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Journal

ISSN

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Publication Date

DOI

Copyright Information

Peer reviewed

Inhalable Constituents of Thirdhand Tobacco Smoke: Chemical Characterization and Health Impact Considerations

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S *Supporting Information*

ABSTRACT: Tobacco smoke residues lingering in the indoor environment, also termed thirdhand smoke (THS), can be a source of long-term exposure to harmful pollutants. THS composition is affected by chemical transformations and by air−surface partitioning over time scales of minutes to months. This study identified and quantified airborne THS pollutants available for respiratory exposure, identified potential environmental tracers, and estimated health impacts to nonsmokers. In a ventilated 18 m^3 laboratory chamber, six cigarettes were machine-smoked, and levels of particulate matter (PM$_{2.5}$) and 58 volatile organic compounds (VOCs) were monitored during an aging period of 18 h. Results were compared with field measurements taken in a smoker's home 8 h after the last cigarette had been smoked. Initial chamber levels of individual VOCs in freshly emitted secondhand smoke (SHS) were in the range of 1−300 μg m^{-3}. The commonly used SHS tracers 3-ethenylpyridine (3-EP) and nicotine were no longer present in the gas phase after 2 h, likely due mostly to sorption to surfaces. By contrast, other VOCs persisted in the gas phase for at least 18 h, particularly furans, carbonyls, and nitriles. The concentration ratio of acetonitrile to 3-EP increased substantially with aging.

This ratio may provide a useful metric for differentiating freshly emitted (SHS) from aged smoke (THS). Among the 29 VOCs detected in the smoker's home at moderate to high concentrations, 18 compounds were also detected in simultaneously sampled outdoor air, but acetonitrile, 2-methyl furan, and 2,5-dimethyl furan appeared to be specific to cigarette smoke. The levels of acrolein, methacrolein, and acrylonitrile exceeded concentrations considered harmful by the State of California. An initial exposure and impact assessment was conducted for a subset of pollutants by computing disability-adjusted life years lost, using available toxicological and epidemiological information. Exposure to PM$_{2.5}$ contributed to more than 90% of the predicted harm. Acrolein, furan, acrylonitrile, and 1,3-butadiene were considered to be the most harmful VOCs. Depending on which criteria are used to establish the separation between SHS and THS, 5−60% of the predicted health damage could be attributed to THS exposure. Benefits and limitations of this approach are discussed.
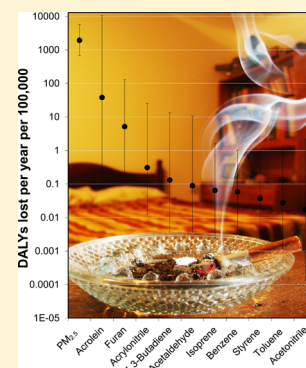
INTRODUCTION

Thirdhand smoke (THS) can be defined as residual tobacco smoke contaminants that remain airborne or are sorbed to indoor surfaces and dust particles many hours after smoking has ended. Some of the chemicals can be emitted back into indoor air, and both gaseous and sorbed compounds can react with atmospheric species (e.g., ozone and HONO) to yield secondary pollutants that were not originally present in fresh smoke.[1−3] The presence of malodorous airborne constituents can often be detected many hours and up to weeks after smoking ends, suggesting that labile organic compounds (including not only VOCs but also some semivolatile compounds) can remain airborne and/or be emitted from surfaces over time scales longer than ventilation-controlled residence times.

While great progress has been made in protecting nonsmokers in public places, tobacco control strategies are less effective in reaching into homes, which are the main sites for exposure of women and children.[4,5] Voluntary restrictions, such as smoking only when nonsmoking family members are not at home, are often implemented to reduce SHS exposures but may not fully address potential hazards associated with THS.[6] For that reason, better definition of the transition between SHS and THS and apportionment of the associated disease burdens could assist the development of policies and practices that better protect nonsmokers.

This study investigated the composition of inhalable THS pollutants, identified VOCs that could serve as reliable tracers to differentiate fresh SHS from THS, and identified

concentrations of compounds exceeding harmful levels. It also explored the applicability and limitations of an exposure and harm assessment model that computes disability-adjusted life years (DALYs). This metric is used by the World Health Organization to assess the global burden of disease, including both morbidity and mortality, by accounting for years of life lost from the life span of a healthy individual.[7−9] Its application to indoor environments allows the identification of priority pollutants that are most critically associated with health hazards, assisting in the development of policy, public guidance, and remediation practices.[10,11]

■ MATERIALS AND METHODS

Generation and Aging of Tobacco Smoke in the Laboratory and in the Field. Fresh tobacco smoke was generated at Lawrence Berkeley National Laboratory (LBNL) in an 18 m³ room-sized chamber equipped with a large mixing fan. The walls and ceiling of the chamber were painted gypsum wallboard (42 m²), and the floor (10 m²) was covered with vinyl tiles. The walls had not been repainted, and floor tiles had not recently been replaced (>5 years); hence, no major VOC contributions from surfaces were expected. The chamber had one closed door, several sampling ports that were not tightly sealed, and no external air supply. Decay rates for the concentrations of the volatile compounds isobutane, acetone, and benzene were used to calculate the air exchange rate (a_c = 0.14 h⁻¹). This decay rate was attributed to leakage from the chamber and is consistent with values found in tight houses.[12] Diluted sidestream smoke was generated to capture the main features of SHS, as in previous studies.[13,14] Operational details are described in the Supporting Information.

