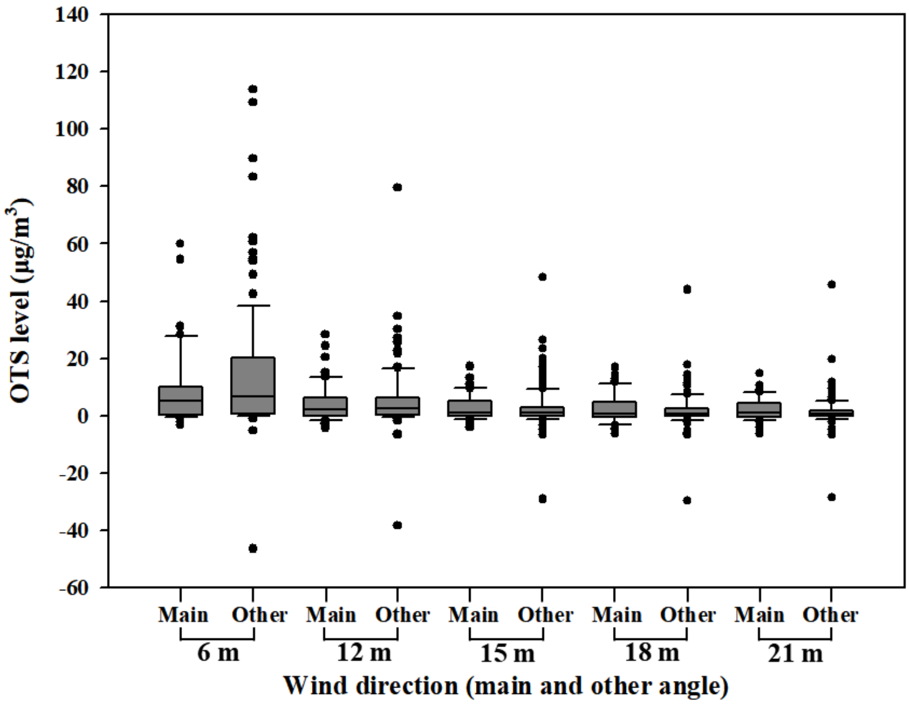

Figure 3. Distribution of the OTS levels of each distance by wind direction

Table 4 and figure 4 show the multiple regression model and the distribution of the OTS levels by main and other angle, excluding outliers of the OTS levels, respectively. In multiple regression model, the OTS levels were significantly associated with distance, which tended to decrease when the distance increased. But the OTS levels were not significantly associated with wind speed and wind direction. The difference of main and other angle was significant at 6 m (p=0.041), but there was not significantly difference at 12 m (p=0.188), 15 m (p=0.973), 18 m (p=0.528), and 21 m (p=0.219) (Figure 4).

Table 4. Multiple regression model of the OTS levels by distance and wind conditions, excluding outliers of the OTS levels (n=129)

Variable	Coefficient (95% CI)	Standard error	p-value
Intercept	8.71 (7.50 ~ 9.92)	0.62	<0.001
Distance	-0.45 (-0.52 ~ -0.38)	0.04	<0.001
Wind direction			
Main angle	Reference		
Other angle	0.62 (-0.17 ~ 1.41)	0.40	0.122
Wind speed	-0.08 (-2.04 ~ 1.88)	0.10	0.935

