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Differential Impacts of Smoke-Free Laws on Indoor Air Quality

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Abstract

The authors assessed the impacts of two different smoke-free laws on indoor air quality. They compared the indoor air quality of 10 hospitality venues in Lexington and Louisville, Kentucky, before and after the smoke-free laws went into effect. Real-time measurements of particulate matter with aerodynamic diameter of 2.5 µm or smaller ($PM_{2.5}$) were made. One Lexington establishment was excluded from the analysis of results because of apparent smoking violation after the law went into effect. The average indoor $PM_{2.5}$ concentrations in the nine Lexington venues decreased 91 percent, from 199 to 18 µg/m^3. The average indoor $PM_{2.5}$ concentrations in the 10 Louisville venues, however, increased slightly, from 304 to 338 µg/m^3. $PM_{2.5}$ levels in the establishments decreased as numbers of burning cigarettes decreased. While the Louisville partial smoke-free law with exemptions did not reduce indoor air pollution in the selected venues, comprehensive and properly enforced smoke-free laws can be an effective means of reducing indoor air pollution.

Introduction

Cigarette smoking is the single most preventable cause of morbidity and mortality (CDC, 2002), and secondhand smoke is the third leading preventable cause of death in the United States (Glantz & Parmley, 1991). Secondhand smoke consists of a mixture of the smoke given off by the burning end of tobacco products (sidestream smoke) and the smoke exhaled by smokers (mainstream smoke). It is a major source of indoor air pollution, containing a complex mixture of more than 4,000 chemicals, more than 50 of which are cancer-causing agents (Jaakkola & Jaakkola, 1997; Rothberg, Heloma, Svinhufvud, Kahkonen, & Reijula, 1998). There is no safe level of exposure to secondhand smoke (Centers for Disease Control and Prevention, 2006). It is a cause of cardiovascular disease (He et al., 1999; Otsuka et al., 2001; Pitsavos et al., 2002), respiratory illness (Das, 2003; Jaakkola, Piipari, Jaakkola, & Jaakkola, 2003; Sturm, Yeatts, & Loomis, 2004), and lung cancer (Brennan et al., 2004) among both smokers and nonsmokers. Approximately 60 percent of the U.S. nonsmoking population shows biological evidence of secondhand-smoke exposure (CDC, 2005).

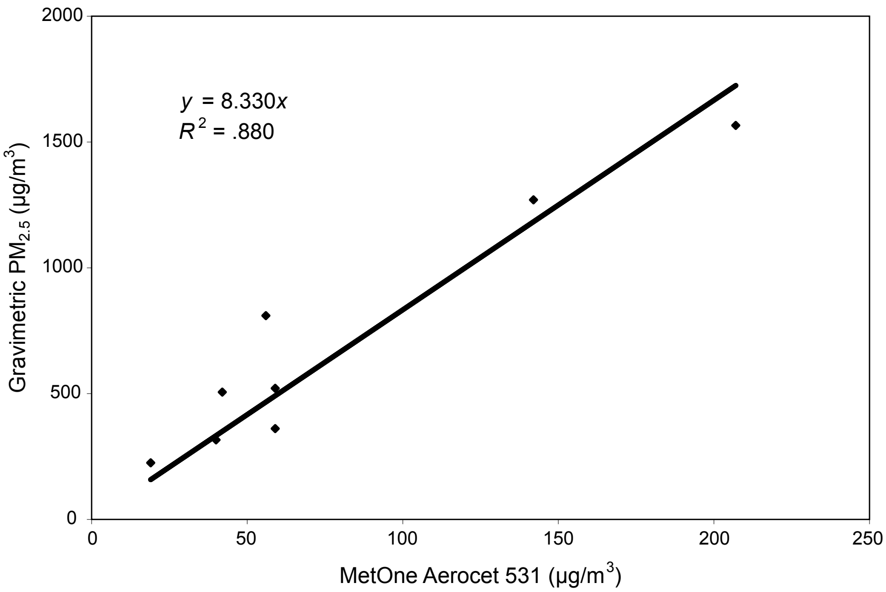
About one-third of the U.S. population is protected by a local or state smoke-free indoor air law (Shopland, Gerlach, Burns, Hartman, & Gibson, 2001). As of July 1, 2006, 2,282 U.S. municipalities had local smoke-free laws, 474 of which provided 100 percent smoke-free protection (American Nonsmokers Rights Foundation, 2006). Although many states and local communities have adopted strong indoor smoking restrictions, the tobacco-growing states lag behind in protecting patrons and workers from the dangers of secondhand smoke.