The smoker's home was a 1100 ft² single-story house with a forced air recirculation system, located in a suburb of Portland, OR. The nearest major road was ∼300 m away. Cigarettes were smoked in the living room and kitchen. Duplicate samples were collected simultaneously in the living room (with windows closed) and on the front porch. Air was sampled for 10 and 20 min at 100 mL min⁻¹ starting 8 h after three cigarettes had been smoked.

Sample Collection and Analysis. Air in the laboratory chamber and in a smoker's home was sampled using multibed sorbent cartridges (180 mg of Carbotrap B and 70 mg of Carboxen 1000) packed in glass tubes with an outer diameter of 0.64 cm and a length of 8.9 cm (Supelco, Bellefonte, PA). The use of different sorbents made possible determination of a wide range of organic species, from very volatile organic compounds (VVOCs) such as 1,3-butadiene, isoprene, and acrolein (vapor pressures of 0.4−3 atm) to semivolatile organic compounds (SVOCs) such as methylnaphthalenes, nicotine, and myosmine (vapor pressures of 10⁻⁵−10⁻⁶ atm).

Unused cartridges were analyzed as field blanks. The chamber air was sampled at 160 mL min⁻¹ for 1 h before smoking started, and the VOC levels determined in the chamber were used for background correction. Immediately after smoking had ended, chamber air was sampled using a pair of sorbent tubes at the same flow rate, starting at the same time. One tube sampled chamber air for 2 min and the other for 20 min. This strategy expanded the range of concentrations accessible for analysis. These samples were considered to represent fresh SHS. The same dual sampling strategy was repeated after 130 min. Seventeen and eighteen hours after smoking had ended, a pair of identical tubes collected chamber

air for 16.5 and 60 min, respectively. The samples collected 17 and 18 h after smoking are termed THS.

After sampling in the laboratory chamber and in the field had been conducted, the sorbent cartridges were sealed and shipped to Portland State University (PSU). They were stored at approximately −20 °C until they were analyzed using a Leco Pegasus 4D two-dimensional gas chromatography/time-of-flight mass spectrometer (GC × GC-TOFMS) (Leco, St. Joseph, MI) equipped with an ATD 400 (PerkinElmer, Waltham, MA) thermal desorption unit.[15] Chromatographic conditions are specified in Table 1S of the Supporting Information.

PM₂.₅ concentrations were determined gravimetrically after drawing chamber air at a rate of 20 L min⁻¹ through two preconditioned Teflon-coated fiberglass filters (TCGF) in series (Fiberfilm T60A20, 47 mm diameter, Pall Corp., Port Washington, NY). PM sampling conditions are described in the Supporting Information. PM sampling periods were coordinated with those for sampling VOCs: 1 h for background, 20 min immediately after smoking, 20 min after aging for 2 h, 46.5 min after aging for 17 h, and 60 min after aging for 18 h. The PM₂.₅ mass concentration for each sampling period was determined as the sum of the aerosol mass on the upstream and downstream filters divided by the air sample volume.

Mass Balance Modeling. When ventilation (dilution) is the only loss mechanism in the chamber, the mass balance equation for nonreactive THS airborne constituents is

$$V_c \frac{dC_i}{dt} = -a_c V_c C_i \tag{1}$$

where V_c is the volume of the chamber (18 m³), C_i is the concentration of compound i (in micrograms per cubic meter), a_c is the air exchange rate (0.14 h⁻¹), and t (in hours) is the time elapsed after smoking stopped. This simple model was used as the baseline for nonsorptive, nonreactive behavior.

Chamber results were used to predict gas phase concentrations in a typical home in the United States. Pollutant levels after a single cigarette had been smoked were estimated by dividing the concentration determined for each analyte in the chamber in each time period (20 min, 2 h, and 18 h) by 6 (the number of cigarettes used). To account for the difference in volume between the chamber and a typical 2000 ft² home (186 m²) with a V_h of 480 m³, a further division by 25 was performed. The temporal profile of the concentration for each compound was generated by interpolating the chamber measurements using the following mass balance relationship:

$$V_h \frac{dC_i}{dt} = -k_i V_h C_i - a_h V_h C_i + R_i \tag{2}$$

where a_h is the air exchange rate (inverse hours), and for each i, k_i is the first-order loss rate (inverse hours) and R_i is the rate of re-emission by desorption from surfaces (micrograms per hour). The loss rate k_i is an aggregate term integrating losses associated with the first-order deposition rate constant and the chemical loss rate. Contributions from indoor chemistry are neglected. R_i can be described as the product of the surface concentration of pollutant i, C_i^S (in micrograms per square meter), the surface area available for sorption, S (in square meters), and the desorption rate k_i^S (in inverse hours):

