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Comparison of Indoor Air Quality in Smoke-Permitted and Smoke-Free Multiunit Housing: Findings From the Boston Housing Authority

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Abstract

Introduction. Secondhand smoke remains a health concern for individuals living in multiunit housing, where smoke has been shown to easily transfer between units. Building-wide smoke-free policies are a logical step to minimize smoke exposure in these settings. This evaluation sought to determine whether buildings with smoke-free policies have less secondhand smoke than similar buildings without such policies. Further, the study assessed potential secondhand smoke transfer between apartments with and without resident smokers.

Methods. Fine particulate matter ($PM_{2.5}$), airborne nicotine, and self-reported smoking activity were recorded in 15 households with resident smokers and 17 households where no one smoked in 5 Boston Housing Authority developments. Of these, 4 apartment pairs consisted of adjacent apartments with and without resident smokers. Halls between apartments and outdoor air were also monitored to capture potential smoke transfer and provide background $PM_{2.5}$ concentrations.

Results. Households within buildings with smoke-free policies showed lower $PM_{2.5}$ concentrations compared to buildings without these policies (median: 4.8 vs. 8.1 µg/m³). Although the greatest difference in $PM_{2.5}$ between smoking-permitted and smoke-free buildings was observed in households with resident smokers (14.3 vs. 7.0 µg/m³), households without resident smokers also showed a significant difference (5.1 vs. 4.0 µg/m³). Secondhand smoke transfer to smoke-free apartments was demonstrable with directly adjacent households.

Conclusion. This evaluation documented instances of secondhand smoke transfer between households as well as lower $PM_{2.5}$ measurements in buildings with smoke-free policies. Building-wide smoke-free policies can limit secondhand smoke exposure for everyone living in multiunit housing.

Introduction

The Surgeon General reports that there is no risk-free level of exposure to secondhand smoke and that it can cause premature death and disease in nonsmokers.[1] Previous research has demonstrated that levels of fine particulate matter ($PM_{2.5}$) in the air are three times higher in smoke-permitted homes than in smoke-free homes and that confining smoking to certain living spaces does not offer protection from secondhand smoke.[2–4] Children living in multiunit housing have more exposure to secondhand smoke than those living in free-standing homes.[5] Furthermore, people living in multiunit housing have little control over their exposure to secondhand smoke since much of the air entering their apartments originates somewhere else in the building.[6,7] Low-income urban populations are especially susceptible to these issues. For example, in Boston, both the prevalence of smoking (34.4% vs. 20.6%) and current asthma symptoms (19.2% vs. 9.0%) are significantly higher among public housing residents compared with other residents.[8] Therefore, interventions that specifically influence the public housing setting could address health disparities. Digenis-Bury et al.[8] demonstrated that public housing residents in Boston were more likely to have children, less likely to have completed high school or college, and more likely to be unemployed or unable to work compared with other Boston residents. Models controlling for gender, age, race/ethnicity, level of education, and income revealed higher rates of hypertension, asthma, and diabetes among Boston public housing residents (prevalence odds ratio: 1.5–1.8). Many of these disparities can exacerbate vulnerability to secondhand smoke exposure.

In September 2012, in an effort to protect vulnerable residents from exposure to secondhand smoke, the Boston Housing Authority (BHA) implemented a smoke-free policy throughout its entire public housing portfolio, which houses 27,000 people in 14,000 units in 64 developments. The policy development process took place over several years, entailing resident involvement and signing of lease addenda acknowledging the policy change. Informational summits were held, residents were surveyed about their level of support for the policy change, and free on-site tobacco cessation counseling was offered to public housing residents and staff. In part because Americans spend the majority of their time in their own homes, smoke-free policies can have meaningful impact on smoke exposure and may thus experience greater reductions in personal exposure.[1,9,10]

Multiple environmental markers exist for the assessment of secondhand smoke; fine particulate matter is one measurable environmental marker, which can estimate secondhand smoke exposure magnitude, duration, and frequency.[1,11] Aerosol monitors measure these $PM_{2.5}$ particles, which have diameters less than 2.5 μm and are easily drawn deep into the lungs where they can damage the cardiovascular system.[12,13] These monitors have been used to investigate secondhand smoke in multiunit housing communities.[14,15] The specificity of nicotine sampling, conducted alongside aerosol monitoring, supports the conclusion that observed particulates originated primarily from tobacco smoke in settings with active smoking.[4] Studies with real-time aerosol monitoring and nicotine sampling taking place concurrently have validated aerosol monitoring as a method of measuring secondhand smoke.[16] The BHA smoke-free policy presents a unique ecological opportunity for assessing changes in indoor air quality.

