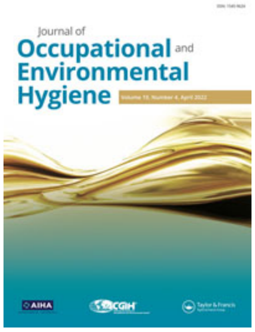

Journal of Occupational and Environmental Hygiene

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uoeh20

Assessment of worker chemical exposures in California vape shops

Kathleen R. Attfield, Marley Zalay, Leonard M. Zwack, Eric K. Glassford, Ryan F. LeBouf & Barbara L. Materna

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2022, VOL. 19, NO. 4, 197–209
https://doi.org/10.1080/15459624.2022.2036341

Assessment of worker chemical exposures in California vape shops

Kathleen R. Attfield[a], Marley Zalay[b], Leonard M. Zwack[c], Eric K. Glassford[c], Ryan F. LeBouf[d], and Barbara L. Materna[e]

[a]Environmental Health Investigations Branch, California Department of Public Health, Richmond, California; [b]Public Health Institute, Oakland, California; [c]Hazard Evaluations and Technical Assistance Branch, National Institute for Occupational Safety and Health, Cincinnati, Ohio; [d]Field Studies Branch, Respiratory Health Division, National Institute for Occupational Safety and Health, Morgantown, West Virginia; [e]Occupational Health Branch, California Department of Public Health, Richmond, California

ABSTRACT

E-cigarettes are battery-operated devices that heat a liquid mixture to make an aerosol that is inhaled, or vaped, by the user. Vape shops are retail environments designed to fulfill customer demand for diverse e-liquid flavors and hardware options, which create unique worker exposure concerns. To characterize exposures to vape shop workers, especially to flavoring chemicals associated with known respiratory toxicity, this study recruited vape shops from the San Francisco Bay Area. In six shops, we measured air concentrations for volatile organic compounds, formaldehyde, flavoring chemicals, and nicotine in personal and/or area samples; analyzed components of e-liquids vaped during field visits; and assessed metals on surface wipe samples. Interviews and observations were conducted over the course of a workday in the same six shops and interviews were performed in an additional six where sampling was not conducted. Detections of the alpha-diketone butter flavoring chemicals diacetyl and/or 2,3-pentanedione were common: in the headspace of purchased e-liquids (18 of 26 samples), in personal air samples (5 of 16), and in area air samples (2 of 6 shops). Two exceedances of recommended exposure limits for 2,3-pentanedione (a short-term exposure limit and an 8-hr time-weighted average) were measured in personal air samples. Other compounds detected in the area and personal air samples included substitutes for diacetyl and 2,3-pentanedione (acetoin and 2,3-hexanedione) and compounds that may be contaminants or impurities. Furthermore, a large variety (82) of other flavoring chemicals were detected in area air samples. None of the 12 shops interviewed had a health and safety program. Six shops reported no use of any personal protective equipment (PPE) (e.g., gloves, chemical resistant aprons, eye protection) and the others stated occasional use; however, no PPE use was observed during any field investigation day. Recommendations were provided to shops that included making improvements to ventilation, hygiene, use of personal protective equipment, and, if possible, avoidance of products containing the alpha-diketone flavoring chemicals. Future research is needed to evaluate the long-term health risks among workers in the vape shop retail industry and for e-cigarette use generally. Specific areas include further characterizing e-liquid constituents and emissions, evaluating ingredient health risks, evaluating the contributions of different routes of exposure (dermal, inhalation, and ingestion), and determining effective exposure mitigation measures.

KEYWORDS
E-cigarette; e-liquid; flavorings; occupational exposures; vaping

Introduction

E-cigarettes are battery-operated devices that heat liquid mixtures (e-liquids), creating an aerosol that is inhaled, a process commonly referred to as vaping. E-liquids generally contain nicotine and flavoring chemicals dissolved in vegetable glycerin and/or propylene glycol, and the avoidance of tobacco combustion is one of the potential product draws. However, use of e-cigarettes has grown among both smoking and nonsmoking young adults and youth. Concerns exist for nonsmokers entering nicotine dependence with the use of e-cigarettes and transitioning to combustible tobacco use (CDPH 2015). In youth surveys in the United States, prevalence of frequent use doubled between 2017 and 2019 (Hammond et al. 2020), with estimates of current e-cigarette users in high school of 3.0 million in 2020 (19.6%) (Wang et al. 2020). Adult use in 2019 reached 4.5% in the United States (Cornelius et al. 2020). In California, current e-cigarette

CONTACT Kathleen Attfield kathleen.attfield@cdph.ca.gov Environmental Health Investigations Branch, California Department of Public Health, 850 Marina Bay Parkway, Richmond, CA 94804, USA.

Supplemental data for this article is available online at https://doi.org/10.1080/15459624.2022.2036341. AIHA and ACGIH members may also access supplementary material at http://oeh.tandfonline.com.

use in 2019 was 4.2% for adults and 12.9% for young adults (CHIS 2020), with 8.2% of high school youth reporting recent use in 2019–2020 (Zhu et al. 2021). While research is ongoing, initial evidence indicates potential links of e-cigarette use with addiction, cardiovascular effects, and inflammatory responses in the lungs (CDPH 2015; Gerloff et al. 2017; D'Amario et al. 2019; Li et al. 2020; Quinones Tavarez et al. 2020).

Assessments of e-liquid and e-cigarette emissions have examined ingredients including propylene glycol, glycerin, and nicotine; products of thermal breakdown or other reactions; and contaminants released from the devices themselves. Formaldehyde, acetaldehyde, and acrolein are thermal breakdown products of propylene glycol and/or glycerin observed in e-cigarette emissions (Hutzler et al. 2014; Kosmider et al. 2014; Klager et al. 2017; Wang et al. 2017). Other volatile organic compounds (VOCs), such as benzene and acrolein, may similarly arise in vape emissions as reaction products or as contaminants in flavoring formulations (LeBouf et al. 2019; Li et al. 2020). Metals liberated from heating filaments or present as contaminants in e-liquid, such as cadmium, nickel, lead, and arsenic, have been detected in e-liquids and aerosols (Fowles et al. 2020).

E-cigarette users are often drawn to e-cigarettes because of the wide variety of flavorings (Rostron et al. 2020). While many flavoring chemicals have been evaluated for safety as additives in foods and beverages, few have adequate inhalation safety data. Diacetyl and 2,3-pentanedione are two flavoring chemicals that came to attention initially for their buttery or creamy flavor use in popcorn production and their lung-damaging properties (Hubbs et al. 2019). Concerns about their use in e-cigarette flavors are acknowledged in the e-cigarette user community and by some manufacturers (Farsalinos et al. 2015), but widespread detection in e-liquids is common (Farsalinos et al. 2015; Allen et al. 2016; Klager et al. 2017; LeBouf et al. 2018). Only a few studies have investigated the presence of flavorings in indoor air impacted by vaping (NIOSH 2017a, 2018a).