$$R_i = k_i^S S C_i^S \tag{3}$$

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dx.doi.org/10.1021/es5036333 | Environ. Sci. Technol. 2014, 48, 13093−13101
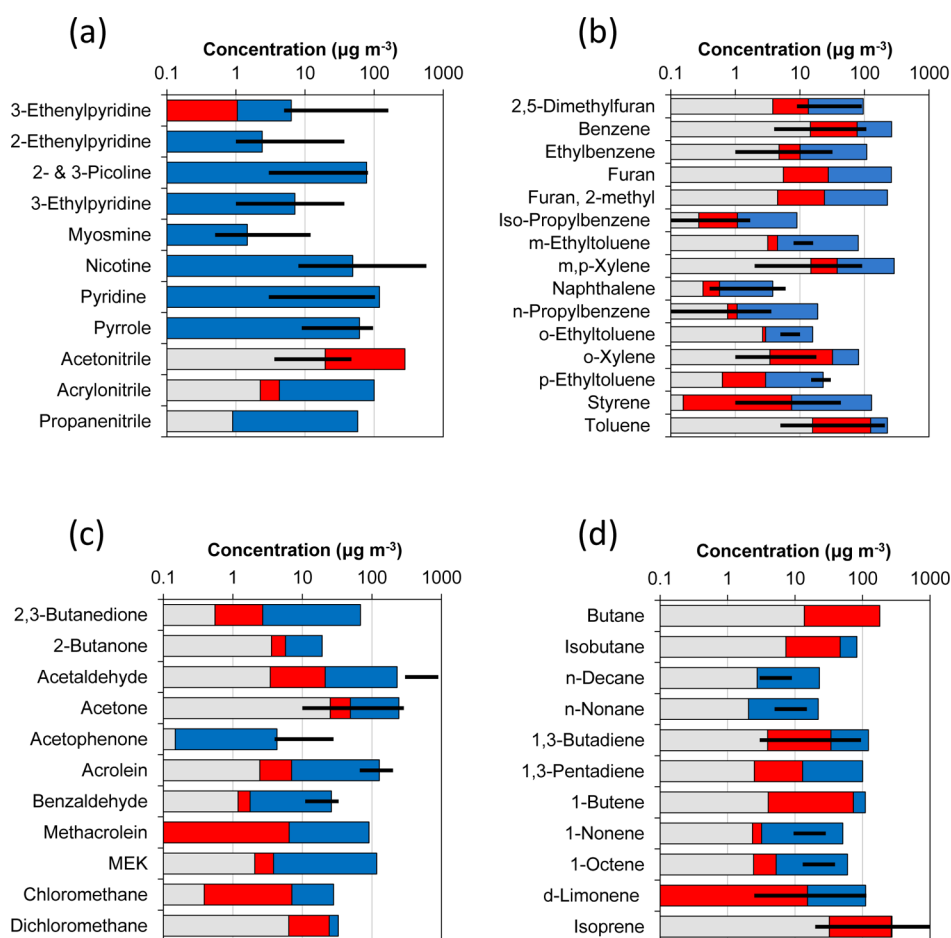
Figure 1. Concentrations of volatile constituents in tobacco smoke aged in an 18 m³ environmental chamber, measured 20 min, 2 h, and 18 h after smoking had ended. Results are presented separately for (a) nitrogenated VOCs (amines and nitriles), (b) aromatic hydrocarbons, (c) carbonyls and chlorinated VOCs, and (d) alkanes and alkenes. The experimental error of each determination (not shown for the sake of clarity) was ±10%. The overlaid black lines show the range of concentrations reported in previous studies of SHS and THS. Detailed concentrations reported in the literature are presented in Tables 4S and 5S of the Supporting Information.

Because surface concentrations were not measured, it is assumed that adsorption is much faster than desorption.[16,17] The mass of compound i sorbed to indoor surfaces is proportional to its mass in the gas phase under quasi-equilibrium conditions:

$$SC_i^S = \gamma_i V_h C_i \tag{4}$$

where γ_i is a unitless partitioning constant. Hence, the desorption rate can be expressed as

$$R_i = k_i^S \gamma_i V_h C_i \tag{5}$$

and the decay curve (solution to eq 2) can be fit to an exponential decay curve according to

$$C_i = C_i^0 \exp(-A_i t) \tag{6}$$

where C_i^0 is the initial gas phase concentration and $A_i = k_i + a_h + k_i^S \gamma_i$. An example of this extrapolation and predicted weekly concentration profiles for $PM_{2.5}$ are shown in Figures 1S and 2S of the Supporting Information. Because deposition and desorption rates determined in the chamber are a function of surface-to-volume ratio and air velocity in the room, the predicted concentrations constitute a first-order approximation.

