Electronic cigarette chemicals transfer from a vape shop to a nearby business in a multiple-tenant retail building

Careen Khachatoorian,[1] Peyton Jacob III,[2] Neal L Benowitz,[3] Prue Talbot[4]

[1]Cell Molecular and Developmental Biology Graduate Program, University of California, Riverside, California, USA
[2]Division of Clinical Pharmacology, University of California, San Francisco, California, USA
[3]Departments of Medicine, Psychiatry and Bioengineering and Therapeutic Sciences, University of California, San Francisco, California, USA
[4]Department of Molecular, Cell and Systems Biology, University of California, Riverside, California, USA

Correspondence to
Dr Prue Talbot, Department of Molecular, Cell and Systems Biology, University of California, Riverside, Riverside, CA 92521, USA; talbot@ucr.edu

ABSTRACT

Background Electronic cigarettes (ECs) are nicotine delivery devices that produce aerosol without combustion of tobacco; therefore, they do not produce sidestream smoke. Nevertheless, many users exhale large clouds of aerosol that can result in passive exposure of non-users. Analogous to thirdhand cigarette smoke, the exhaled aerosol also settles on indoor surfaces where it can produce a residue. We refer to this residue as EC exhaled aerosol residue (ECEAR). Our objective was to determine if exhaled EC aerosol transferred from a vape shop in a multiple-tenant retail building, where it was produced, to a nearby business (field site) where it could deposit as ECEAR.

Methods We examined the build-up of ECEAR in commonly used materials (cotton towel and paper towels) placed inside the field site across from the vape shop. Materials were subjected to short-term (days) and long-term (months) exposures. Nicotine, other alkaloids and tobacco-specific nitrosamines (TSNAs) were identified and quantified in controls and field site samples using analytical chemical techniques.

Results Nicotine and other alkaloids were detected after 1 day of exposure in the field site, and these chemicals generally increased as exposure times increased. TSNAs, which have been linked to carcinogenesis, were also detected in short-term and long-term exposed samples from the field site.

Conclusions In a multiple-tenant retail building, chemicals in EC aerosol travelled from a vape shop into an adjacent business where they deposited forming ECEAR. Regulatory agencies and tenants occupying such buildings should be aware of this potential environmental hazard.

INTRODUCTION

Electronic cigarettes (ECs) deliver nicotine in an aerosol that is produced by heating a fluid containing a solvent, for example, 1,2-propanediol (propylene glycol, PG) and/or glycerol (vegetable glycerin, VG), nicotine and flavour chemicals.[1–4] EC aerosols also contain volatile organic compounds (VOCs), including carbonyls, and metals.[5–10] EC users may exhale large quantities of aerosol that contains nicotine,[11–14] and the exhaled aerosol forms a residue on indoor surfaces,[15 16] in much the same way that thirdhand smoke (THS) forms indoors after secondhand smoke has settled.[17 18] We refer to EC exhaled aerosol residue as ECEAR. Both the exhaled aerosol and ECEAR can result in passive exposure of non-users, and these exposures are a growing environmental and health concern.

Several toxicants including formaldehyde, acetaldehyde and acrolein are created by the oxidation and/or dehydration of VG or PG, and have been reported in EC aerosol.[5 19 20] Significant amounts of 1,2-propanediol, glycerin, nicotine and $PM_{2.5}$ particles were present indoors during 2 hours of vaping.[21] Moreover, an indoor air quality study showed that a large room with active EC users contained $PM_{2.5}$ at concentrations that were higher than in hookah cafes and bars that allow cigarette smoking.[22] Studies done inside the homes of EC users showed airborne nicotine levels of $0.13\,\mu g/m^3$, in contrast to non-smokers' homes which had $0.02\,\mu g/m^3$.[23] In the same study, salivary cotinine concentrations were significantly higher in non-smokers living in a home where ECs were used than in non-smokers living in non-smokers' homes. EC users, as well as bystanders who do not use ECs, can be exposed to the chemicals and particles in suspended EC aerosols, therefore the International Union Against Tuberculosis and Lung Disease has recommended that ECs should not be used in public places, workplaces or on public transportation.[24] A surface sampling study of indoor environments where vaping occurred showed that ECEAR contained nicotine, although concentrations were not as high as in the homes of cigarette smokers.[15] Passive exposure to nicotine and other chemicals in ECEAR could occur through dermal absorption, ingestion or the inhalation of re-emitted chemicals.