Vape shops have emerged as a retail environment to serve customer demand for diverse e-liquid flavors and hardware options. Additionally, they are an environment for customer socialization, illustrated by the presence of TVs, couches, and vape cloud-making contests (Sussman et al. 2016). In 2019, it was estimated that almost 20% of the e-cigarette market was processed through vape shops in the United States (Truth Initiative 2020). In many vape shops, customers can sample e-liquids available for purchase (Sussman et al. 2016). Exhalations of e-cigarette users have been observed to impact indoor air quality (van Drooge et al. 2019), and the few studies of vape shops observed increased particulate matter, aldehydes, and nicotine concentrations (Nguyen et al. 2019; Son et al. 2020; Li et al. 2021) and tracked VOCs and flavoring compounds (NIOSH 2017a, 2018a). In addition to workplace exposures from customer emissions, workers can be at risk for dermal and ocular exposures from in-house mixing of e-liquids (Garcia et al. 2016; NIOSH 2017a, 2018a) or device customization or repair.

To further characterize exposures to workers in this growing industry, especially to exposures from flavoring chemicals, this study recruited vape shops from the San Francisco Bay Area to identify work practices and shop characteristics that may put workers at elevated risk. We measured air concentrations for VOCs, formaldehyde, flavoring chemicals, and nicotine in personal and/or area samples; analyzed components of e-liquids; assessed metals on surfaces; and performed interviews and observed work practices over the course of a workday.

Methods

Shop recruitment

To recruit shops specializing in vaping devices and e-liquids in the nine-county San Francisco Bay Area, a list of vape shops was compiled from information provided by Stanford Prevention Research Center (T. Johnson, Stanford University, personal communication, July 2015), marketing data (Data Axle 2016), and internet searches (using terms such as "vape," "e-cig," "electronic cigarette," "shops," "stores," and cities and towns of the San Francisco Bay Area). Recruitment priorities included: use of vape devices in the shop, varied geographic distribution, moderate to high customer traffic, multiple staff scheduled per day, range of physical shop sizes, and diversity of work tasks, such as custom mixing of e-liquids. In-person initial visits were conducted to evaluate criteria, recruit participants, and obtain informed consent for participation. Six shops were selected for field investigations and six more for onsite interviews only. Of the 117 shops evaluated, 13 had closed, 65 were not good candidates or deemed lower priority, 8 declined, and a further 19 were visited and in consideration when our maximum number of shops for the study was met. No major differences were noted between shops that declined and those that participated, other than one shop owner that declined being concerned about neighboring exposures (car exhaust) impacting study results. The study protocol was approved by the California Health and Human Services Agency Committee for the Protection of Human Subjects.

Field investigations protocol

Field investigations were conducted over single full business days between November 2016 and January 2017. Two to four investigators were present to monitor equipment and conduct observations and interviews. Air samples were collected to represent general area and personal worker exposures, and to evaluate short-term exposures. Area air sampling equipment was co-located at a central location on shop counters, visible to customers but not obstructing business tasks (see online supplementary materials, Figure 1). Area samples ran for the duration of the visit based on shops' business hours (7.25–11.8 hr). Personal samples were collected in the workers' breathing zones for the duration of their shifts (3–11 hr) (supplementary Figure 2). To avoid asking participants to wear more than three devices, more chemicals were monitored with area samples than personal samples. Surface wipe samples from commonly touched surfaces were collected at end of business day. For later laboratory analysis, the e-liquids purchased were those observed most frequently used by customers and staff. Investigators recorded notes on work tasks, ventilation conditions including use of fans and open doors, qualitative air quality appearance (haziness), and customer traffic. A tally of puffing counts by workers and customers was maintained by study staff over the course of the observation period. Participants were interviewed using structured questionnaires designed for employers and employees to collect data on work practices, use of personal protective equipment (PPE), chemical use, ventilation, symptoms, and perceptions of the vape industry.

Air sampling

Personal and area formaldehyde concentrations were measured using UMEX-100 (DNPH treated) passive sampling badges (SKC, Inc.) according to OSHA Method 1007 (OSHA 2005). Area air samples for nicotine were collected with XAD-4 tubes with a flow rate of 200 cubic centimeters per minute (cc/min) following NIOSH Method 2551 (NIOSH 1998).

Personal, area, and short-term samples for the flavoring chemicals diacetyl, 2,3-pentanedione, 2,3-hexanedione, and acetoin (here termed "buttery flavoring chemicals," though uses extend beyond this description) were collected using two silica gel tubes in series with pumps calibrated to 50 cc/min. Multiple samples were collected for full-shift and area air samples (up to 3 hr and aggregated to reflect the entire sampling period). These samples were analyzed according to OSHA Method 1013 and 1016 (OSHA 2008, OSHA 2010) using an alternate detector during analysis to increase method sensitivity (LeBouf and Simmons 2017).

Personal and area air samples for VOCs were collected with fused-silica lined, 450-milliliter (mL) evacuated canisters equipped with a restricted flow controller set to collect at 0.31 cc/min via NIOSH method 3900 (NIOSH 2018b). At the time of sampling, this method was validated for these VOCs: acetone, alpha-pinene, benzene, chloroform, d-limonene, ethanol, ethylbenzene, methyl methacrylate, methylene chloride, toluene, *m,p*-xylene, n-hexane, and *o*-xylene (LeBouf et al. 2012). To qualitatively screen for a wide range of VOCs, multi-bed thermal desorption (TD) tubes (Carbopack Y, Carbopack B, and Carboxen 1003) were used, attached to pumps calibrated to 50 cc/min for up to 3 hr according to NIOSH Method 2549 (NIOSH 1996).

Area air samples were collected and analyzed for glycidol for the duration of shop open hours using charcoal tubes (SKC 226-01, SKC, Inc., Eighty-Four, PA) according to NIOSH Method 1608 (NIOSH 1994). Real-time area samples for carbon dioxide (CO_2), carbon monoxide, relative humidity, and temperature were measured using a TSI VelociCalc (TSI, Inc., Shoreview, MN) during the entire visit.

Surface wipe sampling for metals

Two to four work surfaces were sampled per shop to measure metals according to NIOSH Method 9102 (NIOSH 2003). Palintest pre-moistened wipes were used to systematically wipe a surface within a 100 centimeters squared (cm^2) template and analyzed according to NIOSH Method 7303 (NIOSH 2003). Surfaces sampled included customer counters and sampling areas, e-cigarette device building surfaces, and display cases.