Exposure and Impact Assessment. Exposure levels for SHS and THS in the home were modeled using four different occupancy scenarios, as patterned in the National Human Activity Patterns Study:[18] (a) the smoker and the nonsmoker are both at home most of the time; (b) the smoker is at home most of the time, and the nonsmoker is away during the day (8:30 to 17:30 on weekdays and 14:00 to 16:00 on weekends); (c) the smoker and nonsmoker behaviors are switched; and (d) both are away during the day (same time periods as type b). Chamber data were extrapolated using the mass balance model described from eqs 2−6 assuming that the smoker consumed 28 cigarettes daily at even intervals,[19] of which only those smoked at home were counted. The results estimate the exposure to SHS and THS of a nonsmoker at home; other microenvironments were excluded. The integrated chronic harm caused by inhalation of SHS and THS constituents for each scenario was predicted by calculating the corresponding disability-adjusted life years (DALYs) lost due to resulting illness and death.[7,8] The approach used the impact assessment methodology of Logue et al.[10] to estimate, on a compound-by-compound basis, the health damage to an adult nonsmoker living with a smoker over a lifetime of exposure (50 years). DALYs were estimated from exposure estimates (as described above) and toxicology-derived damage factors (δDALYs/δintake) developed by Huijbregts et al. for VOCs.[20] Damage factors are available only for a subset of 23 pollutants listed in Table 2S of the Supporting Information. Therefore, this
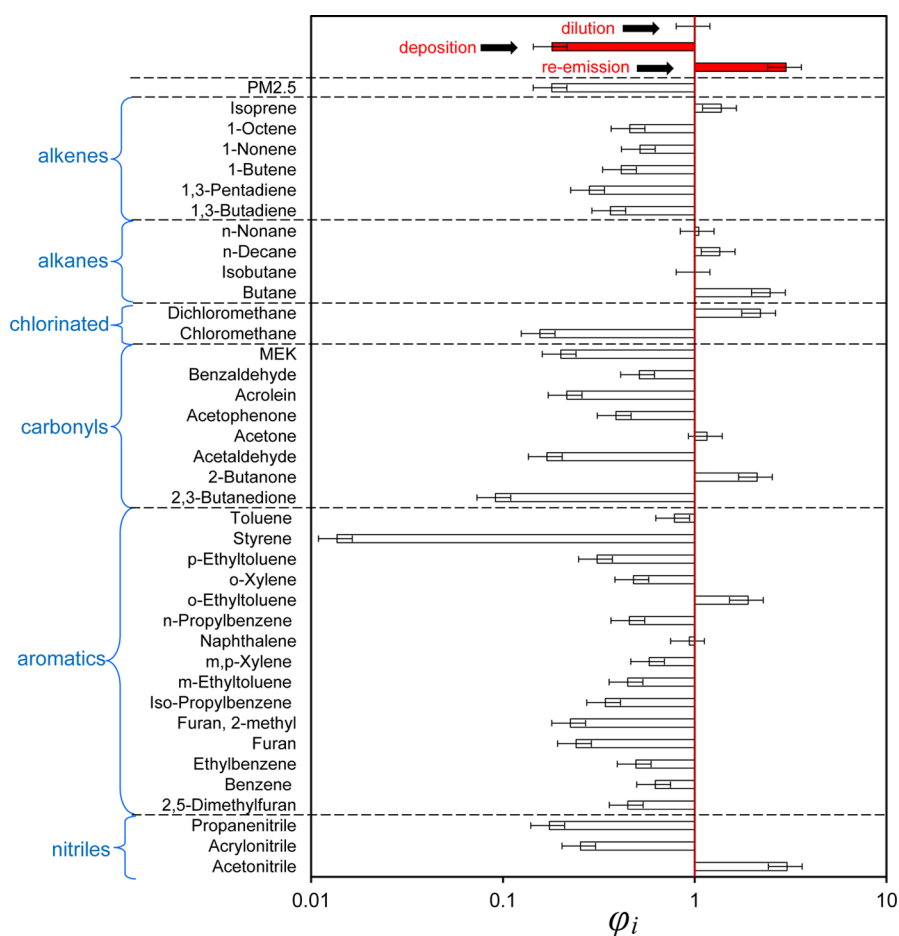
Figure 2. Ratio of measured to predicted VOC concentrations after aging for 18 h (φ_i). Predictions assumed a first-order exponential decay of VOC chamber concentrations due to ventilation (at an air exchange rate of 0.14 h^{-1}) with clean outdoor air ("dilution"). The red bars show estimates of φ_i for typical values for dilution ($\varphi_i = 1$), deposition (at a rate of 0.095 h^{-1}), and re-emission (at a rate of 0.06 h^{-1}).

analysis is only an initial effort to predict harm. Similarly, concentration−response functions are available only for ambient (outdoor air) PM$_{2.5}$, not for PM from tobacco smoke. Our analysis used outdoor air values as surrogates for tobacco-specific PM$_{2.5}$, as supported by the World Health Organization's air quality guidelines.[21]

RESULTS AND DISCUSSION

VOCs and PM$_{2.5}$ in Aged Tobacco Smoke. Figure 1 shows the background-corrected concentrations of VOCs and PM$_{2.5}$ after tobacco smoke aging for 20 min, 2 h, and 18 h in the 18 m^3 chamber. Results are also listed in Table 3S of the Supporting Information. To illustrate how the measured concentrations compared with those reported in the literature for SHS, concentration data for the 58 compounds measured in both chamber and field settings were compiled (Tables 4S and 5S of the Supporting Information). The published concentrations for each constituent were normalized to the chamber conditions (six cigarettes smoked in an 18 m^3 chamber). In Figure 1, the ranges of the normalized values are shown by the black lines overlaid on the experimental results. While known tracers such as 3-ethenylpyridine (3-EP) and nicotine were measured in most of the SHS studies, other compounds were rarely reported (e.g., acrolein, alkanes, and acrylonitrile). Numerous compounds not commonly reported in the SHS literature were detected in the chamber, including methacrolein, methyl vinyl ketone, 2-methyl furan, 1,3-pentadiene, 1-

butene, propanenitrile, chloromethane, and dichloromethane. Some portions of the two chlorinated VOCs found may be due to reaction of chloride ions or chlorinated compounds (e.g., residual pesticides present in the tobacco filler or chlorine-bleached cigarette paper[22,23]).

The total VOC concentration in the chamber decreased from 4 mg m^{-3} at the time point 20 min after smoking had stopped to 1 mg m^{-3} at 2 h and 0.2 mg m^{-3} at 18 h. At 20 min, most VOC concentrations were 10−100 μg m^{-3}, and they were generally consistent with SHS levels reported in the literature. At 2 h, the concentrations of most VOCs had decreased substantially. At 20 min, 2 h, and 18 h, PM$_{2.5}$ concentrations were 1400, 500, and 23 μg m^{-3}, respectively. All volatile and semivolatile amines except 3-EP were not detected after 2 h of aging, indicating very fast sorptive losses to surfaces, as previously reported.[13,16,24,25] In contrast, the concentration of acetonitrile increased after 2 h, suggesting the possible presence of secondary sources such as evaporation from previously deposited SHS and/or decomposition of SHS constituents. Butane and isoprene concentrations also increased during the first 2 h. Compared to the 20 min sample, the 18 h sample contained a higher fraction of carbonyls and nitriles, and it was depleted of volatile amines. The disappearance of amines from air combined with the persistence of acetonitrile might be used to identify a transition from SHS to THS (see below).