The purpose of this evaluation is two-fold: to assess whether there are measurable differences in aerosol levels in BHA buildings with and without smoke-free policies in place and to compare coincident and temporal trends in aerosol levels in the homes of smoking and nonsmoking residents in order to understand how secondhand smoke may transfer between them. This cross-sectional analysis will further describe how smoke-free policies benefit both smoking and nonsmoking populations.

Methods

Sampling Plan

Prior to the portfolio-wide smoke-free policy implementation in September 2012, multiple smoke-free pilot sites were in place. We identified five BHA developments from which we could create pairs of comparable building type (3-story walk-up, mid-rise, and high-rise) with and without smoke-free policies in place prior to September 2012. One development had 3-story walk-up entryways with and without smoke-free policies in place prior to September 2012 and served as its own paired grouping. Although two mid-rise developments were not subject to the pending smoke-free policy due to separate funding and management structures, one already had a building-wide smoke-free policy in place and the other did not. The remaining two high-rise developments transitioned to having a building-wide smoke-free policy as of September 30, 2012 (Table 1). All sampling occurred from August to December 2012, and each sampling event was categorized according to the policy of record on the date of sampling. Household units within each development were selected based on volunteer interest (provided they were adults who comprehended English). We sought to enroll 40 households—20 with and 20 without smoking residents—from these five housing developments and paired them by proximity. Ideal pairs were directly adjacent, but nonadjacent neighbor pairs (with and without smoking residents) who shared a hallway or stairwell were also included. On six occasions, unoccupied units were used in place of nonsmoking households if these locations afforded closer proximity to a household with smoking residents. A smoking household was defined as one that contained at least one smoking resident who agreed to participate in data collection regardless of his or her development's smoke-free policy. These households were designated smoking whether or not the resident smoker(s) abided by the development's smoke-free policy. A nonsmoking household was defined as one that contained no smokers residing in the home as reported by the study participant, regardless of the development's smoke-free policy.

Participant Recruitment

Participants were recruited through community meetings, community liaisons, and door knocking. Each participant gave oral consent to participate in the air quality study, and our confidentiality agreement included protecting residents from being reported to BHA even if they had smoked in designated smoke-free spaces. Participation included keeping a resident log of events, which would affect air quality (e.g., cooking, open windows, lit candles or cigarettes, etc.) during the air sampling period and allowing both the $PM_{2.5}$ monitor and passive nicotine sampler to be placed in the home for a 72-hr sampling period. Participants received $25 gift cards as compensation. Approval of human subjects research was granted by the Boston University Medical Center Institutional Review Board.

Equipment

Co-calibrated DUSTTRAK, DUSTTRAK II, and SidePak aerosol monitors (models 8520, 8530, and AM510, TSI, Inc.) were used to measure $PM_{2.5}$ concentrations in the air. The aerosol monitors were set to record measurements ($PM_{2.5}$ concentration in mg/m^3) at 1-min intervals, which were the average of the previous 60 s of sampling. Manufacturer-specified flow rates were used: 1.7 L/min for model 8520, 1.0 L/min for model 8530, and 1.7 L/min for the SidePak model. We used the size selective inlets provided by the manufacturer of the

