Senate Community Affairs Committee

ANSWERS TO ESTIMATES QUESTIONS ON NOTICE

HEALTH AND AGEING PORTFOLIO

Budget Estimates 2012-2013, 30 & 31 May and 1 June 2012

Question: E12-054

OUTCOME 1: Population Health

Topic: Smoking Bans

Type of Question: Hansard Page CA37, 30 May 2012

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Senator: Senator Furner

Question:

I also understand there has been scientific evidence that clearly demonstrates in relation to ETS – and this was around in 1998 – that there were 23 deaths from environmental tobacco smoke in children aged 14 or younger. Can you concur with those sorts of statistics? (answer to include Ms Halton's offer to include details on the fact that scientifically you cannot necessarily smell that tobacco smoke).

Answer:

As reported by the Australian Institute of Health and Welfare (AIHW), in Ridolfo B., Stevenson C., 2001. *The quantification of drug-caused mortality and morbidity in Australia, 1998*. AIHW cat. No PHE 29. Canberra: AIHW (Drug Statistics Series no. 7) (Table 6.3, pg 98) the number of deaths for children under the age of 14 years attributable to environmental tobacco smoke (ETS) was 23. The publication can be accessed at: http://www.aihw.gov.au/publication-detail/?id=6442467226

In relation to 'third hand smoke', that is tobacco smoke residue that remains on surfaces, clothing and furnishings after the cigarette has been extinguished, the following links are provided to articles relating to this topic.

1. Winickoff JP, et al. (2009). Beliefs About the Health Effects of "Thirdhand" Smoke and Home Smoking Bans. Pediatrics, 2009, 123:374-79
   Accessed at: http://pediatrics.aappublications.org/content/123/1/e74.abstract

2. World Health Organization. (2009). WHO report on the global tobacco epidemic, 2009: Implementing smoke-free environments. Geneva, 2009
   Accessed at: http://whqlibdoc.who.int/publications/2009/9789241563918_eng_full.pdf

3. Schick S. (2011). (Editorial), Thirdhand smoke: here to stay. Tobacco Control, January 2011 Vol 20 No 1.
   Accessed at: http://tobaccocontrol.bmj.com/content/20/1/1.extract

4. Matt GE, et al. (2010).When smokers move out and non-smokers move in: residential thirdhand smoke pollution and exposure. Tobacco Control (2010). Published Online First: 30 October 2010
Accessed at: http://tobaccocontrol.bmj.com/content/early/2010/10/29/tc.2010.037382.full

5. Sleiman M, et al. (2010). Formation of carcinogens indoors by surface-mediated reactions of nicotine with nitrous acid, leading to potential thirdhand smoke hazards. Published online before print February 8, 2010, PNAS April 13, 2010 vol. 107 no. 15 pg. 6576-6581
Accessed at: www.pnas.org/cgi/doi/10.1073/pnas.0912820107

6. Petrick LM, et al. (2011). Thirdhand Smoke: Heterogeneous Oxidation of Nicotine and Secondary Aerosol Formation in the Indoor Environment. Published online: 12 August 2010. Environmental Science & Technology, Vol. 45, No. 1, 2011, pg. 328-333.
Accessed at: http://pubs.acs.org/stoken/presspac/presspac/full/10.1021/es102060v

AH A

Thirdhand smoke: here to stay

Suzaynn Schick

The first time I had any inkling that nicotine might linger in a room was when I listened to a group of nicotine chemists complaining about how hard it is to keep nicotine out of their laboratories. Their gas chromatography and mass spectroscopy machines are expensive, complex and very sensitive. In order to detect nicotine and cotinine in samples from non-smokers exposed to secondhand smoke, they must scrupulously exclude nicotine and tobacco smoke from their laboratories. One chemist told a story of how experiments in his laboratory were ruined for weeks after new data cables were installed in the ceiling of the laboratory. Probable culprit: nicotine in the ceiling tiles and the dust above them, dating back 30 years to when people still smoked in laboratories at the university.

Thirdhand smoke is a new concept in the field of tobacco control. While everyone who has ever noticed the lingering smell of stale smoke knows that something stays around after the smoke clears, exactly what that something is, how long it stays and what it means for human health has been little studied to date.

The paper by Matt *et al*[1] in this issue of *Tobacco Control* advances the study of thirdhand smoke by exploring one of the situations most likely to isolate thirdhand smoke exposure from concurrent exposure to secondhand smoke: rental housing. Their findings demonstrate that nicotine persists in homes previously occupied by smokers, and that non-smokers who move into these units have elevated levels of nicotine on their skin and in their bodies. The design of this experiment was very challenging; one can imagine approaching complete strangers who were in the middle of moving house and asking them to let researchers examine their homes and bodies, and the group is to be commended for persuading as many people to participate as they did.

We do not know what the potential health effects of this low-level exposure to thirdhand smoke may be. Nicotine is a toxin that effects development of the nervous system and the lungs, but we don't know if it has effects at concentrations this low. However, nicotine is not the only chemical to consider. Nicotine on indoor surfaces can react with the low levels of oxidant gases that are normally present in homes to form nitrosamines, including 1-(*N*-methyl-*N*-nitrosamino)-1-(3-pyridinyl)-4-butanal (NNA) and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK).[2] Both of these tobacco-specific nitrosamines are normally found in the particulate phase, which means that once they form on a surface they will tend to stay in place. We do not know whether these nitrosamines, in turn, react and form other compounds, or whether they accumulate over time. If they do accumulate, this could have important implications for the epidemiology of lung cancer. NNK is a lung carcinogen that will cause tumours in the lung whether it is inhaled, injected, or ingested. If concentrations of NNK in rooms where smoking takes place build steadily over time, then this exposure may be partly responsible for the lung cancer seen in smokers and in non-smokers exposed to secondhand smoke. Nicotine can also react to form volatile compounds including formaldehyde.[3] Both formaldehyde and NNK are known human carcinogens for which there is no safe level of exposure.[4 5]

We also do not know what the levels of nicotine and cotinine seen in the study indicate about the level of exposure to the other components of thirdhand smoke. Most studies relating biomarkers of nicotine and nitrosamine exposure have been conducted with smokers. A recent paper by Benowitz *et al* demonstrated that measurement of urinary cotinine can underestimate exposure to tobacco-specific nitrosamines in non-smokers.[6] The ratios observed between 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (NNAL; a metabolite of the nitrosamine NNK) and cotinine in smokers were between 0.09 and 0.28. The ratios observed between NNAL and cotinine in non-smokers were between 1.10 and 5.50. This means that if urinary cotinine data from smokers is used to estimate exposure to the carcinogen NNK in non-smokers, one could underestimate their exposure by 5–60-fold. I hope that Matt *et al* were able to reserve portions of their samples to test for nitrosamines and nitrosamine metabolites, so we can begin to learn what the relationships are for thirdhand smoke exposure.

We may not yet know whether exposure to thirdhand smoke has negative effects on health, but we do know who will be most exposed to it: poor people. In many countries, the poorer you are, the more likely you are to smoke. In the US, 31.5% of adults with incomes below the federal poverty level smoked, while only 19.6% of those above the poverty level did.[7] Internationally, this trend holds among both men and women of high-income nations and among men in mid-income and most low-income nations.[8] Smoking rates in California are the second lowest in the US at only 13.8%, but in a recent survey of cotinine concentrations in patients admitted to the county hospital in San Francisco, which serves the poor and uninsured, 55% were either smokers or exposed to very high levels of secondhand smoke.[9]

Poor people are also more likely to be exposed to secondhand smoke. In the US, geometric mean urinary cotinine levels in children from families with a poverty level income were over five times higher than those from children from families with incomes four or more times the poverty level.[10] Another recent study of nicotine levels in house dust found that non-smoking households with income below the median income for the study had higher nicotine concentrations in dust than non-smoking households with income above the median.[11]

The effect of this disparity on housing stock at the low end of the price range is obvious. If the smoking rate among renters is 13.8%, then a rental home that has been occupied by five different families has a 36% chance of having been occupied by at least one smoker. If the smoking rate is 25%, then the home has a 75% chance of having been occupied by at least one smoker. The median household income of the families in this study was above the poverty level, but not far enough to allow them free choice of rental housing in San Diego County. The median income of the non-smoking households was between $33 000 and $37 200 and the median income of the smoking households was $25 500. The median household income in San Diego county is $62 820[12] and the median rent for a two-bedroom unit is $1324.[13] If thirdhand smoke is a health hazard, then this exposure may

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be yet another contributor to the existing health disparities between the rich and the poor.

I had my first child in 2007 and my first thought upon reading this research was to imagine how stressful it would be for new parents to know that their home was polluted with nicotine and all the other things that go along with it, and to be unable to afford to move. Babies and toddlers, because of their size, the way they play on the floor, their habit of putting everything in their mouths and the fact that they are growing and developing, are most affected by any pollutant in a home. House dust is believed to be the main route of exposure to indoor pollutants for young children and house dust was one of the main reservoirs for nicotine in the homes Matt *et al* studied.

When I speak publicly about secondhand or thirdhand smoke, I am always asked how to clean a home that smells of smoke. Sadly, the answer there is also: 'we don't know'. All the homes in this study were cleaned before the new families moved in. The homes that were occupied by tenants who smoked were more likely than non-smoking homes to have been painted and have new carpets installed, and they also stood vacant longer before being rented again. None of these methods got rid of all the nicotine. Studies of the dynamics of nicotine in furnished rooms suggest that nicotine sticks to surfaces rapidly and comes off very slowly. Increasing ventilation in a home will not remove the nicotine stuck to surfaces and dust.[14]

A recent study of polycyclic aromatic hydrocarbon pollution in house dust found that the strongest predictor of the concentration of this family of carcinogens in house dust was the age of the house.[15] Older homes had higher levels of polycyclics than new homes. A study of nicotine in house dust by the same group found that the smoking status of occupants for the months and years prior to the study was a stronger predictor of elevated nicotine concentrations than whether smoking was allowed in the house at the time of the study.[11] This study also detected a significant correlation between nicotine concentration and the age of the home. Evidence like this suggests that many different kinds of chemical compounds accumulate in homes and that standard cleaning and maintenance methods do not remove them effectively.

When the first evidence that SHS was hazardous to human health began to emerge in the late 1960s, it was hard for many people, including scientists, to believe that an exposure that was so much less concentrated than active smoking could have any effect. It took at least 20 years of research and public health advocacy for the tide to turn, and some scientists dismissed the significance of SHS until very recently. Yet the evidence is now considered definitive[16] and has given new insight how the human cardiopulmonary system works. The health effects of SHS exposure are, in fact, different from those of active smoking: the majority of smoking-attributable mortality is due to cancer,[17] while the majority of SHS exposure-attributable mortality is due to cardiovascular disease.[18 19] Studying how exposure to even low concentrations of inhaled smoke increases risk of cardiovascular disease has revealed new biological mechanisms and is changing how we view the significance of all kinds of particulate air pollution.[20–22]

The emerging science of thirdhand smoke may reveal equally important information about our exposure to indoor pollutants. Many of the phenomena originally observed in outdoor air pollution are now being discovered indoors. Scientists have known for years that gas phase pollutants in the atmosphere can react to form ultrafine particles.[23] Very recently, research has shown that gas phase chemicals from air fresheners, cleaning products and, (just published this month) nicotine can react with normal gases present indoors to form ultrafine particles.[24–26] Likewise one of the signal discoveries of outdoor environmental pollution—the fact that some pollutants (for example, dichlorodiphenyltrichloroethane (DDT)) persist for years—appears to be emerging in the indoor environment.

The evidence Matt *et al* present suggests that nicotine may persist in indoor environments like some pesticides persist outdoors. Like DDT, the nicotine, polycyclic aromatic hydrocarbons and nitrosamines in cigarette smoke are members of a group of chemicals called semivolatile organic compounds. Semivolatile organic compounds are oily or waxy compounds. There are many other chemicals in this group that are used indoors, including phthalates, bisphenol A and flame retardants. Once released indoors, they are more likely to stick to surfaces than to be removed by ventilation. Once on surfaces, they can desorb slowly back into the air or react to form other chemical compounds.[27] Like nicotine, many other semivolatile organic compounds are also found in our bodies.[28] The best solution we found to the persistence of DDT in the environment was to ban its use except to control insects that cause human disease.

Is the current body of evidence on the composition and persistence of the residue from smoking enough to justify laws banning smoking in multiunit and rental housing? Perhaps not yet, but I think the evidence will come and the laws will come even faster. We don't yet know whether exposure to thirdhand smoke is harmful to human health, but we now know that most of the nicotine from every cigarette smoked indoors stays indoors, where it lingers for months, is taken up by the occupants and also reacts to form nitrosamines, formaldehyde and other harmful chemicals. No one wants that in their home.

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When smokers move out and non-smokers move in: residential thirdhand smoke pollution and exposure

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ABSTRACT

Background This study examined whether thirdhand smoke (THS) persists in smokers' homes after they move out and non-smokers move in, and whether new non-smoking residents are exposed to THS in these homes.

Methods The homes of 100 smokers and 50 non-smokers were visited before the residents moved out. Dust, surfaces, air and participants' fingers were measured for nicotine and children's urine samples were analysed for cotinine. The new residents who moved into these homes were recruited if they were non-smokers. Dust, surfaces, air and new residents' fingers were examined for nicotine in 25 former smoker and 16 former non-smoker homes. A urine sample was collected from the youngest resident.

Results Smoker homes' dust, surface and air nicotine levels decreased after the change of occupancy ($p<0.001$); however dust and surfaces showed higher contamination levels in former smoker homes than former non-smoker homes ($p<0.05$). Non-smoking participants' finger nicotine was higher in former smoker homes compared to former non-smoker homes ($p<0.05$). Finger nicotine levels among non-smokers living in former smoker homes were significantly correlated with dust and surface nicotine and urine cotinine.

Conclusions These findings indicate that THS accumulates in smokers' homes and persists when smokers move out even after homes remain vacant for 2 months and are cleaned and prepared for new residents. When non-smokers move into homes formerly occupied by smokers, they encounter indoor environments with THS polluted surfaces and dust. Results suggest that non-smokers living in former smoker homes are exposed to THS in dust and on surfaces.

INTRODUCTION

Secondhand smoke (SHS) is composed of sidestream smoke emitted from the smouldering tip of a cigarette (80% to 90%) and exhaled mainstream smoke (10% to 20%). It contains a complex and dynamic mixture of more than 4000 chemical compounds in the form of gases and particulate matter, and has been classified as a human carcinogen and an indoor air pollutant.[1–4] Immediately after emission, tobacco smoke undergoes physical and chemical changes, and the mixture of chemical compounds interacts with the environment.

The combination of tobacco smoke pollutants remaining in an indoor environment has been referred to as residual tobacco smoke pollution or, more popularly, thirdhand smoke (THS).[5 6] THS includes a mixture of semivolatile compounds found in SHS that have sorbed or settled on surfaces of an indoor space and are later re-emitted into the air. THS also encompasses particulate matter that has deposited and accumulated on surfaces and in dust, or has become trapped in carpets, upholstery, fabrics and other porous materials commonly found in indoor environments. THS also may contain secondary pollutants created from reactions of tobacco smoke pollutants with oxidants and other compounds in the environment.

The constituents of THS that have been identified so far include nicotine, 3-ethenylpyridine (3-EP), phenol, cresols, naphthalene, formaldehyde and tobacco-specific nitrosamines (some absent in freshly emitted tobacco smoke).[7 8] THS exposure results from the involuntary inhalation, ingestion, or dermal uptake of THS pollutants in the air, in dust and on surfaces. It includes inhalation exposure to compounds re-emitted into the air from indoor surfaces and particles resuspended from deposits, and dermal and ingestion exposure to compounds partially derived from cigarette smoke and resulting particles that have settled, deposited and accumulated on surfaces and dust. Some of the compounds in THS are odorant and are experienced as an unpleasant, stale tobacco smoke odour on smokers, in rooms in which smoking has occurred, or on non-smokers or objects that have been in smokers' environments.

Research suggests that THS pollutants in dust, air and on surfaces in homes and cars may persist as long as months after the last known tobacco use occurred.[9 10] Evidence collected in field and controlled laboratory studies shows that indoor environments in which tobacco is regularly smoked become reservoirs of tobacco smoke pollutants, potentially leading to the involuntary exposure of non-smokers to THS in the absence of concurrent smoking and long after smoking has taken place.[11–13] Our previous research found that infants of smoking mothers were exposed to tobacco smoke pollutants through THS even though their mothers had strict indoor smoking bans and never smoked near their children.[9]

This study examined homes of smokers and non-smokers who were about to move out to better understand the persistence of THS during a change of occupancy. Before the first occupants moved out, we measured levels of THS in their homes and the extent to which non-smoking residents were involuntarily exposed to tobacco smoke. We revisited these homes after new non-smoking residents

moved in to determine the extent to which the homes remained polluted with THS and the extent to which new non-smoking residents were exposed to THS.

METHODS

Study design

This study relied on a quasiexperimental design, comparing non-smoker and smoker homes and their residents before (part 1) and after (part 2) a change of occupancy. For part 1, 150 participants were recruited who were planning to move out of a private residence (ie, house, condominium, or apartment) within the next month. Participants were interviewed, environmental sampling was conducted and children's urine samples were collected for analysis of cotinine concentration. For part 2, we recruited the new residents who moved into the part 1 homes. These residents were interviewed, environmental sampling was conducted, and urine samples were collected from the youngest residents.

Inclusion criteria

For part 1, residents were eligible to participate if they were age 18 or older, spoke English, had lived in their current home for at least 6 months, reported that everyone in their household was planning to move within the next month and also that (to the best of their knowledge) the home would be reoccupied after they moved out. In addition, they met criteria for classification as either a 'smoker home' (n=100) or a 'non-smoker home' (n=50). Smoker homes were those in which residents had smoked indoors during at least 5 of the past 6 months, including the current and most recent month, and had smoked a minimum of seven cigarettes per week inside the home during the week prior to study measures. Non-smoker homes were those where no smokers had lived and no visitors had smoked indoors during the past 6 months, and where a *target child* (under age 12, not breastfeeding) who had not been exposed to any SHS in the past month resided full time. For smoker homes, a target child was selected if there was a resident under age 12 who lived in the home full time and was not breastfeeding. Six smoker homes that were measured in part 1 were disqualified because residents smoked fewer than seven cigarettes inside the home during the week preceding study measures, and their data were not included in the following analyses.