Figure 2 compares the measured chamber concentrations of VOCs at 18 h (THS) with the levels predicted assuming a first-
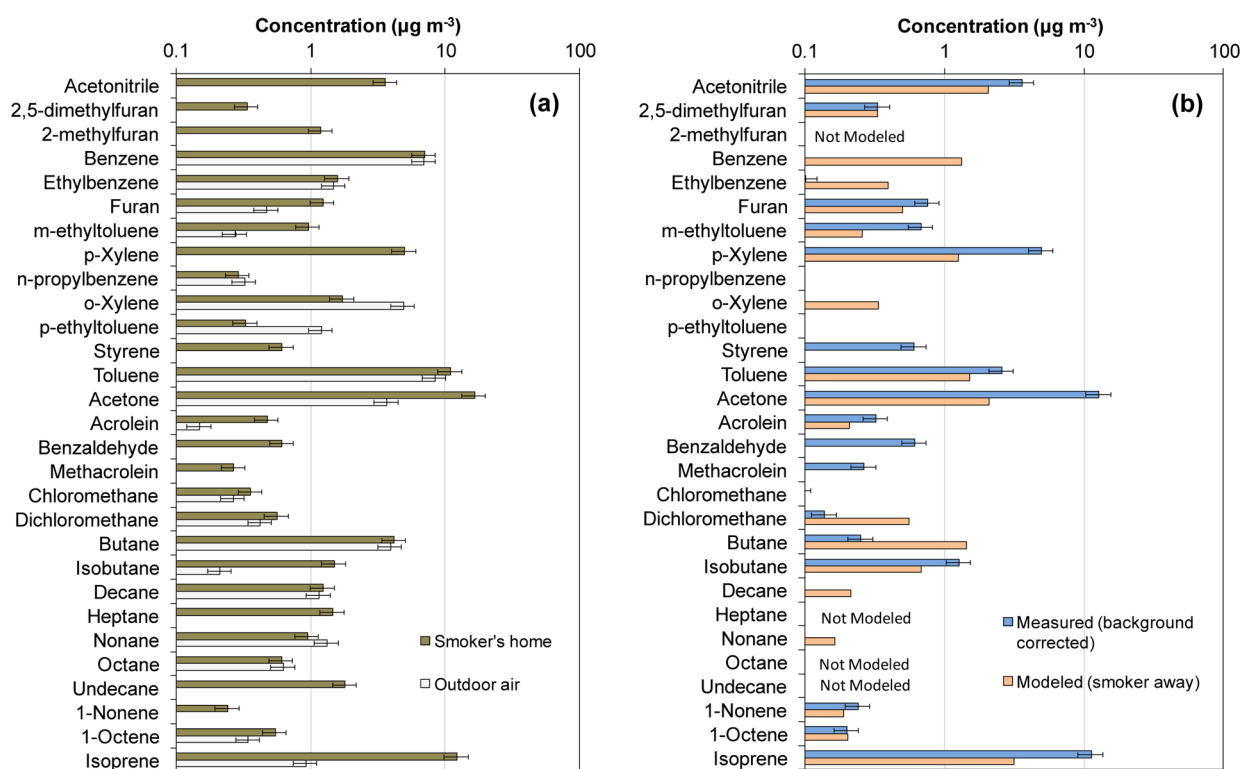
Figure 3. (a) Concentrations of volatile THS constituents measured in a smoker's home 8 h after the last cigarette had been smoked, and outside the home (ambient background). (b) Comparison of background-corrected house measurements (indoor minus outdoor) with levels predicted under a scenario in which the smoker is away during the day.

order exponential decay of VOC concentrations due exclusively to ventilation. For that purpose, the parameter

$$\varphi_i = \frac{C_i(t = 18\,\text{h})}{C_i(t = 20\,\text{min}) \times \exp(-a_c t_{\text{exp}})} \quad (7)$$

was defined as the ratio between the concentration of pollutant i measured after aging for 18 h and the corresponding value calculated using eq 1 (neglecting all other loss mechanisms) over the experimental period t_{exp} starting after the first measurement (20 min) and ending at 18 h. The top of Figure 2 shows estimates of φ_i for scenarios in which $C_i(t = 18\,\text{h})$ corresponds to dilution alone ($\varphi_i = 1$), dilution and deposition at 0.095 h^{-1} ($\varphi_i = 0.18$), and dilution and re-emission at 0.06 h^{-1} ($\varphi_i = 3.0$). Error bars correspond to a 10% measurement uncertainty, based on the average standard deviation of VOC concentrations in duplicate samples. The majority of compounds exhibited $\varphi_i < 1$, indicating loss mechanisms besides air exchange, such as sorption to indoor surfaces and reactions (e.g., oxidation). The φ_i values for some of the VOCs are consistent with reported loss rates due to sorption.[16,24,25] Only a few VOCs showed $\varphi_i > 1$, as if due to sorption followed by re-emission or formation after smoking ended. Of these, acetonitrile and 2-butanone were the compounds emitted and/or formed at the highest rates.

