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Persistent tobacco smoke residue in multiunit housing: Legacy of permissive indoor smoking policies and challenges in the implementation of smoking bans

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ABSTRACT

Secondhand smoke (SHS) is a common indoor pollutant in multiunit housing (MUH). It is also the precursor of thirdhand smoke (THS), the toxic mixture of tobacco smoke residue that accumulates in indoor environments where tobacco has been used. This study examined the levels, distribution, and factors associated with THS pollution in low-income MUH. Interviews were conducted 2016–2018 in a cross-sectional study of N = 220 MUH homes in San Diego, California. Two surface wipe samples were collected per home and analyzed for nicotine, a THS marker, using liquid chromatography-triple quadrupole mass spectrometry. Nicotine was detected in all homes of nonsmokers with indoor smoking bans (Geo Mean = 1.67 μg/m^2; 95% CI = [1.23;2.30]) and smokers regardless of an indoor ban (Geo Mean = 4.80 μg/m^2; 95% CI = [1.89;12.19]). Approximately 10% of nonsmokers' homes with smoking bans showed nicotine levels higher than the average level in homes of smokers without smoking bans from previous studies (≥30 μg/m^2). Housing for seniors, smoking bans on balconies, indoor tobacco use, difficult to reach surfaces, and self-reported African-American race/ethnicity were independently associated with higher THS levels. Individual cases demonstrated that high levels of surface nicotine may persist in nonsmoker homes for years after tobacco use even in the presence of indoor smoking bans. To achieve MUH free of tobacco smoke pollutants, attention must be given to identifying and remediating highly polluted units and to implementing smoking policies that prevent new accumulation of THS. As THS is a form of toxic tobacco product waste, responsibility for preventing and mitigating harmful impacts should include manufacturers, suppliers, and retailers.

1. Introduction

While the health impacts of active smoking and secondhand smoke (SHS) exposure are well established, new research points to additional causes of tobacco-related morbidity from the inhalation, ingestion, and dermal transfer of toxic tobacco smoke residue in nonsmoking environments where tobacco has been previously used or that are frequented by smokers (Health 2006; Matt et al., 2011; Jacob et al., 2017; Sheu et al., 2020). Also known as thirdhand smoke (THS), this residue is a complex mixture of chemical constituents in SHS that remains on surfaces, accumulates in house dust, and becomes embedded in building materials, carpets, upholstery, and furniture (Daisey, 1999; Singer et al., 2002; Singer et al., 2003; Destaillats et al., 2006; Schick et al., 2014; Matt et al., 2019). Infants and children may be at particular risk because of the developmental stages of their organs, immature immune systems, interactions with polluted surfaces and objects (e.g., blankets, toys), and their behaviors (e.g., hand-to-mouth, object-to-mouth, crawling) (Tulve et al., 2002; Xue et al., 2007; Matt et al., 2004; Drehmer et al., 2017; Mahabee-Gittens et al., 2019; Mahabee-Gittens et al., 2018; Northrup et al., 2016; Northrup et al., 2016).

Abbreviations: MUH, Multiunit Housing; SHS, Secondhand Smoke; THS, Thirdhand Smoke

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Similar to SHS, the most abundant tobacco-specific organic chemical constituent of THS is nicotine, a stimulant and toxicant with adverse effects on multiple organ systems (Office of the Surgeon General, 2006; Jacob et al., 2013; Sleiman et al., 2014; England et al., 2017; Gibbs et al., 2016; Holbrook, 2016). Other components include tobacco-specific nitrosamines, polycyclic aromatic hydrocarbons, and other volatile and semi-volatile organic compounds with known adverse human health effects (Sheu et al., 2020; Singer et al., 2002; Singer et al., 2003; Jacob et al., 2013; Sleiman et al., 2014). There is mounting evidence that THS has genotoxic and cytotoxic properties (Bahl et al., 2016a,b; Whitlatch and Schick, 2018), and findings from translational animal experiments suggest that THS is toxic at levels found in human environments (Bahl et al., 2016a,b,c; Hang et al., 2013, 2017, 2018a,b; Karim et al., 2015; Martins-Green et al., 2014; Xu et al., 2015; Bahl et al., 2014).

While SHS exposure occurs concurrently with or shortly after smoking, controlled chamber and field studies show that THS pollution persists and exposure can occur for a long time after tobacco was smoked even if nonsmokers proactively avoid SHS and choose to live in smoke-free homes (Sleiman et al., 2014; Matt et al., 2011; Matt et al., 2017). The pervasiveness of THS has been demonstrated in a variety of nonsmoking settings, including homes of nonsmokers, nonsmoking rooms in hotels, a casino with a smoking ban, homes of former smokers, homes after smokers moved out, neonatal intensive care units, pediatric emergency care, private used cars, rental cars, and public transportation (Matt et al., 2004; Mahabee-Gittens et al., 2018; Matt et al., 2011; Matt et al., 2017; Matt et al., 2014; Matt et al., 2018; Matt et al., 2013; Matt et al., 2008; Santos et al., 2016; Hood et al., 2014; Zhang et al., 2015; Northrup et al., 2016).