In July 2003, the Lexington-Fayette Urban County Council passed Kentucky's first smoke-free law. After a seven-month legal delay, the law went into effect on April 27, 2004. This law, designed to ensure that enclosed public places are smoke free, prohibits smoking in most public places, including, but not limited to, restaurants, bars, bowling alleys, bingo halls, convenience stores, laundromats, and other businesses open to the public. The Louisville Metro Council passed a partial smoke-free law that went into effect on November 15, 2005. Unlike the smoke-free law in Lexington, the law in Louisville allows smoking if establishments derive 25 percent or more of their sales from alcohol or have a bar area that can be physically separated from a dining area by walls, a separate ventilation system, or both.

The impact of smoke-free laws on indoor air pollution has been observed. In a cross-sectional study in Delaware, 90 percent of respirable suspended particles (RSPs) in hospitality venues were attributed to tobacco smoke (Repace, 2004). A longitudinal study from California showed an 82 percent decline in indoor air pollution after smoking was prohibited (Ott, Switzer, & Robinson, 1996). A cross-sectional study from western New York found that average levels of RSPs decreased 84 percent in 20 hospitality venues after a smoke-free law went into effect (Travers, Cummings, & Hyland, 2004).

FIGURE 1

Association Between MetOne Aerocet 531 Monitor and Gravimetric $PM_{2.5}$ Measurements



These findings indicate that tobacco smoke substantially contributes to indoor particle concentrations in hospitality venues and that those concentrations can be greatly reduced by implementation of smoke-free laws.

The purpose of our study was to assess the impacts of two different smoke-free laws in Lexington and Louisville on indoor particulate matter with an aerodynamic diameter of 2.5 µm or smaller ($PM_{2.5}$). Indoor air quality was measured in business venues before and after the smoke-free laws took effect in Lexington and Louisville, Kentucky.

Methods

Monitor Quality Assurance

Fine-particle concentrations were measured with a MetOne® Aerocet 531 Aerosol Particulate Profiler (Grants Pass, Oregon) or a TSI Sidepak monitor (Minneapolis, Minnesota). The MetOne monitor uses a laser diode–based optical sensor to detect, size, and count particles. The particle mass data are measured as PM_1, $PM_{2.5}$, PM_7, PM_{10}, and total suspended particles (TSP) and stored in a data logger. The Sidepak monitor measures particles on the basis of light scattering. An impactor for 2.5-µm particles attached to the inlet of the Sidepak monitor removed particles greater than 2.5 µm at a flow rate of 1.7 liters per minute. The stored data were downloaded to a computer after each monitoring period.

To ensure accuracy, we calibrated the MetOne and Sidepak monitors against gravimetric measurement of $PM_{2.5}$ in a series of laboratory experiments. The MetOne monitor was placed in a chamber along with the $PM_{2.5}$ Personal Environmental Monitor (MSP, Shoreview, Minnesota). The Personal Environmental Monitor (PEM) removes particulates larger than 2.5 µm using impaction and collects $PM_{2.5}$ on filter paper. The PEM sampler was operated at 4 liters per minute, and the flow rate was calibrated before and after the sampling with a flow rate calibrator (Model 4100, TSI). The pre-weighted filter was dried and re-weighted with a Cahn microbalance (Thermo Scientific, Waltham, Massachusetts).