In vape shops, multiple EC users exhale aerosols that could potentially move through the heating, ventilating and air conditioning system (HVAC) to adjacent businesses. The purpose of this study was to determine if tobacco-specific chemicals in the aerosol from an active vape shop transferred into a nearby business in a multiple-tenant retail building (mall) by examining deposition of nicotine and nicotine derivatives in the nearby business.

METHODS
Collection of fabrics

Cotton towels (Easydry, www.easydry.com), paper towels (Bounty, Stater Bros. Riverside, California, USA), terrycloth towels (Jo-Anne Fabric and Craft Stores, Riverside, California, USA) and two air filters (3M high performance $20\times25\times1$ Filtrete air filter (www.amazon.com) and Rabbit Air Classic BioGS Replacement HEPA filter (www.amazon.com)) were placed in the field site for short-term or long-term exposures. The area of 1 g of each fabric is: terrycloth towel $5.5\,cm\times4.75\,cm$ ($26.125\,cm^2$), air filter $10.5\,cm\times9.5\,cm$ ($99.75\,cm^2$), paper towel

15.5 cmx13 mm ($201.5\,cm^2$) and cotton towel 13.5 cmx12.5 cm ($168.75\,cm^2$). Short-term exposure samples were collected after 1 day (24 hours), 4 days (96 hours) and 8 days (192 hours), while long-term exposure samples were collected after 1, 2 and 3 months. Mall control fabrics (terrycloth towel) were exposed in a hallway on a separate HVAC system outside the field site for 1 day (24 hours), 3 days (72 hours) and 1 week. Additional control samples of fabrics (terrycloth towels) were collected from a non-smoker home in the same community after exposure for 1 day (24 hours), 4 days (96 hours) and 1 week. Control samples inside the non-smoker home were placed inside the front room of the house and in the garage. Unexposed samples of each type of fabric (cotton towels, paper towels, terrycloth towels and both air filters) were also used as controls. After exposure, samples were placed in Ziploc bags and/or envelopes and either extracted immediately or stored at −80°C in heat-sealed, cut to size, Mylar bags (ULINE, Pleasant Prairie, Wisconsin, USA).

Extraction of nicotine, other alkaloids and tobacco-specific nitrosamines (TSNAs) from ECEAR fabrics

ECEAR was extracted from controls and ECEAR exposed samples of cotton towel, paper towel, terrycloth towel and air filters. Fabrics were cut into small pieces and immersed into cell culture medium consisting of Dulbecco's Modified Eagle Medium containing 10% fetal bovine serum (Sigma-Aldrich, St Louis, Missouri, USA), 5% horse serum (Invitrogen, Carlsbad, California, USA), 1% sodium pyruvate (Lonza, Walkersville, Maryland, USA) and 1% penicillin–streptomycin (GIBCO, Invitrogen, Carlsbad, California, USA)[25 26] at a concentration of 0.05 g of fabric/mL of medium. This mix was agitated in 50 mL Falcon tubes on a rocker for 1 hour at room temperature.[27] The contents of the tubes were extruded through a 30 mL plastic syringe (Sigma-Aldrich, St Louis, Missouri, USA) to obtain only the medium. The extracts were then filtered using 0.22 µm sterile filters (Pall, Port Washington, New York, USA) and aliquoted into 1.5 mL vials for storage at −80°C and later shipped on dry ice to the Clinical Pharmacology Laboratory at the University of California at San Francisco.