Residents of multi-unit housing (MUH) are known to be at particular risk of SHS exposure, and children living in nonsmoking MUH apartments have been found to have 45% higher serum cotinine levels than children living in nonsmoking detached homes (Wilson et al., 2011). This is the case even though the majority of MUH residents prefer a smoke-free building (Snyder et al., 2016; Gentzke et al., 2018; Hewett et al., 2007; Licht et al., 2012; King et al., 2010; Baezconde-Garbanati et al., 2011; Berg et al., 2015; Kraev et al., 2009; Wilson et al., 2017). To improve indoor air quality and the health of residents, visitors, and staff, the U.S. Department of Housing and Urban Development (HUD) in 2016 instituted smokefree policies that banned the use of prohibited tobacco products in public housing after July 2018. While the policies included all living units, indoor common areas, public housing administrative offices, and outdoor areas within 25 feet from buildings, they excluded electronic cigarettes (EC), tribal housing, and mixed-finance developments (i.e., public and private) (Office of the Assistant Secretary for Public and Indian Housing, 2016).

Although prevalence of smoking in the U.S. has declined for years, research suggests that decades of high smoking rates and unrestricted indoor smoking may have produced substantial reservoirs of THS in MUH (Snyder et al., 2016; Centers for Disease Control and Prevention, 2017; Wilson et al., 2017). Research in San Diego, California, an area with low smoking prevalence (11.3% in 2017 compared to 23.7% in 1988) and mild climate allowing year-round outdoor smoking, has found both geometric mean and median surface nicotine levels of ≤ 1.6 μg/m^2 (Interquartile Range, IQR: [< 1μg/m^2; 2.5 μg/m^2]) in nonsmokers' homes with smoking bans (Matt et al., 2004; Matt et al., 2011). This compares to geometric means ranging from 31 μg/m^2 to 89 μg/m^2 and medians of 22 μg/m^2 to 117 μg/m^2 in homes of smokers who smoke indoors (Matt et al., 2004; Matt et al., 2011; Matt et al., 2017). The IQRs in these studies were [10 μg/m^2; 73 μg/m^2), [30 μg/m^2; 370 μg/m^2], and [6 μg/m^2; 206 μg/m^2], respectively. Application of the same sampling protocols in Columbus, Ohio, in subsidized MUH without smoke-free policies, measured geometric mean surface nicotine levels of 8.9 μg/m^2 in units with voluntary smoking restrictions and 145.6 μg/m^2 in units without voluntary restrictions (Hood et al., 2014). In Columbus, high smoking rates and cold winters likely discourage outdoor smoking (56.6% reported indoor smoking), thereby providing conditions for greater THS buildup. The aims of the present study were to examine the distribution of THS pollution in low-income MUH in San Diego County and to explore how THS levels were associated with characteristics of the buildings (e.g., age, number of units, smoking policies, housing type), apartments (e.g., smoking rules, size, flooring), and occupants (e.g., number of occupants, smoking status, socio-demographics).

2. Methods

2.1. Participants

After approval from the San Diego State University Institutional Review Board, low-income MUH buildings in San Diego County were identified from a Countywide Affordable Housing Inventory (Housing Resources Directory 2016–2018, County of San Diego, Department of Housing and Community Development). All participants lived in buildings where residents met low-income guidelines. Because these buildings were financed through mixed private/public efforts, the HUD smoke-free public housing policies enacted in 2016 (24CFR965.653, 24CFR966.4) did not apply to them (Office of the Assistant Secretary for Public and Indian Housing, 2016; U.S. Department of Housing and Urban Development, 2016). We requested permission from building managers to advertise the study through flyers. Study staff screened residents for eligibility by telephone, and home visits were scheduled with those who were ≥18 years old and spoke English, Spanish, or Somali. The recruitment target was 6% of the units in each building (actual 6.5%). The building's Social Services Coordinator helped schedule visits in one building, and in some buildings, residents were also recruited in-person. Participants received $20 as compensation for their time and effort.

2.2. Measures

2.2.1. Interviews

Pairs of research assistants visited homes to collect samples and conduct interviews with participants (N = 220) between June 2016 to January 2018. Participants reported the number of residents who had used tobacco or electronic cigarettes in the past 12 months, the numbers of residents and visitors who had used these products inside their home in the past 30 days, residents' exposure to SHS away from home in the past 30 days, residents' own rules about smoking inside their apartments, and knowledge of building smoking restrictions inside apartments, on balconies and porches, and in indoor and outdoor common areas. After the completion of laboratory analyses, select participants (N = 6) were contacted because of highly elevated THS levels to ask additional questions about their smoking history.

Research assistants surveyed all building managers (N = 20) by telephone about building policies to determine if residents were allowed to smoke tobacco or use EC inside their apartments, on balconies and porches, and in common areas.

2.2.2. THS on surfaces

Two surface wipe samples were collected in each home. For current users, samples were collected in the room where smoking or EC use most often occurred. For nonusers, samples were collected in the room where residents had smelled the strongest tobacco odor, or if no odor was noted, in the living room. Two pre-screened organic cotton rounds were moistened with 2 mL of 1% ascorbic acid and wiped over a 100 cm^2 area within a paper template (SKC-West, Inc., #225-2415). A wood vertical surface (e.g., door panel) and a wood horizontal surface (e.g., underneath a table) were sampled. In homes where there was no wood horizontal surface, two wood vertical surfaces were sampled. Two field blanks were collected in each home by transporting two cotton rounds to the home and subjecting them to the same handling procedures as samples. Samples and field blanks were transported and stored at −20 °C until analysis for nicotine using liquid chromatography-triple quadrupole mass spectrometry (LC-MS/MS) (Matt et al., 2017). The limit of quantitation (LOQ) was 0.05 ng/wipe or 0.005 μg/m^2 before blank subtraction. The two samples were combined for extraction and analysis, as were the two field blanks, and a single average surface nicotine concentration (μg/m^2) was reported for each home, after subtracting the field blank nicotine level (Quintana et al., 2013). Field blank values ranged from < LOQ to 2.05 ng/wipe (Geo Mean = 0.62 ng/wipe).