E-liquid analyses

Three to five e-liquids frequently vaped during each visit were purchased for headspace analysis. VOCs that volatilized from e-liquid at room temperature over 24 hr were transferred to evacuated canisters and analyzed with gas chromatography/mass spectrometry (GC/MS) (LeBouf et al. 2018).

Table 1. Characteristics of six vape shops and indications of ventilation adequacy on field investigation days.

Shop	Participants working in the shop	Customers who vaped in the shop	Approximate hourly average vape puff rate for customers and participants	Observation time (hr)	Ventilation conditions	Carbon dioxide range (ppm)	Carbon dioxide average (ppm)
A	2	12	31	8	No HVAC system. Door was open the majority of the day.	320–880	370
B	2	8	33	8	HVAC system not used. Door open for a couple of hours during the day, but remained closed the majority of the day.	530–2100	1300
C	2	5	29	8	HVAC system on the automatic setting all day. Door closed all day.	820–2200	1300
D	4	7	180	10	HVAC system on the automatic setting all day. Door closed all day.	810–1900	1200
E	5	20	130	13	HVAC system not in use. Two doors open the majority of the day creating a cross-draft.	440–1100	600
F	5	24	160	12	HVAC system not in use. Door open for approximately the second half of the day.	620–1600	870

HVAC: Heating, ventilation, and air conditioning.

Results

Shop descriptions and conditions

Twelve San Francisco Bay Area vape shops participated in this study. Six received a full-day visit including employee and manager/owner interviews, air and surface wipe sampling, and observations. An additional six shops received onsite interviews with managers/owners only. Shops participating in field visits ranged from 200 to 350 square feet in retail areas, with many attached to one or more adjacent businesses (Table 1). Field visits spanned the entire business day, ranging from 8–12 hr with 2–5 shop staff working.

Common work tasks observed included selling and restocking products, assisting customers in sampling e-liquid varieties and sampling e-liquids themselves, cleaning, and preparing shipments for shops with online sales. In each of two shops, a staff member performed tricks (creating rings, clouds, and other designs with vape exhalations) and two staff members advised on device issues. While areas were set aside in some shops for fixing devices, few building and fixing activities occurred during visits (three times in one shop and once in another). In a single shop, one owner was observed mixing custom e-liquids and one employee dispensing custom-mixed e-liquid into smaller bottles (Supplementary Figures 3 and 4). At no time was any PPE observed in use (gloves, chemical resistant aprons, eye protection, etc.) in any of the shops when staff worked with devices or e-liquids. Staff were observed placing food on work surfaces and eating food at their workstations.

Vaping by staff and customers was permitted in all field visit shops (and 5 of 6 interview-only shops) and customer sampling of e-liquids for a fee was permitted in 10 of 12 shops. All staff vaped throughout their shifts. Customers generally sat at stools across a counter from staff while sampling e-liquids or recreationally vaping; no shops had a separated vaping area. About a quarter of customers vaped in the shops (5–24 vaping customers/shop) with an approximate hourly average puff rate range of 31–180 for all persons vaping in the shop (Table 1).

Hazy indoor air conditions were observed periodically in all field visit shops. One shop had no heating, ventilation, and air conditioning system (HVAC), but used open doors or ceiling fans to increase airflow (Table 1). Two shops relied solely on HVAC systems for ventilation and the remaining supplemented the HVAC with open doors and/or fans for part or all of the day. CO_2 levels were greater than the level considered an indicator of adequate ventilation (1,000 ppm or higher depending on outdoor concentrations) periodically in five shops and on average in three shops, though maximum levels remained below NIOSH-recommended and OSHA occupational exposure limits (OELs) of 5,000 ppm (ASTM International 2018; OSHA 2020).

Air monitoring

Area air samples were co-located in central locations of each shop, with one large shop receiving two area samples. Sixteen participants (2–4 per shop) wore personal air samplers for formaldehyde and specific flavoring chemicals, and 14 also wore an evacuated canister sampler for VOCs (images available in Supplementary Figures 1–2).

Nicotine was detected in four shops (five of seven area samples) and all personal samples. These concentrations were below OELs, with a maximum concentration of 0.26 ppb (Table 2). Formaldehyde was detected in all samples, with a maximum concentration of 34 ppb. Other VOCs frequently detected included ethanol (all area and personal samples);

Table 2. Full-shift area and personal air sampling results in six vape shops.

	Area samples[a]		Personal samples		Occupational Exposure Limits	
	Detection frequency	Maximum (ppb)	Detection frequency	Maximum (ppb)	Cal/OSHA PEL (ppb)	NIOSH REL (ppb)
Formaldehyde	6/7	31	16/16	34	750	16
Nicotine	5/7	0.26	NA	NA	75	75.4
VOCs[b>]						
Acetaldehyde	2/7	24	3/14	19	25,000	Ca
Acetone	2/7	45	13/14	100	500,000	250,000
Acetonitrile	5/7	82	6/14	7.5	40,000	20,000
Ethanol	7/7	1900	14/14	1800	1,000,000	–
d-Limonene	2/7	(7.6)	3/14	(4.4)	–	–
Methylene chloride	1/7	(1.0)	3/14	(4.8)	25,000	Ca
m,p-Xylene	1/7	0.9	6/14	(3.7)	100,000	100,000
o-Xylene	0/7	ND	2/14	(2.2)	100,000	100,000

[a]One shop was monitored with two area sampling locations.
[b]Chemicals not in table include those below the LOQ in both area and personal evacuated canisters (ethyl benzene, n-hexane, and toluene) and those below the Minimum Detectable Concentration (MDC) for both (benzene, chloroform, methyl methacrylate, alpha-pinene, and styrene).
NA = not applicable, Ca = carcinogen with minimal exposure recommended, but no quantitative risk management limit for a carcinogen (RML-CA) yet determined (NIOSH 2017b). Values between the Minimum Detectable Concentration (MDC) and Minimum Quantifiable Concentration (MQC) indicated with parentheses.

Table 3. Air sampling results for buttery flavoring chemicals using silica gel tubes.

	Area samples		Personal samples (3–8.2 hr)		Short-term personal task sample (19 min) concentration (ppb)
Chemical	Detection frequency	Maximum (ppb)	Detection frequency	Maximum (ppb)	
Diacetyl	3/7	0.84	4/16	(0.71)	ND
2,3-Pentanedione	3/7	28	4/16	31[a]	53[b]
2,3-Hexanedione[c]	0/7	ND	0/16	ND	ND
Acetoin[c]	3/7	9.5	2/16	10.4	16.5

[a]One measurement exceeded NIOSH Recommended Exposure Limit of 9.3 ppb.
[b]One measurement exceeded NIOSH Short-Term Exposure Limit of 31 ppb.
[c]No established occupational exposure limit
ND = not detected. Values between the MDC and MQC indicated with parentheses.

acetone (13 of 14 personal samples); and acetonitrile (5 of 6 shops and almost half of personal samples). Other VOCs were detected in fewer shops: acetaldehyde, limonene, methylene chloride, *m,p*-xylene, and *o*-xylene. All VOC levels fell below applicable OELs (individual measurements available in Supplementary Tables 1–4).