For part 2, new residents were eligible if they were age 18 or older, spoke English or Spanish, had not smoked any cigarettes since they moved into the home and if no visitors had smoked inside the home since the new residents moved in. The youngest resident who lived in the home full time and was not breastfeeding was designated the target child.

Participants

Participants received US$100–US$200 for completing an interview, providing urine samples and allowing the collection of environmental samples. All procedures were approved by the San Diego State University Institutional Review Board.

Part 1 recruitment

For part 1, participants were recruited through advertisements in local print (n=82) and electronic news media (n=4), San Diego County Women, Infants, and Children Supplemental Food and Nutrition Program (WIC) offices (n=52), referrals from friends, relatives, or coworkers (n=4), flyers distributed in military housing (n=1) and postcard mailers to a commercially available list of smokers (n=1).

Part 2 recruitment

After part 1 residents confirmed they had moved, research assistants delivered or mailed up to 12 recruitment letters and flyers to the same homes, requesting that new residents contact the research office by telephone for eligibility screening. Homes were visited at varied times of the day on weekdays and weekends, and screening was conducted in person if the new residents were present and agreed. If a home was still vacant and we were unable to gain access through the property manager or owner (6%) or new residents had not responded 6 months after part 1 measures were completed (12%), the home was disqualified from part 2. New residents of 26% of homes were disqualified due to smoking, the part 1 residents did not move from 18% of homes, the new residents declined to participate in 6% of homes, we were unable to schedule measures with 2%, and 1% of homes were completely renovated.

Part 2 measures were completed for 25 former smoker homes and 16 former non-smoker homes. Seven of these homes (four non-smoker and three smoker) were measured while vacant, with permission from the property manager or owner, as no new residents had moved in after 3 months. There were no statistically significant differences in air, surface, finger, or dust nicotine contamination for homes that were measured while vacant versus occupied (all $p>0.23$).

There were no significant differences for any part 1 measures of home contamination or target children's SHS exposure between smoker homes that did or did not participate in part 2. Compared to non-smoker homes that did not participate in part 2, those that participated exhibited higher mean nicotine concentration levels in living room air ($p=0.031$) and on residents' fingers ($p=0.014$) at part 1.

Participant and home characteristics

See table 1 for participant and home characteristics at part 1 and part 2.

Table 1 Participant and home characteristics

Characteristic	Part 1 Non-smoker homes N=50	Part 1 Smoker homes N=94	Part 2 Non-smoker homes N=16	Part 2 Smoker homes N=25
Participant				
Female	86%	75%	85%	76%
Age, years* †	33	38	26	27
Race/ethnicity				
White	38%	37%	46%	38%
Hispanic	28%	12%	46%	19%
Black	24%	31%	8%	29%
Other	10%	20%	0%	14%
Target child				
Female	44%	44%	29%	0%
Age, years*	4.0	4.3	2.9	3.4
Race/ethnicity				
White	24%	19%	29%	14%
Hispanic	26%	25%	43%	57%
Black	22%	31%	0%	29%
Other	28%	25%	29%	0%
Number of residents living in home* †	4	2	3	2
Square footage of home* †	767	591	764	666
Household income* †	US$37220	US$25500	US$32000	US$34000

*Median.
†$p<0.01$ (two sided) part 1 smoker versus non-smoker homes.

Measures

Pairs of research assistants visited participants' homes to conduct in-person interviews and collect environmental samples. Interviews were primarily conducted with the eligible resident who agreed to participate, however questions about smoking inside the home and SHS exposure of non-smokers were asked of each smoker who agreed to participate. If a smoker resident was unavailable, participants provided proxy reports. In smoker homes, samples were collected in the living room and one bedroom (the target child's or a non-smoker's, or the smoker's bedroom in homes with no non-smokers). In non-smoker homes, samples were collected in the living room only.

Indoor smoking and SHS exposure

At each interview, primary interview participants and other parents (spouses or partners living in the home) reported their smoking and the target child's SHS exposure on typical work and non-work days (or week and weekend days if participants didn't work outside the home) during the past 7 days, including exposure from other residents and visitors, and outside of the home including in the car. SHS exposure was defined as the number of cigarettes smoked while the target child was in the same indoor room or car. The target child's weekly exposure to cigarettes in the home and 'total exposure' to all cigarettes in the home, car and elsewhere were computed. These measures have shown acceptable test—retest reliability and validity in relation to cotinine and nicotine assays in our past studies.[14–16]

To examine the test—retest reliability of our measures, selected smoking and SHS exposure questions were asked by telephone again for 32 part 1 respondents who agreed to participate 24–72 h following their home interview. Pearson correlation coefficients for participants' reports at the part 1 interview and 24–72 h retest were r=0.95 for participants' smoking rate inside the home, r=0.92 for other parents' smoking rate inside the home, r=0.90 for visitors' smoking rate inside the home, r=0.97 for participants' overall smoking rate, r=0.89 for other parents' overall smoking rate and r=0.98 for children's SHS exposure from visitors inside the home. Validity correlations between part 1 outcome variables were r=0.61 for living room surface nicotine with dust nicotine, r=0.54 for living room surface nicotine with air nicotine, r=0.63 for living room dust nicotine with air nicotine and r=0.89 for urine cotinine with reported indoor smoking.

Surface nicotine in living room and bedroom

Prescreened cotton wipes (cosmetic 100% cotton facial wipes) were wetted with 1.5 ml of 1% ascorbic acid and wiped over a 100 cm^2 area, typically a wooden door or cabinet unlikely to be frequently cleaned.[9] Nicotine-d_4 was added as an internal standard, then 0.1% aqueous formic acid was added, mixed, and the wipe removed from solution. Then, 1 M KOH (aqueous) was added, vortexed, and 2 ml was transferred to a precleaned solid phase extraction (SPE) column (Isolute C8, International Sorbent Technologies, Hengoed, UK). The column was washed, then the nicotine eluted with acetonitrile/pH4 20 mm ammonium acetate buffer into an amber autosampler phial. Samples were stored at −20C in the dark until analysis. For part 2, samples were collected in a 100 cm^2 area directly adjacent to the area sampled in part 1.

Finger nicotine concentration

A wipe sample of the participant's dominant hand index finger was taken at the home visit. In part 1, this was the smoker or non-smoker about to move out. In part 2, this was the new non-smoking resident. Wipes were prepared and processed as above.

Dust nicotine in living room and bedroom

Dust samples were collected from a 1 m by 1 m area (or from a larger area if needed to collect approximately one-quarter of an inch of dust in a collection bottle) with a High-Volume-Small Surface-Sampler (HVS4, CS3 Inc., Venice, Florida, USA) into methanol-washed amber bottles. Samples were transported cooled, then were weighed and sieved with a stainless steel, methanol-washed, 150 μm mesh sieve to remove large debris such as pet hairs, and weighed again. Samples were stored at −20C until analysis. For analysis of nicotine, 50 mg of sieved dust were used. Samples were processed and analysed in a manner similar to wipe samples except the inlet end of the SPE columns were coupled to a filter cartridge containing a medium porosity filter paper to retain the particulate. Dust concentrations are reported as μg/g (concentration) as well as μg/m^2 (loading). For part 2, samples were collected directly adjacent to the area sampled in part 1.

Air nicotine in living room and bedroom

A passive diffusion monitor badge was used, consisting of a modified 37 mm 3M Organic Vapour Monitor (3-M, St. Paul, Minnesota, USA) with a glass fibre filter coated with a glycerol/phosphoric acid mixture (filter collector was modified from Kuusimaki *et al*).[17] The sampling rate was empirically determined to be 18.4 ml/min. At the home visit, research assistants taped monitors to a wall about 1.5 m (5 feet) above the ground, out of children's reach and away from windows, corners, doors and ashtrays. Inactive monitors were placed in all other rooms of the study homes to enhance reporting accuracy. Research assistants visited the homes 7 days later to retrieve the monitors, and the time in minutes the badge was placed were recorded. Extraction took place as for wipes, as discussed above. For part 2 measures, air monitors were placed in the same exact locations as for part 1.

Urine cotinine concentration

At each part 1 and part 2 home visit, a urine sample was collected from the target child. Samples were obtained using a standard collection cup for older children and adults, or by placing two pieces of a 12.7 cm by 22.9 cm (5 inch by 9 inch) pad (cut into four pieces) in the diaper (TenderSorb Wet-Pruf Abdominal Pads, Kendall # 9190, Kendall, Covidien, Mansfield, Massachusetts, USA). Wet pads were packed into separate sterile 20 ml syringes and expressed into sterile 5 ml plastic phials.

Laboratory analyses

Samples were analysed by D Chatfield at San Diego State University. The method of analysis was by liquid chromatography tandem mass spectrometry (LC-MS-MS) using electrospray ionisation (ESI; Thermo Fisher Scientific, Waltham, Massachusetts, USA). Nicotine was quantified against the internal standard, nicotine-d_4 (CDN Isotopes Inc., Pointe-Claire, Quebec, Canada). The final extracts after sample preparation were injected (1–5 μl) onto a LC silica column (Hypersil, Thermo Fisher Scientific, Waltham, Massachusetts, USA) and separated in hydrophilic interaction chromatography (HILIC) mode using acetonitrile:pH4 20 mM acetate buffer of 70:30 (v/v) at 150 μl/min. Selected reaction monitoring of the MS-MS transitions at 16V collision-induced dissociation (CID) of m/z 163.2 to m/z 117.1 and 130.1 and m/z 167.1 to m/z 121.1 and m/z 134.1 was used for nicotine and the deuterated analogue, respectively. Standard calibration curves were linear over the

concentration range studied, 0.1 to 1000 ng/ml with R^2=0.997. Limits of detection were approximately 0.1 μg nicotine/m^2 for wipe samples, 0.2 μg nicotine/g dust and 0.0058 μg/m^3 in air for a 7 day exposure. The detection limit for urine cotinine was approximately 0.05 ng/ml.

Statistical analyses

Results are presented for study homes that had part 1 and part 2 measures (N=41), and for all part 1 homes (N=144). To control for non-normal distributions and heterogeneous error variances, we subjected response variables to logarithmic transformation and report geometric means. We examined differences in THS pollution and exposure between smoker and non-smoker homes before (part 1) and after (part 2) the change of occupancy using two-sample t tests with unequal variances. Mean changes in THS pollution from part 1 to part 2 were examined with paired t tests. Quantile and Tobit regression analyses for left-censored data were used to explore the contribution of dust, surface and air contamination to participants' finger nicotine and urine cotinine levels. Quantile regression models were examined for 50th and 75th percentiles. Analyses were conducted with Stata IC V. 10.0 and SPSS V. 15.0 statistical software.[18 19] The type I error rate was set at α=0.05, and comparisons between non-smoker and smoker homes were conducted based on directional (one-tailed) hypotheses regarding differences in THS pollution and exposure between non-smoker and smoker homes and between non-smokers residing in former smoker and non-smoker homes. All other hypotheses were tested in a non-directional (two-tailed) fashion.

To investigate how well environmental and biological markers of THS pollution and exposure discriminate between smoker and non-smoker environments, we determined cut-off values for urine cotinine and finger, air, dust and surface nicotine levels that yield the largest per cent difference between correctly identified smoker homes (ie, hits) and incorrectly identified non-smoker homes (ie, false alarms).

RESULTS

Tobacco smoke pollution in homes

Tobacco smoke pollution in smoker and non-smoker homes before the change of occupancy (part 1)

Table 2 shows the geometric means and 95% CIs for the number of cigarettes smoked indoors at home, as well as for nicotine levels in the air, dust and on the surfaces of smoker and non-smoker homes (ie, part 1). Data are reported for all smoker and non-smoker homes, and also separately for the subset of homes for which part 1 and part 2 data were available.

In part 1 smoker homes, participants reported that an average of 60 cigarettes/week were smoked indoors; 52% had 1 smoking resident, 44% had 2 and 4% had 5 smoking residents. In part 1 non-smoker homes, participants reported that no residents had smoked at all in the past 6 months, and that no cigarettes were smoked inside the home for at least 6 months prior to study measures.

Replicating findings from our earlier research, smoker homes showed significantly elevated levels (all p<0.001) of nicotine in the air, in household dust and on surfaces. Air nicotine concentrations were 35–98 times higher than those found in non-smoker homes. The 2 major reservoirs for THS in smoker homes, dust and surfaces, showed nicotine levels approximately 12–21 and 30–150 times higher, respectively, than the reference levels in non-smoker homes. Note that nicotine concentrations in dust were approximately equivalent in living rooms and bedrooms.

Table 2 Tobacco smoke pollution in smoker and non-smoker homes before (part 1) and after (part 2) the change of occupancy

	Part 1: original occupants, N mean (95% CI)	Part 2: new non-smoker occupants, N mean (95% CI)
Indoor smoking, cigarettes/week		
All non-smoker homes	50 0	16 0
All smoker homes	94 60.17 (49.60 to 72.96)	25 0
Same non-smoker homes	16 0	16 0
Same smoker homes	25 68.57 (46.94 to 99.94)	25 0
Air nicotine, μg/m^3		
Living room:		
All non-smoker homes	50 0.02 (0.01 to 0.03)	16 0.14 (0.00 to 0.34)
All smoker homes	81* 1.86 (1.38 to 2.44)	23 0.20 (0.07 to 0.34)
Same non-smoker homes	16 0.04 (0.00 to 0.07)	16 0.14 (0.00 to 0.34)
Same smoker homes	19 1.96 (1.01 to 3.34)	19 0.23 (0.07 to 0.41)
Bedroom:		
All smoker homes	74† 1.44 (1.00 to 1.97)	22 0.12 (0.04 to 0.19)
Same smoker homes	19 1.55 (0.75 to 2.73)	19 0.13 (0.05 to 0.22)
Surface nicotine, μg/m^2		
Living room:		
All non-smoker homes	50 1.6 (0.8 to 3.0)	16 1.5‡ (0.4 to 3.7)
All smoker homes	94 98.7 (61.2 to 158.6)	24 10.0‡ (3.1 to 28.6)
Same non-smoker homes	16 1.4 (0.3 to 3.6)	16 1.5‡ (0.4 to 3.7)
Same smoker homes	24 211.7 (85.2 to 523.9)	24 10.0‡ (3.1 to 28.6)
Bedroom:		
All smoker homes	87 50.1 (29.4 to 84.7)	23 7.5 (1.9 to 24.4)
Same smoker homes	23 66.1 (24.8 to 173.5)	23 7.5 (1.9 to 24.4)
Dust nicotine, μg/g		
Living room:		
All non-smoker homes	50 2.9 (1.1 to 4.0)	16 2.3§ (1.0 to 4.4)
All smoker homes	93 39.6 (30.0 to 52.2)	25 10.9§ (6.4 to 18.2)
Same non-smoker homes	16 2.7 (1.1 to 5.3)	16 2.3§ (1.0 to 4.4)
Same smoker homes	25 47.6 (26.6 to 84.7)	25 10.9§ (6.4 to 18.2)
Bedroom:		
All smoker homes	76 30.7 (22.2 to 42.2)	23 11.0 (6.0 to 19.6)
Same smoker homes	23 40.4 (23.1 to 70.2)	23 11.0 (6.0 to 19.6)
Dust nicotine, μg/m^2		
Living room:		
All non-smoker homes	49 3.6 (2.2 to 5.6)	16 3.1 (0.8 to 8.3)
All smoker homes	92 58.8 (40.9 to 84.3)	25 7.6 (3.6 to 15.3)
Same non-smoker homes	15 4.2 (1.3 to 10.6)	15 3.4 (0.8 to 9.6)
Same smoker homes	25 76.2 (33.1 to 173.8)	25 7.6 (3.6 to 15.3)
Bedroom:		
All smoker homes	73 51.0 (34.7 to 74.8)	21 7.3 (3.0 to 16.3)
Same smoker homes	21 75.4 (36.7 to 153.9)	21 7.3 (3.0 to 16.3)

*Part 1 living room air monitors were not placed in nine smoker homes because residents were moving in <7 days, and air monitors were not returned by residents of four smoker homes.
†Part 1 bedroom air monitors were not placed in nine smoker homes because residents were moving in <7 days, or in six studio apartments, and were not returned by residents of five smoker homes.
‡p=0.0059 (directional) part 2 non-smoker versus former smoker homes.
§p=0.0002 (directional) part 2 non-smoker versus former smoker homes.

Change in tobacco smoke pollution when smokers moved out and non-smokers moved in (part 1 vs part 2)

Of the homes that participated in part 2, smoker homes were vacant a median of 62 days and non-smoker homes were vacant a median of 34 days after part 1 residents moved out. Part 2 measures were obtained a median of 33 days after new residents moved into former smoker homes, and a median of 32 days after new residents moved into former non-smoker homes. Smoker homes were more likely than non-smoker homes to get new flooring in the bedroom, kitchen and living room, and were more likely to have the kitchen painted (as reported by part 2 participants; all χ^2 p<0.05).

Table 2 shows that tobacco pollutants as measured by nicotine concentrations significantly decreased when smokers moved out (part 1) and new non-smoking residents moved into the same homes (part 2) (all $p<0.001$). The largest reductions in smoker homes were observed for nicotine on living room surfaces (95% reduction), and the smallest for dust nicotine concentration (i.e., nicotine per gram of dust) in living rooms and bedrooms (75% reduction). For former non-smoker homes, nicotine levels stayed approximately equivalent to their original levels, suggesting stable levels of background nicotine pollution.

Thirdhand smoke pollution in former smoker homes compared to former non-smoker homes (part 2)

Table 2 shows results comparing THS levels in homes of non-smokers (part 2) who moved into former smoker and non-smoker homes. Homes formerly occupied by smokers showed significantly higher levels of nicotine on living room surfaces (1.52 vs 10.04 $\mu g/m^2$, $p=0.0059$) and in living room dust (2.27 vs 10.94 $\mu g/g$, $p=0.0002$). On average, nicotine contamination was seven times higher on living room surfaces and five times higher in living room dust in former smoker homes compared to former non-smoker homes. Dust nicotine loadings (ie, nicotine per m^2) were higher in smoker as compared to non-smoker homes, but this elevation was not as marked as for dust concentration and was not statistically significant ($p=0.07$).