Chemical analysis of ECEAR fabrics for nicotine, other alkaloids and tobacco-specific nitrosamines

The quantification of nicotine, nicotine derivatives and tobacco-specific nitrosamines (TSNAs) was done by liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) at the University of California San Francisco. Sample prep has been described previously.[27–29] The samples were analyzed on a Thermo Scientific Vantage LC–MS/MS with an Accela UPLC system using a 3 × 150 mm 2.6 µm Phenomenex Kinetex PFP column. An ammonium formate methanol solvent system was held isocratic at 15% methanol for 2 min and then increased to 85% methanol over 7 min. The flow rate was 0.67 ml/min and the column temperature was 50°C. The ion transitions were monitored using the Xcalibur 'Easy Method' software using 1-min retention time windows with a cycle time of 0.3 s. The LOQ was determined as the lowest calibration standard for which back-calculated values were within ±20% of the expected concentration .[27–29] The limits of quantification for each chemical were as follows: nicotine=2 ng/mL, cotinine=1 ng/mL, n-formylnornicotine=1 ng/mL, bipyridine=1 ng/mL, nicotelline=0.2 ng/mL, myosmine=1 ng/mL, N-nitrosoanatabine (NAB)=1 ng/mL, 4-(methylnitrosamino)−1-(3-pyridyl)−1-butanone (NNK)=0.1 ng/mL, N'-nitrosonornicotine (NNN)=0.1 ng/mL, N-nitrosoanatabine (NAT)=0.2 ng/mL,
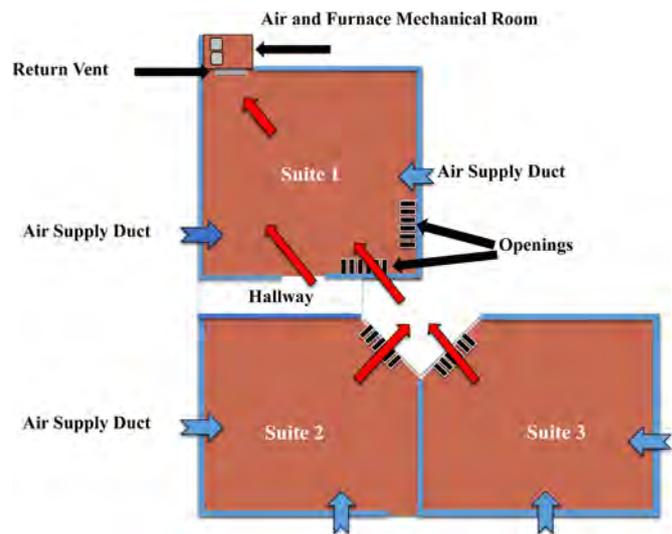
Figure 1 Map of the field site in the mall and airflow between suites. A return vent, located at the back of suite #1, intakes air (red arrows) from the surrounding spaces creating negative pressure inside suite #1. Air can enter suite #1 through the door and also through openings in the upper portion of the front and side walls. Air is redistributed to the three suites through vents (blue arrows) from the air and furnace mechanical room located in the back of suite #1.

1-(N-methyl-N-nitrosamino)−1-(3-pyridinyl)−4-butanal (NNA)=1 ng/mL.

RESULTS
Field site

The field site was located on the basement floor of a two-story mall in a metropolitan area. The commercial building was over 50 years old. The field site for this study included the three basement suites shown in figure 1. Suite #1 was an actively operated shop, and the site where the cotton fabrics, paper towels and filter samples were placed for collection of ECEAR. The Filtrete air filter was placed in the return vent towards the back of suite #1 while the Rabbit air filter was placed in the middle of the suite. Suite #3 was an active vape shop that blends and manufactures refill fluids which they sold in the store and online. The vape shop allowed vaping inside the shop and had a bar and lounge where customers could try out ECs or refill fluids. Suite #2 was a shop that was seldom used during the course of our study. Approximate dimensions of suite #1, suite #2 and suite #3 were 398 ft^2 (37 m^2), 405 ft^2 (37 m^2), 311 ft^2 (28 m^2), respectively.

The air intake to the building was from an adjacent alley. The HVAC system for the suites was a gas-forced air furnace located in a mechanical room in the back of suite #1 (figure 1). All suites had supply ducts in the floor, but only suite #1 had a return vent which drew air from all three suites into the mechanical room. Each suite also contained storefront screen partitions that allowed the air from suites #2 and #3 to enter the return vent in suite #1. Air pulled through suite #1 was recirculated to the three suites through the air supply ducts in the floor. There were no dedicated exhaust systems for any of the suites.

