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The impact of a smoke-free policy on environmental tobacco smoke exposure in public housing developments

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Abstract

Background—Smoke-free housing policies have the potential to reduce secondhand smoke (SHS) exposures for residents of multi-unit housing. Since common areas represent a pathway of SHS movement between units, smoke-free policies would be expected to reduce SHS in these microenvironments.

Methods—Week-long air nicotine and PM_{2.5} (particulate matter below 2.5 micrometers in aerodynamic diameter) samples were collected in the common areas of 10 Boston Housing Authority (BHA) and 6 Cambridge Housing Authority (CHA) buildings from January 2012 to October 2013. We also measured one outdoor PM level at each study building. Samples from BHA included pre and post- smoke-free policy measurements. Each development was visited three times over the course of the study period. The effect of the smoking ban on indoor PM_{2.5} was examined using generalized mixed effect models to accommodate repeated measurement at each site. Changes in nicotine concentrations were modeled using quantile mixed regression to reduce the impact of outliers.

Results—After controlling for season, site, and background PM_{2.5} concentrations, PM_{2.5} levels were 4.05 µg/m³ (p-value = 0.09) lower in BHA after the smoke-free policy was implemented in the summer of 2012, compared with CHA developments, which had no smoking policy in place.

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Competing Interests

The authors declare no competing interests.

Authors Contributions

PM carried out the field work, analysis, and drafted the manuscript. GA helped with the design and implementation of the study as well as drafting the manuscript. RA participated in the field work and in drafting the manuscript. JV helped with the field work. DL conceived of the study, participated in its design, and provided strategic feedback on the manuscript. All authors read and approved the final manuscript.

Similarly, nicotine levels decreased by 57% (p-value = 0.08) in Boston relative to Cambridge after the ban.

Conclusions—Our findings support the use of smoke-free policies as an effective tool to reduce SHS exposure and protect non-smokers, especially residents of multi-unit housing.

Graphical abstract

Keywords

Tobacco Smoke Exposure; Smoking Intervention; Multi-unit Housing; Nicotine; Particulate Matter

Introduction

While there are declines in the prevalence of smoking in the United States (US), about 18% of adults and teens continue to smoke (Agaku et al. 2014). The burden of disease associated with tobacco smoke exposure (TSE) is well documented (Surgeon General 2014). Cardiopulmonary diseases are the leading cause of death in the US, with more than 80% of lung cancer deaths, and 60% of all pulmonary disease deaths attributable to TSE. TSE claim more than 480,000 American lives annually, with about 10% of these deaths from exposure to secondhand smoke (SHS) by non-smokers (Surgeon General 2014). In addition to its disease burden, the economic costs are huge; smoking-related illness costs an estimated \$156 billion in lost productivity per year, including \$5.6 billion from SHS exposure (Surgeon General 2014).

But the burden of TSE is declining over time. For example, between 1990 and 2010, the disability-adjusted life-years (DALYs) related to TSE declined by 9% (Murray et al. 2013). Sustained awareness by the federal public health agencies, and State and local community policies, including smoke-free laws in indoor public spaces and workplaces as well as household voluntary smoke-free rules are important factors for these declines.

By 2014, over 32 States and territories have prohibited smoking in indoor public places such as bars, restaurants, and workplaces, a 400% increase since 2005 (Centers for Disease Control and Prevention 2014). Similarly, the share of households with smoke-free home rules has more than doubled since 1990 (King et al. 2014a). But because many homes and multi-unit housing are not covered by smoke-free laws and policies, millions of non-smokers continue to be exposed to SHS in the home environment, making homes the single most important microenvironment where highest exposures to SHS occur (Surgeon General 2006; U.S. Department of Health and Human Services 2010). Multi-unit housing is a special concern as TS easily transfers between units, affecting the health of many non-smokers across the country, mostly low-income families, the elderly, and persons with disabilities (Arku et al. 2015; King et al. 2010a; King et al. 2010b; Kraev et al. 2009; Russo et al. 2015). Reducing SHS exposures in residential settings, including public multi-unit housing properties, is increasingly important to fully protect non-smokers from exposure to SHS, especially children and pregnant women.