A total of eight calibration tests were conducted on a smoking chamber containing secondhand tobacco smoke. During the chamber experiment, relative humidity ranged from 45 to 50 percent, and the temperature ranged from 21 to 24.5ºC. The cigarettes (Marlboro, Medium and King Size) were smoked at a rate of a 2-second, 35-mL puff each minute by means of a 30-port Heiner Borgwaldt Smoking Machine (Hamburg, Germany). Only secondhand tobacco smoke was introduced to the 0.7-m^3 Hinners-type stainless steel/glass exposure chamber.

Monitoring Procedures

The quasi-experimental study was conducted with two cohorts of hospitality venues in Kentucky, one in Lexington-Fayette County and one in the Louisville Metro area. Purposive sampling was used to identify 10 venues that allowed smoking in Lexington before the smoke-free law was enforced. Ten establishments in Louisville were matched to the Lexington venues on the basis of type and size. The 10 establishments comprised three restaurants, three bars, and four other venues including a coffee house, a comedy venue, a music club, a night club (Lexington), and a bowling alley (Louisville).

The first phase (before the smoke-free law was scheduled to go into effect) was conducted from 7:30 p.m. to 12:30 a.m. on September 19, 20, and 27, 2003, in Lexington and September 24–26, 2004, in Louisville. The second phase (after the law was in effect) was conducted during the same hours September 17–19, 2004, in Lexington and March 10–15, 2006, in Louisville.

The monitor was concealed in either a backpack or a purse and set so that automatic 2-minute samples were collected continuously before entrance into the venue (mean = 14 min, SD = 3.1, range = 7–23 min) and during the visit (mean = 43 min, SD = 19.5, range = 24–114 min). When inside the venue, the researcher selected a central location, as far away as possible from the direct puffs of cigarettes or cigars. In large locations, the researchers collected data by walking up and down in the establishment keeping the monitor 2–4 feet from the floor.

In addition to air quality measurements, information collected on room size, number of people present, number of burning cigarettes and cigars, description of the venue, temperature, relative humidity, air pressure at entryways, and maximum occupancy. Each venue was measured, with a digital ruler for smaller venues (2–50 feet), or with an infrared laser for larger ones (10–700 yards). Total number of people in the venue was counted at the beginning and the end of the sampling period. Number of burning cigarettes/cigars in each venue was counted at the beginning, middle, and end of the sampling period. Smoking density was calculated as the average number of burning cigarettes (bc) per 100 m^3 of indoor volume. Outdoor air particle levels were low during the monitoring periods and had no significant impact on levels in indoor air.

Data Analysis

Arithmetic mean indoor air concentrations were calculated for each location. Concentrations of $PM_{2.5}$ before and after the smoke-free laws were assessed by Student's *t*-test. An analysis of variance (ANOVA) for dependent groups with trend analysis was performed to identify the determinants of indoor particles. Pearson product-moment correlation analysis was employed to assess the association between smoking density and indoor particle concentrations. Log-transformed $PM_{2.5}$ values were used in the ANOVA and Pearson correlation tests; and geometric means (GMs) and geometric standard deviations (GSDs) were obtained. Smoking density was classified into three groups: no burning cigarettes, 0–1 burning cigarettes per 100 m^3, and >1 burning cigarette per 100 m^3.

Results

Figure 1 and Figure 2 show the association between gravimetric $PM_{2.5}$ concentrations and readings from the MetOne and Sidepak monitors for the exposure chamber containing simulated secondhand smoke. The $PM_{2.5}$ readings of the MetOne and Sidepak monitors were 12 percent and 339 percent of the gravimetric $PM_{2.5}$ concentrations, respectively. Time-weighted averages of $PM_{2.5}$ from both monitors showed a linear relationship with gravimetric $PM_{2.5}$ concentrations. All field measurements by the MetOne and Sidepak monitors were adjusted accordingly.