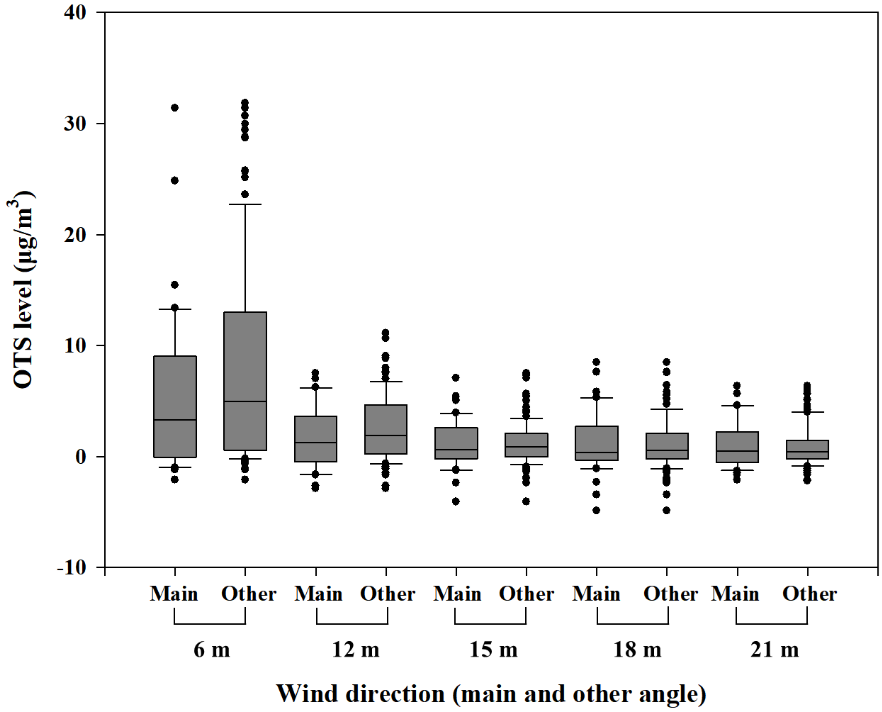

Figure 4. Distribution of the OTS levels of each distance by wind direction, excluding outliers of the OTS levels

To exclude the effect of wind conditions, the OTS levels with 0 m/s of wind speed were conducted for the multiple regression analysis. Total 101 measurements were analyzed. Table 5 shows the multiple regression model of the OTS levels by distance and wind direction. In the multiple regression model, distance was significantly associated with the OTS levels. The OTS levels tended to decrease when the distance increased. The wind direction was not significantly associated. Figure 5 shows the distribution of OTS level between the main angle and other angle at each distance when wind speed of 0 m/s. The difference of main and other angle with 0 m/s wind speed was significant at 6 m ($p=0.017$), but there was not significantly difference at 12 m ($p=0.424$), 15 m ($p=0.975$), 18 m ($p=0.458$), and 21 m ($p=0.241$) (Figure 5).

Table 5. Multiple regression model of the OTS levels by distance and wind conditions when wind speed was 0 m/s (n=101)

Variable	Coefficient (95% CI)	Standard error	p-value
Intercept	8.49 (7.14 ~ 9.84)	0.69	<0.001
Distance	-0.44 (-0.51 ~ -0.36)	0.04	<0.001
Wind direction			
Main angle	Reference		
Other angle	0.58 (-0.32 ~ 1.49)	0.46	0.210