Table 1. Characteristics of Areas Sampled for Particulate Matter

					Area sampled for particulate matter			
Smoke-free policy	Development	Building type	Residential type	Proximity	Units by resident smoking status		Public areas	
Yes	A	3-Story	Family	Nonadjacent	Smoker	Nonsmoker	Hall	Outdoor
Yes	A	3-Story	Family	Nonadjacent	Smoker	Unoccupied unit	Hall	Outdoor
Yes	A	3-Story	Family	Nonadjacent	Smoker	Unoccupied unit	Hall	Outdoor
No	A	3-Story	Family	Nonadjacent	Smoker	Unoccupied unit	Hall	Outdoor
No	B	High-rise	Elderly/disabled	Nonadjacent	Smoker	Nonsmoker	Hall	Outdoor
No	B	High-rise	Elderly/disabled	Nonadjacent	Smoker	Unoccupied unit	Hall	Outdoor
No	B	High-rise	Elderly/disabled	Nonadjacent	Smoker	Nonsmoker	Hall	Outdoor
No	C	High-rise	Elderly/disabled	Adjacent	Smoker	Unoccupied unit	Hall	Outdoor
No	C	High-rise	Elderly/disabled	Nonadjacent	Smoker	Nonsmoker	Hall	Outdoor
No	C	High-rise	Elderly/disabled	Nonadjacent	Smoker	Unoccupied unit	Hall	Outdoor
Yes	D	Mid-rise	Family	Adjacent	Smoker	Nonsmoker	Hall	Outdoor
Yes	D	Mid-rise	Family	Adjacent	Smoker	Nonsmoker	Hall	–
Yes	D	Mid-rise	Family	Nonadjacent	Smoker	Nonsmoker	Hall	Outdoor
No	E	Mid-rise	Family	Adjacent	Smoker	Nonsmoker	Hall	Outdoor
No	E	Mid-rise	Family	Nonadjacent	Smoker	Nonsmoker	Hall	Outdoor
No	E	Mid-rise	Family	Nonadjacent	–	Two nonsmokers	Hall	Outdoor

Note. Developments B and C transitioned to having a building-wide smoke-free policy as of September 30, 2012.

DUSTTRAK and SidePak. We conducted side-by-side comparisons between all the devices which were used in this study prior to them being deployed. We recorded $PM_{2.5}$ concurrently for 72 hr in each of four settings: smoking home, nonsmoking or unoccupied neighboring unit, common entryways or hallway, and outdoors sample. Monitors were connected to an electrical source and placed in the primary living space of the home away from windows or vents. If a table or shelf was unavailable, static-free plastic tubing 4 ft in length was attached to the monitor inlet and affixed to a position closer to breathing level. In all instances, the monitor keypad was locked during the sampling period to prevent tampering or accidental termination.

We placed passive nicotine samplers in all of these same settings to confirm the presence of tobacco smoke. Both positive (double concurrent sampling) and negative (unopened sampler) controls were submitted alongside the other environmental samplers for processing at the University of California at Berkeley.

Data Analysis

Particulate matter aerosol data were downloaded from the $PM_{2.5}$ monitors using TSI TrakPro software (version 4.5.1.0, TSI Inc.) and imported into SAS (version 9.1.3, SAS Institute), where they were analyzed alongside resident log information. $PM_{2.5}$ concentration values were limited to those between 0 μg/m^3 and the 99th percentile in order to eliminate extreme outliers. Our calibration factors (0.366 for indoor $PM_{2.5}$ data and 0.635 for outdoor $PM_{2.5}$ data) were based on a separate dataset of concurrent aerosol monitoring and gravimetric analysis in BHA public housing.[15] These calibration factors control for differences in humidity, which affects the particle size distribution in these settings.

Data from these monitors were used to make four analyses: (a) comparisons of median $PM_{2.5}$ levels between smoke-permitted and smoke-free buildings, (b) comparisons of median $PM_{2.5}$ levels between smoker-occupied and nonsmoker-occupied settings, (c) correlations of nicotine concentrations with $PM_{2.5}$ levels to support evidence that $PM_{2.5}$ levels contained tobacco-related contamination, and (d) real-time instances of smoke transfer between smoker-occupied and nonsmoker-occupied households.

The primary outcome of interest was the median $PM_{2.5}$ level in a given setting.[14] We tested whether levels differed between smoke-permitted and smoke-free buildings. Buildings were considered smoke-free if that was their policy of record at the time of sampling. We also compared $PM_{2.5}$ levels in homes with and without smoking residents during hours in which smoking participants reported smoking occurrences on their resident log compared with hours in which no smoking occurrences were reported. We used the Wilcoxon–Mann–Whitney test to determine whether these nonparametrically distributed sample populations were significantly different from each other.

Real-time instances of smoke transfer from smoking to nonsmoking households were initially explored graphically. This transpired when the resident log documented cigarette use in the smoking household at a time corresponding with increased $PM_{2.5}$ measurements, and when minutes later, an increase in $PM_{2.5}$ levels was measured in the home without smoking residents in the absence of any other type of documented air contaminant. We also assessed air quality in common entryways or shared hallways where smoking was not permitted and expected to see intermediate measurements between those recorded in the homes of smoking and nonsmoking residents.