A measurement in one location in Lexington (with average $PM_{2.5}$ levels of 4,508 μg/m^3) was excluded from further analysis because of apparent smoking after the smoke-free law went into effect. The location allowed smoking in a private area even though the private space was adjacent and open to the public area, thus violating the law. Among the other nine Lexington locations, average indoor $PM_{2.5}$ concentrations varied from 21 to 422 μg/m^3 with a mean of 199 μg/m^3 before the law went into effect (Table 1, Figure 3). Smoking density was 2.29 (± 1.92) bc/100 m^3. After the smoke-free law was implemented, when smoking density was 0, the average indoor $PM_{2.5}$ concentration in the same Lexington locations was 18 μg/m^3, representing 9 percent of the mean before the law went into effect (Figure 3).

When 10 Louisville locations were measured before the law went into effect, average indoor $PM_{2.5}$ concentrations varied from 29 to 1,110 μg/m^3, with a mean of 304 μg/m^3 (Figure 3). Smoking density was 0.73 (± 0.49) bc/100 m^3. After the smoke-free law was implemented, average indoor $PM_{2.5}$ concentrations in the same 10 locations varied from 41 to 1,061 μg/m^3, with a mean of 338 μg/m^3. Smoking density was higher than before the law went into effect, at 1.19 (± 1.22) bc/100 m^3. Only three of the 10 venues in Louisville became nonsmoking facilities after the law went into effect; others qualified for an exemption. The average indoor $PM_{2.5}$ concentration in the three smoke-free locations was 51 μg/m^3, which was 17 percent of the mean before the smoke-free law went into effect. In one additional Louisville venue that had an enclosed smoking room, the $PM_{2.5}$ level in the smoking area was 181 μg/m^3; the level in the nonsmoking area was 178 μg/m^3.

We analyzed the data from both the Lexington and the Louisville establishments to identify factors associated with indoor fine-particle levels. Only smoking density was associated with $PM_{2.5}$ levels (r = .28, p = .091). When smoking density was classified into three groups, a clear linear trend was observed, with levels of indoor fine particles increasing as greater numbers of cigarettes were burned (F = 13.6, p = .001). The mean indoor $PM_{2.5}$ level was 372 μg/m^3 when more than one cigarette was burned in a 100-m^3 room and 207 μg/m^3 when less than one cigarette was burned (Figure 4). When no smoking was observed, the mean indoor $PM_{2.5}$ level was 28 μg/m^3.

The MetOne monitor reported particle concentrations. Coarse-particle concentrations can indicate other particle sources. To estimate the coarse-particle level, we subtracted the $PM_{2.5}$ value from the PM_{10} value. The coarse-particle level before the smoke-free law went into effect in Lexington was 146 ± 46 μg/m^3. After the law went into effect, the coarse-particle level was 108 ± 93 μg/m^3. The difference between coarse-particle levels with and without indoor smoking was not statistically significant (p = .24).

Discussion

When indoor smoking was allowed, average $PM_{2.5}$ levels were 199 μg/m^3 and 304 μg/m^3 in Lexington and Louisville, respectively. Fine-particle concentrations before implementation of the smoke-free laws in Lexington and in Louisville were comparable. The levels were measured without prior notice, and the monitors were concealed. Field technicians tried to avoid direct contact with active smoking during the monitoring. Therefore, the measurements are likely representative of well-mixed concentrations. While there is no federal standard for indoor air quality, the National Ambient Air Quality Standard (NAAQS) for