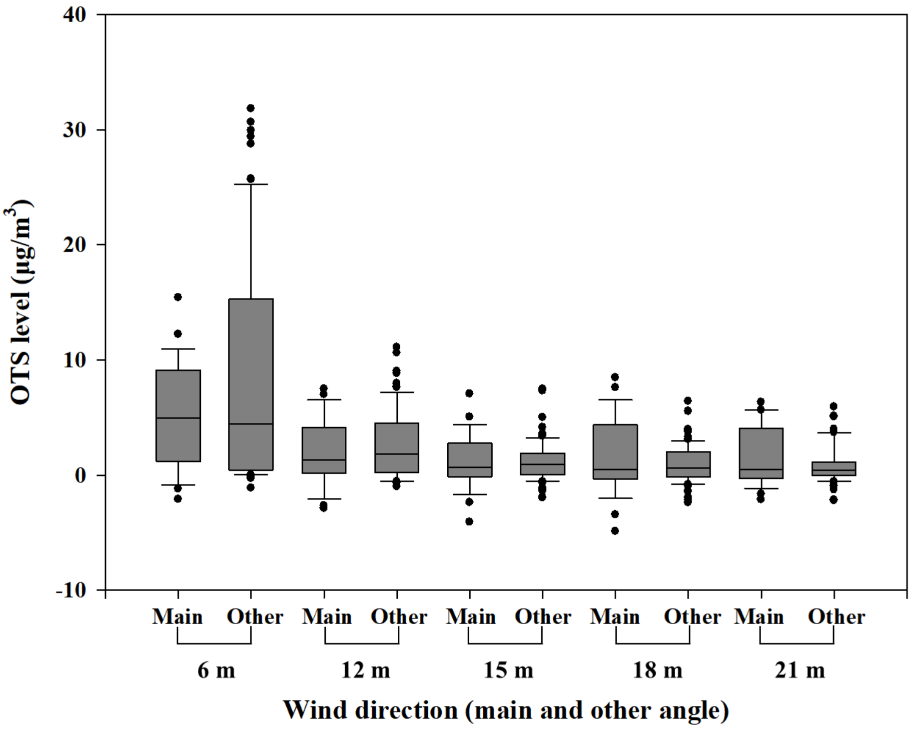

Figure 5. Distribution of the OTS levels with 0 m/s wind speed between wind directions at each distance

4. Discussion

Indoor smoking is prohibited in many countries. However, people were still exposed to OTS. To determine the OTS levels, $PM_{2.5}$ concentration was measured at 6, 12, 15, 18, 21 m, respectively. The OTS levels were derived by the average of $PM_{2.5}$ concentration during smoking subtracting background $PM_{2.5}$ concentration. To determine the factors associated with the OTS levels, multiple regression analysis was conducted with distance and wind conditions.

The OTS levels were significantly higher than 0 μg/m^3 up to 21 m. In previous study, the OTS levels have been determined up to 9 m, which were 4.1 μg/m^3 at 6 m, and 2.6 μg/m^3 at 9 m (Hwang et al., 2014). The OTS levels were detectable up to 21 m from smoking source. The OTS levels up to 21 m were less than the US National Ambient Air Quality Standard of 35 μg/m^3 for 24 h. However, there is no safe level of secondhand smoke (U.S. Department of Health and Human Services, 2006). Therefore, it is necessary to concern about OTS exposure up to 21 m.

The OTS levels were significantly associated with distance. As the distance increased, the proportion of the OTS levels higher than 0 μg/m^3 was decreased. In multiple regression model, the OTS levels had significantly negative association with distance. The finding was consistent with previous studies that the OTS levels had a negative association with the distance (Hwang et al., 2014; Klepeis et al., 2007; Ott et al., 2014). As the distance increased, OTS could be diluted by diffusion.

For wind condition, there was a limited association with the OTS levels in this study. This is different from previous studies. In previous study, main angle and other angle were significantly different at 1 m and 9 m although there were not significantly associated with the OTS levels in regression model (Hwang et al., 2014). The reason for the different association might be low wind speed in this study. As the average of wind speed was 0.1 ± 0.2 m/s, when excluding the cases with wind speed of 0 m/s, there were not significantly different between main angle and other angle. In this study, the wind direction was calculated as an average during the smoking period in measurement. As wind direction can change continuously, it might have a limited effect at low wind speeds. Wind direction can change irregularly and can blow from various directions. Since atmospheric dispersion formed by multiple turbulences could affect the OTS levels, the impact of wind direction might be limited.

This study had some limitations. First, smoking 1 cigarette was applied to measure the OTS levels. OTS could occur by several people in the smoking area. As the number of smokers increases, the OTS levels could increase in far-field. Therefore, the OTS levels in real situation could be much higher than the OTS levels measured in this study. Second, the measurement was conducted with relatively calm wind condition. Other weather condition such as rain was excluded in this experimental condition. The OTS levels could be different in realistic atmospheric dispersion and wind direction. This study was also conducted in an open space. Obstacles could exist in outdoor smoking areas, such as walls, people, and buildings. If there were obstacles near the outdoor smoking area, it would be difficult to apply this study directly. Finally, the OTS levels were measured by $PM_{2.5}$ concentration. Since there are many sources of $PM_{2.5}$ other than OTS, the results could be affected by the other sources. However, to minimize other environmental conditions, we conducted the measurement in university campus without traffic at night. This setting provided minimal impact of transportation sources and smoking near the site.