Three VOCs quantified in this study exceeded concentrations considered harmful. Acrolein concentrations ranged from 128 to 2.4 μg m^{-3} over the 18 h period, while its California noncancer reference exposure levels (RELs) for short-term (1 h) and long-term (8 h) exposure are 2.5 and 0.35 μg m^{-3}, respectively.[26] This is consistent with previous studies reporting high acrolein levels in SHS (up to 134 μg m^{-3}).[19,24,25] The level of methacrolein ranged from 90 to 6.4 μg m^{-3}, while

its Texas short- and long-term noncancer RELs are 16 and 0.32 μg m^{-3}, respectively.[27] Hence, concentrations of these two α,β-unsaturated aldehydes exceeded guidelines not only in freshly emitted smoke but also in THS many hours after smoking had ended. Both compounds cause irritation of the eyes and respiratory system, and acrolein is also a possible lung cancer agent.[28,29] Acrylonitrile was present at concentrations ranging from 100 to 2.2 μg m^{-3}, which, compared to its California 8 h noncancer REL of 5 μg m^{-3}, indicates that levels of this compound exceeded the REL for several hours after smoking had ceased.[26]

Using Environmental Tracers To Differentiate THS from SHS. Simply setting an arbitrary postsmoking waiting time (e.g., 3 h) as a criterion to distinguish THS from SHS may not accurately account for the combined effects of different smoking patterns, varying ventilation rates, filtration, partitioning to surfaces, and indoor chemistry on the composition of aging tobacco smoke.[2,3,13,16,24,25,30] Nor would this approach account for the coexistence of SHS and THS. Following the concentrations of reliable tracers could provide a quantitative indication of the degree of smoke aging at a particular time, as well as the simultaneous presence of SHS and THS. Acetonitrile, 2,5-dimethyl furan, and 2-methyl furan were present at high concentrations and can be considered good THS tracer candidates. In addition, acetonitrile persisted in the gas phase at levels higher than those predicted by ventilation. However, because these compounds are also present in SHS, they could not accurately define a threshold for the transition from SHS to THS. Concentration ratios of acetonitrile or the methylated furans to 3-EP may be more appropriate for identifying the SHS to THS transition after smoking ends. In this study, the acetonitrile/3-EP concentration ratio ($\rho_{\text{ACN/3EP}}$)
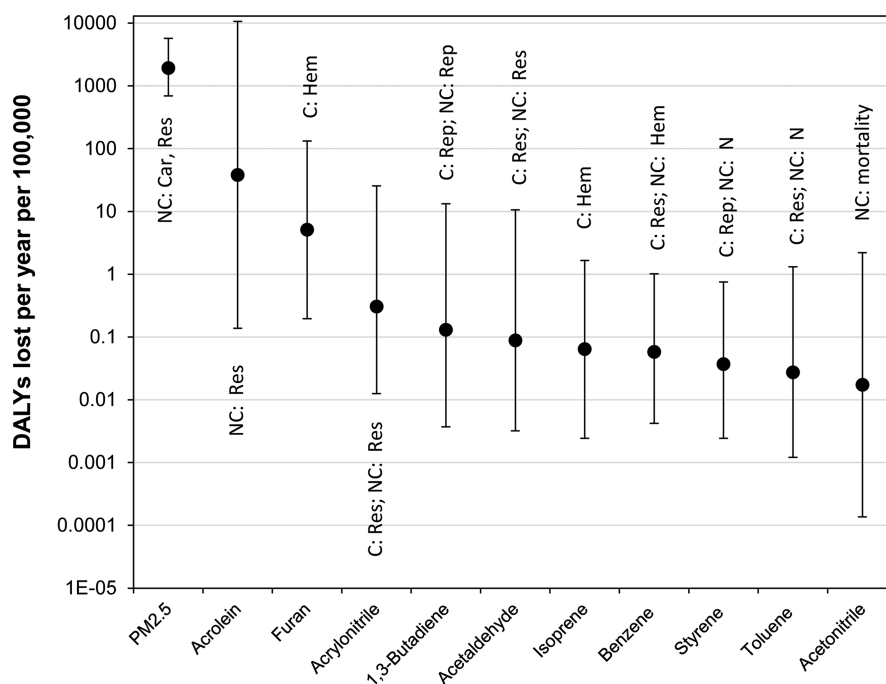
Figure 4. Annual health damage to a population of 100000 nonsmokers living with a smoker, assuming that both stay home most of the time. These estimates include the following primary cancer (C) and noncancer (NC) health end points: Car, cardiovascular; D, developmental; Hem, hematological; Hep, hepatic; N, neurological; Ren, renal; Rep, reproductive; Res, respiratory; S, skin. The symbols represent the central estimate (CE), and the whiskers show the 95th percentile confidence interval.

increased greatly as tobacco smoke aged, from 17 at 20 min (fresh SHS) to 278 after smoke had aged for 2 h. This parameter could not be determined at 18 h because the 3-EP concentration had dropped below its detection limit so that $\rho_{ACN/3EP} \rightarrow \infty$. It may be reasonable to suggest that THS dominates when $\rho_{ACN/3EP} \geq 500$. The determination of this parameter in indoor settings is straightforward. Both VOCs can be sampled and analyzed with common methods and are stable under typical indoor conditions. 3-EP has been used as an SHS tracer for many years.[31,32]

Thirdhand Smoke VOCs in a Smoker's Home. Figure 3a shows the concentrations of 29 VOCs measured in a smoker's home 8 h after the last cigarette had been smoked, along with concurrent outdoor levels of the same compounds. Duplicate measurements agreed within ±10%. A majority of compounds (18 of 29) were detected both indoors and outdoors. Those with the same or higher outdoor concentrations (particularly the aromatics, alkanes, and chlorinated compounds) likely had primarily outdoor sources and so will not be reliable THS tracers. Eleven compounds had either exclusively or predominantly indoor sources, and all were among the THS constituents found in the chamber study (Figures 1 and 2). Of these compounds, acetonitrile and 2-methyl furan were found at measurable concentrations in the home (>1 μg m^{-3}). In contrast, volatile amines were not among the 29, consistent with the $\rho_{ACN/3EP} \geq 500$ criterion for THS discussed above.