FIGURE 2

Association Between Sidepak Monitor and Gravimetric $PM_{2.5}$ Measurements

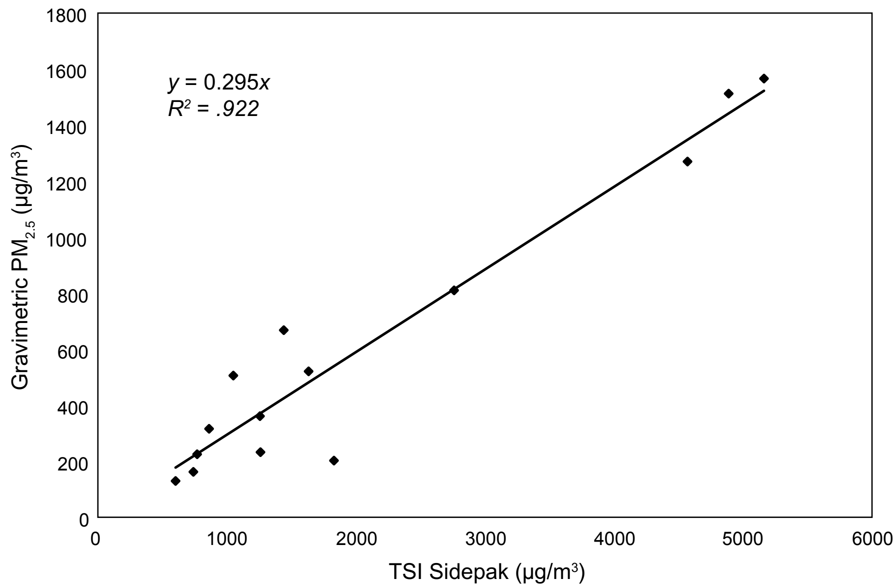


TABLE 1

Indoor Air Quality Measurements in Lexington and Louisville Venues Before and After Implementation of Smoke-Free Laws

	Lexington, Kentucky					
	Before Implementation of Law			After Implementation of Law		
	Mean Particle Concentration (SD) (μg/m³)[a]	Maximum Particle Concentration[a] (μg/m³)[a]	Smoking Density (bc)[b]	Mean Particle Concentration (SD) (μg/m³)[a]	Maximum Particle Concentration (μg/m³)[a]	Smoking Density (bc)[b]
Restaurant A	222 (137)	608	0.32	36 (4)	42	0
Restaurant B	131 (50)	267	0.08	8 (5)	17	0
Restaurant C	156 (32)	200	2.34	4 (4)	8	0
Bar A	422 (158)	550	2.96	9 (6)	17	0.09
Bar B	144 (77)	317	2.89	5 (5)	17	0
Bar C	313 (196)	716	5.45	24 (5)	33	0
Music venue	311 (104)	483	1.97	53 (18)	75	0
Coffee house	21 (8)	33	4.49	26 (6)	33	0
Bowling alley	72 (11)	92	0.09	0 (0)	0	0
Nightclub[c]	21 (27)	158	0.32	4508 (3683)	12195	NA

	Louisville, Kentucky					
	Before Implementation of Law			After Implementation of Law		
	Mean Particle Concentration (SD) (μg/m³)[a]	Maximum Particle Concentration (μg/m³)[a]	Smoking Density (bc)[b]	Mean Particle Concentration (SD) (μg/m³)[a]	Maximum Particle Concentration (μg/m³)[a]	Smoking Density (bc)[b]
Restaurant A	47 (25)	125	0.38	65 (13)	99	0.00
Restaurant B	223 (44)	292	1.19	154 (54)	211	1.09
Restaurant C	72 (21)	108	0.55	46 (5)	54	0.00
Bar A	347 (168)	700	1.76	361 (122)	580	4.11
Bar B	29 (15)	58	0.48	597 (263)	1416	1.77
Bar C	1110 (167)	1266	0.58	1061 (232)	1562	1.37
Music venue	64 (33)	117	0.24	390 (79)	532	1.40
Comedy venue	763 (280)	1524	1.13	313 (98)	503	1.23
Bowling alley	164 (57)	300	0.20	41 (9)	70	0.00
Nightclub	217 (48)	300	0.80	352 (79)	606	0.89

[a] Fine-particle measurements were adjusted by calibration against gravimetric measurements.
[b] bc = number of burning cigarettes per 100 m³.
[c] This venue was excluded from the analysis because smoking was apparent in a private area adjacent to the public space.

$PM_{2.5}$ is 35 μg/m³ for 24 hours. Before the smoke-free laws went into effect in both cities, the average $PM_{2.5}$ levels were about six to nine times higher than the NAAQS.