Air monitoring for the buttery flavoring chemicals indicated the presence of diacetyl and 2,3-pentanedione in two shops (three area samples) and five personal samples (Table 3, Supplementary Tables 5 and 6). One full-shift personal sample indicated a level of 2,3-pentanedione (31 ppb) exceeding the NIOSH Recommended Exposure Limit (REL) of 9.3 ppb. In the same shop, a short-term task sample collected during a custom mixing task by a different person in a separated area had a level (53 ppb) exceeding the NIOSH short-term exposure limit (STEL) of 31 ppb. Acetoin was detected in this shop's area and personal sample as well as in one other shop, in the low ppb range. In all, three personal samples had two or more detections of these buttery flavoring chemicals.

Screening methods using TD tubes detected a large variety of other possible flavoring chemicals in shop area samples. Eighty-two flavoring chemicals were identified in one or more shops and 13 were detected in all six: acetaldehyde, acetic acid, decanal, ethyl acetate, ethyl butyrate, ethyl methyl butyrate, hexanal, isoamyl acetate, isobutyl acetate, isopropyl myristate, d-limonene, menthone, and vanillin (Supplementary Table 7). An additional 12 possible flavoring chemicals were found in five shops, including benzaldehyde, menthol, methyl cinnamate, and nonanal.

E-liquids

Headspace analysis of 26 purchased e-liquids frequently indicated buttery flavoring chemicals—diacetyl was in 17 products and 2,3-pentanedione in 7 (Table 4). Nineteen products had one or more of diacetyl, 2,3-pentanedione, and 2,3-hexanedione. Limonene and alpha-pinene were found in 19 and 13 e-liquids, respectively. Several carcinogens were detected: acetaldehyde and methylene chloride in four products each and benzene in two.

Surface wipe samples

In the 18 surface wipe samples taken from work surfaces throughout the six shops, low levels (<0.5 μg/

Table 4. Volatile organic compounds (VOCs) detected in purchased e-liquids (N = 26 products) using headspace analysis.

Flavor type	Diacetyl	2,3-Pentanedione	2,3-Hexanedione	Acetaldehyde	Acetone	Acetonitrile	Benzene	d-Limonene	Ethanol	Ethyl benzene	Isopropyl alcohol	Methyl methacrylate	Methylene chloride	Toluene	alpha-Pinene	m,p-Xylene	o-Xylene	# of VOCs detected[a]
Strawberry, lychee menthol								X	X						X			3
Watermelon, fruit, menthol								X	X		X		X		X			5
Strawberry, kiwi, fruit, menthol	X							X	X						X			3
Strawberry	X	X							X									3
Strawberry, guava	X						X	X	X						X			5
Strawberry	X	X		X				X	X									5
Strawberry, coconut cream									X									1
Strawberry, vanilla cream	X	X							X		X							4
Milky fruit cereal									X									1
Vanilla cream, tobacco	X	X		X	X			X	X		X				X			8
Salted caramel, coffee	X	X					X	X	X						X			6
Crème brûlée					X	X		X	X		X							5
Peanut butter and jelly		X							X									2
Mango, pineapple	X							X	X						X			4
Mango			X					X	X				X		X			5
Cantaloupe, mango, papaya	X							X	X	X		X		X		X	X	8
Fruit cocktail	X				X				X		X							4
Honeydew, fruits	X							X	X									3
Blueberry									X									1
Mint mojito	X	X			X			X	X						X			6
Limeade	X			X				X	X						X			5
Orange creamsicle	X							X	X						X			4
Raspberry, cherry	X							X	X									3
Peach				X				X	X									3
Cinnamon toast, caramel	X							X	X				X		X			5
Cinnamon, sugar, milk	X							X	X				X		X			5
# of e-liquids containing each VOC (out of 26):	17	7	1	4	4	1	2	19	26	1	5	1	4	1	13	1	1	

[a]Chloroform, styrene, and n-hexane were not detected in any e-liquid samples.

100 cm^2) of the 31 metals tested were detected. Surfaces where current or former building activities occurred (e.g., assembling and repairing vape devices, making coils, replacing other device components) had higher levels of detected metals than other work surfaces within individual shops (Supplementary Table 8). Nickel was detected on 13 surfaces (72%) in six shops; chromium on 10 surfaces (55%) in five shops; and aluminum on surfaces in all shops except one.

Interviews

Interviews were conducted with one owner and/or manager from each of the 12 shops and one to four employees from the six field visit shops (total = 12 employers and 16 employees). Few employees reported receiving formalized health and safety training, though employees from four of six shops reported some instruction on nicotine safety. No owner reported having an Illness and Injury Prevention Program (a regulatory requirement in California). Only one employer reported keeping Safety Data Sheets onsite, and most employees noted use of internet searches to supplement their knowledge of products and product safety. However, many noted knowledge gaps on specific chemical compounds in the e-liquids beyond propylene glycol, vegetable glycerin, and nicotine. When asked whether they had any concerns about the vape shop retail industry, of the 28 interviewed, five participants mentioned ventilation issues, 10 mentioned e-liquid ingredients of concern and/or lack of information on vape emission components, and two mentioned concerns about cleanliness of (other) vape shops. Employees' main concerns for the safety of their customers and other vapers were battery safety and user error.

Almost all participants (27 of 28) reported regular e-liquid contact with their hands during work tasks. However, many participants reported low concern about dermal exposures due to the nicotine concentrations in e-liquids mostly encountered in the shop (3 or 6 mg/mL). Exposure to the mouth was also reported, though mostly from personal vaping ("spit-back" or when hot e-liquid is expelled into the mouth). Eye exposure was reported to have occurred a few times (by 4 of 28 participants). Of the three shops that conducted custom e-liquid mixing onsite, two employers reported restricting this task to themselves to limit employee exposure to concentrated nicotine.

About half of those interviewed (12 of 28) reported that PPE, such as gloves, was not used, and five viewed it as unnecessary. Fifteen participants reported access to and occasional use of nitrile or latex gloves for cleaning tasks, building activities, mixing e-liquids, or handling concentrated nicotine. Some employees reported occasionally using gloves when handling customers' vape devices or e-liquids. When asked about other types of PPE, participants reported using aprons (one participant), goggles (three participants), and/or a dust mask (two participants), but only rarely and in the context of mixing, dispensing, or cleaning after mixing e-liquids.