Isoprene is commonly present in biogenic emissions and is often found in ambient air.[33] Its concentration in the smoker's home was 1 order of magnitude higher than in outdoor air. Isoprene may therefore be a useful, if not completely specific, tracer for THS. Acrolein was present at concentrations 3 times higher in the smoker's home (0.47 μg m^{-3}) than in outdoor air (0.15 μg m^{-3}). This result is in agreement with an earlier

study[19] that estimated acrolein concentrations to be twice as high in smokers' residences as in nonsmoker homes.

Estimating the Exposure of Nonsmokers and Harm Caused by Inhalable THS Constituents. As part of the exposure modeling, concentrations were estimated in the smoker's home over the course of a typical week. Figure 3b compares the measured concentrations of each compound 8 h after the last cigarette had been smoked with those predicted by extrapolation of our chamber data for the scenario in which the smoker was away during the day. Field concentrations presented in Figure 3b were background-corrected by subtracting outdoor levels. The model predicted the values measured in the home reasonably well. Discrepancies between some of the modeled and experimental values can be explained by the presence of other indoor pollutant sources (i.e., aromatic hydrocarbons from cooking and indoor materials) and different furnishings in the home compared with those in the laboratory chamber. Assuming that the smoke-related VOCs 8 h after smoking correspond to THS, these results indicate that our simple modeling approach for extrapolating our chamber data can provide useful estimates of the concentrations of many volatile constituents of THS under realistic conditions.

Figure 4 shows the estimated damage corresponding to the top 11 SHS and THS pollutants in the most severe scenario (both the smoker and the nonsmoker are home most of the time). Our analysis suggests that PM$_{2.5}$ accounts for >90% of the total harm caused by the SHS and THS pollutants considered. Acrolein, furan, acrylonitrile, 1,3-butadiene, and acetaldehyde are the most harmful VOCs in inhaled SHS and THS. Table 1 presents the added damage for each of the four exposure scenarios calculated for the 23 pollutants with sufficient health information. A nonsmoker living with a smoker for 50 years is predicted to lose on average between 0.7 and 1.1 years. When the uncertainties are considered, the

Table 1. Disability-Adjusted Life Years (DALYs) Lost by Nonsmokers Living with Smokers under Four Different Scenarios

scenario of exposure[a]	DALYs lost annually by 100000 nonsmokers exposed to SHS and THS	DALYs lost by a nonsmoker living 50 years with a smoker
	central estimate (range)	central estimate (range)
smoker and nonsmoker mostly at home	2210 (1370−11740)	1.1 (0.4−7.0)
smoker away most of the day, non smoker at home	1520 (980−7310)	0.8 (0.3−4.4)
smoker at home, nonsmoker away most of the day	1740 (1110−8370)	0.9 (0.3−5.0)
both the smoker and the nonsmoker away most of the day	1440 (930−6750)	0.7 (0.3−4.1)

[a]The modeled "away from home" period for the smoker and/or the nonsmoker includes periods outside of the home between 8:30 and 17:30 on weekdays and between 14:00 and 16:00 on weekends. The model assumes also that the smoker consumed 28 cigarettes per day at even intervals throughout the day, from which only those smoked at home were counted as a source of nonsmoker exposure.

range is 0.3−7 years. These numbers are consistent with recent estimates showing DALYs for the chronic impacts from indoor air in the United States to be 400−1100 DALYs/100000 people annually.[10] With an estimated value between $60000 and $150000 per DALY,[34,35] the economic impact could be substantial, particularly considering that this value accounts only for loss of life and of quality of life in the United States but does not include costs such as lost productivity or health care expenses.[36] In U.S. homes where there is a resident smoker (11%), SHS and THS have an impact that is at least on par with (and likely higher than that of) all other indoor pollutants.[19]

The exposure and harm estimation method used here is a novel approach that needs to be expanded and validated. Toxicants that do not yet have concentration−response functions should be incorporated in future applications of this methodology. For PM, the use of log−linear concentration response functions involves assumptions that may oversimplify the effects of very low and very high concentrations. The toxicity of tobacco $PM_{2.5}$ should be assessed, for example, by using a recently proposed specific tobacco smoke PM tracer and biomarker, nicotelline,[37] and explicitly incorporating the marker into the model. No synergistic or antagonistic effects due to simultaneous exposure to the numerous toxicants in SHS and THS were considered. The method presented here accounts for chronic exposures via inhalation. However, other known harmful tobacco toxicants with low vapor pressures, such as tobacco-specific nitrosamines (TSNAs) or polycyclic aromatic hydrocarbons (PAHs), are likely to be present in surfaces and dust[1,38−40] and can also cause harm through dermal uptake or ingestion.[41−43] A refined exposure and harm assessment method should incorporate these additional pathways.