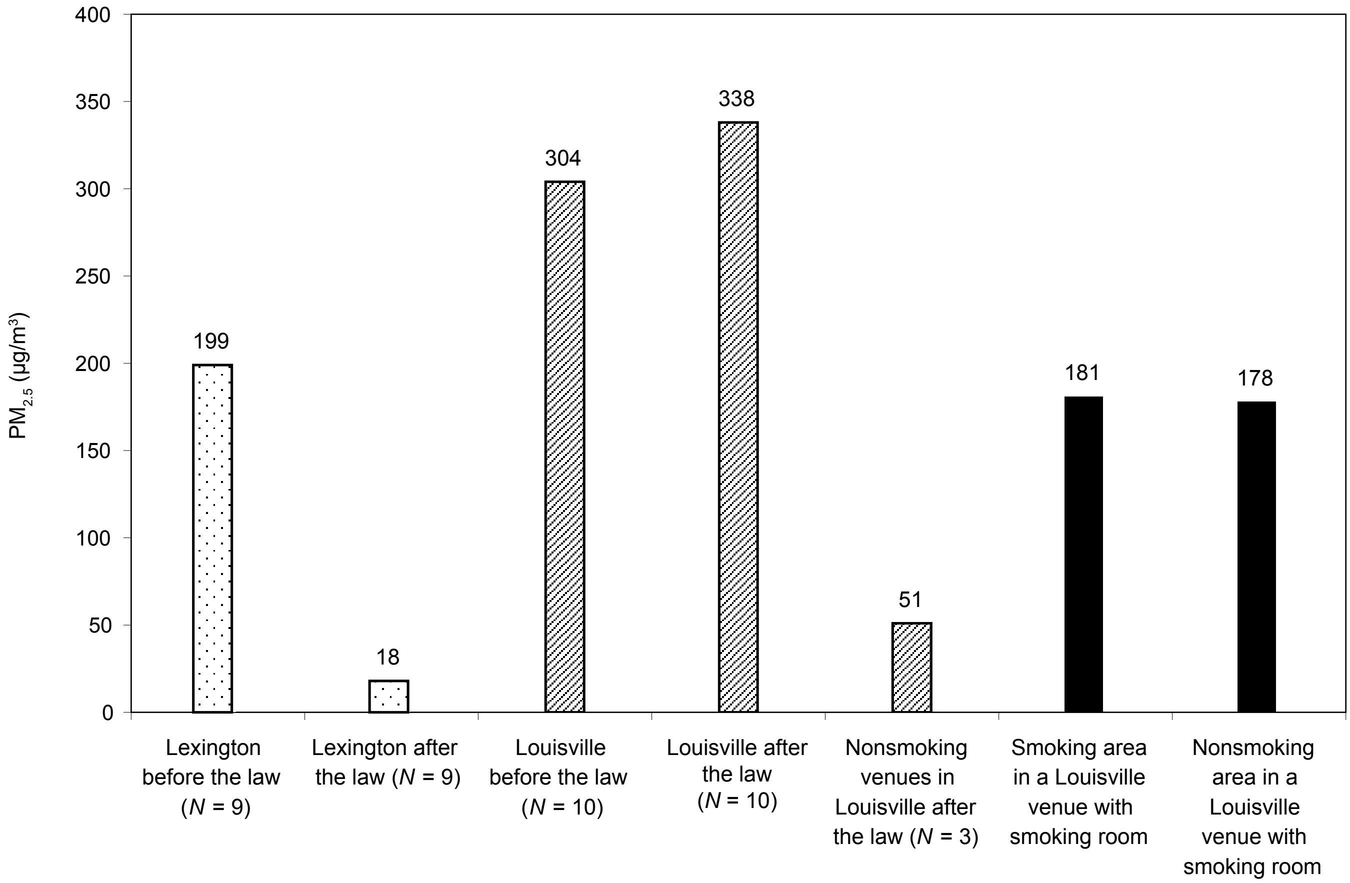
Reduction of indoor fine particles in Lexington after implementation of the smoke-free law was similar to reductions achieved in Delaware and New York. When indoor respirable particles were measured in eight hospitality venues in Delaware before and after implementation of a statewide smoke-free law, RSP levels decreased 90 percent, and particle-bound polycyclic aromatic hydrocarbons decreased 96 percent (Repace, 2004). In 20 hospitality venues in western New York, average levels of RSP decreased 84 percent in these venues after smoke-free law took effect (Travers et al., 2004). In our study, however, one Lexington venue was found to have a high level because of an apparent smoking violation. The venue had had low concentrations before the smoke-free law went into effect; we had observed no smoking on the premises. This finding shows the need for adequate enforcement of smoke-free laws.