The furnace in the mechanical room was produced by International Comfort Products (Lewisburg, Tennessee, USA) and the manufacturer's model number was GNE150J20A. Air flow through the field site was approximately 39.67-48.39 m3/min . The air filter in the return vent was a 3M Filtrete healthy living

Table 1 Samples and exposure dates

Cotton towel			Paper towel		
	Sample	Exposure date		Sample	Exposure date
Short term	SF 1D	March 5, 2014	Short term	SF 1D	March 5, 2014
	SF 1D	March 15, 2015		SF 4D	March 1, 2014–March 5, 2014
	SF 4D	March 1, 2014–March 5, 2014		SF 4D	March 15, 2014–March 19, 2014
	SF 10D	January 27, 2015–February 6, 2015		SF 8D	March 7, 2014–March 15, 2014
Long term	SF 28D	January 27, 2015–February 24, 2015	Long term	SF 18D	February 6, 2015–February 24, 2015
	SF 35D	January 31, 2015–March 7, 2015		SF 28D	January 27, 2015–February 24, 2015
	SF 31D	March 7, 2015–April 7, 2015		SF 30D	March 15, 2014–April 15, 2014
	SF 31D	March 7, 2015–April 7, 2015		RV 59D	February 2014–April 2014
	SF 74D	October 1, 2014–December 13, 2014		SF 61D	May 2014–July 2014
	Filter A 181D	February 2014–August 2014		RV 61D	May 2014–July 2014
	Filter B 365D	April 2014–April 2015		RV 74D	October 1, 2014–December 13, 2014
				SF 75D	August 1, 2014–October 15, 2014

RV, return vent; SF, store front. The 3M Filtrete is labelled as Filter A while the Rabbit air filter is labelled as Filter B.

air filter (50.8 cm (length) x 63.5 cm (width) x 2.54 cm (depth)), which was made of polypropylene. The basement also had a locked thermostat in the hall that controlled the furnace in the mechanical room.

Table 1 summarises the types of samples collected from the field site (suite #1) and their exposure dates. All short-term and some long-term samples were exposed at the front top openings of suite #1 in the field site, while some long-term samples were exposed at the back near the return vent (figure 1).

Nicotine, other alkaloids and TSNAs detected in suite #1 ECEAR samples

Nicotine, other alkaloids and TSNAs were detected in ECEAR extracts of cotton towels (figure 2) and paper towels (figure 3) from suite #1. Nicotine was the most abundant marker of EC aerosol contamination in suite #1 (figures 2A,B and 3A,B) (highest concentration=23,260 ng/g of fabric). Nicotine was present in extracts of both short-term and long-term samples of cotton towel, paper towel and terrycloth towel, and its concentration generally increased with exposure time (figures 2A,B and 3A,B). Even samples exposed for only 1 day had detectable amounts of nicotine (eg. paper towel exposed for 1 day had 154 ng of nicotine/g of paper towel). Both air filter A and air filter B had high concentrations of nicotine (figure 2B). Control samples of paper towels and terrycloth towels exposed both in the home of a non-smoker and in the mall had no detectable nicotine except for a low level (107 ng/g and 93 ng/g) in two samples (online supplementary table 1).

Several tobacco alkaloids (cotinine, nicotelline, N-formylnornicotine, 2,3'-bipyridine and myosmine) were found in ECEAR extracts from suite #1, and their concentrations generally increased as exposure time increased (figures 2C–L and 3C–L). The alkaloids were found more frequently in paper towel extracts than in cotton towel, and their concentrations were generally higher in paper towel samples. The air filters appeared to trap nicotine and the alkaloids, except for 2,3' bipyridine and myosmine which were not detected in the filter samples.

