Thirdhand Smoke: State of the Science and a Call for Policy Expansion

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Thirdhand smoke (THS) is the persistent residue generated from aged secondhand smoke (SHS) that adheres to indoor dust and surfaces and reemits into the air, which is of concern as a public health hazard.[1–4] Despite the recent emergence of THS research findings (compared with 40 years of SHS research),[5] available evidence supports making greater attempts to eliminate THS from public places and private residences/cars. We provide a brief overview of the current knowledge in this area and argue that THS should be considered in the development of smoke-free policies to reduce tobacco-related morbidity and mortality.[6]

FORMATION OF THIRDHAND SMOKE

Overall smoking prevalence in the United States has fallen to 17.8% from a high of 42.4% in 1965; however, the downward trend has decelerated, and 23% to 42% of adults with low education or living in poverty still smoke.[7] As a result, 22% of infants and children are exposed to SHS/THS in their homes each year, comprising a major proportion of the 126 million nonsmokers exposed to harmful tobacco products annually.[8] SHS exposure has borne much of the blame for smoking-related harm experienced by nonsmokers; however, projections estimate that 5% to 60% of this SHS-related harm may be attributable to THS exposure.[9] This reattribution of harm is due in part to recent understanding of THS's chemical properties, including exposure pathways (e.g., hand-to-mouth and dermal exposure experienced by children), the long-term-exposure profile (e.g., from in utero to the time a child leaves the home, for children conceived

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and living in smoking households), and remediation difficulties. Simply stated, THS exposure can take place during much longer time frames than SHS exposure, and THS components are difficult to remove from carpets, furniture, and surfaces, including walls, compared with SHS that is removed by ventilation.

Of special concern relative to THS is that nicotine and other post-combustion tobacco constituents can interact with other environmental chemicals to form new toxicants and carcinogens.[10–14] For example, carcinogenic tobacco-specific nitrosamines (TSNAs) can be formed when the common indoor pollutant, nitrous acid, comes into contact with nicotine.[13] One TSNA, called 4-(methylnitrosamino)-1-(3-pyridinyl)-1-butanone, is a potent lung-specific carcinogen ubiquitous in tobacco smoke and smokers' homes.[15] Another TSNA, 4-(methylnitrosamino)-4-(3-pyridyl) butanal, is an additional genotoxic compound formed from nicotine in the environment and is often found in THS but rarely in SHS or mainstream tobacco smoke.[16,17] Once formed, it can take months to years for these compounds in THS to dissipate.[18] Particulate matter from THS is repeatedly resuspended,[19] and volatile and semi-volatile compounds (i.e., compounds that easily evaporate or sublimate from liquid or solid form to gaseous form) in THS residue are slowly reemitted into the gas phase (off-gassing).[20] Also, other carcinogenic and mutagenic compounds, called polycyclic aromatic hydrocarbons, are formed during the incomplete burning of tobacco, and smokers homes' have been shown to have higher concentrations of these compounds in settled house dust.[10]

MEASUREMENT OF THS CONTAMINATION AND EXPOSURE

Residual nicotine accumulates after tobacco combustion and is a convenient proxy for other semi-volatile constituents that comprise THS. Various methods have been used to detect and characterize THS, including measuring nicotine found in dust, nicotine adsorbed to myriad indoor surfaces (e.g., walls and cabinets), and nicotine in air. Studies have found THS in cars, homes, and hotel rooms that ban indoor/in-car smoking,[11,20–24] and a recent investigation detected THS in a highly protected, smoke-free neonatal intensive care unit caring for medically fragile infants.[25] These data underscore THS's property to potentially off-gas or transfer from residue on smokers' hands, hair, clothes, and other objects (e.g., mobile telephones) and adsorb to new surfaces or environments (e.g., furniture).[11,13,14] Furthermore, research has demonstrated that nonsmoking adults who moved into homes previously occupied by smokers or stayed overnight in smoking-designated hotel rooms, have elevations of finger nicotine, urine cotinine (i.e., nicotine's primary metabolite), and urine metabolites of nicotine-derived tobacco-specific carcinogens,[11,23] demonstrating human exposure likely to be caused by THS contamination.