Indoor fine particles in Louisville were not reduced after implementation of the partial smoke-free law in that jurisdiction. The smoke-free law in Louisville allows smoking if establishments derive 25 percent or more of their sales from alcohol or if they have a bar that can be physically separated from a dining area by walls, that has a separate ventilation system, or both. Only three venues in our sample became nonsmoking after the law took effect. Seven business venues remained smoking venues. Because of the exemptions, the smoke-free law in Louisville was not effective in reducing indoor fine-particle concentrations in these venues.

Light-scattering instruments can respond differently because of particle characteristics. The MetOne and Sidepak monitors are factory-calibrated against Arizona road dust. Since Arizona road dust has different particle char-

FIGURE 3

Average Indoor $PM_{2.5}$ Level in Lexington and Louisville



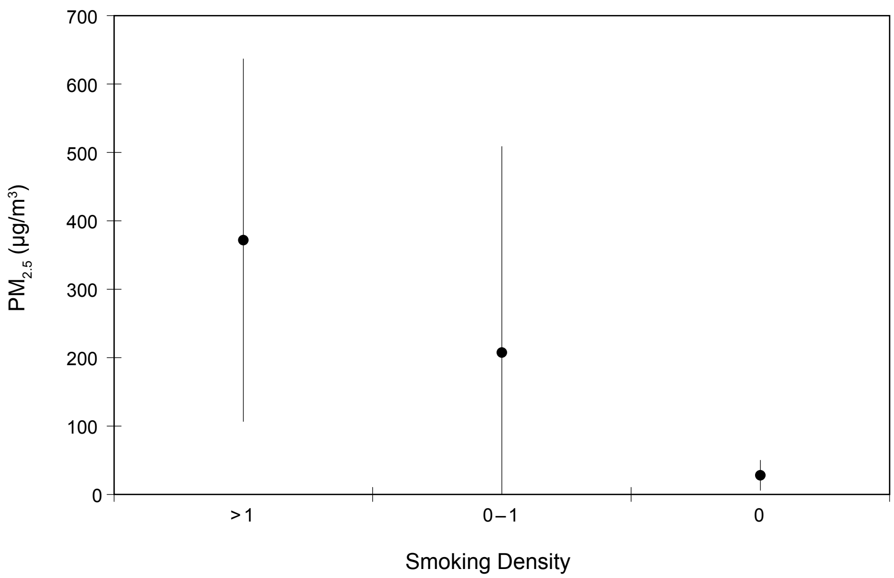
acteristics, it is expected to elicit a different response than secondhand smoke. The MetOne monitor underestimated the gravimetric $PM_{2.5}$ concentration of secondhand smoke by a factor of 8.33. The Sidepak monitor overestimated the gravimetric $PM_{2.5}$ concentration of secondhand smoke by a factor of 3.39. Accordingly, all field data reported in this paper were adjusted. The comparisons performed in our study were based on the assumption that the conversion factor should be consistent over the range of concentrations. Comparisons with a continuous particle monitor (like Piezobalance), as made in a study by Repace (2004), may provide a better understanding of the accuracy of the monitor.