TSNAs were found in many of the paper towel extracts and in some of the terrycloth towel samples (figures 2M–T and 3M–T). When TSNAs were found in the cotton towel extracts, concentrations were generally higher after long-term exposure (figure 2M–T). In paper towel samples, NNK and NNN tended to increase with long-term exposure, while NAT and NAB were only present in the short-term paper towel samples

(figure 3Q–T). Both NNK and NNN were detected in air filter A, but not in air filter B (figure 2N). NNA was analysed but not found in any of the samples.

The frequency with which chemicals appeared in paper and cotton samples is given in online supplementary table 2. Almost all samples contained nicotine. Cotinine, nicotelline, NNK and NNN were detected more frequently in paper towels than in cotton towels. N-formylnornicotine, 2,3'-bipyridine, myosmine, NAT and NAB appeared with about equal frequency in cotton towels and paper towels. Both air filters contained nicotine, cotinine, nicotelline and n-formylnornicotine. However, they did not contain 2,3 bipyridine, NAT and NAB. Air filter A did contain myosmine, NNK and NNN, while air filter B did not.

DISCUSSION

Our results demonstrate that EC aerosols generated in a vape shop can travel into a nearby business where they deposit on surfaces forming ECEAR. In our field site, this likely occurred because air circulated from suites #2 and #3 (vape shop) to suite #1, where samples were collected. The ECEAR in suite #1 contained nicotine, other alkaloids and nitrosamines, consistent with it originating in the vape shop. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, environmental tobacco smoke (ETS) includes emissions produced by electronic smoking devices,[30] and air should not recirculate or transfer from an ETS area to an ETS-free area (5.17.5). The transfer of exhaled EC aerosol to suite #1 may have been avoided or reduced if each suite had its own air distribution system. Since many types of HVAC systems are currently in buildings worldwide, the possibility of transfer of EC chemicals to businesses near vape shops should be addressed in building codes and regulated.