And we conducted 164 measurements to provided sufficient statistical power to determine the OTS levels under conditions of low wind. Therefore, this study concluded that the OTS levels could be significantly higher than 0 μg/m^3 at 21 m.

5. Conclusion

OTS levels in outdoor by distance were analyzed by measuring $PM_{2.5}$ concentration. To conduct the measurements, the real-time aerosol monitors were used by locating at 6 m, 12 m, 15 m, 18 m, and 21 m simultaneously from the smoke source. The OTS levels were significantly higher than 0 $\mu g/m^3$ at all distances up to 21 m. The OTS levels were decreased by increase of distance from the smoking source. The OTS levels were affected by distance, but the effect of wind conditions was limited. This study concluded that the OTS could reach up to 21 m. Therefore, the regulations of outdoor smoking areas should include sufficient distance from the smoking sources.

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Supplementary Information

Table S1. Multiple regression model of wind conditions by distance (n=129)

Distance	Variable	Coefficient (95% CI)	Standard error	p-value
6 m	Intercept	5.27 (2.27 ~ 8.27)	1.52	<0.001
	Wind direction			
	Main angle	Reference		
	Other angle	3.26 (-0.18 ~ 6.69)	1.74	0.063
	Wind speed	2.07 (-6.47 ~ 10.60)	4.31	0.633
12 m	Intercept	1.88 (0.90 ~ 2.86)	0.49	<0.001
	Wind direction			
	Main angle	Reference		
	Other angle	0.72 (-0.40 ~ 1.84)	0.57	0.205
	Wind speed	-0.48 (-3.26 ~ 2.30)	1.40	0.734
15 m	Intercept	1.20 (0.56 ~ 1.83)	0.32	<0.001
	Wind direction			
	Main angle	Reference		
	Other angle	0.004 (-0.72 ~ 0.73)	0.37	0.992
	Wind speed	-0.19 (-2.00 ~ 1.62)	0.91	0.834

Distance	Variable	Coefficient (95% CI)	Standard error	p-value
18 m	Intercept	1.34 (0.61 ~ 2.07)	0.37	<0.001
	Wind direction			
	Main angle	Reference		
	Other angle	-0.34 (-1.18 ~ 0.49)	0.42	0.419
	Wind speed	-0.74 (-2.83 ~ 1.34)	1.05	0.481
21 m	Intercept	1.34 (0.74 ~ 1.94)	0.30	<0.001
	Wind direction			
	Main angle	Reference		
	Other angle	-0.53 (-1.22 ~ 0.16)	0.35	0.129
	Wind speed	-1.06 (-2.77 ~ 0.65)	0.86	0.222