A number of studies have examined the impact of smoke-free policies on SHS exposure through its indicators (e.g. nicotine) and biomarkers (e.g. cotinine) in public indoor areas (e.g. restaurants, bars, hospitals) and have consistently found significant reduction in exposure to SHS following prohibitions (Jensen et al. 2010; Wilson et al. 2012). Beneficial effects of smoking prohibitions on health outcomes as well as cost savings have also been established (Jacobs et al. 2013; King et al. 2013; King et al. 2014b; Wilson et al. 2010). But very little is known about the impact of smoke-free policies on SHS exposure in the nation's 1.2 million households in public multi-unit housing developments. The few studies of the effect of smoke-free policies on SHS exposure in multi-unit housing mainly focus on self-reported rather than objectively measured evidence (Drach et al. 2010; Pizacani et al. 2012; Snyder et al. 2015).

In this paper, we assess the impact of a smoke-free policy on environmental tobacco smoke exposure in Boston public housing developments. This study is among the first to use both pre-and post-implementation data to assess the impact of a smoking ban on markers of SHS exposure in public housing properties. In October of 2012, Boston implemented a city wide smoke-free policy in public housing developments that banned smoking inside buildings or within a specified distance from the buildings. The public housing units in Cambridge, MA, were concurrently assessed as control sites.

Methods

Study location

Sampling was conducted in Boston and Cambridge Housing Authority developments, which houses low-income families, elders and disabled individuals. As the largest public housing authority in New England, Boston Housing Authority (BHA) accommodates about 60,000 residents, approximately a tenth of the city's residents. The Cambridge Housing Authority (CHA) serves more than 5,500 families. Cambridge is situated directly north of the city of Boston, across the Charles River. BHA adopted comprehensive smoke-free policy in October, 2012. CHA has no smoke-free policy, and thus the measurements from the CHA developments served as controls for the BHA samples. We selected developments in BHA

that represent the range of building and occupant characteristics within their properties for our study. The seven largest developments in Cambridge were selected.

Study Design

Week-long air nicotine and PM_{2.5} (particulate matter below 2.5 micrometers in aerodynamic diameter) samples were collected in the common areas of 10 BHA and 6 CHA buildings from January 2012 to October 2013. In each development, two to three pumps were used to collect PM_{2.5} on Teflon filters in hallways on multiple floors. We also measured PM_{2.5} levels in one outdoor location at each study buildings. Five to ten airborne nicotine samples were collected simultaneously at each building for each monitoring session. Field measurements started at five BHA developments in winter of 2012, followed by the remaining seven (BHA) and six (CHA) developments in the summer of 2012. Each development was visited three times over the course of the study period. Vacant units were not available at 7 out of the 54 site visits, and thus no pumps could be deployed at these sites due to the lack of security of the instruments (Table 1).

Measurement methods

We deployed pumps in vacant units at the developments to collect the gravimetric PM_{2.5} samples (Harvard T.H. Chan School of Public Health, HSPH, Boston, MA, USA) (Demokritou et al. 2001). All filter preparations were conducted on a Mettler Toledo MT5 (Columbus, OH, USA) microbalance maintained at HSPH laboratory. Continuous PM_{2.5} samples were measured at 1-min intervals using SidePak model AM510 monitors (TSI Inc., Shoreview, MN, USA), and adjusted for the effect of temperature and humidity as detailed elsewhere (Arku et al. 2015). We distributed passive nicotine monitors in the hallways across multiple floors to collect integrated airborne nicotine samples in each study building (Hammond and Leaderer 1987). The nicotine monitors were analysed in a laboratory maintained at the University of California, Berkeley. Samples below the limit of detection of 2 ng/m³ were assigned a value equal to one half the limit of detection. Detailed methods are described in previous publications (Arku et al. 2015).

In addition to the field measurements, background PM_{2.5} levels were obtained from a central monitoring station located on the Countway Library of HSPH. All study buildings in both Boston and Cambridge were within 5 miles of this central station. Background PM_{2.5} levels were estimated and assigned to each site-week using a seven-day moving average.