Exposure to tobacco smoke pollutants in homes

SHS and THS exposure in smoker and non-smoker homes before change of occupancy (part 1)

Table 3 shows urine cotinine and finger nicotine levels, and reported measures of involuntary exposure to tobacco smoke among the target children in smoker and non-smoker homes. Data are reported for participants in all non-smoker and smoker homes, and also separately for the subset of participants in homes for which part 1 and part 2 data were available.

Children living in homes with active smokers were reportedly exposed to an average of 14 cigarettes/week at home. No exposure was reported for children living in non-smoker homes. Geometric mean urine cotinine levels among children in smoker homes were 5.42 ng/ml, compared to 0.15 ng/ml among children in non-smoker homes. Finger nicotine levels were, on average, 660.21 ng/wipe among smokers in smoker homes, compared to 0.47 ng/wipe among non-smokers in non-smoker homes. Part 1 smoker and non-smoker homes differed significantly on urine cotinine ($p=0.002$) and finger nicotine ($p<0.001$).

Table 3 Exposure to tobacco smoke pollution in smoker and non-smoker homes before (part 1) and after (part 2) occupants move

	Part 1: original occupants, N mean (95% CI)	Part 2: new non-smoker occupants, N mean (95% CI)
Urine cotinine, ng/ml		
All non-smoker homes	50 0.15 (0.09 to 0.21)	13 0.13* (0.00 to 0.27)
All smoker homes	31 5.42 (3.88 to 7.46)	20 0.45* (0.13 to 0.86)
Same non-smoker homes	13 0.14 (0.00 to 0.29)	13 0.13† (0.00 to 0.27)
Same smoker homes	5 3.66 (1.49 to 7.70)	5 0.61† (0.00 to 2.26)
Finger nicotine, ng/wipe		
All non-smoker homes	50 0.47 (0.04 to 1.08)	11 0.75‡ (0.00 to 3.06)
All smoker homes	91 660.21 (441.58 to 986.84)	19 5.19‡ (0.81 to 20.12)
Same non-smoker homes	11 1.35 (0.00 to 8.02)	11 0.75§ (0.00 to 3.06)
Same smoker homes	18 803.85 (387.84 to 1664.96)	18 5.85§ (0.90 to 23.72)
Reported exposure, cigarettes/week		
All non-smoker homes	50 0	12 0
All smoker homes	31 14.19 (7.16 to 27.28)	20 0.40 (0.00 to 1.15)
Same non-smoker homes	12 0	12 0
Same smoker homes	5 18.49 (0.10 to 343.13)	5 1.52 (0.00 to 20.01)

*p=0.0344 (one sided) part 2 smoker versus part 2 non-smoker homes.
†p=0.1176 (one sided) part 2 smoker versus part 2 non-smoker homes.
‡p=0.0402 (one sided) part 2 smoker versus part 2 non-smoker homes.
§p=0.0339 (one sided) part 2 smoker versus part 2 non-smoker homes.

Residents' exposure to tobacco smoke pollutants after the change of occupancy (part 1 vs part 2)

Table 3 shows that the geometric mean urine cotinine concentrations of new non-smoking youngest residents in former smoker homes (part 2) were lower than the levels exhibited by the children who previously resided in these same homes ($p<0.05$ all homes). New residents' finger nicotine levels were also lower in part 2 smoker homes ($p<0.001$). In non-smoker homes, there were no differences in mean urine cotinine levels ($p>0.20$) or finger nicotine levels ($p>0.20$) between part 1 and part 2.

THS exposure among non-smokers occupying former smoker and non-smoker homes (part 2)

Table 3 shows urine cotinine and finger nicotine levels among non-smokers who moved into homes formerly occupied by smokers and non-smokers. Nicotine levels found on the index fingers of non-smokers residing in former smoker homes were 7–8 times higher than for those residing in former non-smoker homes (same homes: 5.85 vs 0.75 ng/wipe, $p=0.0339$; all homes: 5.19 vs 0.75 ng/wipe, $p=0.0402$). Urine cotinine levels were 3–5 times higher among the youngest occupants of former smoker homes compared to former non-smoker homes (same homes: 0.61 vs 0.13 ng/ml, $p=0.1176$; all homes: 0.13 vs 0.45 ng/ml, $p=0.0344$).

Reported tobacco odour and discolouration

The new residents of four former smoker homes reported tobacco odour in their homes, and the new residents of one additional former smoker home reported tobacco discolouration (yellow spots on the living room and dining room ceilings). No residents of former non-smoker homes reported tobacco odour or discolouration.

Exploring the contribution of dust, surface and air contamination to overall thirdhand smoke exposure

To explore how THS in dust, air and on surfaces may contribute to non-smokers' overall exposure to THS, we first examined the associations between finger nicotine levels and THS on surfaces and in dust. Tobit regression models of finger nicotine levels showed statistically significant associations with surface nicotine levels (pseudo $R^2=0.08$, $p=0.037$) and dust nicotine levels (pseudo $R^2=0.11$, $p=0.009$). When entered jointly, surface and dust nicotine yielded a statistically significant model fit (pseudo $R^2=0.13$, $p=0.025$).

We then examined the associations between urine cotinine levels and THS, as measured by dust and surface nicotine levels. Using Tobit regression models, urine cotinine showed statistically significant associations with dust nicotine (pseudo $R^2=0.18$, $p=0.035$) and surface nicotine (pseudo $R^2=0.21$, $p=0.027$). In a Tobit regression model, dust and surface nicotine levels jointly produced a statistically significant model fit (pseudo $R^2=0.29$, $p=0.031$).

Lastly, we examined the association between urine cotinine and finger nicotine. Tobit (pseudo $R^2=0.69$, $p<0.001$) and quantile regression (pseudo $R^2=0.28$, $p<0.001$) models, as well as Pearson ($r=0.70$, $p<0.001$) and Spearman ($r=0.67$, $p<0.001$) correlations showed a strong association between nicotine on part 2 residents' fingers and their urine cotinine levels.

When urine cotinine was regressed on finger nicotine, surface nicotine and dust nicotine as explanatory variables, only finger nicotine level was statistically significant (p=0.001; dust and surface nicotine, both p>0.20). This suggests that finger nicotine in non-smokers may be a robust measure of THS on polluted surfaces and dust.

In part 2 homes, air nicotine levels were not associated with urine cotinine or finger nicotine levels. Models that included reported SHS exposure and reported number of days participants smelled smoke drifting inside the home were not statistically significant, nor were bivariate correlations of these variables with urine cotinine.

Cut-off levels discriminating between smoker and non-smoker homes

Table 4 shows the percentages of smoker and non-smoker homes with above threshold levels of air, surface and dust nicotine, urine cotinine and finger nicotine. These findings indicate that dust nicotine best discriminates between smoker and non-smoker homes. Specifically, 84% of smoker homes' living rooms still exhibited above threshold levels of nicotine in dust when non-smokers moved in (part 2), compared to 90% when smokers still lived there (part 1) and 19% of part 2 non-smoker homes. Similarly, 54% of the former smoker homes' living rooms (part 2) had surfaces above threshold levels, compared to 19% of former non-smoker homes. Among the part 2 occupants of smoker homes (all non-smokers), 40% had above threshold levels of THS exposure (urine cotinine) and 35% had above threshold levels of finger nicotine. This compares to 8% and 0%, respectively, among occupants of part 2 non-smoker homes.

Table 4 Percentage of homes with detectable levels of cotinine in non-smoker's urine, nicotine on non-smoker's fingers and nicotine in house household dust, air and surfaces

	Cut-off*	Part 1: original occupants, percentage ≥ cut-off value	Part 2: new non-smoker occupants, percentage ≥ cut-off value
Urine cotinine	0.30 ng/ml		
Non-smoker homes		10	8
Smoker homes		97	40
Finger nicotine	50.0 ng/wipe†		
Non-smoker homes		2	0
Smoker homes		93	35
Air nicotine living room	0.10 $\mu g/m^3$		
Non-smoker homes		6	25
Smoker homes		90	44
Air nicotine bedroom	0.10 $\mu g/m^3$		
Non-smoker homes		NA	NA
Smoker homes		78	39
Surface nicotine living room	5.0 $\mu g/m^2$		
Non-smoker homes		16	19
Smoker homes		86	54
Surface nicotine bedroom	5.0 $\mu g/m^2$		
Non-smoker homes		NA	NA
Smoker homes		75	44
Dust nicotine living room	5.0 $\mu g/g$		
Non-smoker homes		28	19
Smoker homes		90	84
Dust nicotine bedroom	5.0 $\mu g/g$		
Non-smoker homes		NA	NA
Smoker homes		84	70
Dust nicotine living room	5.0 $\mu g/m^2$		
Non-smoker homes		31	25
Smoker homes		91	60
Dust nicotine bedroom	5.0 $\mu g/m^2$		
Non-smoker homes		NA	NA
Smoker homes		64	52

*Cut-offs were established to discriminate between smoker and non-smoker homes.
†Wipes were 0.1 m × 0.1 m; 50 ng/wipe is equivalent to 5.0 $\mu g/m^2$.

DISCUSSION

This was the first study to examine residential THS pollution and exposure after smokers moved out and non-smokers moved in. Findings replicate those from an earlier study of smoking mothers with infants,[9] showing that smoker homes have become significant reservoirs of THS pollutants at the time smokers prepare to move out.

Even 2 months after smokers moved out and non-smokers moved in, nicotine in dust and on surfaces still exceeded threshold levels in 84% and 54% of homes, respectively. Even though mean levels of nicotine significantly declined when non-smokers moved into former smoker homes, dust and surface nicotine levels were still significantly higher than in non-smoker homes that underwent a similar change of occupancy. This is particularly notable because these homes were vacant for an average of 2 months during the change of occupancy, and because all of these homes underwent cleaning and many were repainted and had carpets replaced before new occupants moved in (especially smoker homes). In summary, these findings demonstrate that smokers leave behind a legacy of THS in the dust and on the surfaces of their homes that persists over weeks and months.

Non-smokers moving into former smoker homes are exposed to the THS left in dust and on surfaces by the former smoker occupants. This is shown by increased finger nicotine and urine cotinine levels among non-smokers living in former smoker homes. This exposure pathway is further supported by significant correlations of dust and surface nicotine levels with finger nicotine levels, and between finger nicotine and urine cotinine levels. Air nicotine levels were not associated with biological exposure measures. This suggests that the main reservoirs of exposure to THS are in dust and surfaces. Air concentrations of THS may remain low relative to dust and surfaces because airborne THS is more rapidly transported outside the home through passive air exchanges and active ventilation.

It should be noted that smoker homes in this study were more expensive to prepare for new occupants than non-smoker homes. Smoker homes remained vacant for on average an extra month, and they were more likely to get new flooring in the bedroom, kitchen and living room and to have the kitchen painted. These findings parallel results from our study of the resale value of used cars sold by smokers, showing that their cars lost 7% to 9% in value relative to non-smoker cars of equivalent age, make, model and condition.[20] These results suggest economic consequences for owners, sellers and renters of cars and homes. Theoretically, such economic penalties, if communicated to the community, create incentives to reduce smoking as well as THS contamination of cars and homes.[21]

Limitations

Markers of THS have not been comprehensively studied, and there remain important questions regarding the extent to which nicotine represents other chemical compounds known and suspected in THS. Similarly, it is unclear how well cotinine represents biological exposure to THS compounds beyond nicotine, such as tobacco-specific nitrosamines.[7 8] This study was not designed to investigate health outcomes of exposure to THS. Future research on surface chemistry and biological mechanisms, as well as behavioural studies of exposure

pathways are needed to better understand the nature of THS, associated health outcomes, and the behavioural and economic factors influencing THS pollution and exposure in the field.

The subject matter of this field study precluded a randomised trial, creating some ambiguity about the causal origins of the THS pollutants detected in part 1 homes. The fact that the THS marker is tobacco specific (ie, nicotine) and strongly associated with reported smoking behaviour of part 1 occupants makes this validity concern implausible. The voluntary nature of participation in this study, typical vacancy rates in the housing market, participation refusals and our efforts to exclude from part 2 participants who were exposed to SHS decreased sample sizes for part 2 analyses. This lowered the statistical power of our hypothesis tests and could have contributed to differential attrition. To address these issues, we report findings based on data collected from all eligible homes and from homes for which part 1 and part 2 data were available. We also report geometric means with 95% CIs and exact p values of hypothesis tests to allow the reader to evaluate their statistical and practical significance, given the relatively small sample sizes. We examined and found no plausible evidence for differential attrition.

Conclusions

Homes remain reservoirs of tobacco smoke pollutants after smokers move out, creating a source for involuntary exposure to non-smokers moving into these homes. Infants and young children are likely most at risk for exposure to THS in dust and surfaces and its health consequences because of age-specific behaviours (eg, crawling, sucking, ingesting non-food items, hand-to-mouth contact). Known susceptibility of infants due to immature respiratory and immune systems, lower metabolic capacity and the many years of life remaining make exposure to the potent carcinogens reported in THS a concern. It has been previously demonstrated that house dust can be a major route of exposure to lead for young children.[22 23]

What this paper adds

- Thirdhand smoke (THS) consists of tobacco smoke pollutants that remain on surfaces and in dust after tobacco has been smoked, are re-emitted and resuspended back into the air, or react with oxidants and other compounds in the environment to yield secondary pollutants.
- Evidence collected in field and controlled laboratory studies shows that indoor environments in which tobacco is regularly smoked become reservoirs of THS, potentially leading to the involuntary exposure of non-smokers to THS in the absence of concurrent smoking and long after smoking has taken place.
- This study is the first to examine whether private homes of smokers remain contaminated with THS after the smokers move out and non-smokers move in, and whether non-smokers who move into homes formerly occupied by smokers are exposed to THS through contaminated dust, surfaces and air in these homes.
- Findings indicate that THS accumulates in smokers' homes and persists when smokers move out even after homes remain vacant for 2 months and are cleaned and prepared for new residents. When non-smokers moved into homes formerly occupied by smokers, they encountered indoor environments with measurable THS polluted surfaces and dust. Results suggest that non-smokers living in former smoker homes are exposed to THS in dust and on surfaces.

Based on the current limited evidence on the chemistry, biology and behavioural science of THS, it is premature to rule on its significance as a cause, moderator, mediator, or contributor to health outcomes. This and other studies suggest caution in trivialising the relatively low levels of pollutants found 2 months after the last cigarette was smoked. The limited existing research warrants rigorous further investigations into the chemical, physical, biological, environmental, behavioural and economic aspects of THS to more comprehensively understand its impact on human health in the social and policy contexts in which smoking occurs throughout the world.

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When smokers move out and non-smokers move in: residential thirdhand smoke pollution and exposure

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Notes

Thirdhand Smoke: Heterogeneous Oxidation of Nicotine and Secondary Aerosol Formation in the Indoor Environment

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Tobacco smoking is well-known as a significant source of primary indoor air pollutants. However, only recently has thirdhand smoke (THS) been recognized as a contributor to indoor pollution due to the role of indoor surfaces. Here, the effects of relative humidity (<10% RH and ~45% RH) and substrate (cellulose, cotton, and paper) on secondary organic aerosol (SOA) formation from nicotine-ozone-NO_x reactions are discussed. SOA formation from the sorbed nicotine-ozone reaction ($[O_3]$ = 55 ppb) varied in size distribution and number, depending on RH and substrate type, indicating the role of substrate and water interactions in SOA formation. This led to SOA yields from cellulose sorbed nicotine-ozone reaction of ~1 and 2% for wet and dry conditions, respectively. SOA formation from nicotine-NO_x reactions was not distinguishable from background levels. Simultaneously, cellulose sorbed nicotine-ozone reaction kinetics ($[O_3]$ = 55 ppb) were obtained and revealed pseudofirst-order surface rate constants of $k_1 = (1 \pm 0.5) \times 10^{-3}$ and $k_1 < 10^{-4}$ min^{-1} under <10% and ~45% RH, respectively. Given the toxicity of some of the identified products and that small particles may contribute to adverse health effects, the present study indicates that exposure to THS ozonation products may pose additional health risks.

Introduction

Although the adult smoking population, media awareness on health implications of direct and passive smoking, and smoke-free legislation in public and workplaces varies from country to country, smoking indoors and in the presence of children may still take place in a relatively high proportion of households with smoker(s) (*1*–*3*). In fact, prenatal, infant, and childhood exposure to passive smoke has been associated with a plethora of behavioral, cognitive, and respiratory problems (*4*, *5*) with a scientific consensus (from over 150 epidemiological studies) that ETS results in noncancer respiratory effects in children (*6*). Thus, passive smoking, particularly in private houses, continues to provoke health concerns.

These indirect exposures can occur via two processes: unintentional inhalation of smoke, termed "secondhand smoke" (SHS), or as a consequence of residual smoke contamination that remains on surfaces after a cigarette is extinguished, termed "thirdhand smoke" (THS) (*7*). THS has several exposure routes: re-emitting as a source of inhalation exposure (*8*) remaining on surfaces as a source of ingestion or dermal exposure, particularly for infants and young children (*9*), or the combination of processes where THS transfers from one surface to another. In addition, heterogeneous reactions may contribute greatly to indoor exposures. Gas phase monitoring of nicotine in the presence of moderate ozone levels ($[O_3]$ = 42 ppb) suggested heterogeneous reaction to form gas and condensed phase products such as methylformamide, formaldehyde, myosmine, and cotinine (*10*). Surface monitoring of nicotine-ozone reaction at high ozone levels ($[O_3]$ = 200 ppb) showed similar oxidation products (*11*). Additionally, surface nicotine-HONO reactions were shown to result in the formation of tobacco specific nitrosamines (*12*). The potential adverse health effects associated with these oxidation products has highlighted the importance of understanding indoor nicotine transformations.

In addition to primary surface and gas phase product formation, secondary aerosol formation (SOA) can result from oxidant initiated reactions (*13*–*15*). In fact, SOA formation as a result of gaseous SHS- and nicotine-ozone reaction in Tedlar bags has been observed (*16*), although homogeneous nicotine-ozone reaction is not expected to play a dominant role in indoor environments due to relatively slow reaction rates. Both epidemiological and toxicological evidence exists for associations between airborne particulate matter and ill health effects, particularly on the small diameter scale (<2.5 μm). Once particles are inhaled, deposition, solubility in the mucous membrane or respiratory fluids, transfer within the body, and resulting toxicological implications are dependent on both particle size and chemistry (*17*). Thus, secondary organic aerosol (SOA) formation from nicotine-oxidant reactions indoors may play a role in the observed adverse health effects associated with passive smoking.