Bar and restaurant workers are at particularly great risk for adverse health effects from exposure to secondhand smoke at work (Jones, Love, Thomson, Green, & Howden-Chapman, 2001). Bar workers encounter significantly higher levels of secondhand smoke than do restaurant wait staff (Jenkins & Counts, 1999). Before the smoke-free law went into effect, bars in Lexington had higher mean $PM_{2.5}$ levels than restaurants (293 µg/m³ versus 169 µg/m³). After the smoke-free law went into effect in Lexington, $PM_{2.5}$ levels in bars and restaurants were similar (13 µg/m³ versus 16 µg/m³). This suggests a potential significant impact on the health of hospitality workers, especially bar workers. Hair nicotine levels dropped 56 percent among bar and restaurant workers just three months after Lexington's smoke-free law took effect; the average decrease among bar workers was significantly greater than that among restaurant workers (Hahn et al., 2006). Disparity of exposure did not decrease in Louisville. Bars in Louisville had higher mean $PM_{2.5}$ levels than did restaurants: 495 µg/m³ versus 114 µg/m³ before the law went into effect and 673 µg/m³ versus 88 µg/m³ after the law went into effect. Since only 15 percent of bartenders in the United States are protected from job-related secondhand-smoke exposure (Shopland, Anderson, Burns, & Gerlach, 2004), such laws could have important effects on the health of bar workers by reducing an occupational health hazard for this vulnerable population.

Smoking was the major contributing factor in $PM_{2.5}$ levels. Although $PM_{2.5}$ is a scientifically accepted marker for secondhand-smoke levels, it can be generated by several other sources. In hospitality venues, possible sources include cooking, human activity (e.g., dancing), and outdoor air pollution. Cooking and human activity may be associated with occupant density, as an increase in the number of people in the venue may increase such activities. In our study, however, only smoking density, estimated by the number of burning cigarettes per 100 m³, was closely associated with indoor $PM_{2.5}$. In addition, no difference in coarse-particle (PM_{10}–$PM_{2.5}$) levels was observed between smoking and no-smoking environments. This finding demonstrated that the difference in $PM_{2.5}$ levels

FIGURE 4

Association Between Indoor $PM_{2.5}$ Level and Smoking Density



Smoking density = number of burning cigarettes per 100 m^3.

before and after the smoke-free laws was due to smoking.

Indoor smoke-free laws may reduce population exposure. Personal exposure to $PM_{2.5}$ was not measured in Lexington, Kentucky, however. Two studies have reported personal $PM_{2.5}$ exposure measurement data from population-based studies in Toronto (Pellizzari et al., 1999) and Switzerland (Oglesby et al., 2000). Average personal exposures were 28.4 and 23.7 µg/m^3, respectively, for those studies. When no exposure to secondhand smoke occurred, the level was reduced to a mean personal $PM_{2.5}$ exposure of 17.5 µg/m^3 (Oglesby et al., 2000). Population 24-hour exposures can be estimated by microenvironmental concentration and exposure time. An estimate of population exposures in Lexington made according to the stochastic human exposure and dose simulation (SHEDS-PM) model (Burke, Zufall, & Ozkaynak, 2001) found that estimated population exposures were reduced by 40 percent after the smoke-free law took effect. The population exposure level observed in Switzerland was reduced by 26 percent (Oglesby et al., 2000). Further studies are needed to determine the impact of reduced $PM_{2.5}$ levels in public indoor environments on population exposure due to smoke-free laws.

Conclusion

Indoor air quality was monitored in business establishments before and after smoke-free laws were implemented in Lexington and Louisville, Kentucky. Indoor fine-particle pollution levels decreased 91 percent as a result of implementation of the smoke-free law in Lexington. In Louisville, however, high indoor fine-particle pollution was observed both before and after implementation of the partial smoke-free law. Since the law in Louisville allowed smoking under certain conditions, seven of the 10 venues remained smoking venues. The exemptions in the smoke-free law in Louisville prevented reduction of indoor smoking in many venues and contributed to high levels of indoor fine particles. Reduction of exposure to secondhand smoke in public environments is important for prevention of prevent excess exposure to hazardous indoor air pollution.

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Did You Know

The U.S. Department of Agriculture's Office of Inspector General has released USDA's *Implementation of the National Strategy for Pandemic Influenza.* It is available at www.usda.gov/oig/webdocs/33701-01-HY.pdf