Statistical analysis

The effect of the smoking ban on indoor PM_{2.5} and airborne nicotine concentrations was examined using regression analyses. We conducted separate analyses for PM_{2.5} (equation 1) and airborne nicotine (equation 2) concentrations. We used the following generalized mixed effect models to accommodate repeated measurement at each site and adjust for background PM_{2.5} levels and/or season.

$$PM_{ij} = \beta_1 + \beta_2(\text{Smoking ban}) + \beta_3(\text{Season}) + \beta_4(\text{City}) + \beta_5(\text{Smoking ban} * \text{City}) + \beta_6(PM_{\text{ambient}}) + b_{1i} + \varepsilon_{ij} \quad (1)$$

$$\ln(\text{Nicotine}_{ij}) = \beta_1 + \beta_2(\text{Smoking ban}) + \beta_3(\text{Season}) + \beta_4(\text{City}) + \beta_5(\text{Smoking ban} * \text{City}) + b_{1i} + \varepsilon_{ij} \quad (2)$$

- PM_{ij} = 7-day indoor $PM_{2.5}$ concentration ($\mu\text{g}/\text{m}^3$) at development i during visit j
- Nicotine_{ij} = 7-day airborne nicotine concentration (ng/m^3) at development i during visit j
- $i = 1, \dots, 16$ developments
- $j = 1, \dots, 3$ visits
- *Smoking ban* = indicator variable for smoking prohibition (ban; no ban)
- *Season* = indicator variable for season of the year in which measurement was conducted (winter: January–May; summer: June–October)
- *City* = indicator variable for the housing authority (BHA; CHA)
- b = vector of random intercepts for each development i
- ε = vector of within-site errors over time

Because nicotine concentrations were non-normally distributed, even after log transformation, we also modeled nicotine samples using quantile mixed regression to reduce the impact of outliers. We tested the impact of the smoking ban on airborne nicotine concentrations in each city at the 10th, 50th, and 90th percentiles after controlling for season. Gradient-search optimization with 9 nodes was used in the quantile regressions (Geraci, 2014).

All analyses were performed using the open-source statistical package R version 3.0.0 (R Project for Statistical Computing, Vienna, Austria).

Results

Over two winters and two summers, we measured 107 week-long integrated and continuous $PM_{2.5}$ and 269 airborne nicotine samples from 16 multi-unit housing buildings located in two public housing developments. About two thirds of the total samples (66% of $PM_{2.5}$ and 62% of nicotine) were collected in the 10 BHA developments. Of the total number of samples, 62% of the $PM_{2.5}$ and 74% of the nicotine samples were measured indoors in the hallways as opposed to outdoor.

Average $PM_{2.5}$ and nicotine concentrations across study site and time period are summarized in Table 1. Mean indoor $PM_{2.5}$ (SD) levels across all measurement sites and seasons was 9.4 (7.4) $\mu\text{g}/\text{m}^3$ in Boston compared with 7.4 (3.9) $\mu\text{g}/\text{m}^3$ in Cambridge. Overall, indoor $PM_{2.5}$ levels exceeded outdoor during all seasons by between 15–51%, with the exception of the summer of 2013. Average indoor nicotine levels were 169 ng/m^3 (SD = 404 ng/m^3) in Boston and 105 ng/m^3 (SD = 242 ng/m^3) in Cambridge.

In multivariate analysis, the smoke-free policy had a beneficial effect on $PM_{2.5}$ concentration in common areas in BHA developments. After controlling for season, site, and

background PM_{2.5} concentrations, PM levels went down 4.05 µg/m³ (p-value = 0.09) more in BHA post-policy, where smoke-free policy was implemented in the summer of 2012, compared with CHA developments, which had no smoking policy in place (Table 2). Prior to the ban, CHA had lower PM_{2.5} levels in their developments than did BHA, but levels were higher in CHA compared with BHA after the ban. In both HAs, outdoor PM_{2.5} infiltration contributed to increased indoor levels; a unit increase in outdoor PM_{2.5} concentration was associated with a 1.51 µg/m³ increase in indoor levels.

Similarly, by exponentiating the estimate for the interaction between Boston and smoking ban we see that nicotine levels decreased by 57% (p-value = 0.084) in Boston relative to Cambridge after the ban (Table 2). Similar to the PM_{2.5} model, Boston generally had higher nicotine levels than Cambridge as estimated by the model, except after the ban.