This study investigated surface reactions between nicotine-ozone-NO_x on model indoor surfaces (cellulose powder, cotton, and paper). For the first time, SOA formation as a result of nicotine-ozone heterogeneous chemistry was observed, and surface reaction kinetics were extracted from direct surface monitoring, all within typical concentration ranges of indoor oxidants and RH (*18*). Additionally, near-mouth chemistry was investigated employing NO levels in the range of those exhaled by asthmatic patients (*19*). The health implications of THS surface transformation are also discussed.

Experimental Section

Fourier transform infrared spectroscopy with attenuated total reflectance element (FTIR-ATR) was used in tandem with a scanning mobility particle sizing (SMPS) system containing a differential mobility analyzer (TSI 3080 L) and a condensation particle counter (TSI 3022A) to monitor surface nicotine-ozone-NO_x reactions and SOA formation. The FTIR-ATR experimental system, ozone generation, and humidification are described in detail elsewhere (*11*) (see Figure S1 in the Supporting Information for experimental schematic). Low and moderate RH experiments were performed at <10% and 45 ± 3% RH, respectively. To monitor particle size distribution, the SMPS was set to collect and count particles in the range of 13–200 nm over the course of 200 s, every 5 min. NO gas (Praxair, EPA protocol, 50.4 ppm) was mixed with dry N_2 to desired concentrations and measured by chemiluminescence NO_y analyzer (API Teledyne, Model 200E). The calculated concentrations after mixing at the entrance point

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TABLE 1. Experimental Parameters for NO_x Experiments

exp no.	$[O_3]_0$[a] (ppb)	$[NO]_0$ (ppb)	RH[b]	τ (s)	$[O_3]_r$[c] (ppb)	$[NO]_r$ (ppb)	$[NO_2]_r$ (ppb)	$[NO_3]_r$ (ppt)
1	0	99	L	NA[d]	0	99	0	<1
2	0	97	M	NA[d]	0	97	0	<1
3	82	97	M	0.5	81	96	2	<1
4	53	105	M	0.5	52	105	1	<1
5	100	114	M	180	6	20	94	<1
6	62	100	M	205	1	39	61	<1

[a] Concentrations at point of mixing (subscript 0). [b] RH levels: 'M' stands for moderate (~45%) and 'L' for low (<10%). [c] Calculated concentrations after mixing at entrance point of reactor (subscript r). [d] NA means that mixing was not applicable.

of the reactor (subscript r) were determined using Acuchem software (*20*) given the total flow rate, dilutions, length of mixing (τ), the concentrations at point of mixing (subscript 0), and reaction rate constants (*21, 22*) depicted in Table S1. Experimental conditions involving NO_x are summarized in Table 1.

Substrates included cellulose powder (Sigma), locally purchased white cotton cloth, and chromatography paper (Whatman). The effective surface area of the cotton and paper was determined with BET-N_2 measurements. Samples were conditioned at 50 °C for 20 h under a dry N_2 flow (FlowPrep 060, Micromeretics) followed by N_2 surface gas adsorption analysis at 77 K (TriStar 3000 Micromeritics).

Nicotine-cellulose films were prepared by placing 100 μL of a suspension containing nicotine (62 mM) and cellulose powder (2 g L^{-1}) in chloroform on the ATR crystal. For cotton and paper experiments, 100 μL of nicotine-chloroform solution (62 mM) were doped on 8 × 1 cm^2 sized samples placed over the ATR crystal. For all experiments, the reactor was sealed (V = 0.16 L), and the solvent was allowed to evaporate without significant nicotine loss.

Once the solvent evaporated, temporal spectra collection started simultaneously with exposure of the sorbed nicotine to wet or dry oxidant gas (N_2/O_3 or $N_2/O_3/NO_x$) at a total flow of 155 ± 10 mL min^{-1} entering the reactor). Generated aerosols were detected downstream of the reactor (V_{tubing} = 0.017 L) after dilution with N_2 in order to achieve SMPS system flow requirements (300 mL min^{-1}). Both surface data and aerosol data were recorded simultaneously.

After exposure of the nicotine-cellulose film to oxidants, the crystal was rinsed with 300 μL of methanol, and the extract was concentrated by evaporation under N_2 to ~20 μL. The resulting sample was analyzed by GC-MS (Varian CP-3800, DB-5 Varian FactorFour 30 m column with ion-trap and MS detector, Varian Saturn 2000, run in EI mode) through standard comparison and NIST MS Search 2.0 software. The GC-MS method included an injector temperature of 240 °C, run in the splitless mode. The oven temperature was varied from 90 °C (1 min hold) to 160 at 5 °C min^{-1} and then raised to 220 at 20 °C min^{-1}. Ions were collected in the range of 40—400 m/z for detection.

Results and Discussion

SOA Formation. Heterogeneous reaction (rather than homogeneous) of surface sorbed nicotine with ozone ($[O_3]$ = 55 ppb) resulted in the formation of SOA (Figure 1).

Heterogeneous reaction is believed to be the major contributor of SOA formation due to both kinetic limitations and mass balance estimates. Under the present experimental conditions, the air exchange rate in the reactor was 0.9 min^{-1} which was several orders of magnitude faster than the predicted gas phase nicotine-ozone reaction rate constant, $k_1 = 6.3 \times 10^{-4}$ min^{-1}, at $[O_3]$ = 55 ppb. The trimethylamine-ozone reaction rate constant (k = (7.84 ± 0.87) × 10^{-18} cm^3 $molec^{-1}s^{-1}$) (*23*) was used as an approximation for the former, due to the lack of a published rate for nicotine-ozone reaction.

Furthermore, total particle counts (which are discussed more thoroughly in reference to Figure 2) were used as a first approximation mass balance of total SOA and nicotine. Nicotine desorption into the gas phase was determined under similar experimental conditions as during dry ozonolysis (N_2 flow = 150 mL min^{-1}, total volume 177 mL). Gaseous nicotine emitted during the first 40 min was collected in a methanol impinger and allowed determination of average gaseous nicotine concentration ($[Nic]_g$ = 0.02 ng cm^{-3}). Again, the homogeneous reaction rate of trimethylamine-ozone (*23*) was used as an approximation for the nicotine-ozone reaction rate. The amount of nicotine reacted during residence time in the reactor (70.7 s prior to reaching the SMPS) at $[O_3]$ = 55 ppb was estimated as (1.7 ± 0.2) × 10^{-5} ng cm^{-3}. During the initial 40 min of reaction, 4.5 × 10^8 SOA particles formed with an estimated total particle mass of 2.6 × 10^{-4} ng cm^{-3}, approximately 1 order of magnitude more than the nicotine available in the gas phase. Thus, SOA formation under the present experimental setup is primarily due to heterogeneous reaction.

Consistent with heterogeneous reaction, SOA formation was affected by both humidity and substrate type. Under all conditions where SOA formation was observed, maximum particle number occurred approximately 10 min into reaction, coinciding with full air exchange in the reactor (i.e., ~10 air exchanges). Under dry conditions, nicotine-doped cellulose and cotton showed similar SOA counts and size distributions (d < 25 nm) (Figure 1a,c and Figure S2a,b). An initial burst of SOA formation was observed for both substrates, followed by a gradual decrease in SOA during the first 40 min of reaction as surface nicotine was consumed. SOA formation continued only from reaction on cellulose, albeit at a much lower amount (Figure 1b,d and Figure S2a,b), in agreement with the much larger nicotine:substrate mass ratio for cellulose (Table S2). This suggests continued availability of surface sorbed nicotine on cellulose which was not available on cotton and that nicotine-ozone surface reaction may be limited by nicotine diffusion from bulk to surface of the substrate.

Under wet conditions less SOA formation was observed for both cellulose and cotton (a decrease in maximum particle number by a factor of ~10) (Figure 1e,f and Figure S1d,e), most likely due to additional SOA sinks (e.g., adsorbed water in the system) or the inhibition of surface nicotine-ozone reaction by sorbed water (*10, 11*). Additionally, particle size distribution from nicotine-ozone reaction on cellulose increased under moderate RH to d_{av} ≈ 27 nm (opposed to d_{av} ≈ 14 nm under dry conditions), suggesting very high water uptake by hydrophilic products and possible aerosol deliquescence (*24*). This 2-fold diameter increase is similar to that observed during SOA formation from gaseous nicotine-ozone reaction under dry and 50% RH (*16*). Interestingly, similar experiments performed on cotton showed the formation of aerosols with d_{av} ≈ 14 nm under dry conditions and the formation of a small bimodal distribution with particles of d_{av} ≈ 18 nm under moderate RH (Figure 1f).

Complete SOA inhibition was observed from reaction on paper under either humidity condition (Figure S2c,f). While nicotine loading for both cotton and paper was performed by liquid doping, the dense structure of the paper may have limited nicotine diffusion to the surface.

To investigate the role of water in SOA formation, the system was prehumidified for 10 min prior to exposure to humidified ozone and spectral data collection. SOA formation under this condition (termed prehumidified condition from henceforth) resulted in a much larger size distribution and a factor of 100 decrease in particle number (Figure 1g and

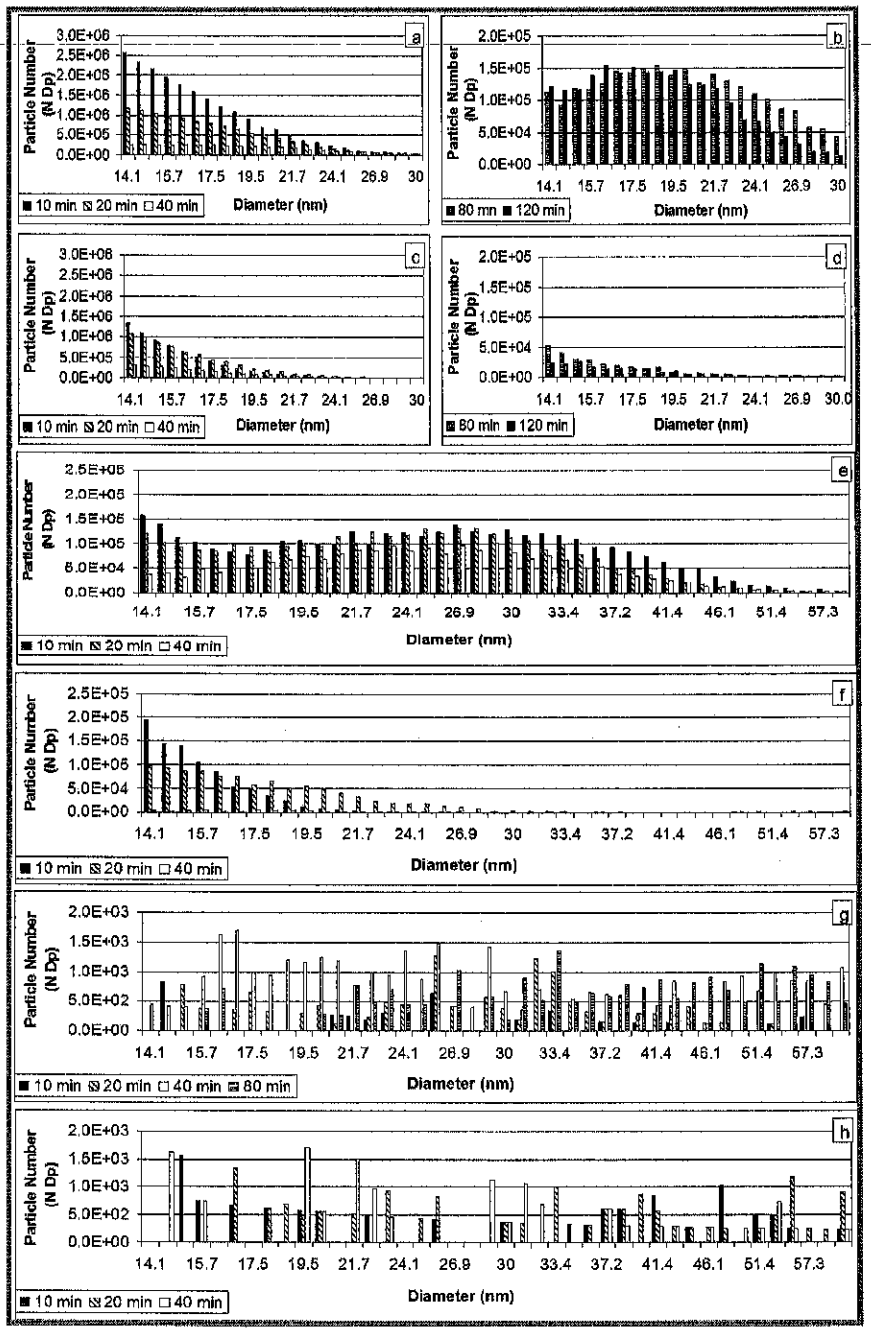

FIGURE 1. Aerosol distributions from dry nicotine-ozone reaction on cellulose (a and b) and cotton (c and d) during time durations of 10, 20, 40, 80, and 120 min; wet nicotine-ozone reaction on cellulose (e) and cotton (f); prehumidified nicotine-ozone reaction on cellulose (g); and distribution from wet ozone exposure to cellulose (h).

S2g), in support of slower reaction in the presence of water vapor. While it is possible that nicotine dissolution in water contributed to reaction site inactivation, previous studies show a higher affinity of surface cellulose sites to water than nicotine (*11*). In this case, the most accessible sorbed nicotine molecules are quickly replaced by water molecules, thereby reducing the overall reaction rate. Again, this supports nicotine surface diffusion limitations.

In addition to particle distributions, total particle count was determined for each experimental condition (Figure 2). For comparison, the total particle count is an integrated sum of all particles with $d < 100$ nm for the first 40 min of exposure. Background aerosol count was quantified by exposure of nicotine-cellulose film to nitrogen and of substrate to ozone (Discussion of ozone-substrate particle formation can be found in the Supporting Information, Figure S3 and Table S3). While statistics for most experiments could not be obtained due to limited data ($n = 2$ for each), replicate experiments were within a factor of 2 allowing qualitative comparisons. As with particle number distributions, total particle counts from dry nicotine-ozone reaction on cotton and cellulose were similar (on the order 10^8) while much lower for exposure on paper (10^6) (Figure 2a). In addition, wet exposure of nicotine to ozone resulted in the formation of SOA with total particle counts following the trend of cellulose > cotton > paper (Figure 2b). Wet conditions reduced aerosol formation on both substrates (by a factor of ~10 and ~5 on cotton and cellulose, respectively), while prehumidification of the surface reduced it even further (15 times less than wet). The difference in total particle counts between

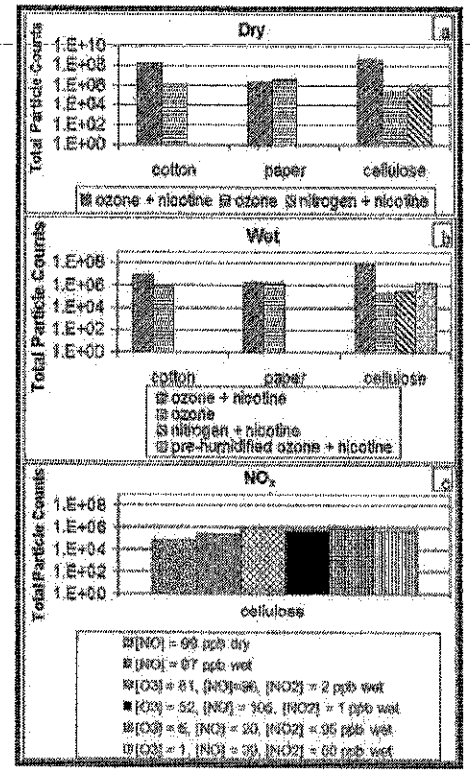

FIGURE 2. Total particle count of SOA with d < 100 nm collected during first 40 min exposure of sorbed nicotine to ozone under dry (a) and wet (b) conditions and in the presence of NO_x (c).

wet and dry reaction on cellulose was found to be statistically significant (Mann−Whitney U-test, $\alpha = 0.05$, $n = 5$).

NO_x experiments were also performed, as described in Table 1. Even though SOA formation during exposure to comparable levels of O_3 and NO (Experiment #3 of the NO_x experiments) could be visually distinguished from background (Figure S2h), total particle counts were not different than background (Figure 2c). Furthermore, all experiments performed under NO_x conditions (Figure 2c) showed a reduction in particle formation (compared to ozone alone), in agreement with previous studies (*25*−*27*). As with the present experiments, this could not be explained by ozone loss via reaction with NO_2 (*25*). The reduced SOA formation in the presence of NO_x is likely due to formation of more volatile nitrogen-containing products or an altered product distribution toward volatile products (*26*, *27*). Thus, SOA formation as a result of near-mouth chemistry for asthmatics with enhanced NO levels ($[NO]_{exhaled} \sim 10$−100 ppb (*19*)) is not likely to be greater than that of nonasthmatics.

The discussed observations and mass balance calculations demonstrated heterogeneous reaction and substrate effects. Since all substrates were chemically similar (cellulosic backbone), and substrate surface area could not explain the differences in SOA formation (Table S2), other factors must play a role. Substrate microstructure (e.g., morphology) may affect nicotine penetration and bulk-surface transfer, while water-substrate effects may 1) coat the nicotine molecules, limiting accessibility of the sorbed nicotine to ozone, or 2) reduce the amount of surface nicotine by occupation of the substrate surface sites.