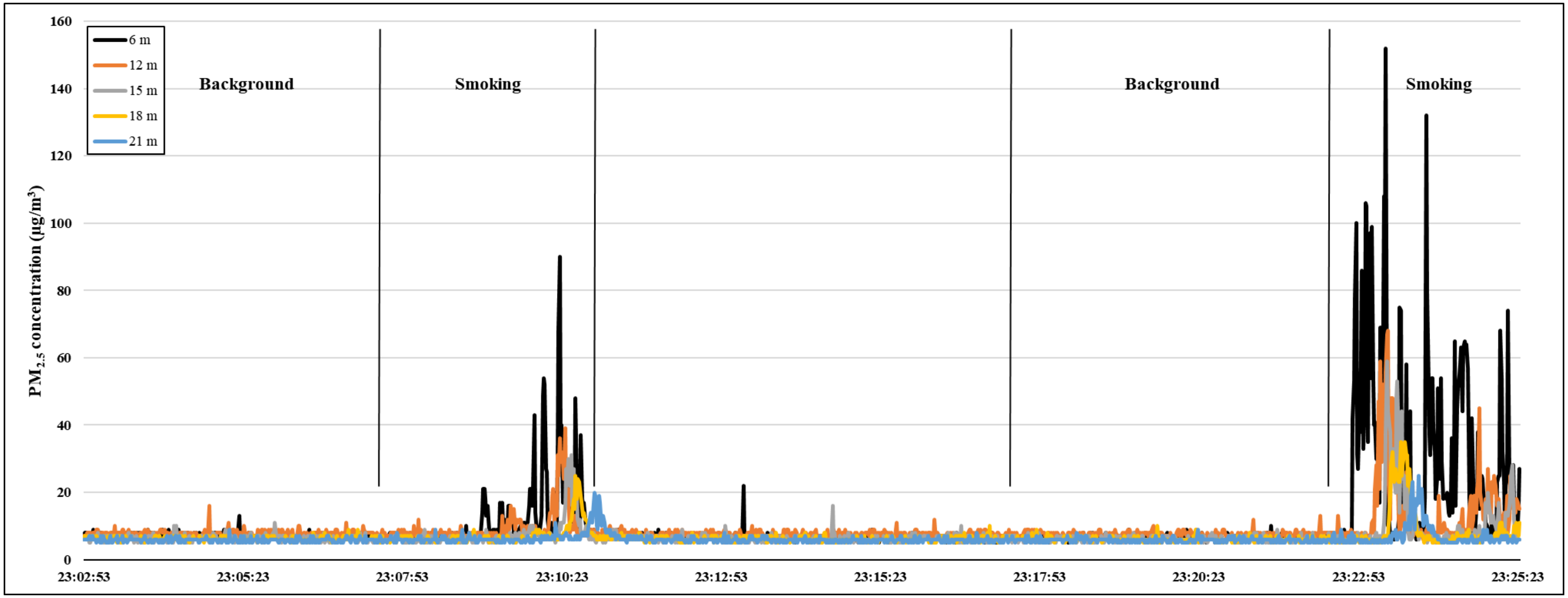

Figure S1. Real-time $PM_{2.5}$ concentration of each distance during measurement

국문초록

거리에 따른 실외 간접흡연 노출 평가

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간접흡연에 노출되면 여러 건강 영향이 나타날 수 있으며 간접흡연 노출에 대한 안전 수준이 없다. 이에 여러 국가에서 간접흡연의 노출로부터 보호하기 위해 실내 금연 정책을 시행하고 있으며 일부 국가에서는 실외 금연 구역을 지정하였지만 실외 금연구역 지정에 대한 기준이 명확하지 않다. 따라서 본 연구의 목표는 거리에 따른 실외 간접흡연(OTS) level을 측정하고 풍향 및 풍속과 같은 실외 간접흡연과 관련된 요인을 고려하여 실외 금연구역 관련 거리 기준을 제안하는 것이다.

OTS level을 파악하기 위해 에어로졸 모니터를 사용하여 6 m, 12 m, 15 m, 18 m, 21 m의 거리에서 $PM_{2.5}$ 농도를 측정하였다. 측정은 2022년 8월부터 10월까지 5일 동안 이루어졌으며 담배를 피우기 전 5분 동안 배경농도를 측정하고 인형을 사용하여 3분 동안 담배를 피웠으며 각 측정마다 2분 이상 간격을 두어 총 164회 측정을 진행하였다. OTS level은 흡연 시간 3분에서 첫 1분을 제외한 2분 동안의 평균 $PM_{2.5}$ 농도와 5분 동안의 배경농도의 평균의 차이를 구하여 분석하였다. 거리별 OTS level이 0 μg/m^{3}보다 유의하게 높은 지 파악하기 위해 one-sampled t-test를 실시했으며, 풍속, 담배로부터의 거리, 풍향 등 OTS level에 영향을 미치는 요인

을 파악하기 위해 다중회귀분석을 실시하였다.

바람의 영향이 적은 조건에서 모든 거리에서 평균 OTS level이 0 μg/m^{3}보다 유의하게 높게 나타났다. 다중회귀분석 결과 OTS level은 거리와 유의한 상관관계를 가지는 것으로 나타났으며 거리가 증가할수록 OTS level이 감소하는 경향을 보였다. 본 연구에서는 21 m에서 실외 간접흡연의 영향을 받을 수 있음을 확인하였으며 추후 실외 금연 구역 지정에 대한 근거로 사용될 수 있을 것이다.

주요어 : 간접흡연, 실외흡연, $PM_{2.5}$, 다중회귀분석

학번 : 2021-22529