Finally, we used passive nicotine samplers to absorb ambient nicotine in all of the same settings where the $PM_{2.5}$ monitors were placed in order to confirm that higher levels of particulate matter in the air were correlated with elevated environmental tobacco smoke levels. Nicotine concentrations were calculated based on the duration of deployment. We used the Spearman rank correlation coefficient to determine whether $PM_{2.5}$ levels correlated with nicotine concentration absorbed by passive nicotine samplers, where $r_s = 1$ is perfect positive correlation.

Results

$PM_{2.5}$ levels were sampled from 32 households in 5 BHA developments; 15 of these were inhabited by smokers, 11 by nonsmokers, and 6 were unoccupied units used as nonsmoking proxies (Table 1). Households with smoking residents averaged 2.0 inhabitants including 0.5 children per unit with a median age of 38.5 years (range:

1–74). Households without smoking residents averaged 1.6 inhabitants including 0.5 children per unit with a median age of 24.5 years (range: 5–76). Both household types had an average of three-and-a-half rooms (excluding kitchens and bathrooms). Continuous $PM_{2.5}$ data were collected for an average of 78.1 hr in smoking households and 77.0 hr in nonsmoking households.

The five housing developments included two high-rise, two mid-rise, and one 3-story walk-up building. Four of the 16 sampling pairs included a nonsmoking or unoccupied unit directly adjacent to the enrolled smoking household (Table 1). One sampling pair in Development D did not include an outdoor site due to equipment malfunction. In one sampling pair in Development E, an eligible smoking participant could not be recruited, so instead an additional nonsmoking household was included within this smoke-permitted building. These values contributed to the pooled nonsmoking $PM_{2.5}$ samples but could not be used to inform us about smoke transfer between households. Median $PM_{2.5}$ concentrations for each sampled setting revealed that households with resident smokers had the highest levels (10.6 μg/m³), followed by outdoor spaces (8.3 μg/m³), hallways/shared entryways (5.1 μg/m³), and lastly nonsmoking/unoccupied units (4.8 μg/m³); these distributions were significantly different ($p < .0001$).

Comparisons of Median $PM_{2.5}$ Levels Between Smoke-Permitted and Smoke-Free Buildings

Figure 1 shows the differences in $PM_{2.5}$ distributions between buildings with smoke-permitted and smoke-free policies in place. Pooled $PM_{2.5}$ data from both smoking and nonsmoking/unoccupied units showed buildings with smoke-free policies in place had lower $PM_{2.5}$ concentrations at each quartile, with a median of 4.8 μg/m³ compared with 8.1 μg/m³ in buildings with smoke-permitted policies. The differences are most striking at the 75th percentile: 10.2 μg/m³ compared with 19.8 μg/m³.

Comparisons of Median $PM_{2.5}$ Levels Between Smoker-Occupied and Nonsmoker-Occupied Settings

These differences were also demonstrated when apartments with smoking residents and those without smoking residents were pooled separately. Median $PM_{2.5}$ concentrations in apartments with smoking residents were lower in buildings with smoke-free policies (14.3 vs. 7.0 μg/m³). Unoccupied apartments or those with no resident smokers also had lower median $PM_{2.5}$ concentrations in buildings with smoke-free policies in place (5.1 vs. 4.0 μg/m³). All differences were significant using the Wilcoxon–Mann–Whitney test ($p < .0001$).

Median $PM_{2.5}$ levels measured in both the smoking and adjacent nonsmoking households during hours in which the participant smoker reported smoking compared with hours during which no smoking was reported showed significant differences (Table 2). The households with smoking participants demonstrated sharp differences in $PM_{2.5}$ levels between those hours with reported smoking (29.6 μg/m³) and those without (9.2 μg/m³, $p < .0001$). Nonsmoking households located directly adjacent to these smoking participants also experienced differences in $PM_{2.5}$ levels during hours in which their smoking neighbor reported smoking (5.9 μg/m³) compared with hours in which no smoking was reported (3.3 μg/m³, $p < .0001$). This relationship is not observed with nonadjacent pairs of smoking and nonsmoking/unoccupied households, in which a small, statistically significant difference in $PM_{2.5}$ levels was observed during smoking hours (4.0 μg/m³) and nonsmoking hours (4.4 μg/m³). This opposing relationship explains the nonsignificant difference in $PM_{2.5}$ levels when all nonsmokers are combined. Common areas also showed a significant, but small magnitude difference in $PM_{2.5}$ levels in hours with reported smoking (5.9 μg/m³) compared with hours in which no smoking was reported (5.1 μg/m³).