The majority of participants reported no symptoms associated with working, such as cough, shortness of breath, chest tightness, or skin irritation. Three participants reported experiencing lightheadedness after skin or respiratory exposure to highly concentrated nicotine, including rinsing nicotine containers with hot water. Skin irritation (burning or rashes) after skin exposure to e-liquid (citrus or cinnamon flavors) or nicotine concentrates was reported by participants in two shops. One participant reported feeling groggy at the end of days when shop doors had been closed.

Several participants reported symptoms they associated with their personal vaping, such as dry mouth, drowsiness (from nicotine wearing off), thirst, greater frequency of urination, nausea after vaping (attributed to nicotine), and throat irritation after vaping lemon-flavored e-liquid. Many reported improved respiratory symptoms, which they attributed to cessation of tobacco cigarette use.

All employees and employers reported current vaping, and most stated they vaped more at work than in other settings such as home or school (81% of employees and 67% of employers). Some work-related reasons reported for vaping included learning about new products, creating a welcoming environment, demonstrating use of the devices, and personal reasons of socializing and as a pastime. Fifteen of 16 employees reported they were ex-tobacco users (tobacco cigarettes, chewing tobacco, or hookah).

Discussion

This study aimed to investigate potential occupational exposures in San Francisco Bay Area vape shops to multiple chemicals associated with e-cigarettes and e-liquids. The flavor family representing creamy, buttery flavors, which have known respiratory toxicity, was specifically targeted for investigation. Employer and employee interviews were conducted to reveal more about this emerging industry and work environment. Notably, diacetyl and 2,3-pentanedione were detected in many sample types: area air samples, personal air samples, and in the headspace of the majority of purchased e-liquids. This is the first study to measure an exceedance of both the short-term NIOSH REL as well as the 8-hr time-weighted average REL for 2,3-pentanedione in a vape shop. Substitutes for these compounds such as acetoin and 2,3-hexanedione were also detected, as well as a large variety of other flavorings and compounds that may be contaminants or impurities.

In our sampled e-liquids, the high frequency of diacetyl detections (65%) was similar to other studies of purchased e-liquids, while 2,3-pentanedione was found in lower frequency (27% in our study vs. 45% and 74%, Allen et al. (2016) and Farsalinos et al. (2015), respectively). When including 2,3-hexanedione, e-liquids frequently (73%) contained at least one compound with the reactive alpha-dicarbonyl chemical structure implicated in diacetyl's toxicity to lung tissue (Hubbs et al. 2019). Additionally, acetoin was detected in several area and personal air samples and while this buttery flavoring chemical appears to be used as a less toxic alternative or supplement to diacetyl use, it has also been shown to be associated with diacetyl generation in e-liquids (Vas et al., 2019). NIOSH has RELs for diacetyl and 2,3-pentanedione because of their association with bronchiolitis obliterans in workers and observed airway epithelial necrosis and airway fibrosis post-exposure in rodents (NIOSH 2016; Hubbs et al. 2019). However, OELs do not yet exist for other buttery flavoring chemicals (including other alpha-diketones), but since chemicals with similar chemical structures to diacetyl can have a combined negative effect on the respiratory system (NIOSH 2016; Hubbs 2019), exposure should be limited. Avoidance of diacetyl and 2,3-pentanedione will likely be difficult in the current market since these chemicals are components of a wide range of flavors beyond the predicted buttery-, caramel-, and creamy-flavored e-liquids, e.g., fruit flavors (this study, Klager et al. 2017; LeBouf et al. 2018; Azimi et al. 2021). Even e-liquids and flavorings purported to lack them have had diacetyl detected (Allen et al. 2016; LeBouf et al. 2019).

Few other flavoring compounds have been quantified in indoor vaping environments. The probable human carcinogen acetaldehyde (IARC 1999) is a food flavoring with cherry characteristics but can also be a thermal breakdown product of propylene glycol and glycerin (Hutzler et al. 2014; Klager et al. 2017). Similar acetaldehyde levels to our findings were observed in NIOSH health hazard evaluations at three vape shops (NIOSH 2017a, 2018a), though a three-fold drop after business hours in a separate vape shop study has been observed (Son et al. 2020). d-Limonene was frequently detected in our purchased e-liquids and by LeBouf et al. (2018), while this chemical conveys citrus characteristics, it can act as a respiratory irritant with sensitizing properties (ACGIH 2017). Similar airborne levels were observed in two occupational studies (NIOSH 2017a, 2018a) and higher levels compared with studies where volunteers vaped in an observation room (Schober et al. 2014; O'Connell et al. 2015). Cleaning products can also be a source of limonene in indoor air.

Looking broadly at other airborne flavoring chemicals in air, several were identified with ingredients designated by the Flavoring and Extract Manufacturing Association (FEMA) as "high priority" flavoring chemicals that "may pose potential respiratory hazards when improperly handled" (FEMA 2012). Besides diacetyl and 2,3-pentanedione, these included acetaldehyde, benzaldehyde, and furfural. The latter two were also detected by NIOSH in Texas vape shops (NIOSH 2018a). The lower-priority FEMA flavors, three chemicals (ethyl acetate, isoamyl acetate, and isobutyl acetate) that were detected in all shops were also detected in the Texas study. Four more low-priority compounds were seen in 1–3 shops (cinnamaldehyde, isopropyl formate, methyl acetate, and butyl acetate) but not noted elsewhere. Eleven of the flavoring VOCs identified here have also been observed in prior e-liquid chemical analyses (Hutzler et al. 2014; Tierney et al. 2016). While many flavoring chemicals are considered "Generally Recognized as Safe" by the U.S. Food and Drug Administration (FDA) for food and beverage products, this designation does not consider inhalation safety. Exposures to aldehydes, including acetaldehyde, pose a concern because of associations with health effects including upper respiratory tract and eye irritation (Tierney et al. 2016; ACGIH 2017). Though few flavoring chemicals have been assessed for inhalation toxicity, *in vitro* studies are indicating cell toxicity, cell membrane damage, reactive oxygen species production, and inflammatory cytokine release from flavoring chemicals such as cinnamaldehyde, vanillin, nonanal, ethyl maltol, diacetyl, and 2,3-pentandione (Gerloff et al. 2017; Muthumalage et al. 2017; Morris et al. 2021).