Findings for children are more troubling, as even in smoking households with indoor smoking bans, children have 5–7 times more nicotine exposure than those from nonsmoking households.[20] THS constituents in indoor dust and on surfaces can be ingested, inhaled, and absorbed dermally,[19,26] making children especially vulnerable to THS (e.g., due to activity near the ground and hand-to-mouth behaviors).[27] This exposure to nicotine and TSNAs (particularly for toddlers who frequently mouth household materials) may be up to seven and 16 times greater in THS, respectively, compared with passive SHS exposure, suggesting that THS may play a substantial role in health problems attributed to SHS exposure. Indeed, the lifecycle of SHS compared with THS is brief.[18]

THS REMEDIATION METHODS

Traditional cleaning methods may not adequately remove nicotine that adsorbs to indoor surfaces due in part to nicotine's ability to permeate all parts of enclosed environments, such as dust and air, porous building materials (e.g., sheetrock and drywall), doors, cabinets, curtains, furniture/upholstery, bedding/pillows/mattresses, clothing materials, and carpets.[11,14,28–30] Vacuuming and wiping may resuspend particles and fail to remove nicotine due to its ability to strongly adsorb to surfaces and penetrate materials.[28] For example, vacuuming and dashboard wiping were not associated with lower air-, surface-, or dust-nicotine levels in smokers' cars,[28] and THS was present weeks and months after smokers' homes were cleaned after smokers moved out.[11] This finding is not surprising, as 80% to 90% of combusted cigarette nicotine adsorbs to surfaces,[31] and nicotine may desorb or resuspend from non-cleaned surfaces and adsorb or redeposit elsewhere,[28] including previously cleaned surfaces. Carpets and sheetrock/drywall are especially challenging for these reasons. Aqueous remediation may be effective for removal of THS constituents from cotton, but less is known about other household/clothing materials.[18] We know of only one study (of tobacco harvesters at risk for "green tobacco sickness" [nausea, vomiting, headache, and dizziness] from dermal exposure) exploring handwashing for nicotine removal, and results showed incomplete hand-nicotine removal post handwashing.[32]

No research has explored the removal of nicotine from hands of smokers or those exposed to SHS/THS.

Research on outside smoking practices to reduce the amount of THS that enters homes and buildings is needed. For example, how far from open windows and doors and heating/air conditioning units should smokers stand to eliminate SHS and THS entry to a building? Also, a smoker can exhale particulate matter for up to 90 seconds after a final puff,[33] and, for up to 10 minutes after finishing a cigarette, the breath and clothing of smokers have higher concentrations of benzene (a carcinogenic solvent), toluene (a neurotoxic solvent), 2,5-dimethylfuran (a neurotoxic and cilatoxic substance [i.e., it adversely affects lung cilia in respiration]), and other toxic chemicals that then emit to the indoor air.[34] An outdoor, post-cigarette waiting period of 10 minutes before entering a building may reduce these forms of indoor air pollution.

THS-RELATED HARM AND PUBLIC HEALTH IMPLICATIONS

Children are the most susceptible to THS-related harm,[14,26,35] and as many as 3 million children younger than 6 years of age are estimated to be exposed to SHS/THS ≥4 days a week.[36] Exposed children tend to have more cough and sputum-related symptoms than non-exposed children;[1] however, the level of risk attributable to THS (vs. SHS) is unknown. In any indoor environment where people habitually smoke, nonsmokers will be exposed to SHS/THS, with exposure profiles ranging from chronic low-dosage to short-term high-dosage exposure.[9] Finally, it is possible that early-life exposure to nicotine may increase the risk of smoking initiation later in life. Research is needed to fully understand the risks of THS exposure.

Recent in-vitro assay and animal-model investigations have explored mechanisms of THS-related harm, and these mechanisms include DNA damage,[16] altered fibroblast migration involved in wound healing,[37] and impaired respiratory development in unborn, premature rat fetuses.[38] TSNAs have also been linked to pancreatic cancer in experimental models with rodents and human pancreatic duct assays.[39] Animals exposed to THS have shown increased lung collagen production, upregulated inflammatory cytokines, and down-regulated anti-inflammatory cytokine activity, which are findings often seen in respiratory disease processes (e.g., asthma).[40] Similar to SHS exposure,[41] THS exposure may contribute to epithelial cell apoptosis and microbiome alteration.