Heterogeneous Kinetics. Simultaneous to monitoring SOA formation, spectral changes due to heterogeneous reaction were observed with FTIR-ATR. Nicotine loss due to desorption could be observed during all nicotine-cellulose film experiments (see Figure 3a). However, during film exposure to ozone, additional peak formation could be

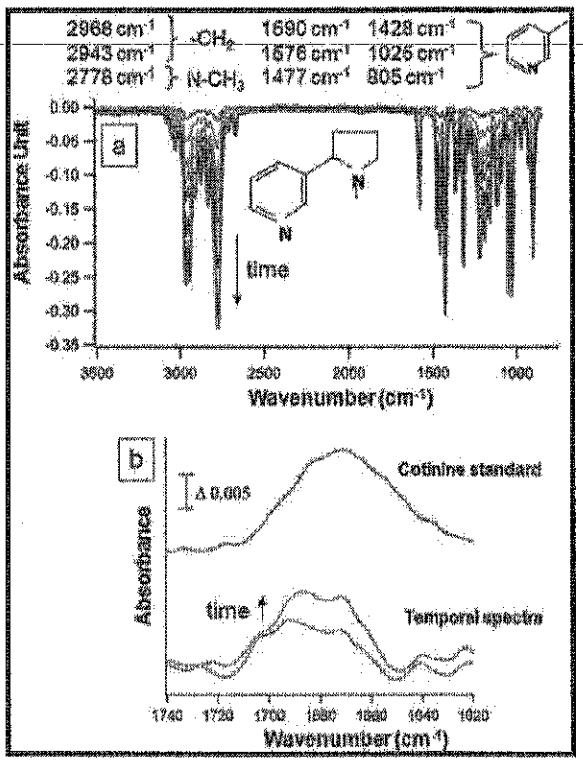

FIGURE 3. Temporal spectra showing nicotine desorption (a). Zoom of temporal spectra showing product formation and cotinine standard spectra (b).

observed at 1690 cm^{-1} similar to the carbonyl stretch of cotinine (the major surface oxidation product of nicotine-ozone reaction *10*, *11*) (Figure 3b).

Assuming that the rate of nicotine loss due to reaction is equal to rate of formation of products, the experimental data (i.e., peak area at 1690 cm^{-1}) can be fit to a negative exponential growth model (see eqs 1−2 and SI for more details). As absorbance is linearly proportional to concentration according to the Beer−Lambert law, the ratios between concentrations or absorbances will yield the same observed reaction rate constant. Thus absorbance values were used instead of concentrations, for simplicity. The pseudofirst-order rate constant (k_s) can be extracted from the initial linear fit of the data for the first 20 min (based on Taylor expansion of eq 2). Under dry conditions, k_s was calculated as $(1 \pm 0.5) \times 10^{-3}$ min^{-1} ($n = 5$), while wet conditions resulted in a k_s below 10^{-4} min^{-1} ($n = 3$) with large spectral noise. No reaction was observed under the prehumidified conditions. Although the extracted rate constants contained a large error, the results can be compared to Destaillats et al. (*10*) who reported kinetics under $[O_3] = 42$ ppb. Linear extrapolation of their data to $[O_3] = 55$ ppb showed similar results under prehumidified conditions and within the range of error under dry conditions ($5.4 \pm 0.4 \times 10^{-4}$ min^{-1}).

$$\frac{d[nic]_s}{dt} = -k[O_3]_s[nic]_s = -k_s[nic]_s \text{ where: } k_s = k[O_3] \quad (1)$$

$$[P]_t = [P]_\infty(1 - \exp(-k_1 t)) \quad (2)$$

Where: $[nic]_s$ is the surface nicotine concentration, $[O_3]_s$ is the surface ozone concentration, k is the second-order nicotine-ozone surface rate constant, k_s is the pseudofirst-order nicotine-ozone surface rate constant, and $[P]_t$ and $[P]_\infty$ are the product concentration at time t and time infinity, respectively. See SI for ozone transport considerations.

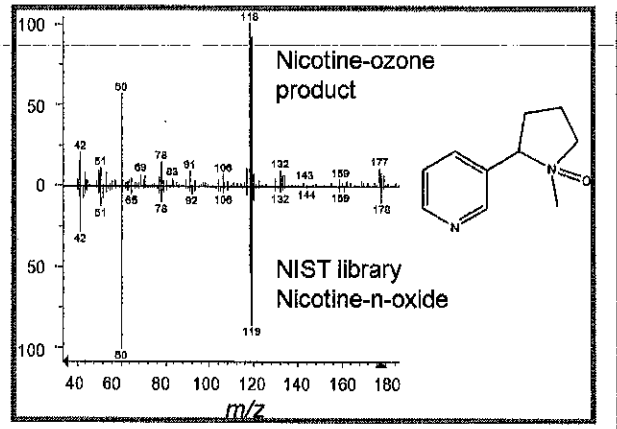

FIGURE 4. Head-to-tail comparison of NIST library nicotine-n-oxide and product MS-spectra observed following nicotine-ozone reaction under wet conditions.

In the presence of NO_x, nicotine evaporation accounted for all observed spectral changes during nicotine-cellulose film exposure, supporting limited SOA formation under these conditions.

SOA Yields. The number of particles ($d < 100$ nm) formed after 40 min of exposure served for determining SOA yield (i.e., amount of aerosol produced/amount of nicotine reacted). For this purpose, SOA was assumed to be spherical and composed solely of cotinine. Summation of all size distributions over the whole measurement time, multiplying each bin count by its corresponding particle volume, density and molecular mass, gave the total aerosol mole production. As with determining the rate constants, nicotine loss due to reaction was estimated based on cotinine formation, where quantification of cotinine on the ATR surface after 40 min of reaction was determined by comparison to an absorption calibration curve at 1690 cm^{-1}. The SOA yields from nicotine-cellulose film exposure to ozone were determined as ~2% and ~1% under dry and wet conditions, respectively. However, since oxidation products such as cotinine are hydrophilic, significant water uptake on the aerosols under humid conditions is likely, leading to overestimation in the calculated particle yield.

Surface Product Analysis. In agreement with previous observations, myosmine and cotinine were observed as major surface oxidation products under both wet and dry conditions. In addition, the formation of two unique compounds was observed during oxidation under humid conditions.

Nicotine-n-oxide was observed during wet ozonolysis (Figure 4). This suspected nicotine-ozone reaction intermediate suggests that initial electrophilic attack of ozone occurs at the amino group (*23*) (See SI). Additionally, β-nicotyrine, previously observed during nicotine-ozone (*11*) and nicotine-HONO exposure (*12*), was observed during the NO_x Experiments #3–6, suggesting that surface reactions of nicotine with NO_x (i.e., NO and NO_2) may follow some similar pathways as HONO-nicotine reactions. Myosmine, cotinine, and nicotyrine have all been previously identified in the particulate phase of environmental tobacco smoke (ETS) (*28*). This highlights the relevance of indoor surface reactions to real indoor environments.

Health Implications. It has been shown that nicotine, a major constituent of THS, participates in surface reactions with indoor oxidants, such as ozone or NO_x, resulting in the formation of SOA and surface products. Mutagenicity tests, Quantitative Structure Activity Relationships (QSAR) analysis, and exposure calculations were performed in order to gain perspective on the possible health implications.

In accordance with the observed formation of nitrosamines from HONO-nicotine surface reactions (*12*), Ames-assay mutagenicity tests (*29*) were performed on surface products from ozone-NO_x-nicotine reactions. The tests were performed using the *Salmonella typhimurium* bacterial tester strains YG1024, TA98, TA100, and TA1535, in the absence of S9 (mammalian liver metabolizing system). While pro-mutagenic activity (presence of S9) has been observed for environmental tobacco smoke (*30*), no statistically significant direct mutagenicity effect was observed for all strains under the experimental conditions and concentrations employed here. Details of the test are provided in the Supporting Information.

In addition to mutagenicity, oral and developmental toxicity of nicotine and its oxidation products was investigated. While nicotine, cotinine, and myosmine are suspected to be harmful, nicotine was shown to reduce white blood cell activity in humans (*6*), cotinine has shown potential mutagenicity and teratogenicity (*31*), and myosmine has recently been confirmed with mutagenic effects (*32*); very little quantitative health data are available regarding them. Thus, toxicity comparisons of these compounds were performed using QSAR and Toxicity Estimation Software Tool (T.E.S.T.) (*33*) in order to predict measures of toxicity from physical characteristics of the compound structures (see the SI for additional details). While oxidation products showed less toxicity than nicotine according to predicted LD_{50}, the predicted "Development Toxicities" indicated that both nicotine and cotinine compounds were developmental toxicants at similar levels (while myosmine and β-nicotyrine were predicted as developmental NON-toxicants). Additionally, asthma hazard indexes of nicotine and its oxidation products show byproducts that are more likely to cause or exacerbate asthma than nicotine itself (*16*). Therefore, products of nicotine-ozone reaction are likely to pose health concerns.

In addition to the chemical composition as discussed above, toxicological effects of SOA are impacted by parameters such as surface area, particle diameter, and solubility. The SOA observed under the current ozone-nicotine reactions had $d < 45$ nm and hydrophilic properties (consistent with compounds containing carbonyl and amine functionalities). This small particle size introduces a higher surface to volume ratio for greater biological interaction, potential pro-inflammatory effects, higher particle deposition probability in the deeper respiratory regions, and easier translocation within the body (*17, 34–36*).

As has been shown, THS can lead to exposure of potentially harmful compounds. The high sorption capacity of nicotine to household furnishings and clothing make these surfaces a potentially dominant source for exposures (*8, 11*). In addition to desorption and dermal contact, the sorbed nicotine may participate in heterogeneous ozone reactions resulting in the formation of SOA and gas and condensed phase products. Furthermore, cumulative exposures to these airborne species may be greater for an infant than an adult when both breathing rate and body weight are considered. A hypothetic scenario modeling such personal exposures is provided in the SI.

In addition to inhalation exposure, dermal and hand-to-mouth exposures should also be considered. While the half-life of sorbed nicotine is approximately 11.5 h at $[O_3]$ = 55 ppb, unpublished studies of cotinine oxidation estimate a half-life of 5 d at the same ozone concentration. Thus, personal exposures may continue to occur on the order of hours to days.

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Supporting Information Available

Scheme of experimental set up, time-resolved figure of SOA formation under various experimental conditions, list of reactions used to determine NO_x concentrations, nicotine-substrate characterization, SOA formation from substrates, detailed derivatization of pseudofirst-order kinetics, proposed reaction mechanism, detailed description of mutagenicity tests, and exposure model describing hypothetical smoking scenario. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Formation of carcinogens indoors by surface-mediated reactions of nicotine with nitrous acid, leading to potential *thirdhand smoke* hazards

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This study shows that residual nicotine from tobacco smoke sorbed to indoor surfaces reacts with ambient nitrous acid (HONO) to form carcinogenic tobacco-specific nitrosamines (TSNAs). Substantial levels of TSNAs were measured on surfaces inside a smoker's vehicle. Laboratory experiments using cellulose as a model indoor material yielded a >10-fold increase of surface-bound TSNAs when sorbed secondhand smoke was exposed to 60 ppbv HONO for 3 hours. In both cases we identified 1-(*N*-methyl-*N*-nitrosamino)-1-(3-pyridinyl)-4-butanal, a TSNA absent in freshly emitted tobacco smoke, as the major product. The potent carcinogens 4-(methylnitrosamino)-1-(3-pyridinyl)-1-butanone and *N*-nitroso nornicotine were also detected. Time-course measurements revealed fast TSNA formation, with up to 0.4% conversion of nicotine. Given the rapid sorption and persistence of high levels of nicotine on indoor surfaces—including clothing and human skin—this recently identified process represents an unappreciated health hazard through dermal exposure, dust inhalation, and ingestion. These findings raise concerns about exposures to the tobacco smoke residue that has been recently dubbed "thirdhand smoke." Our work highlights the importance of reactions at indoor interfaces, particularly those involving amines and NO_x/HONO cycling, with potential health impacts.

exposure | indoor environment | nitrosamine | nitrogen oxides | heterogeneous chemistry

Tobacco use causes 20% of cancer deaths worldwide. The International Agency for Research on Cancer predicts 10 million tobacco-related deaths annually by 2020, of which 70% will occur in the developing world (1). Over the past decade, the United States (US) and other countries have successfully reduced the exposure of nonsmokers to *secondhand smoke* (SHS, smoke inhaled unintentionally) in public spaces and the workplace. Nevertheless, the US Surgeon General 2006 report warned that progress has been slower in the protection of young children, for whom the most important exposure setting is the home (2). Whereas direct inhalation of SHS is an exposure pathway of concern, nonsmokers, especially infants, are at risk through contact with surfaces and dust contaminated with residual smoke gases and particles (3). This type of lingering residue of tobacco smoke has recently been called *thirdhand smoke* (THS) (4). Whereas desorption from indoor surfaces to air has been recognized for some time as a source of subsequent exposure (5–7), the potential for chemical transformation has been examined only recently (8). Reactions of atmospheric species [O_3, nitrous acid (HONO), NO_x] with residual smoke on surfaces (furniture, walls, skin, clothing) have been overlooked as a source of long-term exposure to harmful pollutants.

This study is an exploration of the in situ reaction of nicotine sorbed to indoor surfaces with HONO to form tobacco-specific nitrosamines (TSNAs). These chemicals are among the most broadly acting and potent carcinogens present in unburned tobacco and tobacco smoke (9, 10). Nicotine, their precursor, is the most abundant organic compound emitted during smoking (up to 8 mg per cigarette). It deposits almost entirely on indoor surfaces and persists for weeks to months (6, 7). HONO is often present in indoor environments at higher levels than outdoors. Typical indoor levels are 5–15 ppbv, with [HONO]/[NO_2] ratios ~0.15 to 0.4 (vs. ~0.03 outdoors). Indoor levels up to 100 ppbv have been reported (11–13). The main indoor sources of HONO are direct emissions from unvented combustion appliances (14, 15), smoking (16), and surface conversion of NO_2 and NO (17–22). Heterogeneous formation of HONO also occurs inside automobiles, leading to [HONO] up to 30 ppbv and [HONO]/[NO_2] ~ 0.4 in polluted urban areas (23). Pitts et al. (24) first described the atmospheric production of *N*-nitrosamines by reactions of nitrogen oxides and HONO with amines. *N*-nitrosamines were found to be unstable in sunlight, rendering the reaction unimportant in outdoor daytime conditions. However, this process can be relevant indoors where *N*-nitrosamines and HONO are less vulnerable to photochemical decomposition.

Results and Discussion

Indoor Nitrosation of Nicotine. Three main TSNAs are formed in the reaction of sorbed nicotine and gaseous HONO: 1-(*N*-methyl-*N*-nitrosamino)-1-(3-pyridinyl)-4-butanal) (NNA), 4-(methylnitrosamino)-1-(3-pyridinyl)-1-butanone (NNK), and *N*-nitroso nornicotine (NNN). In field measurements, we detected TSNAs on interior surfaces of a truck driven by a heavy smoker. Fig. 1*A* shows the concentrations of surface-bound TSNAs on the stainless-steel glove compartment (Truck-A) and on cellulose substrates attached next to it (Truck-B), for 3 days in which smoking occurred in the vehicle. In both samples, two TSNAs, NNA and NNK, were detected at appreciable levels (1–5 ng cm^{-2}).

Whereas NNK is known to be present in tobacco smoke particles, NNA has not been reported previously, probably because of its reactivity and instability at high temperatures during tobacco pyrolysis (9). A mechanism to explain the in situ formation of surface-bound TSNAs measured in this study is proposed below. The predominance of NNA is consistent with results by Hecht et al. (25), who showed that NNA was the main product of nicotine nitrosation in acidic $NaNO_2$ solution (pH 5.4–5.9). We hypothesize that similar processes occur on indoor surfaces exposed to ambient HONO.

Author contributions: M.S., L.A.G., J.F.P., P.J., B.C.S., and H.D. designed research; M.S., L.A.G., and H.D. performed research; P.J. contributed new reagents/analytic tools; M.S., L.A.G., J.F.P., P.J., B.C.S., and H.D. analyzed data; and M.S., L.A.G., J.F.P., P.J., B.C.S., and H.D. wrote the paper.

The authors declare no conflict of interest.

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Laboratory experiments using cellulose as a model surface were carried out to test this hypothesis. Cellulose substrates were exposed to vaporized nicotine in a tubular-flow reactor, obtaining a loading of 9.1 $\mu g\,cm^{-2}$, before equilibration with HONO (65 ppbv). The resulting production of surface-bound NNA and NNK (with [NNA]/[NNK] = 7) confirms that both TSNAs derive from nicotine (sample Nic, Fig. 1*A*). NNN was detected at levels too low for accurate quantification. Similar results were found when cellulose substrates containing sorbed tobacco smoke (sorbed SHS) were exposed to HONO for 3 hours. In the resulting sample (THS), TSNA surface concentrations increased at least 10-fold. Furthermore, in all samples exposed to HONO (THS, Nic, Truck-A, Truck-B), the steady-state ratio of total TSNA concentrations to surface nicotine expressed in mass units

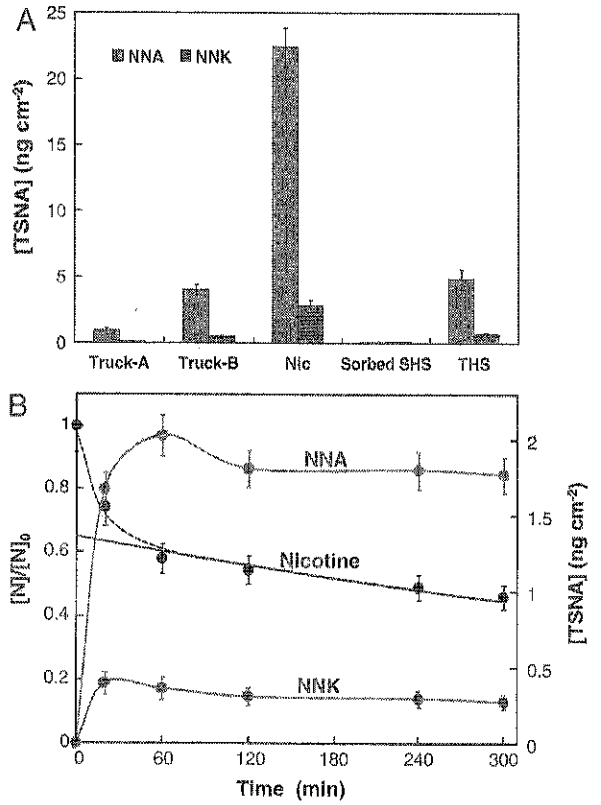


Fig. 1. Formation of TSNAs from nitrosation of nicotine. (*A*) Surface concentrations of NNA and NNK. In field experiments, sample Truck-A was obtained inside the cabin of a smoker's truck by wiping the stainless-steel surface of the door of the glove compartment, on which 0.6 $\mu g\,cm^{-2}$ of nicotine was present. Another sample (Truck-B) was collected on clean cellulose substrates that were attached to cabin surfaces for 3 days, over which 34 cigarettes were smoked. The cellulose surface sorbed nicotine passively (1.4 $\mu g\,cm^{-2}$) and also served as reaction medium for the formation of TSNAs. In lab experiments, cellulose substrates were exposed to nicotine vapor (9.1 $\mu g\,cm^{-2}$) and subsequently exposed to HONO (Nic). The same substrates were exposed to sidestream smoke in an environmental chamber, leading to loadings of 1.9 $\mu g\,cm^{-2}$ nicotine, with negligible levels of NNA and NNK (Sorbed SHS). After a 3-hour exposure of this sample to HONO, formation of NNA and NNK on the surface was observed (THS). (*B*) Time course of nicotine loss and production of NNA and NNK. Cellulose substrates were impregnated with nicotine with an initial surface concentration $[N]_0$ of 1.45 $\mu g\,cm^{-2}$ and subsequently exposed to $[HONO]_0 = 95$ ppbv in a tubular-flow reactor over different periods of time (relative humidity 45%). A biexponential model was fitted to the nicotine surface concentration profile to derive the contributions of desorption and chemical reaction processes. [TSNA] corresponds to the surface concentrations of NNA and NNK, and [N] represents the surface concentration of nicotine. Concentrations were determined by using the exposed geometric areas.

was about 1:250 (equivalent to 1:320 in mole units), corresponding to nicotine conversions of $\chi_{NNA} = [NNA]/[N] = 3.5 \times 10^{-3}$ and $\chi_{NNK} = [NNK]/[N] = 0.5 \times 10^{-3}$ (for concentrations expressed in mass units). In a separate experiment, a cellulose substrate loaded with similar nicotine levels was exposed to high levels of NO and NO_2 (290 and 560 ppbv, respectively), in the absence of gas-phase HONO. We observed formation of only trace amounts of NNA and NNK (close to the limit of detection) together with a slight decrease in NO_2 concentration, on the order of ~5 ppbv. These results are consistent with surface-mediated conversion to HONO and subsequent nitrosation of nicotine.