Mean nicotine concentrations decreased in Boston after the ban. However, the ban did not have an equal effect at all sites. From the quantile mixed regression, the median nicotine levels were 35.4 ng/m³ lower in Boston than Cambridge following the smoking ban after adjusting for season and specific developments. This effect was even more pronounced at the upper end of the distribution; 90th percentile nicotine levels were 191 ng/m³ lower in Boston than Cambridge after the smoking ban compared to 1.96 ng/m³ at the 10th percentile. These reductions amount to only 7.3% at the 10th percentile compared to 36.1% and 26.4% at the 50th and 90th percentiles respectively. The smoking ban appeared to alter the distribution of nicotine levels in Boston by having the largest impact at the sites with the highest levels of smoking, at a time when nicotine concentrations were getting more disparate at the control sites as evidenced by the positive effect estimates for the smoking ban term (Figure 1).

To investigate the possible influence of smoking on indoor PM_{2.5} levels, we stratified the data into sites where indoor PM_{2.5} concentration were lower than outdoor levels vs sites with higher indoor PM_{2.5} than outdoors (Figure 2). This stratification was intended to broadly categorize locations by the likelihood that PM_{2.5} came primarily from indoor sources. Given that these buildings typically do not filter outdoor air, indoor sources build on a base level of pollution resulting from infiltration and natural ventilation. Nicotine and PM_{2.5} concentration are uncorrelated in the first stratum ($r = 0.05$, p-value = 0.88) but positively correlated in the second stratum ($r = 0.46$, p-value = 0.040) when indoor sources are present.

Discussion

While there have been studies examining the impact of smoke-free policies on SHS exposure in public indoor areas, there have been no longitudinal assessments in public housing properties spanning a smoke-free policy. This study assesses the impact of smoke-free policies on fine particle and airborne nicotine pollution in public multi-unit housing developments. Before the ban on smoking, we found higher fine particles and airborne nicotine levels in BHA than in CHA. After the ban, particle and airborne nicotine levels were lower in BHA compared with CHA. By measurement sites, we found that sites with the highest pre-ban concentrations in BHA had the largest reduction in nicotine levels, whereas the opposite was seen in CHA.

We have also observed some differences in the distribution of nicotine concentrations. These distributional changes may reflect an overall reduction in smoking activity, but not an elimination of smoking activity. As with other lease violations, flouting the smoking policy can result in fines up to \$250.00 or eviction; however, in practice, these penalties have rarely been pursued. Eviction is a last resort as public housing is the only housing option for tenants. Given the difficulty in achieving full compliance with a smoke-free policy, it may be the case that buildings with high levels of smoking activity experience the biggest reduction in exposure. Increased focus on “problem” buildings after the smoking ban may explain the larger percentage reduction in nicotine levels at these locations.

Our study has several limitations. Rather than having direct observation of smoking behaviors, we have employed two proxies for SHS levels in common areas: airborne nicotine and fine particulate matter (PM_{2.5}). Airborne nicotine has been widely used in studies of SHS since it serves as a convenient and specific marker of tobacco smoking. Therefore, we assume that the observed reductions in nicotine likely reflect reduction in smoking activity within apartments and common areas. In recent years, the increased use of electronic cigarettes raises the possibility that some airborne nicotine originates from the use of these products. If some smokers shifted their activities from conventional to e-cigarettes (which were not affected by the smoke-free policy), this would mitigate the effects of the ban observable by measuring differences in airborne nicotine. Our second measure, PM_{2.5}, is not specific to smoking; rather, indoor PM_{2.5} levels are driven not only by combusted tobacco use, but also by ambient pollution, cooking activity, candle burning and other combustion-related activities. Therefore, the change in PM_{2.5} exposures associated with a smoke-free policy may be more difficult to attribute with certainty to tobacco use. We do believe that the observed trend toward reductions in PM_{2.5} likely reflects reductions in smoking activity as shown by our correlations between nicotine and PM_{2.5}.