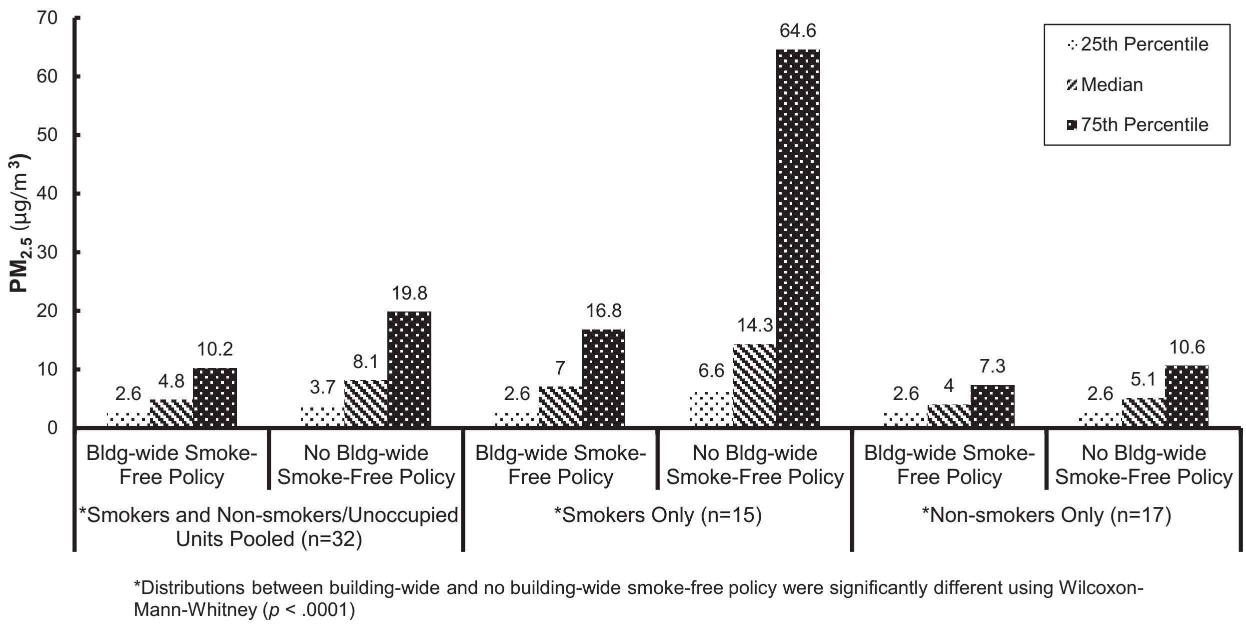

Figure 1. $PM_{2.5}$ distributions by smoke-free policy.

Correlations of Nicotine Concentrations With $PM_{2.5}$ Levels to Support Evidence That $PM_{2.5}$ Levels Contained Tobacco-Related Contamination

Smoking households had the highest mean nicotine concentrations (3.07 μg/m³) compared with common areas (0.43 μg/m³), nonsmoking/unoccupied households (0.04 μg/m³), and outdoor settings (0.02 μg/m³, which was the lowest concentration detected by these nicotine samplers; data not shown in tables). Higher $PM_{2.5}$ levels were correlated with higher nicotine concentrations in all sampling settings (r_s = .58, p < .0001), but particularly so within smoking households (r_s = .90, p < .0001).

Real-Time Instances of Smoke Transfer Between Smoker-Occupied and Nonsmoker-Occupied Households

In Figure 2, we display an instance consistent with tobacco smoke from a smoking participant infiltrating an adjacent unoccupied unit some minutes later. Arrows indicate times at which smoking was self-reported, and the unoccupied unit's $PM_{2.5}$ levels show a steady increase shortly thereafter. There was no other known source of air contamination in this unoccupied unit. Note the different y-axis scales of the smoking and nonsmoking household $PM_{2.5}$ levels. The smoking household's $PM_{2.5}$ levels of higher amplitude show more dynamic response to the smoking events, with higher peaks followed by sharper declines. In contrast, the unoccupied unit shows gradual increases at lower amplitude, which are sustained longer. Specific instances such as these with clear occurrences of smoke transfer corroborated by resident log were rare.