Fig. 1*B* shows time-concentration profiles for surface nicotine and TSNAs in laboratory experiments. Both NNA and NNK formed rapidly, reaching maximum concentrations within the first hour. Formation rates of TSNAs were $R_{NNA} = \partial[NNA]/\partial t = (8.4 \pm 0.6)10^{-2}$ ng cm^{-2} min^{-1} $(0.24 \pm 0.02\ \mu mol\,m^{-2}\,h^{-1})$ and $R_{NNK} = \partial[NNK]/\partial t = (2.0 \pm 0.4)10^{-2}$ ng cm^{-2} min^{-1} $(0.06 \pm 0.01\ \mu mol\,m^{-2}\,h^{-1})$, respectively, estimated from the initial slope ($t < 20$ min) in Fig. 1*B*, assuming that the initial decomposition rate was negligible. The shapes of the NNA and NNK curves suggest that freshly formed TSNAs are protected from attack by HONO by chemical and/or physical processes (e.g., diffusion into the cellulosic media). A biexponential model was fitted to the surface nicotine concentration profile to estimate contributions from chemical reaction and desorption. The fitted rate constant for nicotine reaction of $k_N = 1.25 \times 10^{-3}$ min^{-1} corresponds to nicotine reactive loss rates in the range $R_N = -\partial[N]_S/\partial t = 1.5 - 1.1$ ng cm^{-2} min^{-1} $(5.5 - 4.1\ \mu mol\,m^{-2}\,h^{-1})$. The nicotine reaction rate was almost identical to the HONO reactive uptake rate ($R_{HONO} = 5.5\ \mu mol\,m^{-2}\,h^{-1}$; see *SI Text*), corresponding to a HONO mass transfer coefficient of 2.1 $m\,h^{-1}$. This value is the same order of magnitude as the boundary-layer mass transfer coefficient in buildings (26, 27), suggesting that reaction with nicotine may be a strong sink for HONO indoors.

Assuming first-order reaction kinetics, the relative yield (ϕ_{TSNA}) of TSNAs can be estimated from initial reaction rates as

$$\phi_{TSNA} = \frac{R_{NNA} + R_{NNK}}{R_N} * 100. \qquad [1]$$

TSNA yields were $\phi_{TSNA} = 6.7$–9.1% by mass (5.4–7.3% by mole). These relatively high yields call attention to the importance of this reaction as a source of tobacco carcinogens on indoor surfaces.

Additional tests were carried out to assess the stability of TSNAs in the presence of HONO. Cellulose substrates were spiked with TSNAs dissolved in water-methanol (95/5) and were subsequently exposed to HONO (60 ppbv) under the same conditions as reported above. Slightly more than 50% of the initial NNA was lost in 2 hours, but NNN and NNK were more stable, with just 20–30% loss over the same period. These findings are in agreement with results shown in Fig. 1*B* and suggest that after their fast initial formation TSNAs undergo partial degradation by HONO, to reach steady-state concentrations.

Reaction Mechanism and Products. Fig. 2*A* presents a schematic representation of the main physical-chemical processes involved in the surface-mediated nitrosation of nicotine. In Fig. 2*B*, we propose a mechanism for heterogeneous TSNA formation consistent with the products observed in our experiments. The main reactive species is assumed to be NO^+, which removes one electron from the pyrrolidine nitrogen of nicotine to form an unstable cation intermediate. A second NO^+ abstracts a hydrogen atom from one of the three α-carbon atoms (a, b, and c) yielding an iminium ion. Successive reaction of iminium with water and HONO generates the corresponding TSNA. The prevalence of NNA can be

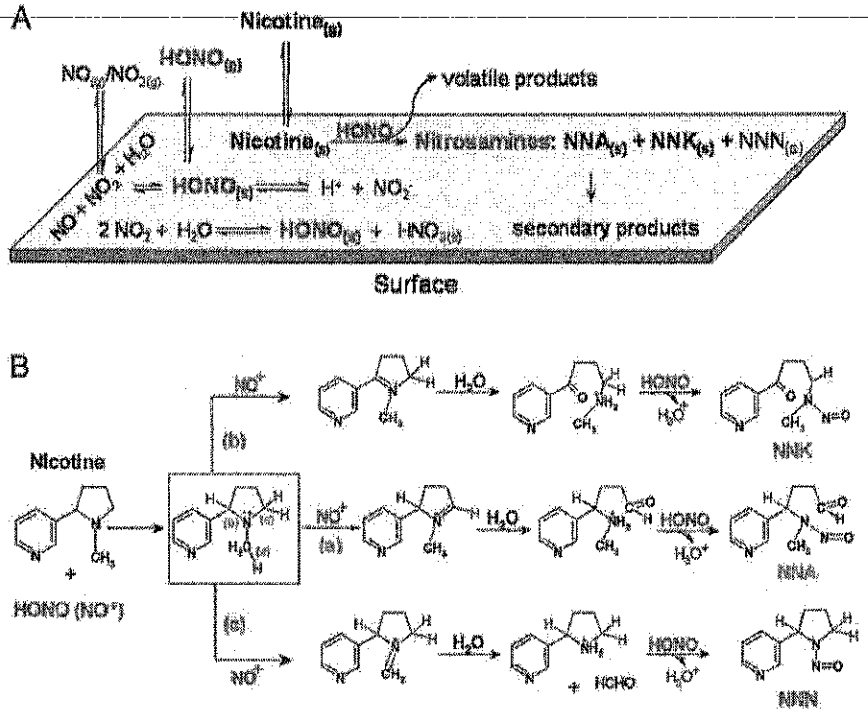


Fig. 2. Physical-chemical processes involved in the formation of TSNAs. (*A*) Illustration of surface-mediated nitrosation of nicotine. $HONO_{(s)}$ can be formed through three pathways: (*i*) direct adsorption of $HONO_{(g)}$, (*ii*) heterogeneous disproportionation of NO_2, and (*iii*) surface-catalyzed reaction between NO and NO_2. $HONO_{(s)}$ reacts with nicotine generating NNA and NNK. NNN was also produced with lower yields. Secondary products are listed in Table 1. (*B*) Proposed mechanism for the formation of TSNAs. The first step involves the electrophilic attack of NO^+ on nicotine, leading to the formation of the unstable cationic intermediate shown in the box. The second step is initiated with abstraction of a hydrogen atom to form an iminium cation, which is then hydrolyzed by sorbed water molecules. Finally, HONO nitrosates the secondary amines to form NNA, NNK, and NNN.

attributed to a regioselective abstraction of a 5′ hydrogen atom (position a), in analogy to chemical and biological oxidation of nicotine, in which that position is most susceptible to attack by electrophilic species (28). An alternative mechanism, similar to that proposed by Hecht et al. (25) is presented in *SI Text* and leads to identical products. The acidity of the aqueous surface layer [pH ~5–6 in the absence of HONO (29)] plays a key role by inducing the formation of NO^+ and affecting regioselectivity. In addition to TSNAs, we observed the formation of secondary products in the gas phase and on surfaces, as summarized in Table 1. These included TSNA degradation products such as *N*-nitrosopyrrolidine (*2*, a carcinogenic volatile nitrosamine), a surface-bound product formed through *C*-nitrosation of NNK (*5*), and a stable pyrazole compound (*7*), resulting from NNA decomposition. For the latter, we describe two possible reaction pathways for its formation from NNA in *SI Text* (25, 30). The pyrazole (*7*) was formed with a higher yield than the total TSNAs, and it has not been reported in freshly emitted SHS. Therefore, it could be used as a tracer for the THS products formed by HONO-nicotine chemistry.

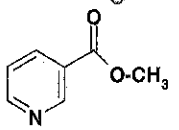
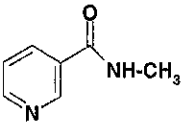
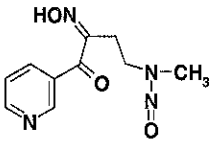
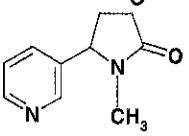
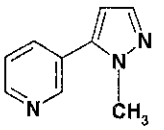
Implications for Indoor Exposures. The in situ formation of TSNAs presents a specific concern about the hazards of THS. NNK is a strong carcinogen, with reported cancer potency of 49 $kg\,mg^{-1}\,d^{-1}$ (10). It has been shown to induce mutations, DNA strand breaks, and oxidative damage under sunlight, in the absence of metabolic activation (31). NNA carcinogenicity has not been reported, but its mutagenic activity is similar to that of NNN (32). Our findings warrant further investigation of the NNA toxicity and human intake. Monitoring of its likely metabolite 4-(methylnitrosamino)-4-(3-pyridyl)-1-butanol (iso-NNAL) could be used to assess nonsmokers' intake of NNA, by analogy to the current use as a biomarker of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (NNAL), formed by metabolic reduction of NNK (33). The precursor to iso-NNAL, NNA, has not been identified in tobacco (34, 35).

There are several potentially important exposure routes through which surface-formed TSNAs may enter the body. Direct inhalation of gas-phase TSNAs is likely negligible, given their very low vapor pressures [in pressure units of mm Hg, $\mathrm{Log}_{10}P^0_{\mathrm{NNA}} = -6.67$ and $\mathrm{Log}_{10}P^0_{\mathrm{NNK}} = -6.72$ (36)]. Instead, dermal contact with surfaces contaminated by TSNAs (skin, clothing, and furnishings), as well as inhalation and ingestion of TSNA-loaded dust, are likely the main exposure pathways. On the basis of the framework developed by Weschler and Nazaroff (37) to assess indoor exposures to semivolatile organic compounds, we estimated the surface loading of nicotine (M_N) as

$$M_N = K_{\mathrm{oa}}\delta[\mathrm{N}]_g S_H, \qquad [2]$$

where K_{oa} is the octanol-air partition coefficient of nicotine ($\log K_{\mathrm{oa}} = 7.8$) (7), δ is the thickness of an organic film on the skin surface (using 10 nm as a conservative estimate), $[\mathrm{N}]_g$ is the gas-phase concentration of nicotine, and S_H is the exposed surface of the human skin [calculated as 20% of the total estimated human envelope surface, 2 m^2 (37)]. We predict nicotine levels on human skin to be 0.63–63 $\mu g\,m^{-2}$ ($M_N = 0.25$–25 μg), in equilibrium with gas-phase nicotine concentrations between 1 and 100 $\mu g\,m^{-3}$, corresponding to typical and high levels reported in homes and public places where smoking takes place, respectively (2). This is consistent with reported levels >80 $\mu g\,m^{-2}$ on the index fingers of smokers (an extreme-case scenario for skin levels) (3). In the presence of HONO, skin-bound nicotine could react to produce TSNAs at the concentrations shown in Table 2. Nicotine surface concentrations ranging from 5 to 100 $\mu g\,m^{-2}$ have been measured in dust, on surfaces inside vehicles

Table 1. Secondary products of nicotine heterogeneous nitrosation by HONO.

	Product no.	Product name	Product structure	*m/z*	Yield %*
Gas-phase products	1	Formaldehyde		N/A†	<0.05
	2	*N*-nitroso-pyrrolidine		100, 70, 68	<0.05
	3	Methyl 3-pyridinecarboxylate (Methyl nicotinate)		137, 106, 78	<0.05
	4	N-methylnicotinamide		136, 106, 78	0.1
Cellulose-sorbed species	5	4-(N-methyl-N-nitrosamino)-2-oxi-mino-1-(3-pyridyl)-1-butanone		219, 106, 130, 165, 78	<0.05
	6	1-methyl-5-pyridin-3-yl-pyrrolidin-2-one (Cotinine)		176, 118, 98	0.3
	7	1-methyl-5-(3 pyridinyl) pyrazole		159, 158, 130, 118, 104, 78	0.8

*Yields were determined on the basis of the ratio of peak areas of each product over nicotine.
†Formaldehyde was determined by dinitrophenylhydrazine derivatization and HPLC analysis with UV detection.

(dashboards) (38), and in households of smokers (tables and bed frames) (3) (Table 2). Cotton, a material commonly used in clothing, upholstery, and draperies, sorbs substantial amounts of nicotine, up to 100 mg m^{-2}, with ~1 mg m^{-2} remaining after one week of desorption in a clean air flow (8). The levels of TSNAs formed in each of those surfaces under typical HONO levels, also presented in Table 2, were estimated as [NNA] = [N] $*\chi_{NNA}$ and [NNK] = [N] $*\chi_{NNK}$. TSNA-laden particles abraded from clothes and skin may enter the breathing zone as part of the personal reactive cloud, thus contributing to additional intake through inhalation (39–41).

Given the low volatility of TSNAs and the high levels of nicotine typically found in environments contaminated with tobacco smoke, these carcinogens can persist indoors (42) and on the human envelope. Because of their frequent contact with surfaces and dust, infants and children are particularly at risk. At approximately 0.05–0.25 g day^{-1}, the dust ingestion rate in infants is estimated to be more than twice that of adults (3). Moreover, considering that infants have a higher respiration rate (by a factor of 3–8) and a lower body weight than adults (by a factor of 10–20), low doses of TSNAs such as those reported in Table 2 may represent a potential long-term health hazard.

Various mitigation and remediation approaches can be considered to limit the impact of these carcinogenic pollutants indoors. Implementation of 100% smoke-free environments in public places and self-restrictions in residences and automobiles are the most effective tobacco control measures, through elimination of the primary pollution source. In buildings where substantial smoking has occurred, replacing nicotine-laden furnishings, carpets, and wallboard can significantly reduce exposures to THS hazards. More research is needed on the identification and characterization of specific biomarkers to assess human intake of NNA and other THS pollutants and to better understand their health implications. Research is also needed to explore other reactions of atmospheric species at indoor interfaces that may impact human health (43).

Materials and Methods

Tubular-Flow Reactor, Ancillary Laboratory Setup, and Methodology. Laboratory experiments were performed by using a glass tubular-flow reactor (length: 33 cm; diameter: 1 cm; flow rate: 0.5 L min^{-1}). Upstream, "zero" grade air was humidified to 45% relative humidity by passage through an impinger before entering the reactor containing two identical cellulose substrates (23 cm × 1 cm × 3 mm, Whatman 3030-153). HONO was generated continuously, by following the method described by Taira and Kanda (44). Two syringe pumps delivered H_2SO_4 (0.022 M) and $NaNO_2$ (0.001 M) into a Teflon reaction vessel, where the evolved HONO vapor was entrained in the air flow to the reactor. Downstream of the reactor, the flow could be split into three streams to determine (a) HONO/NO/NO_2 by using a NO_x analyzer, (*b*) HONO by ion chromatography, and (c) volatile products. *SI Text* illustrates the experimental setup.

Adsorption of nicotine on cellulose substrates. Nicotine vapor was generated upstream of the reactor by circulating a dry air stream over

Table 2. Nicotine and TSNA concentrations on households, vehicle surfaces, and human skin. Calculations were based on the nicotine conversions to NNA (0.35%) and NNK (0.05%), expressed in mass units

Surface		[N] ($\mu g\ m^{-2}$)	[NNA] ($ng\ m^{-2}$)	[NNK] ($ng\ m^{-2}$)
Households	Furniture*	11–73	37–256	5.3–36.5
	Dust*	0.89–4.43	3–15	0.44–2.2
Vehicles	Dashboard*	5.0–8.6	17–30	2.5–4.3
	Dust*	11.6–19.5	41–68	6.1–9.7
Skin and clothing	Skin*	>80	>280	>40
	Skin†	0.63–63	2.2–220	0.31–31
	Cotton‡	1000	3500	500

*Values estimated from Matt et al. (3).
†Estimates based on Weschler and Nazaroff (37).
‡Determined based on Destaillats et al. (8).

a beaker containing liquid nicotine (>99%; Aldrich) placed in a sealed vessel at 23 °C. The nicotine vapor supply concentration was 153 ± 17 nmol L^{-1} (8). The nicotine-containing air stream was mixed with humid air to reach relative humidity of 45% and directed to the reactor during the initial adsorption phase of each experiment (10 min to 2 hours). At the end of this period, one substrate was removed to determine the initial nicotine loading, and the nicotine source was disconnected prior to introduction of HONO (or NO/NO_2).

Reaction of nicotine with HONO and with a NO/NO_2 mixture. Once nicotine adsorption was completed, HONO was introduced into the reactor. In a few experiments we evaluated the reaction of nicotine with nitrogen oxides (*in lieu* of HONO) by directly introducing a diluted mixture of NO and NO_2 (290 and 560 ppb, respectively) into the reactor airstream from a Tedlar bag.