Our conclusion regarding the transfer of exhaled EC aerosols to a nearby business is based mainly on finding chemicals known to be present in EC aerosols in suite #1, but not in the mall away from suite #1 or in the control home. Nicotine and other alkaloids have been found in EC liquids and aerosols[31] and in exhaled EC aerosols.[11] The chemical markers did not come from cigarette smoke as smoking had been banned in the mall since 2009 (Public Act 188, www.michigan.gov). TSNAs have been reported in both refill fluids[32] and EC aerosols,[5] and those found in the field site may have originated in the aerosol and/or formed after deposition in suite #1 through interconversion of nicotine, as described previously for THS.[33] Laboratory studies have
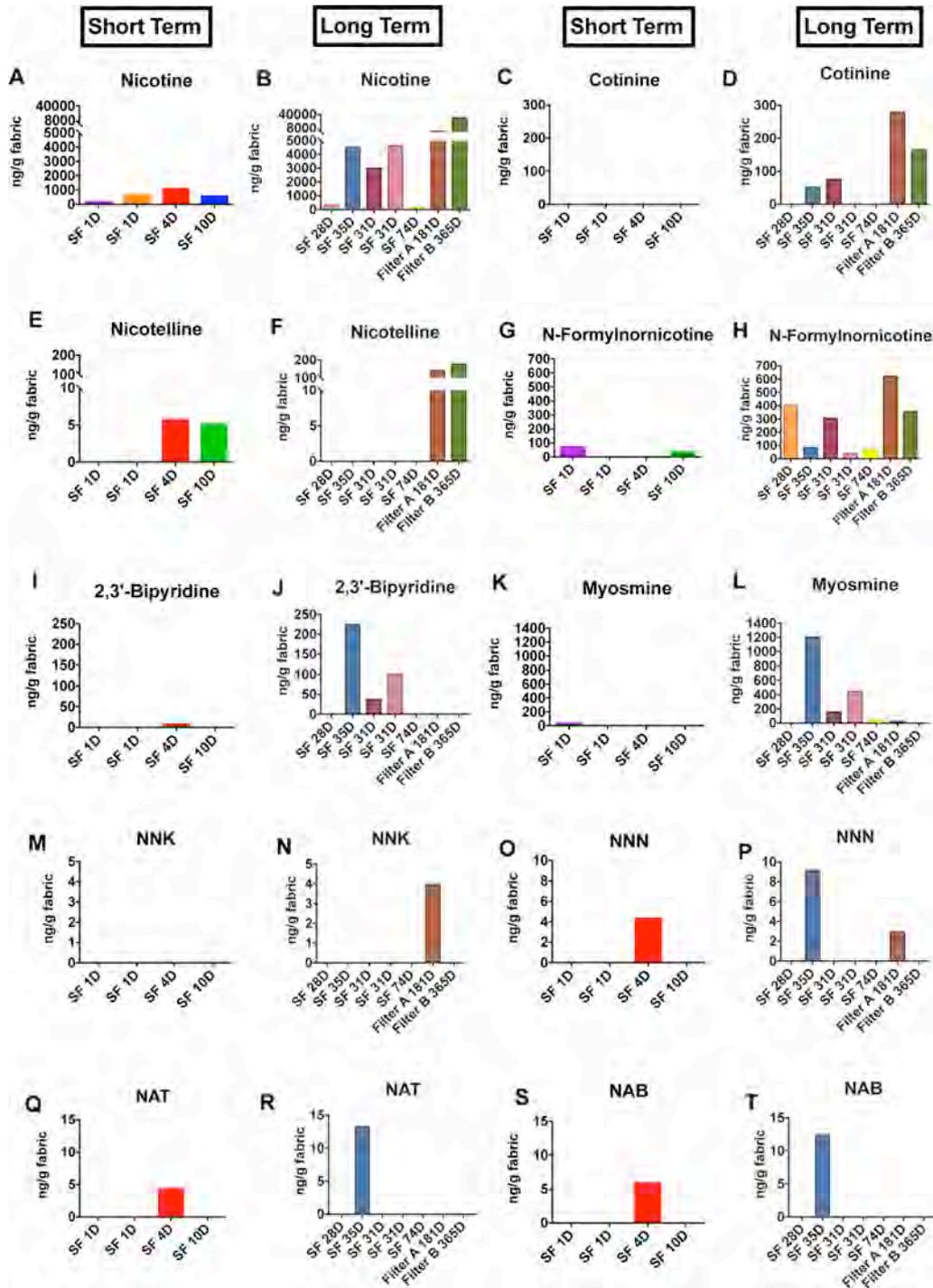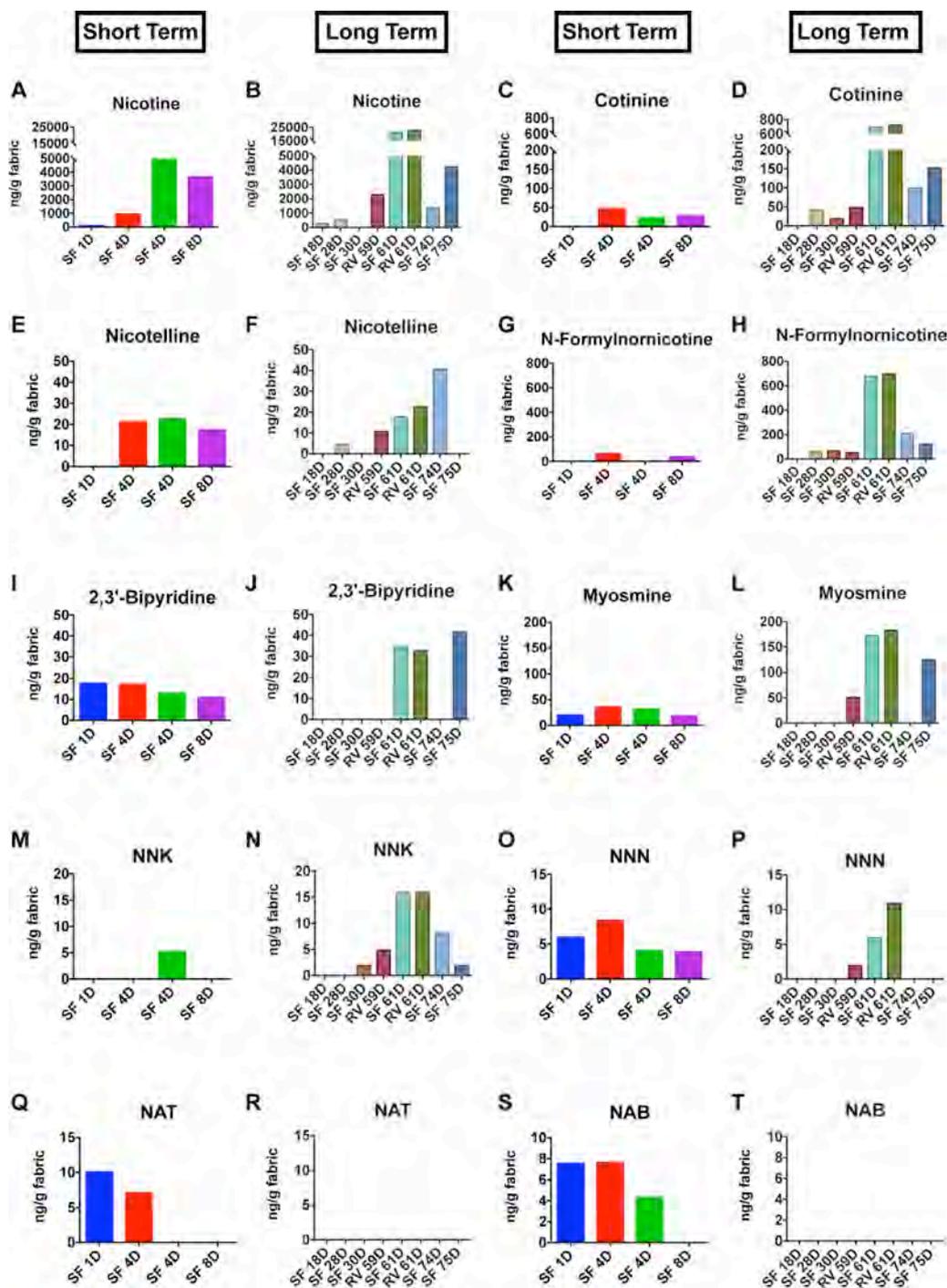
Figure 2 Concentrations of nicotine, nicotine alkaloids and TSNAs in cotton towels and air filters from the field site. Short-term versus long-term samples are shown for each sample collected from the field site. Nicotine (A–B), cotinine (C–D), nicotelline (E–F), n-formylnornicotine (G–H), 2,3'-bipyridine (I–J), myosmine (K–L), NNK (M–N), NNN (O–P), NAT (Q–R), NAB (S–T). Air Filter A=3M Filtrete air filter. Air Filter B=Rabbit Air HEPA filter. NAB, N-nitrosoanatabine; NAT, N-nitrosoanatabine; NNK, 4-(methylnitrosamino)−1-(3-pyridyl)−1-butanone; NNN, N'-nitrosonornicotine; SF, store front; TSNA, tobacco-specific nitrosamine.