2.3. Statistical analyses

Surface nicotine levels were subjected to logarithmic transformation to adjust for positive skew, and we report geometric means, confidence intervals, and quartiles. Nicotine was detected in each home, with no evidence of censored or truncated distributions. Because apartments were nested within buildings, we employed linear mixed models and conventional linear regression models with cluster-adjusted variances. Both types of models showed equivalent results, and we only report findings from the linear mixed models. Stata (Version 16) was used for all analyses, and Type I error rate was set at $\alpha = 0.05$, two tailed (StataCorp, 2019).

3. Results

3.1. Characteristics of participants, apartments, and buildings

Table 1 shows that the majority of participants (N = 220) were women (84%) of Latino/Hispanic background (60%). Approximately 52% of participants lived in MUH serving multiple target groups (i.e., seniors, families, or disabled), 37% lived in MUH for seniors only, and 11% in MUH for families only. The median number of units in a building was 33 (IQR: 8–150), and the median building age was 45 years (IQR: 30–49). The median apartment had two residents and two bedrooms, and residents had lived there for 6.5 years. Approximately 39% of residences had at least one occupant < 18 years.

Table 1
Participant and home characteristics (N = 220).

Characteristics	
Participants	
Gender	
Female	83.6%
Age (years, Q1-Mdn-Q3)*	65–71.5–76
Race/Ethnicity	
African American/Black	13.6%
Asian	4.5%
Caucasian/White	19.1%
Latino/Hispanic	60.0%
Multiracial and other	2.7%
Survey language	
English	35.5%
Spanish	54.1%
Somali	10.5%
Housing	
Years living in unit (Q1-Mdn-Q3)*	2.9–6.5–10.8
Number of bedrooms (Q1-Mdn-Q3)*	0–2–2
Number of other rooms (Q1-Mdn-Q3)*	3–3–4
Adult Occupants	
1	53.6%
2	32.7%
≥3	13.7%
Child Occupants	
Children < 6 years	22.3%
Children 6-13 years	27.3%
Children 14-17 years	13.2%
Type of Housing	
Seniors	37.3%
Families	10.5%
Seniors and families	10.0%
Seniors and disabled	2.7%
Any population	39.6%
Age of building (years, Q1-Mdn-Q3)*	30–45–49
# Units in building (Q1-Mdn-Q3)*	8–33–150

Note. *Q1: 1st quartile; Mdn: Median; Q3: 3rd quartile.

Table 2
Smoking policies as reported by property management (N = 20) and by residents (N = 220).

	Property	Residents' Perception of Policy		
Smoking Policy According to Property Management	N	Correct N (%)	Incorrect N (%)	Don't Know N (%)
Tobacco Smoking Inside Apartments				
Permitted in all apartments	9	23 (26.4)	26 (29.9)	38 (43.7)
Prohibited in all apartments	8	107 (96.4)	1 (0.9)	3 (2.7)
Exceptions for long-time residents	3	8 (36.4)	11 (50.0)	3 (13.6)
EC Use Inside Apartments				
Permitted in all apartments	9	18 (20.7)	22 (25.3)	47 (54.0)
Prohibited in all apartments	10	89 (72.4)	4 (3.2)	30 (24.4)
Exceptions for long-time residents	0	2 (33.3)	1 (16.7)	3 (50.0)
Management doesn't know policy	1	-	3 (75.0)*	1 (25.0)
Tobacco Smoking on Apartment Balconies and Porches				
Permitted in all apartments	7	29 (43.3)	19 (28.4)	19 (28.4)
Prohibited in all apartments	11	105 (81.4)	12 (9.3)	12 (9.3)
No porches or balconies	2			
EC Use on Apartment Balconies and Porches				
Permitted in all apartments	7	21 (31.3)	19 (28.4)	27 (40.3)
Prohibited in all apartments	10	91 (72.8)	6 (4.8)	28 (22.4)
Management doesn't know policy	1	–	3 (75.0)*	1 (25.0)
No porches or balconies	2			
Tobacco Smoking in Indoor Common Areas				
Permitted	2	11 (36.7)	7 (23.3)	12 (40.0)
Prohibited	18	158 (83.6)	4 (2.1)	27 (14.3)
Tobacco Smoking in Outdoor Common Areas				
Permitted	6	37 (60.7)	4 (6.6)	20 (32.8)
Prohibited	13	83 (56.5)	42 (28.6)	22 (15.0)
Management doesn't know policy	1	–	7 (63.7)*	4 (36.4)

Note.
*Participants' positive and negative responses were coded as incorrect when management reported not knowing the policy.
EC: electronic cigarettes.

3.2. Smoking policies according to property management and residents

Table 2 shows that according to property managers (N = 20), 45% of properties permitted cigarette smoking in all apartments, and an additional 15% allowed smoking for long-time residents. Of the residents in buildings where smoking was permitted inside all apartments and those of long-term residents, only 26% and 36% knew this was the policy, respectively. Similar results were found for EC use in apartments and for smoking and EC use on porches and balconies. In 90% of properties, managers reported smoking was prohibited in common areas (e.g., hallways, laundry rooms, lobbies). Of residents in properties permitting smoking in common areas, 36% knew this was policy, 23% thought this was prohibited, and 40% did not know the policies.