Discussion

This evaluation demonstrates that indoor air pollution is lower in apartments covered by building-wide smoke-free policies compared to apartments in buildings without these policies. These findings lend support to the potential effectiveness of residential smoke-free policies in multiunit housing and bolster existing evidence indicating that smoke cannot be confined to designated smoking areas within buildings. Segregating smokers and nonsmokers by entire buildings with different smoking policies is not a favorable alternative to

Table 2. Comparisons of $PM_{2.5}$ (μg/m³) Aerosol Levels Measured During Hours When Smokers Self-Reported Smoking or Nonsmoking

Area observed	Smoking or nonsmoking hours reported by smoker	25th Percentile	Median	75th Percentile	90th Percentile	*p* value[a]
Smokers	Nonsmoking hours	3.7	9.2	23.4	92.6	<.0001
	Smoking hours	8.1	29.6	113.1	230.2	
All nonsmokers	Nonsmoking hours	2.6	4.4	7.7	15.0	.581
	Smoking hours	2.2	4.0	8.1	16.1	
Nonsmokers living adjacent to smoker	Nonsmoking hours	2.2	3.3	8.8	27.1	<.0001
	Smoking hours	2.6	5.9	24.2	64.8	
Nonsmokers not living adjacent to smoker	Nonsmoking hours	2.9	4.4	7.7	12.4	<.0001
	Smoking hours	2.2	4.0	7.7	12.1	
Common areas	Nonsmoking hours	2.9	5.1	8.8	15.7	<.0001
	Smoking hours	2.9	5.9	10.2	16.1	

[a]Wilcoxon–Mann–Whitney test.

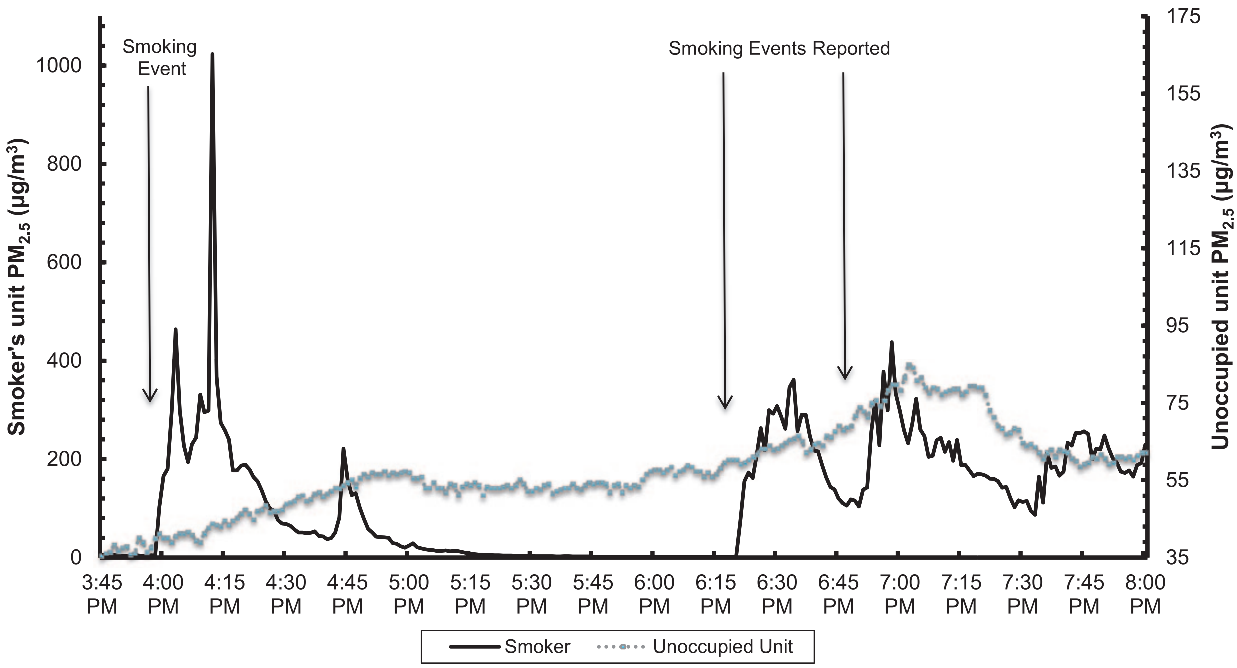

Figure 2. Overlay of two real-time $PM_{2.5}$ axes: levels in smoker's unit and adjacent unoccupied unit.