shown that 93%–99% of the inhaled nicotine in EC aerosols is retained in the lungs by EC users,[14][34] but the extent of nicotine exhalation depends on the user's propensity to produce clouds of aerosol. In our real world study, nicotine generated by vape shop occupants reached suite #1 and contributed to ECEAR.

The 3M Filtrete air filter and Rabbit Air HEPA filter, which were in the field site for 6 months and 1 year, respectively, picked up nicotine, cotinine, nicotelline and n-formylnornicotine, and

the 3M Filtrete also trapped NNK and NNN. Concentrations of the chemical markers in these filters were likely higher than in the paper towel and terrycloth towel samples due to their longer exposure period. These data suggest that filtering air helps reduce exposure to nicotine and its' alkaloids, but several chemicals (2,3' bipyridine and myosmine) were not trapped in either filter. Our study did not determine the efficiency with which these filters removed the chemical markers; however, ECEAR

Figure 3 Concentrations of nicotine, nicotine alkaloids and TSNAs in paper towels from the field site. Short-term versus long-term samples are shown side by side for each sample collected from the field site. Nicotine (A–B), cotinine (C–D), nicotelline (E–F), n-formylnornicotine (G–H), 2,3′-bipyridine (I–J), myosmine (K–L), NNK (M–N), NNN (O–P), NAT (Q–R), NAB (S–T). NAB, N-nitrosoanatabine; NAT, N-nitrosoanatabine; NNK, 4-(methylnitrosamino)−1-(3-pyridyl)−1-butanone; NNN, N′-nitrosonornicotine; RV, return vent; SF, store front; TSNA, tobacco-specific nitrosamine.

clearly collected on our cotton towel and paper towel samples before air circulated through the filters.

ECEAR chemicals in suite #1 could be internalised passively through dermal contact and/or inhalation. Ingestion could also occur if a toddler mouthed fabrics or surfaces in suite #1. Nicotine, the most abundant chemical we detected in ECEAR, is water and lipid soluble. It readily permeated an in vitro skin model exposed to refill fluids containing nicotine, even when the period of dermal contact with refill fluids was short (10 min).[35] [36] Research into dermal uptake of nicotine from

contact with ECEAR in realistic scenarios, such as the one in this study, is needed. VOCs, which are present in EC aerosols[8] [37] and were found in ECEAR,[38] could be passively inhaled. Acrolein and formaldehyde have been reported in EC aerosols[39] and likely contributed to ECEAR, although we did not analyse them in this study. Inhalation of these and related VOCs would be a concern given their known toxicity.[40] [41]

While EC refill fluids can produce cytotoxic effects in vitro[42–44] and adverse health effects have been reported in EC users,[45–47] the effects of exposure to ECEAR chemicals on human health

are not yet known. The concentrations of these chemicals are likely much higher in the vape shop, but those chemicals reaching suite #1 could build up over time. After 35 days in the field site, a cotton towel collected 4.571 µg of nicotine. If a toddler mouthed on $0.3\,m^2$ or about $1\,ft^2$ of cotton fabric from suite #1, they would be exposed to 81.26 µg of nicotine. Surface wipes measuring indirect exposure to cigarette smoke inside households, where smokers only used cigarettes outside the home, contained about 3.2 µg of nicotine/per $0.3\,m^2$ at the average of the mean nicotine level per household,[48] indicating greater transfer of nicotine from the vape shop to suite #1 than to the household with indirect cigarette smoke exposure.

Others have shown that secondhand tobacco smoke also settles on indoor surfaces and forms THS.[18 48] While the health effects of THS are not fully known, it does have toxicity both in vitro and in mice.[25 28 49 50] Further monitoring of ECEAR and its health effects would be important in the future.

The data collected in this study pertains to a specific commercial vape shop and may not be generalisable to multiple-tenant residences or to vape shops in malls with alternative HVAC systems. ECEAR was not measured on all surfaces in the field site, and its extraction may vary with different surfaces.

Store owners and tenants of malls should be aware that EC aerosols from nearby vape shops can enter their units and deposit as ECEAR. Chemicals in ECEAR include nicotine, minor alkaloids and TSNAs, the latter of which are potential carcinogens. Passive and unwanted exposure to these chemicals could occur through dermal contact, ingestion or inhalation. The identification of chemicals, their concentrations and their secondary products in ECEAR will be a necessary first step towards understanding the health and environmental effects of ECEAR. Building codes will need to be developed and enforced to protect those who do not wish to be exposed to ECEAR. Vape shop air quality is not currently regulated nor has it been thoroughly studied. Regulatory agencies should exercise authority over malls to ensure that employees and tenants do not receive unwanted exposure to EC aerosols and its residues.

What this paper adds

► Similar to thirdhand smoke (THS) EC exhaled aerosols can settle on surfaces producing a residue.
► EC exhaled aerosol residue (ECEAR) containing nicotine, other alkaloids and tobacco-specific nitrosamines was detected and quantified in a business adjacent to a vape shop.
► ECEAR was detected after only 1 day and generally increased over time.
► ECEAR is a potential environmental hazard that should be evaluated for regulation.

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