Monitoring of HONO, NO, and NO_2. The concentration of HONO was measured in real time downstream of the reactor by using a NO_x analyzer (API Model 200 E; TELEDYNE instruments). Gas-phase HONO concentrations were recorded as NO_2 concentration. The absence of NO_2 in the system was verified by scrubbing HONO with a $CaCO_3$-impregnated quartz filter upstream of the NO_x monitor. HONO was also trapped in an impinger filled with a NaOH aqueous solution (pH 10, volume = 5 mL) and analyzed by ion chromatography (Dionex ICS-2000). When NO and NO_2 were injected, their concentrations were followed by using the NO_x analyzer.

Analysis of gas-phase species. Nicotine and volatile products formed during its reaction with HONO were collected by using (*i*) an impinger filled with methanol (5 mL) in an ice bath, analyzed by gas chromatography–ion trap–tandem mass spectrometry (GC-IT-MS/MS); (*ii*) dual sorbent glass tubes containing Tenax-TA and Carbosieve SIII, followed by analysis on an Agilent 6890 GC equipped with an automated thermal desorption inlet with autosampler (Gerstel 3A) and an Agilent 5973 mass selective detector operated in electron impact mode, under operational parameters reported previously (8); and (*iii*) dinitrophenylhydrazine-coated silica cartridges (Waters Sep-Pak Xposure, WAT047205) to collect volatile aldehydes, followed by extraction using acetonitrile (2 mL) and HPLC-UV analysis (Agilent 1200 series).

Surface products extraction and analysis. Nicotine and its reaction products were extracted from cellulose surfaces with methanol. Each cellulose substrate was cut into two halves and weighed. Each half was transferred to a 40-mL amber flask, where 5 mL of methanol spiked with quinoline (internal standard) were added. Next, the flasks were stirred for 25 min and slurries centrifuged for 20 min at 10,000 rpm to separate the supernatant from suspended paper particles. A 1-mL aliquot was transferred to an amber vial for GC-IT-MS/MS analysis, whereas the remaining supernatant was archived. Recoveries of nicotine, NNA, and NNK ranged from 90 to 115%. The same procedure was followed for extraction of the passively exposed cellulose samplers and wipe samples collected in field measurements.

Preparation of SHS-Coated Cellulose Samples and SHS Characterization. SHS-coated cellulose substrates were collected in an Lawrence Berkeley National Laboratory (LBNL) room-sized 18-m^3 environmental chamber with low background concentrations of airborne contaminants. SHS was generated in the chamber by using a smoking machine (ADL/II smoking system; Arthur D. Little, Inc.). Nine cigarettes of a major US brand were smoked at equal intervals over a 3-hour period. The main experimental conditions for the chamber test are summarized in *SI Text*. Three different types of samples were collected.

Sorbed SHS (passive sampling). Passive samples were collected on cellulose substrates placed on a horizontal surface, to simulate deposition of SHS pollutants on indoor surfaces. Rectangular cellulose strips (Whatman cat. no. 3030-153, 23 cm × 1 cm × 3 mm) were placed on a table covered with aluminum foil at a distance of ~1 m from the smoking machine.

Particle-bound TSNAs (active sampling). Active sampling of airborne SHS particles was carried out continuously during the 3-hour period by using two Teflon-coated glass filters (Pall TCGF, 90 mm diameter) in series, at 100 L min^{-1}. The filters were preceded by a cyclone (URG Corporation) to remove any particles larger than 2.5 μm diameter. After collection, the TCGF filters were individually wrapped in clean aluminum foil envelopes, placed in clean plastic containers, and stored in the freezer at −30 °C prior to extraction and analysis.

Gas-phase nicotine. Gas-phase nicotine was actively sampled by using Tenax-TA sorbent glass tubes. Tenax tubes were analyzed as described previously (8), by using an HP 5890 GC equipped with an ATD400 thermal desorption inlet (Perkin Elmer) and a nitrogen and phosphorous-sensitive detector (DET Engineering).

Field Sampling. Two samples were collected inside the passenger compartment of an old (1966) light duty pickup truck in which the driver routinely smoked while commuting. Sample Truck-A, representing the background loading of nicotine and TSNAs, was collected by wiping an area (12 cm × 15 cm) on the outside of the metal door of the glove compartment with clean laboratory tissue that had been wetted with 5 mL spectroscopic grade ethanol. The tissue was transferred to a clean glass vial for storage in a freezer (−30 °C) prior to analysis. Sample Truck-B was collected on a cellulose substrate (identical to those used in lab experiments) with exposed area of 12 cm × 15 cm, with no direct exposure to sunlight. The cellulose substrate was secured in a frame made from clean aluminum foil and mounted over the area that had been wiped to generate sample Truck-A. The cellulose was exposed to SHS over the next 3 days during which the driver smoked 34 cigarettes inside the vehicle.

TSNA Analysis. ***GC-IT-MS/MS.*** Extracts were analyzed by GC-IT-MS/MS by using a Varian 3800 gas chromatograph (Varian Chromatography Systems) equipped with a CP8400 autosampler and ion trap mass detector Varian 2000. Methanol extracts were injected directly into the GC operating in splitless mode at 200 °C. Representative GC-IT-MS/MS chromatograms are shown in *SI Text*. Nicotine and TSNAs were separated on a 30 m VF-5 MS, low bleed column. The mass spectrometer was operated in the electron ionization mode at 70 eV in the mass range 50 to 350 *m/z*. For MS/MS, precursor ions of NNN (*m/z* 147), NNA (*m/z* 148), and NNK (*m/z* 177) were used, whereas fragment ions selected for quantification were 105, 130, and 132 for NNN, 148 for NNA, and 146, 149, and 159 for NNK. Quinoline was used as an internal standard for quantification. Additional experimental details are reported in ref. 45.

Liquid chromatography–tandem mass spectrometry. Liquid chromatography–tandem mass spectrometry analyses were carried out with an Agilent 1200 HPLC interfaced to a TSQ Quantum Ultra triple-stage quadrupole mass spectrometer (Thermo-Finnigan, San Jose, CA). An HSF5 column (4.5 × 150 mm, 5 μm, Supelco) was used for LC separation. The internal standards (NNN-d_4 and NNK-d_4, 10 μL of 1 μg mL^{-1}) and 0.5 mL of 1 M H_2SO_4 were added to 100-μL aliquots of the methanol extracts. The solutions were washed with 4 mL of 1:2 (vol/vol) toluene/ethyl acetate. The aqueous phases were made basic with 0.5 mL of 50% aqueous potassium carbonate and then extracted with 4 mL of 1:2 toluene/ethyl acetate. The extracts were evaporated by using a centrifugal vacuum evaporator, reconstituted in 150 μL of 10% methanol in 12 mM aqueous HCl, and chromatographed with a methanol and water solvent system containing 10 mM ammonium formate at 0.9 mL/min by using a linear gradient from 25% to 100% methanolic buffer. Atmospheric pressure chemical ionization was used. The mass spectrometer was operated in the selected reaction monitoring mode. The transitions 178 to 148 and 182 to 152 at a collision energy of 8 eV were used for NNN and the internal standard, NNN-d_4, respectively. The transitions 208 to 122 and 212 to

126 at a collision energy of 12 eV were used for NNK and the internal standard, NNK-d_4, respectively.

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Beliefs About the Health Effects of "Thirdhand" Smoke and Home Smoking Bans

Jonathan P. Winickoff, Joan Friebely, Susanne E. Tanski, Cheryl Sherrod, Georg E. Matt, Melbourne F. Hovell and Robert C. McMillen

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ARTICLE

Beliefs About the Health Effects of "Thirdhand" Smoke and Home Smoking Bans

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What's Known on This Subject

There is no safe level of exposure to tobacco smoke. Thirdhand smoke is residual tobacco smoke contamination that remains after the cigarette is extinguished. Children are uniquely susceptible to thirdhand smoke exposure.

What This Study Adds

No studies have explored whether beliefs toward thirdhand smoke are associated with behaviors that affect the health of children, such as setting rules/smoking policies in the home.

ABSTRACT

OBJECTIVE. There is no safe level of exposure to tobacco smoke. Thirdhand smoke is residual tobacco smoke contamination that remains after the cigarette is extinguished. Children are uniquely susceptible to thirdhand smoke exposure. The objective of this study was to assess health beliefs of adults regarding thirdhand smoke exposure of children and whether smokers and nonsmokers differ in those beliefs. We hypothesized that beliefs about thirdhand smoke would be associated with household smoking bans.

METHODS. Data were collected by a national random-digit-dial telephone survey from September to November 2005. The sample was weighted by race and gender within Census region on the basis of US Census data. The study questions assessed the level of agreement with statements that breathing air in a room today where people smoked yesterday can harm the health of children.

RESULTS. Of 2000 eligible respondents contacted, 1510 (87%) completed surveys, 1478 (97.9%) answered all questions pertinent to this analysis, and 273 (18.9%) were smokers. Overall, 95.4% of nonsmokers versus 84.1% of smokers agreed that secondhand smoke harms the health of children, and 65.2% of nonsmokers versus 43.3% of smokers agreed that thirdhand smoke harms children. Strict rules prohibiting smoking in the home were more prevalent among nonsmokers: 88.4% vs 26.7%. In multivariate logistic regression, after controlling for certain variables, belief that thirdhand smoke harms the health of children remained independently associated with rules prohibiting smoking in the home. Belief that secondhand smoke harms the health of children was not independently associated with rules prohibiting smoking in the home and car.

CONCLUSIONS. This study demonstrates that beliefs about the health effects of thirdhand smoke are independently associated with home smoking bans. Emphasizing that thirdhand smoke harms the health of children may be an important element in encouraging home smoking bans. *Pediatrics* 2009;123:e74–e79

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Key Words

smoking, tobacco, pediatrics, family practice, parents, smoking cessation, secondhand smoke, environmental tobacco smoke, tobacco control

Abbreviations

SHS—secondhand smoke
BCS-TCS—Behavioral Risk Factor Surveillance System Tobacco Control Supplement
aOR—adjusted odds ratio
CI—confidence interval

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THE 2006 SURGEON General's report on involuntary smoking concluded that more than 126 million people are exposed to secondhand smoke (SHS), 50 000 deaths per year are caused by SHS, and there is no "safe" level of exposure.[1] An increasing number of states have created laws on smoking to protect employees in restaurants, bars, and workplaces, but the home remains a place of intense and consistent exposure for nonsmoking children and adults.[2] The home is the predominant location for exposure of children and adults to tobacco smoke.[1]

The majority of adults are aware that visible SHS is harmful to health, and some smokers take measures to protect nonsmokers from this widely recognized harm.[3] These measures of highly variable efficacy, include opening windows, smoking in other rooms, turning on fans, or simply waiting until the smoke dissipates to mitigate the harmful effects of their smoking on others. Research has documented the association between smoking in the home

and persistently high levels of tobacco toxins well beyond the period of active smoking.[1,4–6] These toxins take the form of particulate matter deposited in a layer onto every surface within the home: in loose household dust; and as volatile toxic compounds that "off gas" into the air over days, weeks, and months.[6,7] Smoking indoors on 1 day thus exposes people to tobacco toxins within that space in the future. We use the new term "thirdhand" smoke to name this complex phenomenon and define it as residual tobacco smoke contamination that remains after the cigarette is extinguished. This study is the first to examine the thirdhand smoke concept and home smoking bans.

The toxicity of low levels of tobacco smoke constituents has been proved. According to the National Toxicology Program, these 250 poisonous gases, chemicals, and metals include hydrogen cyanide (used in chemical weapons), carbon monoxide (found in car exhaust), butane (used in lighter fluid), ammonia (used in household cleaners), toluene (found in paint thinners), arsenic (used in pesticides), lead (formerly found in paint), chromium (used to make steel), cadmium (used to make batteries), and polonium-210 (highly radioactive carcinogen).[1] Eleven of these compounds are group 1 carcinogens (most carcinogenic designation).[1] For some of these compounds, such as radioactive polonium-210, the cumulative dose is especially concerning, leading health professionals to call for immediate disclosure and warnings about exposure.[8]

Strict no-smoking policies in the home have been associated with significantly lower levels of biochemical markers of tobacco exposure and lower health risks in nonsmokers.[3,9–12] Individual adult smokers who are not yet prepared to quit can therefore provide some relative protection to others by setting strict "no smoking" policies in their homes. The pressures of strict rules also may be important for encouraging smoking cessation among household members,[13–19] discouraging smoking initiation in youth,[20–26] and decreasing the risk for house fires.[27] Previous work showed that having children in the home, other nonsmoking adults in the home, and presence of smoke-free public places are associated with having smoking bans.[28] Among smokers, longer time to first cigarette and being in the preparation stage of change are associated with home smoking bans.[19]

This study uses a nationally representative sample of adults to determine the prevalence of recognizing the dangers associated with thirdhand smoke and the association with household smoking bans. We hypothesized that belief about the harmful health effects of thirdhand smoke would be associated with higher rates of strict no-smoking policies within the home.

METHODS

This study reports data from the Social Climate Survey of Tobacco Control (SCS-TC), an annual cross-sectional survey that was designed to operationalize the concept of the social climate on tobacco into a comprehensive set of quantifiable social and environmental indicators across social institutions that characterize society: (1) family and friendship groups; (2) education; (3) workplace; (4) government and political order; (5) health and medical care; (6) recreation, leisure, and sports; and (7) mass culture and communication. Survey items were developed and selected on the basis of an extensive review of extant tobacco control surveys and then reviewed by a panel of tobacco control researchers.

The SCS-TC was administered to a representative sample of US adults in September to November of 2005. Households were selected by using random-digit-dialing procedures. Once a household was reached, the adult to be interviewed was selected by the interviewer's asking to speak with the person in the household who was ≥18 years of age and would have the next birthday. When not at home, 5 attempts were made to contact the selected adult. The sample was weighted by race and gender within each census region, on the basis of 2005 US Census estimates. The institutional review board at Mississippi State University reviewed and approved this project. Informed consent was obtained orally as part of the introduction to the telephone interview by trained interviewers. No compensation was given to study participants. A detailed description of the survey method can be found on the SCS-TC Web site.[29]

Measures

Two questions from the Behavior Risk Factor Surveillance System and the National Health Interview Survey were used to assess the current smoking status of respondents. Respondents were asked, "Have you smoked at least 100 cigarettes in your entire life?" Respondents who reported that they had were then asked, "Do you now smoke cigarettes every day, some days, or not at all?" Respondents who reported that they now smoke every day or some days were categorized as current smokers.

Home Smoking Policies

One question was used to assess the current household's rules about smoking. Respondents were asked which of the following best describes their household's rules about smoking: (1) smoking is allowed in all parts of the home; (2) smoking is allowed in some parts of the home; (3) smoking is not allowed in any part of the home; or (4) don't know/not sure. Respondents who reported that they did not allow smoking in any part of the home were categorized as having strict rules prohibiting smoking in the home. Respondents who reported that they allowed smoking in all parts of the home or some parts of the home or did not know/were not sure were categorized as not having strict rules prohibiting smoking in the home.

Health Beliefs About SHS and Thirdhand Smoke

One question was asked to assess health belief about SHS. Respondents were asked whether they strongly agreed, agreed, disagreed, or strongly disagreed with the following statement: "Inhaling smoke from a parent's cigarette can harm the health of infants and children." Respondents who strongly agreed and agreed with this statement were categorized as holding the belief that

SHS harms the health of children. Respondents who disagreed or strongly disagreed with these statements were categorized as not holding the belief that SHS in the home harms the health of children.

One question was asked to assess health belief about thirdhand smoke. Respondents were asked whether they strongly agreed, agreed, disagreed, or strongly disagreed with the following statement: "Breathing air in a room today where people smoked yesterday can harm the health of infants and children." Respondents who strongly agreed and agreed with this statement were categorized as holding the belief that thirdhand smoke harms the health of children. Respondents who disagreed or strongly disagreed with these statements were categorized as not holding the belief that thirdhand smoke harms the health of children. The "don't know" category was handled consistently for both the SHS and thirdhand smoke variables as a third level.

Self-report of Local Smoking Policies

Our expert panel hypothesized that knowledge of a local no-smoking policy in restaurants and bars would be associated with home smoking ban. Respondents were asked whether restaurants in their community are completely smoke-free, have designated smoking areas, or permit smoking anywhere. Similarly, respondents were asked whether bars and taverns in their community are completely smoke-free, have designated smoking areas, or permit smoking anywhere. Responses to these 2 questions were dichotomized as completely smoke-free or not.

Statistical Analysis

We used χ^2 procedures to compare differences between age, gender, race, education, smoking status, smoking status of others in the home, rural/urban residence, health beliefs about smoking in bars, health beliefs about smoking in restaurants, and health beliefs toward SHS for the outcome variable of strict rules prohibiting smoking in the home. Associations were considered significant at the $\alpha < .05$ level. In our analyses, we treated "refused to answer the question" as missing data. The proportion of respondents who answered each question in each question set is reported in the footnotes of each data table. A multiple logistic regression model that controlled for demographic variables and known confounders was developed, with the dependent variable of having a strict rule prohibiting smoking in the home. All analyses were conducted by using SPSS 14 (SPSS, Inc, Chicago, IL).

RESULTS

Table 1 shows the characteristics of the 1478 adults in the sample. Consistent with national smoking rates,[30] 18.9% of adults in this sample were current smokers. A total of 15.6% of the sample reported a smoker living in the home, and, among nonsmokers, 8.4% lived with a smoker. The total prevalence of homes with a smoker was 25.6%. A large majority (93%) of the respondents believed that SHS harms the health of children as opposed to only 61% of respondents who believed that thirdhand smoke harms the health of children. Significant numbers (22%) of respondents reported not knowing whether thirdhand smoke harms the health of children, whereas only 3.4% of respondents reported not knowing whether SHS harms the health of children. In bivariate analysis (Table 2), strict smoking rules were much more prevalent among nonsmokers than smokers (88.4% vs 26.7%; $P < .001$).