FUTURE CONSIDERATIONS

THS exposure may contribute acutely and/or chronically to poorer health outcomes across many populations. The decades-long public health-led legislative effort to reduce and eliminate nonsmokers' exposure to SHS has achieved measurable improvements to human health,[5,42] such as reduced risks for preterm births.[43] However, the pervasive nature of THS poses a challenge to the same underlying problem of SHS exposure: unwanted, unsafe exposure to tobacco-related contamination.

No safe level of SHS exposure[8] exists, and definitive THS thresholds for harm have not been established. Specifically, acute and chronic human exposure levels and associated health risks are difficult to quantify, due to the comingling of SHS and THS, the myriad substances comprising THS, and the difficulty in isolating the unique contributions of THS exposure to long-term health outcomes. These methodological challenges make it difficult to establish public standards for "safe" levels of THS exposure. The limit of detection for surface nicotine is defined as the lowest quantity of a substance distinguishable from the absence of the substance (e.g., 0.1 micrograms per square meter [$\mu g/m^2$] for surface nicotine).[22,44] The designation of environments as smoke-free/THS-contaminated should be made empirically[45] based on the importance and expense of correct-and-false identification. For example, in cars, a value of ≥ 0.14 $\mu g/m^2$ (surface nicotine) correctly classified 82% of smokers' cars that did not have smoking bans, and 100% of nonsmokers' cars were below this level.[44] Until we have further information, we suggest using these thresholds (or lower thresholds in protected medical settings) as a starting point to guide further policy, research on health risks, and remediation efforts. This guidance is similar to advice from the Centers for Disease Control and Prevention for individuals with asthma to avoid THS-contaminated environments.[46]

The data we cited raise a host of issues, including the difficulty of quantifying nonsmokers' cumulative THS exposure. Similar to quantifying traditional cigarette usage (e.g., years of smoking), a measure to quickly and accurately determine a person's lifelong exposure to THS would be meaningful clinically and in research. This measure could incorporate estimates related to growing up in a smoke-free or smoking household, whether in-home/in-car smoking occurred, frequency of working in environments where smoking was permitted, and other potential exposures to THS. Future work is needed to understand the potential for exposure and health consequences for those who

come in contact with THS. Further, the rising use of electronic nicotine delivery systems (e.g., e-cigarettes that heat up a nicotine solution and flavoring agents to be inhaled as vapor), which are widely perceived to be "safer" alternatives to traditional cigarettes among cigarette users,[47–49] are very likely to contribute new sources of THS, nicotine, and other chemical contaminants. These devices are still relatively new, with recent rises in prevalence,[50,51] and data on their contributions to THS are lacking. Nicotine emitted through e-cigarette use (i.e., thirdhand nicotine) is likely to age and interact with other pollutants in a similar fashion to nicotine from traditional cigarettes. Attitudes toward regulating e-cigarettes similarly to traditional cigarettes are mixed, and a survey of adult smokers found that support for restricting their indoor use may be as low as 41%.[52] Some devices have been shown to contain other contaminants in e-cartridges,[53] and allowing e-cigarettes to be used indoors undermines the social norm of not smoking, thereby contributing to public health concerns.[54,55]

CONCLUSIONS

We believe all individuals, especially children, have the universal, human right to live in an environment free of nicotine- and tobacco-derived carcinogenic/toxicant matter, pursuant to the United Nations' Article 25 of The Universal Declaration of Human Rights.[56] Given what is known (e.g., toxicity in THS from animal/in-vitro studies), we call attention to the "precautionary principle" of risk management[57–60] and "extended producer responsibility."[61] The precautionary principle, which is a "strategy to cope with possible risks where scientific understanding is yet incomplete," is widely used in Europe[62] and in radiation protection in the United States.[63] Extended producer responsibility promotes total-lifecycle environmental improvements, placing economic, physical, and informational responsibilities onto the tobacco industry. A strong case can be made for plausible risk of harm due to THS. By extension of the precautionary principle and the extended-producer-responsibility principle,[61] the burden of proof falls on the tobacco industry to demonstrate that THS is not harmful to individuals and groups for both acute and cumulative exposures. This approach is especially important because of the relatively long persistence of THS in indoor environments and limited effective means of cleaning.

We encourage the scientific community to support greater efforts to eradicate all forms of tobacco exposure, through further research and policy development targeting THS reduction. Efforts to further reduce SHS/THS exposure may ultimately reduce tobacco-related diseases[1,64] and preserve the health of nonsmoking adults and children.[55]

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