3.3. Tobacco product and electronic cigarette use by residents and visitors

Table 3 shows that the vast majority of residences (N = 193, 88%) were occupied by persons who did not use any tobacco products or ECs over the past year. Of the 27 residences with users of tobacco and EC products, 72% smoked regular cigarettes only; the use of smokeless

Table 3
Use of tobacco products and electronic cigarettes (N = 220).

Type of Tobacco Product Used	
Current residents use past 12 months	
Smoked cigarettes	9.1%
Used smokeless tobacco	0.5%
Used ECs	0.9%
Smoked cigarettes and used ECs	1.4%
Other combinations of tobacco products	0.9%
Nonusers	87.7%
Current residents inside home use past 30 days	
Smoked cigarettes	2.3%
Used smokeless tobacco	0.5%
Used electronic cigarettes	0%
Nonusers	97.2%
Visitors to the home inside use past 30 days	
Used any tobacco products	0.9%
Nonusers	99.1%
Any previous residents used tobacco	
Yes	7.7%
No	22.3%
Don't know	70.0%
Any close neighbors used tobacco products	
Yes	49.6%
No	26.8%
Don't know	23.6%
Residents noticed drifting tobacco smoke	
Ever	60.0%
# Days past 30 days (Q1-Mdn-Q3)*	2-4-11.5

Note.
EC: electronic cigarette.
*Q1: 1st quartile; Mdn: Median; Q3: 3rd quartile.

tobacco only (1 residence), EC only (2), regular cigarettes and EC (2), and other product combinations (2) was rare. Using any tobacco or EC inside apartments was unusual among participants (N = 6, 3%) and their visitors (N = 2, 1%). Nevertheless, 50% (N = 109) of participants reported that some of their neighbors smoked, and 60% (N = 132) had ever smelled tobacco smoke inside their apartment.

3.4. Thirdhand smoke on apartment surfaces

Fig. 1 shows the rank-ordered surface nicotine levels for all 220 homes, distinguishing two groups of nonsmokers' homes (light and dark blue) and two groups of smokers' homes (dark orange and red). All residences showed nicotine loadings above the background level from field blanks, and the range of nicotine levels covered six orders of magnitude (0.002 μg/m^2-3,926 μg/m^2). The overall median was 1.47 μg/m^2 (IQR 0.48–6.04), and the overall geometric mean was 1.90 μg/m^2 (95% CI: 1.41–2.58).

Fig. 2 and Table 4 show boxplots and descriptive statistics for the two subgroups of nonsmokers and smokers. Nonsmokers' and smokers' homes with smoking bans showed similar levels with medians ranging from 1.34 to 2.42 μg/m^2. In contrast, homes where residents or visitors smoked inside showed significantly higher levels with a median and mean of 297 μg/m^{2}and 113 μg/m^2, respectively (see Table 4).

Figs. 1 and 2 show that a large number of nonsmokers' homes had unusually high nicotine levels. In the 122 homes of nonsmokers with smoking bans and no SHS exposure, 13.1% had levels above the average found in previous studies of smokers with indoor smoking (> 30 μg/m^2), and 4.1% had levels similar to those found in a previous study of a casino that allowed smoking (> 200 μg/m^2) (Matt et al., 2004; Matt et al., 2011; Matt et al., 2017; Matt et al., 2018). The two highest levels observed in the study were measured in homes of current nonsmokers with smoking bans (see Fig. 1).

3.5. Follow-up interviews with extreme cases

Of the six nonsmoking units with levels > 200 μg/m^2, four participants agreed to follow-up interviews. In the apartment with the highest surface concentration (3,926 μg/m^2), the resident had lived there for more than 20 years, was previously a one pack/day smoker, quit 9 years prior to sampling, and had not smoked or allowed smoking in the apartment since. In the apartment with the second highest nicotine level (2,586 μg/m^2), the current residents had lived there for 10 years and were nonsmokers. A prior resident, however, had smoked 15 cigarettes/day until 3.5 years prior to sampling, and no one had smoked in the apartment since. In two other apartments of nonsmokers with very high THS levels (550 μg/m^2 and 212 μg/m^2), residents had smoking bans, had lived in their apartments for two and 10 years respectively.

3.6. Multivariable models of surface nicotine levels

Variable selection and model building is described in the online supplement. Estimates for the mixed linear regression model are given in Table 5.

3.6.1. Building variables

Type of housing ($\chi^2(4) = 20.11$, $p < 0.001$) was significantly associated with nicotine level independent of other variables. Controlling for other variables, senior housing had significantly higher nicotine levels than housing dedicated to families (3.79 μg/m^2 vs. 0.33 μg/m^2; $p < 0.001$). Moreover, surface nicotine levels were lower in buildings where managers reported that smoking on balconies and porches was permitted compared to banned (1.18 μg/m^2 vs. 2.58 μg/m^2; $p = 0.022$).

3.6.2. Apartment variables

Type of surface was significantly associated with nicotine levels ($\chi^2(11) = 40.02$, $p < 0.001$). Controlling for other variables, the lowest levels were consistently observed when both sampled surfaces were doors (0.23 μg/m^2), and the highest levels were observed when the horizontal surfaces were undersides of furniture: counters (25.23 μg/m^2; $p < 0.001$), tables (3.57 μg/m^2; $p < 0.001$), entertainment centers (2.56 μg/m^2; $p = 0.002$), and shelves (1.69 μg/m^2; $p = 0.018$).