As a thermal decomposition product of propylene glycol, formaldehyde is often tracked in e-cigarette emissions studies. Area and personal air formaldehyde levels found in this study were comparable with three other vape shops and a vaping convention (NIOSH 2017a, 2018a, Johnson et al. 2018), though lower than in a recent vape shop study (Son et al. 2020). While three personal air measurements here and one in the Texas shops exceeded the NIOSH REL, they are generally similar to concentrations found in other indoor environments including offices (CARB 2004; Lemen 1987; NIOSH 2019). Studies where volunteers vaped in a room showed similar or lower formaldehyde levels (Schober et al. 2014; O'Connell et al. 2015; Maloney et al. 2016; Liu et al. 2017; Melstrom et al. 2017; Van Drooge et al. 2019; Oldham et al. 2021). Another potential breakdown product of glycerin is glycidol, a probable carcinogen (IARC 2000), which has been observed in a laboratory emissions study (Sleiman et al. 2016) but not detected in this study. The study did not include sampling methylglyoxal, a breakdown product of propylene glycol that has recently been observed to cause respiratory epithelial necrosis at concentrations lower than diacetyl (Hubbs et al. 2019; Azimi et al. 2021). Excepting ethanol, other VOCs (xylenes, methylene chloride, acetonitrile, acetone) were at low ppb levels (<1% of OELs), comparable with other studies (O'Connell et al. 2015; Maloney et al. 2016; Liu et al. 2017; NIOSH 2017a, 2018a; Johnson et al. 2018; Van Drooge et al. 2019; Oldham et al. 2021).

This study identified lower nicotine levels than in both NIOSH occupational studies (also below the Cal/OSHA PEL), and similar to other vape shop and mock scenario studies (Ballbè et al. 2014; Schober et al. 2014; O'Connell et al. 2015; Maloney et al. 2016; Liu et al. 2017; Melstrom et al. 2017; Khachatoorian, Jacob, Sen et al. 2019; Son et al. 2020; Li et al. 2021; Oldham et al. 2021). While not sampled here, thirdhand exposures of accumulated nicotine and its transformation products including carcinogenic tobacco-specific nitrosamines, have been detected on surfaces and materials in a vape shop or neighboring establishment (Khachatoorian, Jacob, Benowitz et al. 2019; Khachatoorian, Jacob, Sen et al. 2019; Son et al. 2020).

Detectable levels of some metals, e.g., chromium and nickel, on surfaces here were consistent with other occupational studies (NIOSH 2017a, 2018a). Metals have been detected in tests of vaping aerosols and e-liquids and mostly ascribed to contributions from heating filaments (Williams et al. 2013; Mikheev et al. 2016; Williams et al. 2017; Fowles et al. 2020). Metal exposures from vaping, especially to nickel and chromium, raise concerns for respiratory irritation, allergic responses, and increased cancer risk (Fowles et al. 2020).

PPE use was not observed in this study though half of those interviewed cited occasional use of gloves at other times. In the NIOSH vape shop studies, mixing tasks were more frequently performed and also more frequent glove use observed (NIOSH 2017a, 2018a). Almost all of our participants reported regular e-liquid exposure to their hands while in the Texas NIOSH study, only one individual had regular skin exposure and others occasional (NIOSH 2018a). In a survey of 77 vape shop staff in Los Angeles, the majority reported access to safety equipment such as gloves but about 65% still reported dermal contact with nicotine-containing e-liquids (Garcia et al. 2016). In both the Texas NIOSH study and our study, few respiratory symptoms were reported, as well as one or more eye splashes and some skin and eye irritation associated with flavorings (cinnamon and citrus) (NIOSH 2018a). Only participants in our study mentioned light-headedness from handling concentrated nicotine. Similar to our study, few participants of the LA survey (17%) reported safety training, including on handling of nicotine, despite frequent spills. Resultant dermal, ocular, and ingestion exposures from spills and splashes might lead to irritation and sensitization from some flavorings but also acute nicotine poisoning (ACGIH 2017; NIOSH 2017a). Nicotine is quickly absorbed through the skin, within 3–5 min if not washed off (Zorin et al. 1999), underscoring the need for proper PPE and cleaning procedures, especially if e-liquid mixing is occurring. We recommend education for shop owners and workers regarding appropriate use of protective gloves (e.g., nitrile) and eye protection (e.g., chemical splash goggles) when handling bulk e-liquids or nicotine and when mixing e-liquids.

Participants received reports of findings along with health and safety recommendations including increased hand washing hygiene and provision of protective gloves. For shop owners, information stressed developing an Injury and Illness Prevention Program consistent with Cal/OSHA requirements (8 Cal. Code Regs. §3203). Based on common observations, procedures should include regular cleaning of shop surfaces, avoiding eating at work counters, and acquiring more information on e-liquid ingredients and quality control testing from manufacturers, especially to guide reduction of use of diacetyl and 2,3-pentanedione. Although not specifically recommended to participating shops as a policy they should adopt, limiting or eliminating staff personal vaping and/or customer vaping could also assist in lower exposure levels of many compounds.

With hazy conditions common, elevated CO_2 levels, and several shops with limited ventilation options, we recognized a need for improved ventilation. Although contaminant air concentrations varied among shops, a clear pattern between ventilation conditions, puffing rates, and measurements was not apparent, likely due to the interplay of different factors (store dimensions, HVAC settings or use, product type, etc.). CO_2 levels served as a crude indicator of inadequate ventilation but did not warrant further analysis. We recommended HVAC systems be professionally evaluated for optimization. In shops with limited ventilation options, opening doors and windows might increase fresh air introduction and air exchanges. Other studies of vape shops also indicated the need for ventilation improvement, especially after similarly observing workers opening doors and windows for this purpose (Son et al. 2020; Li et al, 2021). Ventilation efforts can also impact workers in adjacent businesses. In a study where neighboring businesses documented airborne nicotine transfer (Li et al., 2021), the authors observed that opening doors reduced particle counts in the neighboring business.

A limitation of this study is that findings are based on a small sample of shops and from single sampling days. It is not possible to draw extensive conclusions from these limited results, or to state they are representative of the entire vape shop industry. With variations in different environmental factors (outdoor weather, ventilation, and vaping patterns of occupants), exposures could be higher or lower on different days. Since our measurement of chemicals in bulk e-liquids, in air, or on surfaces primarily reflects vaping products used that day or recently, participants could be exposed to a wider range of chemicals of concern. Additionally, these measurements will not reflect what people directly inhale from a vape device since sampling reflects chemicals present in the general shop air or worker breathing zones; first-hand vaping would add to the secondhand exposures measured by our protocols.