We have observed significant variability in our measured exposures, which is likely driven by several factors. Due to the difficulty in deploying and securing some of our sampling equipment in the same locations during our successive sampling sessions, we have not sampled in the identical within-development and within-building locations throughout the study. Given some degree of housing turnover (on average 10% per year) and temporal variability in smoking behaviors, this variability is expected.

Conclusion

As shown in previous studies, smoking-related exposures in multi-unit housing developments are widespread. In this study, we compared indoor PM_{2.5} and airborne nicotine concentrations in common areas of buildings within housing developments that transitioned to a smoke-free policy, along with similar measures in developments without such a policy. While we observed significant within-authority variability, our multivariate analysis showed a reduction in PM_{2.5} concentrations in common areas where a smoke-free policy was established. Similarly, we observed reductions in common-area airborne nicotine levels associated with the smoke-free policy. We have also shown that, within many of these sites, common-area PM_{2.5} concentrations are associated with smoking activity, based on

correlation between PM_{2.5} and nicotine in locations where indoor PM levels exceed outdoor concentrations.

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Highlights

- Measured common area nicotine and particulate matter concentrations in public housing developments before and after smoke-free policy
- Modeled changes in concentration controlling for ambient concentrations and site
- PM_{2.5} levels were 4.05 µg/m³ lower in BHA after the smoke-free policy was implemented
- Nicotine levels decreased 57% compared to control sites after the smoke-free policy was implemented
- Smoke-free policies are an effective tool to reduce secondhand smoke exposures in public housing

Figure 1. Cumulative distribution function of nicotine concentration in Boston and Cambridge before and after the smoking ban.

Figure 2. Correlation (and correlation coefficients) between $PM_{2.5}$ and nicotine concentrations, stratified by site visits with higher $PM_{2.5}$ indoors than outdoors and site visits with lower $PM_{2.5}$ indoors than outdoors.

Table 1Summary of PM_{2.5} and nicotine concentrations by sampling period, sample location, and city.

	Indoor		Outdoor	
	Boston	Cambridge	Boston	Cambridge
<i>PM_{2.5} (µg/m³) – Mean (Standard Deviation, N)</i>				
Pre-ban	9.24 (5.85, 27)	8.58 (3.67, 10)	6.10 (3.82, 12)	7.45 (4.40, 7)
Post-ban	10.43 (6.72, 18)	7.45 (7.45, 11)	11.6 (12.2, 14)	5.72 (3.72, 8)
<i>Nicotine (ng/m³) – Mean (Standard Deviation, N)</i>				
Pre-ban	208 (458, 48)	72.5 (119, 40)	252 (850, 14)	46.7 (57.6, 8)
Post-ban	186 (309, 77)	181 (380, 34)	21.9 (18.8, 29)	60.5 (101, 19)
<i>Nicotine (ng/m³) – Median (Median Absolute Deviation, N)</i>				
Pre-ban	71.1 (71.9, 48)	36.4 (52.5, 40)	14.2 (19.6, 14)	13.8 (19.0, 8)
Post-ban	78.2 (85.2, 77)	46.8 (50.4, 34)	17.5 (19.6, 29)	32.2 (44.5, 19)

Coefficients for multivariate analysis of the association of smoking ban with indoor $PM_{2.5}$ and nicotine concentrations.

Table 2

Parameter	$PM_{2.5}$ ($\mu g/m^3$)		Nicotine (ng/m^3)			
	Mean	$\log(Mean)$	10th %ile	Median	90th %ile	
Intercept	β (<i>p</i> -value) −2.81 (0.29)	β (<i>p</i> -value) 2.95 (<0.001)	β (<i>p</i> -value) 1.00 (0.99)	β (<i>p</i> -value) 33.8 (0.23)	β (<i>p</i> -value) 283 (<0.001)	
Smoking ban	2.92 (0.16)	1.17 (0.0022)	12.1 (0.85)	20.9 (0.79)	176 (0.19)	
Boston	2.78 (0.16)	0.984 (0.037)	13.9 (0.99)	43.6 (0.33)	261 (0.19)	
Boston*Smoking ban	−4.05 (0.094)	−0.849 (0.084)	−1.96 (0.98)	−35.4 (0.69)	−191 (0.13)	
Background $PM_{2.5}$	1.51 (<0.001)	NA	NA	NA	NA	