3.6.3. Occupant variables

Smoking status and smoking bans of occupants were significantly associated with nicotine levels ($\chi^2(3) = 31.08$, $p < 0.001$). Controlling for other variables, apartments with residents or visitors who used tobacco and EC products but had an indoor ban (4.61 μg/m^2, $p = 0.011$) and users allowing indoor smoking (78.67 μg/m^2, $p < 0.001$) had significantly higher nicotine levels than apartments of nonsmoking residents and visitors with smoking bans (1.40 μg/m^2 and 1.88 μg/m^2 without and with SHS exposure, respectively). Apartments of nonsmokers with and without SHS exposure did not differ from each other ($p = 0.937$). Independent of other variables, participants' ethnic background was associated with nicotine levels ($\chi^2(4) = 22.99$, $p < 0.001$). Latino/Hispanic (1.34 μg/m^2, $p < 0.001$) and White/Caucasian (1.33 μg/m^2, $p = 0.001$) residents had significantly lower nicotine levels than African-American residents (49.36 μg/m^2).

4. Discussion

This study found that THS is a ubiquitous indoor pollutant in low-income MUH in San Diego, even in apartments occupied by nonusers of tobacco products and ECs and with strict indoor smoking bans. While the average surface nicotine level in MUH residences of nonsmokers was similar to those found in previous studies of nonsmokers (Matt et al., 2004; Matt et al., 2011; Matt et al., 2017), we observed a remarkable range of levels. Of particular concern are nonsmoker residences with smoking bans that had THS levels at or above averages observed in previous studies of smokers with similar socioeconomic

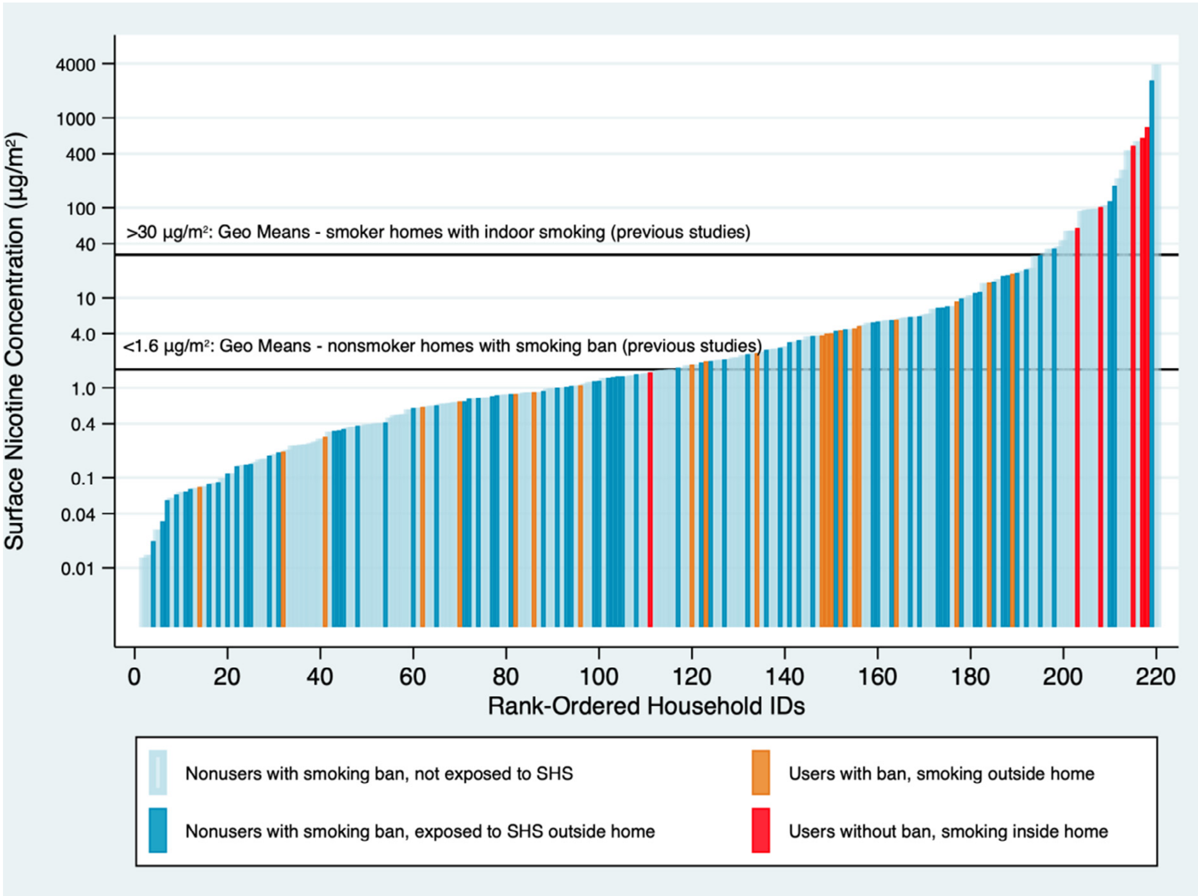

Fig. 1. Nicotine levels on surfaces in 220 low-income apartments in San Diego County. Colors indicate groups differing in tobacco product use, secondhand smoke exposure, and home smoking bans. Horizontal lines indicate reference levels from previous studies. (Matt et al., 2004, 2017, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Light Blue: Nonusers with smoking ban, not exposed to SHS. No residents smoked any cigarettes, cigars, or tobacco pipes; or used any snuff, dip, or chewing tobacco; or used any EC in the past 12 months; and no one who had used any of these products in the past 30 days visited the home; and no residents were exposed (in the same indoor room) to tobacco smoke in the past 7 days away from home. *Dark Blue: Nonusers with smoking ban, exposed to SHS outside home*. No residents smoked any cigarettes, cigars, or tobacco pipes; or used any snuff, dip, or chewing tobacco; or used any EC in the past 12 months; and no visitors used any of these products inside the home in the past 30 days; and residents were exposed (in the same indoor room) to tobacco smoke in the past 7 days away from home. *Dark Orange: Users with smoking ban, smoking outside of home*. Residents or visitors were smokers with a home ban and who only smoked outside the home. *Red: Users without ban, smoking inside home*. Residents or visitors were smokers and smoked inside at home.