Since initiation of this study, the e-cigarette market has greatly expanded, and the vape shop industry has been subject to many market and regulatory influences including impacts from the COVID-19 pandemic on customers' shifting use and purchasing habits and allowed operations (Sussman et al. 2016; Levy et al. 2019; Berg et al. 2021). E-cigarette products were deemed tobacco products by both the FDA and California law in 2016 (81 FR 28973, Electronic

Cigarettes Act 2015). Updated California indoor smoking prohibitions related to vaping in 2016 and local regulations should translate to fewer vaping exposures in California workplaces, though vaping is still permitted in retail and wholesale tobacco (and vape) shops (CA HSC Section 104559.5). Vape shops may be further impacted by bans on flavored tobacco products, currently enacted in over 100 localities of California, while the 2020 statewide ban is on hold preceding an upcoming ballot initiative referendum (Campaign for Tobacco Free Kids 2021; Gardiner 2021).

Conclusions

This study examined many potential chemical exposures in a vape shop worker environment, detecting some exceedances of NIOSH RELs for diacetyl and 2,3-pentanedione. We identified areas where safety improvements may be warranted that include improving ventilation; limiting exposures to flavoring ingredients with recognized potential respiratory effects; and addressing workplace safety through an Injury and Illness Prevention Program that would include hazard identification, effective controls, surface cleaning, staff training, and use of appropriate PPE. More research is needed to evaluate long-term health risks in the vape shop retail industry and for e-cigarette use generally; specific areas include further characterizing e-liquid constituents and emissions, evaluating ingredient health risks, evaluating the contributions of different routes of exposure (dermal, inhalation, and ingestion), and determining effective exposure mitigation measures.

Acknowledgments

We would like to acknowledge the contributions of staff from NIOSH: field staff Stephen Jackson, field support staff Donnie Booher and Kevin Moore, and laboratory analysis assistance by Anand Ranpara and Dru Burns. We would also like to acknowledge the assistance of the following CDPH staff in the conception and planning of the study: Rick Kreutzer, Jefferson Fowles, Kazukiyo Kumagai, Ping Wang, and Wenhao Chen.

Funding

This study was partially funded by the California Cigarette & Tobacco Products Surtax Fund, Research Account. The authors would like to acknowledge the support of the NIOSH Health Hazard Evaluation Program and Field Studies Branch. Onsite technical assistance and laboratory support were provided by NIOSH.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention or the views or opinions of the California Department of Public Health or the California Health and Human Services Agency.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

ORCID

Kathleen R. Attfield http://orcid.org/0000-0001-9264-5399
Ryan F. LeBouf http://orcid.org/0000-0002-9894-9251
Barbara L. Materna http://orcid.org/0000-0003-2033-3884

References

Allen JG, Flanigan SS, LeBlanc M, Vallarino J, MacNaughton P, Stewart JH, Christiani DC. 2016. Flavoring chemicals in e-cigarettes: diacetyl, 2,3-pentanedione, and acetoin in a sample of 51 products, including fruit-, candy-, and cocktail-flavored e-cigarettes. Environ Health Perspect. 124(6):733–739. doi:10.1289/ehp.1510185

American Conference of Governmental Industrial Hygienists (ACGIH). 2017. 2017 TLVs® and BEIs®: threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati (OH): American Conference of Governmental Industrial Hygienists.

ASTM International. 2018. Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation. ASTM International: Designation: D6245 – 18. West Conshohocken (PA).

Azimi P, Keshavarz Z, Lahaie Luna M, Cedeno Laurent JG, Vallarino J, Christiani DC, Allen JG. 2021. An unrecognized hazard in e-cigarette vapor: preliminary quantification of methylglyoxal formation from propylene glycol in e-cigarettes. IntJ Environ Res Public Health. 18(2):385. doi:10.3390/ijerph18020385

Ballbè M, Martínez-Sánchez JM, Sureda X, Fu M, Pérez-Ortuño R, Pascual JA, Saltó E, Fernández E. 2014. Cigarettes vs. e-cigarettes: passive exposure at home measured by means of airborne marker and biomarkers. Environ Res. 135:76–80. doi:10.1016/j.envres.2014.09.005

Berg CJ, Callanan R, Johnson TO, Schliecher NC, Sussman S, Wagener TL, Meaney M, Henriksen L. 2021. Vape shop and consumer activity during COVID-19 non-essential business closures in the USA. Tob Control. 30(e1):e41–e44. doi:10.1136/tobaccocontrol-2020-056171

California Health Interview Survey (CHIS). 2020. CHIS 2016-2019 adult public use files. Los Angeles (CA): UCLA Center for Health Policy Research; Accessed October 1, 2020.

California Air Resources Board. 2004. Indoor air quality guideline; formaldehyde in the home. Indoor air quality guide. Sacramento (CA). Guidance Document: 2004 = 0800. https://ww3.arb.ca.gov/research/indoor/formaldgl08-04.pdf.

California Department of Public Health (CDPH), California Tobacco Control Program. 2015. State Health Officer's report on e-cigarettes: a community health threat. Sacramento (CA); Accessed January 11, 2021.

California Health and Safety Code. Tobacco sale prohibition. 2021. Section 104559.5. https://leginfo.legislature.ca.gov/faces/billCompareClient.xhtml?bill_id=201920200SB793&showamends=false; Accessed January 11 2021.

Campaign for Tobacco Free Kids. 2021. States and localities that have restricted the sale of flavored tobacco products. Washington (DC); [accessed 2021 Jan 11]. https://www.tobaccofreekids.org/assets/factsheets/0398.pdf.

Cornelius ME, Wang TW, Jamal A, Loretan CG, Neff LJ. 2020. Tobacco product use among adults—United States, 2019. MMWR Morb Mortal Wkly Rep. 69(46): 1736–1742. doi:10.15585/mmwr.mm6946a4

D'Amario D, Migliaro S, Borovac JA, Vergallo R, Galli M, Restivo A, Bonini M, Romagnoli E, Leone AM, Crea F. 2019. Electronic cigarettes and cardiovascular risk: caution waiting for evidence. Eur Cardiol. 14(3):151–158. doi:10.15420/ecr.2019.16.2

Data Axle. 2016. Reference solutions (formerly Reference USA Gov). Dallas, TX: Data Axle; [accessed 2016 Oct 1]. https://www.referenceusa.com/Home/Home.

Electronic Cigarettes Act. 2015. Cal. Senate. B. 5 (2015-2016), Chapter 7 (Cal. Stat. 2016).

Farsalinos KE, Voudris V, Poulas K. 2015. E-cigarettes generate high levels of aldehydes only in 'dry puff' conditions. Addiction. 110(8):1352–1356. doi:10.1111/add.12942

[FEMA] Flavor and Extract Manufacturers Association of the United States. 2012. Respiratory health and safety in the flavor manufacturing workplace—2012 update. Washington (DC): The Flavor and Extract Manufacturers Association of the United States. https://www.femaflavor.org/sites/default/files/2018-06/FEMA%202012%20Respiratory%20Health%20and%20Safety%20in%20Workplace.pdf.