removing the source throughout the property because it increases the smoke exposure to both smoking and nonsmoking residents in those smoking-permitted buildings.

In buildings with smoke-free policies in place, households with resident smokers had over 50% lower median $PM_{2.5}$ concentrations. This difference suggests that smoke-free policies may reduce indoor smoking and exposure to secondhand smoke. Differences were even more striking at the higher percentiles, consistent with the episodic nature of smoking-associated increases in secondhand smoke-related pollutants. Even small magnitude changes in annual aerosol exposure (i.e., 10 µg/m^3) are associated with health impacts and increased risk of all-cause mortality.[18–21] Of note, the U.S. Environmental Protection Agency's health-based $PM_{2.5}$ annual standard is 12 µg/m^3.[22] The 3-day sampling period medians in this evaluation cannot be directly correlated with annual means, but it is possible that these differences cumulated over a longer time period might have meaningful health implications.

We attribute the higher $PM_{2.5}$ concentrations in smoking-permitted households directly to tobacco smoke. Ambient nicotine concentrations showed the strongest correlation in smoking homes where aerosol levels were also the highest. Using self-reported instances of smoking to classify each hour as a "smoking hour" or "nonsmoking hour" was another measure of the direct impact smoking had on aerosol levels. Smoking households, directly adjacent units, and shared hallways or stairwells all showed significantly higher aerosol levels during hours in which smoking was reported. Classifying a whole hour as smoking or nonsmoking created a conservative estimate for imprecise reporting of the time of smoking events and built in a "lag time" for smoke to transfer to other areas.

Similar to previous studies that measured $PM_{2.5}$ in multiunit housing, we observed significantly higher aerosol levels in smoking compared with nonsmoking households.[14,15] These apartments with resident smokers had more than twice the $PM_{2.5}$ concentration of nonsmoking/unoccupied units regardless of whether some of these smokers may have chosen to smoke outside their homes. Our findings, embedded in building-wide policy differences, underscore the importance of building-wide smoke-free policies since households with self-imposed smoke-free policies in smoking-permitted buildings demonstrated higher levels of $PM_{2.5}$ than did nonsmoking households in buildings with smoke-free policies in place. We attribute this, in part, to smoke transfer within the building.

We acknowledge that our survey of air quality was limited to concurrent sampling in four settings for each sampling period in the five housing developments. We cannot account for contaminants that may have transferred from a nonparticipating smoker in the same vicinity as our grouped smoking/nonsmoking pairs. Therefore, evidence of peaks in $PM_{2.5}$ in nonsmoking/unoccupied units in response to documented smoking activity represents an underestimate of smoke transfer. We relied on self-reported logs of smoking activity, which is susceptible to variably precise record-keeping, which we addressed by broadening each smoking event to an hour. Although we chose building pairs that were of similar building style and construction, there are still inter-building differences which account for changes in how air is transferred between spaces. Additionally, sampling occurred during warm and cold weather periods of variable humidity, which may affect monitor performance and human behavior (e.g., opening/closing windows, smoking frequency, etc.). Furthermore, this cross-sectional survey has limited generalizability due to its use of a convenience sample and the fact that $PM_{2.5}$ itself is not specific to secondhand smoke.

Despite advances in smoke-free policy adoption in public places, exposure to secondhand smoke in the home continues to impose a risk to vulnerable populations who live in multiunit housing. The department of Housing and Urban Development has urged housing authorities to adopt complete smoke-free policies across the country, and BHA is one of the first large housing authorities to implement this far-reaching policy recommendation.[23] The implications of this evaluation are that the implementation of a smoke-free policy would reduce secondhand smoke in multiunit housing.

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Declaration of Interests

None declared.

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