backgrounds and home characteristics (e.g., median family income: \$18,000–\$25,000; median apartment size: 500 sqft-600 sqft; Non-White/Non-Caucasian: 40–70%) (Matt et al., 2004; Matt et al., 2011; Matt et al., 2017). Approximately 10% of nonsmokers' units had surface nicotine > 30 µg/m^2, and approximately 3% of units showed levels similar to those found in a casino (> 200 µg/m^2) (Matt et al., 2018). The two units with the highest THS levels (2,586 µg/m^2 and 3,926 µg/m^2) were occupied by current nonsmokers with strict smoking bans for the previous 9 and 3.5 years, respectively, and who reported heavy indoor smoking prior to that time.

Building, apartment, and occupant variables showed independent associations with THS pollution. With respect to building variables, THS levels were higher in housing dedicated to seniors and when smoking on balconies and porches was prohibited. Higher levels of THS in housing for seniors were surprising, because current smoking prevalence in housing for seniors was lower (5% vs 22%) and indoor smoking bans were more common (70% vs 23%) than in housing for all low-income groups. While this study cannot identify the causal mechanisms that underlie these associations, the higher THS levels in housing for seniors may be the result of "grandfather" policies that allowed long-term residents to continue to smoke in their apartments when a new smoke-free policy was adopted. All 32 participants who reported such policies lived in housing for "seniors only" or for "seniors and disabled". Under such circumstances, nonsmokers would encounter higher levels of smoke intrusion that would contribute to THS in their units. In addition, new residents could be moving into units that formerly housed someone who was permitted to smoke indoors under this exception. Higher THS levels may also be the result of older furniture and accessories that were in use when family members still smoked and that remain polluted with THS. The finding that allowing smoking on balconies and porches was associated with lower THS levels suggests that such policies might reduce THS buildup in the apartments of smokers, although it may increase THS in neighboring apartments of nonsmokers through migrating smoke. Additional research is needed to examine exactly why housing for seniors may be more vulnerable to THS pollution and which smoking bans are more effective in protecting indoor environments from tobacco smoke pollution.

With respect to apartment variables, we found that THS pollution is not equally distributed within an apartment. We observed the lowest levels on the vertical surfaces of doors and higher levels on less accessible horizontal surfaces such as the undersides of counters, entertainment centers, and tables. Because the majority of surfaces in an apartment are difficult to access (e.g., back side of cabinets, interior surfaces of drawers), hidden (e.g., carpet padding), and difficult to

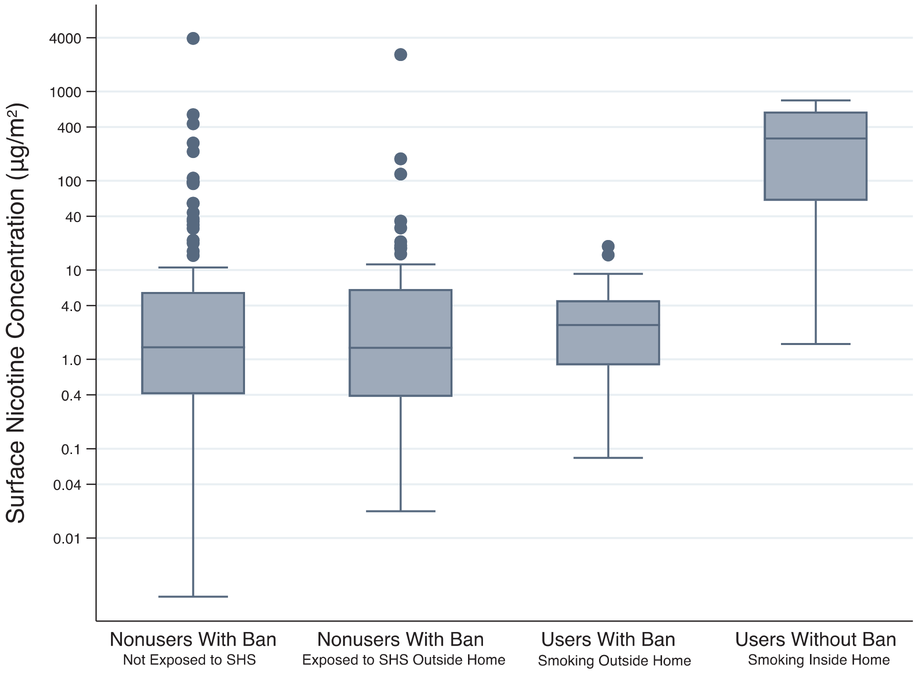

Fig. 2. Boxplots showing nicotine levels (μg/m^2) on surfaces in 220 low-income apartments in San Diego County for four different tobacco product user groups and home smoking bans. Each box shows the 25th percentile (lower hinge), Median (center line), and 75th percentile. Individual values are shown if they are larger than the 75th percentile plus 1.5 times the interquartile range or less than the 25th percentiles minus 1.5 times the interquartile range.
Nonusers With Ban Not Exposed to SHS: No residents smoked any cigarettes, cigars, or tobacco pipes; or used any snuff, dip, or chewing tobacco; or used any EC in the past 12 months; and no one who had used any of these products in the past 30 days visited the home; and no residents were exposed (in the same indoor room) to tobacco smoke in the past 7 days away from home. Nonusers with Ban Exposed to SHS Outside Home: No residents smoked any cigarettes, cigars, or tobacco pipes; or used any snuff, dip, or chewing tobacco; or used any EC in the past 12 months; and no visitors used any of these products inside the home in the past 30 days. Users with Ban, Smoking Outside of Home: Residents or visitors were smokers with home smoking ban and only smoked outside the home. Users Without Ban, Smoking Inside Home: Residents or visitors were smokers and smoked inside at home.