Apportioning the Relative Contributions of SHS and THS to Health Effects. To apportion the SHS and THS
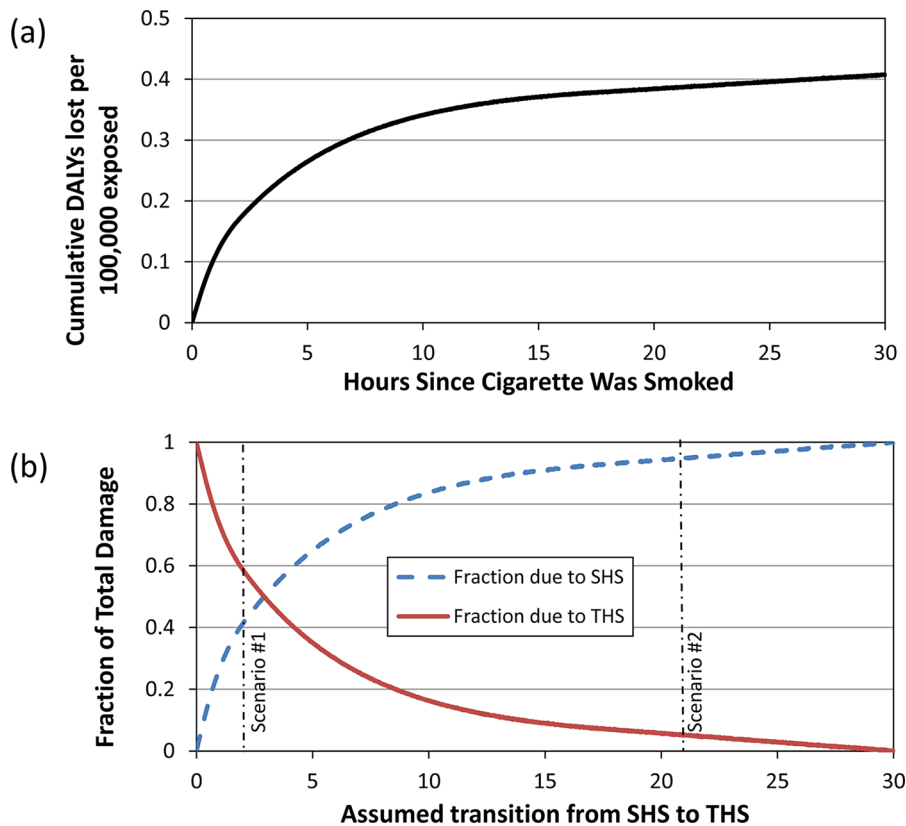

Figure 5. (a) Cumulative damage due to exposure to SHS and THS from a single cigarette smoked in the modeled home. Only the central estimate of DALYs lost is plotted. (b) Relative contribution of SHS and THS to the total health damage caused by a single cigarette, plotted as a function of when the transition between SHS and THS is arbitrarily assumed to occur. Vertical lines identify two different scenarios discussed in the text.

contributions to DALYs lost in the model scenarios, the aggregate damage per cigarette to nonsmokers was estimated over a period of 30 h starting immediately after a single cigarette had been smoked in the model home. The contributions from cigarettes smoked previously were not included, and no additional smoking occurred during that period. Figure 5a shows the predicted cumulative damage due to integrated exposure to SHS and THS. The fractions of the damage corresponding to SHS and THS (shown in Figure 5b) depend on when the SHS to THS transition is arbitrarily set. If the transition occurs shortly after smoking ends, a larger fraction of the damage will be assigned to THS. For example, in these chamber experiments, nicotine was not detected and 3-EP was near its detection limit 2 h after smoking had ended. Thus, it would be reasonable to assume that the SHS to THS transition occurred around 2−3 h (as shown by the left vertical line in Figure 5b). In that case (scenario 1), THS would account for ∼60% of the total damage. An alternative criterion (scenario 2) could set the transition at three air exchanges. On the basis of the experimental air exchange rate of 0.14 h^{-1}, the home would have experienced three air changes around 21 h after smoking had ended. Using this alternative criterion, the contribution of THS to the total damage would be ∼5%, as shown by the vertical line on the right side of Figure 5b.

Implications for Tobacco Control in Homes. PM$_{2.5}$ and many VOCs persist long after smoking ends. Volatile and semivolatile amines, including SHS tracers such as 3-EP and nicotine, are quickly removed from indoor air, but acetonitrile, 2,5-dimethyl furan, and 2-methyl furan are promising THS tracers. Application of DALYs as a metric for estimating the harm showed that exposure of a nonsmoker to SHS and THS in a tight home over 50 years of living with a smoker that consumes 28 cigarettes a day could result in 0.7−1.1 life years lost. This analysis does not consider other exposure routes such as dermal uptake or dust ingestion. The most harmful constituents for chronic exposure through inhalation are PM$_{2.5}$, acrolein, furan, acrylonitrile, 1,3-butadiene, acetaldehyde, isoprene, toluene, and benzene. Depending on how the transition from SHS to THS is arbitrarily established, exposure to THS can account for 5−60% of the total harm caused by exposure to tobacco-related pollutants indoors. These predictions have a high level of uncertainty because of the limited number of measurements, and thus, additional studies are required for a more accurate assessment of the health impacts of SHS and THS. In spite of the limitations of this model, this initial study provides important insights into the chemical composition of THS and preliminary estimates of the harm that may be caused through inhalation. Implementation of effective tobacco control policies and practices to mitigate the exposure of nonsmokers to THS in residences should consider their long-term persistence and contributions to health impacts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information
Supplementary figures and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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