In multivariate analysis (Table 3), controlling for sociodemographics and possible confounders, we found an independent association between belief that thirdhand smoke harms children and presence of a strict home smoking ban (adjusted odds ratio [aOR]: 2.19 [95% confidence interval (CI): 1.36–5.52]). In this multivariate analysis, belief that SHS harms children was not

TABLE 1 Characteristics of National Survey Sample

Variable	Total Sample Valid ($N = 1478$), %[a]
Age, y	
18–24	9.4
25–44	28.3
45–64	40.3
≥65	22.1
Gender	
Male	46.9
Female	53.1
Race	
Nonwhite	20.6
White	79.4
Education	
<12 y	6.4
High school graduate	29.2
Some college	25.8
College graduate	38.6
Residence	
Rural	25.0
Urban	75.0
Smoker status	
Current smoker	18.9
Not current smoker	81.1
Other smokers in the home	
Yes	15.6
No	84.4
Child in the home	
Yes	33.8
No	66.2
Reported presence of smoking bans in bars	
Local ban present	29.0
Local ban not present	71.0
Reported presence of smoking bans in restaurants	
Local ban present	45.0
Local ban not present	55.0
Believe that SHS harms children	
Agree	93.2
Disagree	3.3
Don't know	3.4
Believe that thirdhand smoke harms children	
Agree	61.0
Disagree	16.7
Don't know	22.3

[a] Percentage of respondents who answered each question in this question set ranged from 99% to 100%.

TABLE 2 Presence of Strict Home Smoking Ban According to Respondent Characteristic

Characteristic	Strict Home Smoking Ban Valid (N = 1478), %[a]	P
Age, y		.407
18–24	81.2	
25–44	76.0	
45–64	75.2	
≥65	78.4	
Gender		.003
Male	73.3	
Female	79.9	
Race		.625
Nonwhite	75.7	
White	77.0	
Education		<.001
<12 y	58.7	
high school graduate	70.5	
Some college	74.1	
College graduate	86.4	
Residence		.318
Rural	74.8	
Urban	77.3	
Smoker status		<.001
Current smoker	26.7	
Not current smoker	88.4	
Other smokers in the home		<.001
Yes	43.1	
No	82.5	
Child in the home		<.001
Yes	83.5	
No	73.2	
Reported presence of smoking bans in bars		.712
Local ban present	76.4	
Local ban not present	77.2	
Reported presence of smoking bans in restaurants		.554
Local ban present	73.5	
Local ban not present	75.2	
Believe that SHS harms children		<.001
Agree	79.0	
Disagree	51.0	
Don't know	40.0	
Believe that thirdhand smoke harms children		<.001
Agree	82.1	
Disagree	57.5	
Don't know	76.2	

[a] Percentage of the 1478 respondents who answered each question in this question set ranged from 99% to 100%.

TABLE 3 Final Logistic Regression Model Showing Odds of Having a Strict Home Smoking Ban

Predictor	Strict Home Smoking Ban, aOR (95% CI)
Thirdhand smoke and SHS beliefs	
Believe that thirdhand smoke harms children	2.190 (1.360–3.520)
Don't know whether thirdhand smoke harms children	1.910 (1.100–3.320)
Believe that SHS harms children	0.980 (0.390–2.470)
Don't know whether SHS harms children	0.230 (0.070–0.830)
Smoking status	
Nonsmoker	12.830 (8.470–19.460)
No other smokers in home	2.900 (1.840–4.590)
Presence of child living in home	
Child in home	2.900 (1.860–4.520)
Community smoking bans	
Reported local ban in bars	1.630 (0.995–2.680)
Reported local ban in restaurants	0.580 (0.370–0.910)
Race	
White	2.090 (1.370–3.280)
Education	
High school	1.920 (0.880–4.200)
Some college	2.320 (1.040–5.160)
College	4.300 (1.900–9.720)

Model also included age, gender, and rural/urban residence, all not significant.

independently associated with a strict home smoking ban. When thirdhand smoke was removed from the model, SHS still did not achieve significance (aOR: 1.60 [95% CI: 0.69–3.60]). This lack of significance may reflect low SHS variability, with only 3.3% of the sample not believing that SHS harms the health of children. When the multivariate analysis was restricted to the 500 households that had children, SHS remained nonsignificant (aOR: 0.2 [95% CI: 0.0–1.6]).

Because current programs emphasize the harms of SHS, we wanted to explore the notion that increased strength of agreement with the SHS variable might be associated with strict home smoking ban. For the SHS variable, 38% of the sample strongly agreed and 55% agreed that SHS harms the health of children. Using disagree as the reference group for SHS, we found a positive but nonsignificant relationship between strong agreement that SHS harms the health of children and strict home smoking ban (aOR: 1.53 [95% CI: 0.58–4.00]). When we recoded the SHS reference group as agree, we found a significant relationship between strong agreement that SHS harms the health of children and strict home smoking ban (aOR: 1.87 [95% CI: 1.24–2.81]). In both cases, the OR for thirdhand smoke remained independently associated with strict home smoking ban (aOR: 2.07 [95% CI: 1.28–3.35]).

DISCUSSION

In this large nationally representative sample, we identified an independent association between the health belief that thirdhand smoke harms children and strict no-smoking policies in the home. This novel finding is important because the thirdhand smoke concept could easily be incorporated into current and future tobacco counseling messages, tobacco control programs, policy initiatives, and guidelines. To date, programs have emphasized the harmful effects of visible SHS, a health belief that a large majority of adults already endorse. We were unable to find an association between simple belief that SHS harms children and strict home smoking ban. Our exploratory results do suggest a difference in protective home rules between those who simply agree that SHS is harmful to children and those who strongly agree that SHS is harmful to children. Emphasizing a high degree of harm caused by visible SHS may still have activity for encouraging home smoking bans. The SHS health message dates back to the 1986 Surgeon General's report, a transformative report that is now more

than 20 years old.[31] The 2006 Surgeon General's Report summarized the intervening years of research, concluding that there is no safe level of tobacco smoke.[1] Meanwhile, an expanding body of evidence demonstrates that indoor spaces become contaminated with tobacco toxins after the visible smoke dissipates.[4,6,7]

New information emerging about thirdhand smoke exposure may offer families needed additional information about sources of possible toxic exposure of their children and may enhance their motivation to alter home smoking practices to protect better the health of their children. Thirdhand smoke health education campaigns might be more powerful motivators for these families than simply reiterating information about visible SHS exposure that most families already know. It also seems plausible that clinicians' advice about thirdhand smoke and toxic liabilities for children will enhance the motivation of parents to protect their children even when they already believe that thirdhand smoke exposure is harmful. These possibilities warrant formal experimental testing to inform public education, clinician services delivery, and improved environmental health strategies for single and multi-unit dwellings.

Children are especially susceptible to thirdhand smoke exposure because they breathe near, crawl and play on, touch, and mouth contaminated surfaces. At up to 0.25 g/day, the dust ingestion rate in infants is more than twice that of adults.[32] Urine cotinine levels of children in homes with strict no-smoking policies are 6 times lower than in homes without strict policies.[6] Thirdhand smoke may remain inside even when smoking took place earlier.[4–7,33,34] Similar to low levels of lead exposure,[35] low levels of tobacco smoke markers have been associated with cognitive deficits among children.[36] The highest tobacco exposure levels were associated with the lowest reading scores; however, the lowest levels of exposure were associated with the steepest slope in the decrement in reading levels.[36] These facts underscore the possibility that compounds in tobacco smoke are neurotoxic at extremely low levels and the prudence of advocating for absolute restriction of all smoking in indoor areas that are inhabited by children.

Even when absolute bans are maintained, nonsmokers can be exposed to tobacco toxins by off-gasing from the smoker's clothing, through open windows and doors,[3] and from exhaled toxins for several minutes after the cigarette is extinguished.[37] Therefore, strict smoking restrictions should be encouraged as an adjunctive strategy as the smoker is treated for tobacco dependence and advances toward the goal of permanent abstinence.

Previous research showed that reported presence of smoking bans in public places was associated with a no-smoking policy in the home.[26] We found a nonsignificant positive trend for reported local smoking ban in bars being associated with a strict no-smoking policy in the home. This finding may indicate that a strong community social norm affects home policy. Conversely, reported local smoking bans in restaurants was associated with a lower likelihood of a no-smoking policy in the home. Having a restaurant but not a bar ban may represent a community social norm that actively chose to allow smoking in bars. Having no ban in bars or restaurants may reflect a community with a less permissive social norm that simply had not considered the local ordinance yet at the time of the survey.

This is the first study to examine the notion of thirdhand smoke and its associations with health beliefs and home smoking policies. The sample is nationally representative (and items related to smoking status ascertainment have been validated with other national survey). Limitations of the study include that the data come from a cross-sectional survey and possible causal relationships cannot be assumed. In addition, there may be residual confounding by unmeasured or unknown confounders, although we have included the common known confounders in our analyses. Our logistic model included a number of theoretical and empirical correlates of home smoking bans and represents a severe test of an independent association when most theoretical models assume interactive relationships among variables such as these. Finally, this national survey cannot give definitive answers as to which types of specific messaging may have activity in prospectively establishing strict home smoking bans; however, we have created a possible messaging strategy for researchers who are interested in using the thirdhand smoke concept and posted it as part of a free programmatic tobacco control Web site (www.ceasetobacco.org).

CONCLUSIONS

This study demonstrated that beliefs about the health effects of thirdhand smoke are independently associated with home smoking bans. Emphasizing that thirdhand smoke harms the health of children may be an important element in encouraging home smoking bans. Health messages about thirdhand smoke contamination could be easily incorporated into current tobacco control campaigns, programs, and routine clinical practice.

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Beliefs About the Health Effects of "Thirdhand" Smoke and Home Smoking Bans

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Att F

- Berkeley Lab News Center - http://newscenter.lbl.gov -

Study reveals dangers of nicotine in third-hand smoke

Posted By lcyarris On February 8, 2010 @ 1:00 pm In News Releases | Comments Disabled

Nicotine in third-hand smoke, the residue from tobacco smoke that clings to virtually all surfaces long after a cigarette has been extinguished, reacts with the common indoor air pollutant nitrous acid to produce dangerous carcinogens. This new potential health hazard was revealed in a multi-institutional study led by researchers with the Lawrence Berkeley National Laboratory (Berkeley Lab).

In tests at Berkeley Lab of cellulose surfaces contaminated with nicotine residues from third-hand smoke, levels of newly formed TSNAs rose 10 times following a three hour exposure to nitrous acid. TSNAs are potent carcinogens. (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

[1]

In tests at Berkeley Lab of cellulose surfaces contaminated with nicotine residues from third-hand smoke, levels of newly formed TSNAs rose 10 times following a three hour exposure to nitrous acid. TSNAs are potent carcinogens. (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

"The burning of tobacco releases nicotine in the form of a vapor that adsorbs strongly onto indoor surfaces, such as walls, floors, carpeting, drapes and furniture. Nicotine can persist on those materials for days, weeks and even months. Our study shows that when this residual nicotine reacts with ambient nitrous acid it forms carcinogenic tobacco-specific nitrosamines or TSNAs," says Hugo Destaillats, a chemist with the Indoor Environment Department of Berkeley Lab's Environmental Energy Technologies Division. "TSNAs are among the most broadly acting and potent carcinogens present in unburned tobacco and tobacco smoke."

Destaillats is the corresponding author of a paper published in the Proceedings of the National Academy of Sciences (PNAS) titled "Formation of carcinogens indoors by surface-mediated reactions of nicotine with nitrous acid, leading to potential third-hand smoke hazards."

Co-authoring the PNAS paper with Destaillats were Mohamad Sleiman, Lara Gundel and Brett Singer, all with Berkeley Lab's Indoor Environment Department, plus James Pankow with Portland State University, and Peyton Jacob with the University of California, San Francisco.

The authors report that in laboratory tests using cellulose as a model indoor material exposed to smoke, levels of newly formed TSNAs detected on cellulose surfaces were 10 times higher than those originally present in the sample following exposure for three hours to a "high but reasonable" concentration of nitrous acid (60 parts per billion by volume). Unvented gas appliances are the main source of nitrous acid indoors. Since most vehicle engines emit some nitrous acid that can infiltrate the passenger compartments, tests were also conducted on surfaces inside the truck of a heavy smoker, including the surface of a stainless steel glove compartment. These measurements also showed substantial levels of TSNAs. In both cases, one of the major products found was a TSNA that is absent in freshly emitted tobacco smoke – the nitrosamine known as NNA. The potent carcinogens NNN and NNK were also formed in this reaction.

"Time-course measurements revealed fast TSNA formation, up to 0.4 percent conversion of nicotine within the first hour," says lead author Sleiman. "Given the rapid sorption and persistence of high levels of nicotine on indoor surfaces, including clothing and human skin, our findings indicate that third-hand smoke represents an unappreciated health hazard through dermal exposure, dust inhalation and ingestion."

Since the most likely human exposure to these TSNAs is through either inhalation of dust or the contact of skin with carpet or clothes, third-hand smoke would seem to pose the greatest hazard to infants and toddlers. The study's findings indicate that opening a window or deploying a fan to ventilate the room while a cigarette burns does not eliminate the hazard of third-hand smoke. Smoking outdoors is not much of an improvement, as co-author Gundel explains.

Berkeley Lab chemists Lara Gundel and Hugo Destaillats led a research team that revealed the potential health hazards posed by residual nicotine in third-hand smoke when it reacts with ambient nitrous acid. (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

[2]

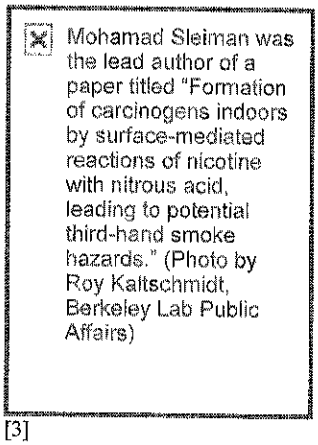
Berkeley Lab chemists Lara Gundel and Hugo Destaillats led a research team that revealed the potential health hazards posed by residual nicotine in third-hand smoke when it reacts with ambient nitrous acid. (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

"Smoking outside is better than smoking indoors but nicotine residues will stick to a smoker's skin and clothing," she says. "Those residues follow a smoker back inside and get spread everywhere. The biggest risk is to young children. Dermal uptake of the nicotine through a child's skin is likely to occur when the smoker returns and if nitrous acid is in the air, which it usually is, then TSNAs will be formed."

The dangers of mainstream and secondhand tobacco smoke have been well documented as a cause of cancer, cardiovascular disease and stroke, pulmonary disease and birth defects. Only recently,

however, has the general public been made aware of the threats posed by third-hand smoke. The term was coined in a study that appeared in the January 2009 edition of the journal "Pediatrics," in which it was reported that only 65 percent of non-smokers and 43 percent of smokers surveyed agreed with the statement that "Breathing air in a room today where people smoked yesterday can harm the health of infants and children."

Anyone who has entered a confined space – a room, an elevator, a vehicle, etc. – where someone recently smoked, knows that the scent lingers for an extended period of time. Scientists have been aware for several years that tobacco smoke is adsorbed on surfaces where semi-volatile and non-volatile chemical constituents can undergo reactions, but reactions of residual smoke constituents with atmospheric molecules such as nitrous acid have been overlooked as a source of harmful pollutants. This is the first study to quantify the reactions of third-hand smoke with nitrous acid, according to the authors.


Mohamad Sleiman was the lead author of a paper titled "Formation of carcinogens indoors by surface-mediated reactions of nicotine with nitrous acid, leading to potential third-hand smoke hazards." (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

[3]

Mohamad Sleiman was the lead author of a paper titled "Formation of carcinogens indoors by surface-mediated reactions of nicotine with nitrous acid, leading to potential third-hand smoke hazards." (Photo by Roy Kaltschmidt, Berkeley Lab Public Affairs)

"Whereas the sidestream smoke of one cigarette contains at least 100 nanograms equivalent total TSNAs, our results indicate that several hundred nanograms per square meter of nitrosamines may be formed on indoor surfaces in the presence of nitrous acid," says lead-author Sleiman.

Co-author James Pankow points out that the results of this study should raise concerns about the purported safety of electronic cigarettes. Also known as "e-cigarettes," electronic cigarettes claim to provide the "smoking experience," but without the risks of cancer. A battery-powered vaporizer inside the tube of a plastic cigarette turns a solution of nicotine into a smoky mist that can be inhaled and exhaled like tobacco smoke. Since no flame is required to ignite the e-cigarette and there is no tobacco or combustion, e-cigarettes are not restricted by anti-smoking laws.

"Nicotine, the addictive substance in tobacco smoke, has until now been considered to be non-toxic in the strictest sense of the term," says Kamlesh Asotra of the University of California's Tobacco-Related Disease Research Program, which funded this study. "What we see in this study

is that the reactions of residual nicotine with nitrous acid at surface interfaces are a potential cancer hazard, and these results may be just the tip of the iceberg."

The Berkeley Lab researchers are now investigating the long-term stability in an indoor environment of the TSNAs produced as a result of third-hand smoke interactions with nitrous acid. The authors are also looking into the development of biomarkers to track exposures to these TSNAs. In addition, they are conducting studies to gain a better understanding of the chemistry behind the formation of these TSNAs and to find out more about other chemicals that are being produced when third-hand smoke reacts with nitrous acid.

"We know that these residual levels of nicotine may build up over time after several smoking cycles, and we know that through the process of aging, third-hand smoke can become more toxic over time," says Destaillats. "Our work highlights the importance of third-hand smoke reactions at indoor interfaces, particularly the production of nitrosamines with potential health impacts."

In the PNAS paper, Destaillats and his co-authors suggest various ways to limit the impact of the third hand smoke health hazard, starting with the implementation of 100 percent smoke-free environments in public places and self-restrictions in residences and automobiles. In buildings where substantial smoking has occurred, replacing nicotine-laden furnishings, carpets and wallboard might significantly reduce exposures.

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Additional Information

For more information about Berkeley Lab's Indoor Environment Department and its researchers visit the Website at http://eetd.lbl.gov/r-indoor.html [5]

For more information on the research of James Pankow visit the Website at http://www.pdx.edu/chem/profile/dr-james-f-pankow [6]

For more information on the research of Peyton Jacob visit the Website at http://cancer.ucsf.edu/people/jacob_peyton.php [7]

For more information on the University of California's Tobacco-Related Disease Research Program (TRDRP) visit the Website at http://www.trdrp.org/ [8]

For a list of health experts who may be able to provide comments and quotes, contact Kamlesh Asotra at kamlesh.asotra@ucop.edu [9] or 510-287-3366.

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