clean (e.g., upholstery), this poses a challenge to remediation efforts. The differences in THS pollution between surfaces also raises the possibility that THS pollution may be specific objects (e.g., an old sofa). These objects may pollute the rest of the home releasing volatile THS into air, which can then be absorbed by other objects in the home (Singer et al., 2003). All of this makes it critical to examine multiple samples when evaluating an apartment for THS.

Among the occupant variables, actual smoking behavior and lack of home smoking bans played critical roles. It should be noted that many residents either did not know the smoking policies for their building or their perceptions were incorrect. This may explain some of the discrepancies between policies and behavior and points to the importance of educating residents and implementing effective smoking bans to avoid additional build-up of THS reservoirs. Finally, a resident's ethnic background was associated with THS level independent of smoking behaviors, smoking ban, building, and apartment variables. The literature on racial/ethnic disparities in tobacco use suggests ethnic background serves as a proxy for other more proximal factors that affect THS pollution. This includes smoking patterns, preferences for tobacco products, use of cessation services, and duration of smoking (Pagano et al., 2018; Jones et al., 2018). Ethnic backgrounds may also reflect preferences for furnishings (e.g., drapes, window covers, rugs), cleaning practices, and social norms related to tobacco use.

Compared to the study of MUH in Columbus, Ohio, the average surface nicotine levels in nonsmokers' homes of our San Diego sample were lower by a factor of five (8.9 μg/m^2 vs 1.8 μg/m^2) (Hood et al., 2014). This is likely due to differences in smoking prevalence between San Diego (11.3% in 2017) and Columbus (21.3% in 2017), building smoking bans (40% vs 0%), and climatic conditions that lead to more indoor smoking in Columbus (Centers for Disease Control and Prevention, 2017). The data from two regions of the U.S. with very different smoking norms suggest that a substantial proportion of MUH throughout the U.S. may be affected by THS (Hood et al., 2014). Based on homes of smokers in San Diego with surface nicotine levels > 30 μg/m^2, we estimate that 10% of units occupied by nonsmokers in low-income MUH in San Diego and 20% of units in Columbus (based on Fig. 1 in Hood et al.) are affected by significant THS reservoirs (Matt et al., 2004; Matt et al., 2011; Matt et al., 2017; Hood et al., 2014).

This study also has implications for indoor pollution caused by marijuana smoking and vaping, hookah and water pipes, and electronic cigarettes. Each of these products releases a mixture of chemical compounds in the form of gases or vapors and particulate matter. These constituents spread throughout a unit and can migrate into neighboring units, where they can accumulate over time, leaving behind a persistent chemical residue (Kassem et al., 2014; Khachatoorian et al., 2019; Bush and Goniewicz, 2015; Goniewicz and Lee, 2015; Sempio et al., 2019).

As this was a cross-sectional study of volunteer participants, the estimated proportions of homes affected by THS and causal associations between building, apartment, and occupant variables and THS pollution should be interpreted with caution. The confounding of explanatory variables and the small numbers of observations for certain combinations of interacting variables (e.g., smoking status of resident, housing type, and building policies) made it impossible to test their role moderators. While we statistically controlled for plausible confounders, only a randomized experiment could conclusively rule out alternative interpretations, and random sampling is required to obtain valid probability estimates of THS pollution.

5. Conclusions

Decades of high smoking prevalence and permissive indoor smoking policies have left a legacy of toxic tobacco smoke residue in MUH to which current occupants may be involuntarily and unknowingly exposed. As MUH properties transition to smoke-free building policies, they are facing difficult and potentially expensive challenges. The successful transition to MUH free of persistent tobacco smoke pollutants requires effective building-wide indoor smoking bans as well as the identification and remediation of highly polluted units, the cost of which can be considerable. Similar to other hazardous postconsumer waste products (e.g., paints, pesticides, old motor oil, electronic waste), THS is a form of product waste for which manufacturers, suppliers, and retailers should assume responsibility to prevent and mitigate harmful environmental impacts (WHO, 2017; Curtis et al., 2017; Nash and Bosso, 2013). The growing body of research on the persistence and toxicity of THS supports legislative initiatives to broadly ban tobacco use in all indoor settings and to require the beneficiaries of tobacco sales to help clean up the continuing toxic legacy of tobacco product pollution.

Table 4
Nicotine surface concentration for homes with different types of tobacco product use and smoking bans.

Tobacco Product Use	Nicotine Loading ($\mu g/m^2$)
Nonusers with Inside Smoking Ban (N = 193)	
Geo Mean [95%]	1.67 [1.23;2.30]
Min-Q1-Mdn-Q3-Max	0.002 – 0.41 – 1.34 – 5.70 – 3,926.24
% > 30 $\mu g/m^2$	10.4%
% > 200 $\mu g/m^2$	3.1%
Not exposed to SHS (N = 122)	1.72 [1.14; 2.61][A]
Geo Mean [95%]	0.002–0.41–1.37–5.69–3,926.24
Min-Q1-Mdn-Q3-Max	13.1%
% > 30 $\mu g/m^2$	4.1%
% > 200 $\mu g/m^2$	
Exposed to SHS Outside Home (N = 71)	
Geo Mean [95%]	1.59 [0.96; 2.63][B]
Min-Q1-Mdn-Q3-Max	0.02–0.38 – 1.34 – 6.14 – 2586.16
% > 30 $\mu g/m^2$	5.6%
% > 200 $\mu g/m^2$	1.4%
Users (N = 27)	
Geo Mean [95%]	4.80 [1.89;12.19]
Min-Q1-Mdn-Q3-Max	0.08 – 0.89 – 4.01 – 14.75 – 792.96
% > 30 $\mu g/m^2$	18.5%
% > 200 $\mu g/m^2$	11.1%
With Inside Smoking Ban (N = 21)	
Geo Mean [95%]	1.94 [1.02; 3.69][C]
Min-Q1-Mdn-Q3-Max	0.08–0.86 – 2.42 – 4.59 – 18.41
% > 30 $\mu g/m^2$	0%
% > 200 $\mu g/m^2$	0%
With Inside Ban (N = 6)	
Geo Mean [95%]	113.10 [9.47; 1,350.45][A,B,C]
Min-Q1-Mdn-Q3-Max	1.48 – 59.70 – 297.14–595.91 – 792.96
% > 30 $\mu g/m^2$	83.3%
% > 200 $\mu g/m^2$	50.0%
Overall (N = 220)	
Geo Mean [95%]	1.90 [1.41; 2.58]
Min-Q1-Mdn-Q3-Max	0.002 – 0.48 – 1.47 – 6.04 – 3,926.24
% > 30 $\mu g/m^2$	11.4%
% > 200 $\mu g/m^2$	4.1%

Note A, B, C: Groups with same letters show significant mean differences, $p < 0.001$.
Min: lowest observed value. Q1: 1st quartile. Mdn: median. Q3: 3rd quartile/. Max: highest observed value.

Table 5
Mixed linear regression model of surface nicotine concentration (log10) with overall model fit Wald $\chi^2(25) = 143.52$, $p < 0.001$.

Surface nicotine (log10)	Coef.	Std. Err.	z	p-value
Building Variables				
Smoking permitted on porches, balconies (Reference: No)				
Yes	−0.340	0.148	−2.29	0.022
Don't Know	−0.509	0.262	−1.95	0.052
Housing Type (Reference: Seniors)				
Families	−1.058	0.257	−4.11	< 0.001
Seniors & Families	−0.403	0.225	−1.79	0.073
Seniors & Disabled	0.431	0.346	1.25	0.212
Any	−0.404	0.190	−2.12	0.034
Apartment Variables				
Wiped surfaces[A] (Reference: two vertical wipes on door)				
Counter U + Door	2.032	0.479	4.24	< 0.001
Entertainment Ctr. U + Door	1.038	0.329	3.15	0.002
Desk U + Door	0.797	0.382	2.09	0.037
Table U + Door	1.183	0.344	3.44	0.001
Coffee Table U + Door	0.836	0.386	2.17	0.03
Shelf U + Door	0.858	0.361	2.37	0.018
Closet + Door	0.568	0.382	1.49	0.137
Cabinet + Door	0.434	0.428	1.01	0.31
Bookcase + Door	0.420	0.448	0.94	0.349
Cabinet U + Door	0.073	0.423	0.17	0.863
other combinations	1.067	0.335	3.19	0.001
Occupant Variables				
Ethnicity (Reference: Latino/Hispanic)				
Black/African-American	0.844	0.194	4.340	< 0.001
White/Caucasian	−0.002	0.195	−0.010	0.990
Asian American	0.502	0.267	1.880	0.060
Other	0.546	0.349	1.560	0.118
Smoking status (Reference: users w/inside smoking)				
Nonuser w/ban, no SHS	−1.749	0.335	−5.210	0.000
Nonuser w/ban, with SHS	−1.638	0.337	−4.850	0.000
User w/ban	−1.232	0.374	−3.290	0.001
Number of Children (0-17y)	−0.013	0.017	−0.280	0.779
Constant	1.275	0.475		

Note A. The sampling protocol included separate wipes from a horizontal and a vertical surface, combined in the laboratory for analysis. When suitable horizontal surfaces were not available, two vertical samples were collected from a door; the homes where this was the case serve as the reference group. The other homes were grouped with respect to the objects that were sampled, listing in order the objects of which the horizontal and (+) the vertical surfaces were sampled. A "U" indicates that the underside of the object was sampled.
SHS: secondhand smoke.

CRediT authorship contribution statement

Georg E. Matt: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Penelope J.E. Quintana:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Eunha Hoh:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing - original draft, Writing - review & editing. **Joy M. Zakarian:** Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing. **Nathan G. Dodder:** Writing - review & editing, Resources, Supervision, Validation. **Rachael A. Record:** Writing - review & editing, Conceptualization. **Melbourne F. Hovell:** Writing - review & editing, Validation, Conceptualization. **E. Melinda Mahabee-Gittens:** Writing - review & editing, Conceptualization. **Samuel Padilla:** Investigation, Writing - review & editing. **Laura Markman:** Writing - review & editing, Investigation. **Kayo Watanabe:** Writing - review & editing, Investigation. **Thomas E. Novotny:** Writing - review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics approval

This study was conducted with the approval of the San Diego State University Institutional Review Board.

Appendix A. Supplementary data

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