Food and Drug Administration, Health and Human Services. 2016. Deeming tobacco products to be subject to the Federal Food, Drug, and Cosmetic Act, as amended by the Family Smoking Prevention and Tobacco Control Act; Restrictions on the sale and distribution of tobacco products and required warning statements for tobacco products. 81 FR 28973.

Fowles J, Barreau T, Wu N. 2020. Cancer and non-cancer risk concerns from metals in electronic cigarette liquids and aerosols. Int J Environ Res Public Health. 17(6):2146. doi:10.3390/ijerph17062146

Garcia R, Allem JP, Baezconde-Garbanati L, Unger JB, Sussman S. 2016. Employee and customer handling of nicotine-containing e-liquids in vape shops. Tob Prev Cessat. 2(Suppl):1–6. doi:10.18332/tpc/67295

Gardiner D. 2021. California law banning flavored tobacco on hold as referendum qualifies for ballot. Jan 24, San Francisco Chronicle. https://www.sfchronicle.com/politics/article/California-law-banning-flavored-tobacco-on-hold-15891757.php.

Gerloff J, Sundar IK, Freter R, Sekera ER, Friedman AE, Robinson R, Pagano T, Rahman I. 2017. Inflammatory response and barrier dysfunction by different e-cigarette flavoring chemicals identified by gas chromatography-mass spectrometry in e-liquids and e-vapors on human lung epithelial cells and fibroblasts. Appl in Vitro Toxicol. 3(1):28–40. doi:10.1089/aivt.2016.0030

Hammond D, Rynard VL, Reid JL. 2020. Changes in prevalence of vaping among youths in the United States, Canada, and England from 2017 to 2019. JAMA Pediatr. 174(8):797–800. doi:10.1001/jamapediatrics.2020.0901

Hubbs AF, Kreiss K, Cummings KJ, Fluharty KL, O'Connell R, Cole A, Dodd TM, Clingerman SM, Flesher JR, Lee R, et al. 2019. Flavorings-related lung disease: a brief review and new mechanistic data. Toxicol Pathol. 47(8): 1012–1026. doi:10.1177/0192623319879906

Hutzler C, Paschke M, Kruschinski S, Henkler F, Hahn J, Luch A. 2014. Chemical hazards present in liquids and vapors of electronic cigarettes. Arch Toxicol. 88(7): 1295–1308. doi:10.1007/s00204-014-1294-7

[IARC] International Agency for Research on Cancer. 1999. Monographs on the evaluation of carcinogenic risks to humans. Re-evaluation of some organic chemicals, hydrazine and hydrogen peroxide, vol. 71. Lyon (France): International Agency for Research on Cancer.

IARC. 2000. Monographs on the evaluation of carcinogenic risks to humans. Some industrial chemicals, vol. 77. Lyon (France): International Agency for Research on Cancer.

Injury and Illness Prevention Program. 2021. 8 Cal. Code Regs. Section 3203. https://www.dir.ca.gov/title8/3203.html.

Johnson JM, Muilenburg JL, Rathbun SL, Yu X, Naeher LP, Wang JS, 2018. Elevated nicotine dependence scores among electronic cigarette users at an electronic cigarette convention. J Community Health. 43(1):164–174. doi:10.1007/s10900-017-0399-3

Khachatoorian C, Jacob P, 3rd, Sen A, Zhu Y, Benowitz NL, Talbot P. 2019. Identification and quantification of electronic cigarette exhaled aerosol residue chemicals in field sites. Environ Res. 170:351–358. doi: 10.1016/j.envres.2018.12.027.

Khachatoorian C, Jacob P, III Benowitz NL, Talbot P. 2019. Electronic cigarette chemicals transfer from a vape shop to a nearby business in a multiple-tenant retail building. Tob Control. 28(5):519–525. doi:10.1136/tobaccocontrol-2018-054316

Klager S, Vallarino J, MacNaughton P, Christiani DC, Lu Q, Allen JG. 2017. Flavoring chemicals and aldehydes in e-cigarette emissions. Environ Sci Technol. 51(18): 10806–10813. doi:10.1021/acs.est.7b02205

Kosmider L, Sobczak A, Fik M, Knysak J, Zaciera M, Kurek J, Goniewicz ML. 2014. Carbonyl compounds in electronic cigarette vapors: effects of nicotine solvent and battery output voltage. Nicotine Tob Res. 16(10): 1319–1326. doi:10.1093/ntr/ntu078

LeBouf RF, Burns DA, Ranpara A, Attfield K, Zwack L, Stefaniak AB. 2018. Headspace analysis for screening of volatile organic compound profiles of electronic juice bulk material. Anal Bioanal Chem. 410(23):5951–5960. doi:10.1007/s00216-018-1215-3

LeBouf RF, Hawley B, Cummings KJ. 2019. Potential hazards not communicated in Safety Data Sheets of flavoring formulations, including diacetyl and 2,3-pentanedione.

Ann Work Exposures Health. 63(1):124–130. doi:10.1093/annweh/wxy093
LeBouf R, Simmons M. 2017. Increased sensitivity of OSHA method analysis of diacetyl and 2,3-pentanedione in air. J Occup Environ Hyg. 14(5):343–348. doi:10.1080/15459624.2016.1252846
LeBouf RF, Stefaniak AB, Virji MA. 2012. Validation of evacuated canisters for sampling volatile organic compounds in healthcare settings. J Environ Monit. 14(3):977–983. doi:10.1039/c2em10896h
Lemen RA. 1987. Letter of February 9, 1987, to Tom Hall, U.S. Department of Labor, regarding NIOSH additional material pertaining to the proposed revision of the regulation for occupational exposure to formaldehyde. Cincinnati (OH): U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.
Levy DT, Warner KE, Cummings KM, Hammond D, Kuo C, Fong GT, Thrasher JF, Goniewicz ML, Borland R. 2019. Examining the relationship of vaping to smoking initiation among US youth and young adults: a reality check. Tob Control. 28(6):629–635. doi:10.1136/tobaccocontrol-2018-054446
Li L, Lin Y, Xia T, Zhu Y. 2020. Effects of electronic cigarettes on indoor air quality and health. Annu Rev Public Health. 41:363–380. doi:10.1146/annurev-publhealth-040119-094043
Li L, Nguyen C, Lin Y, Guo Y, Fadel NA, Zhu Y. 2021. Impacts of electronic cigarettes usage on air quality of vape shops and their nearby areas. Sci Total Environ. 760:143423 doi:10.1016/j.scitotenv.2020.143423
Liu J, Liang Q, Oldham MJ, Rostami AA, Wagner KA, Gillman IG, Patel P, Savioz R, Sarkar M. 2017. Determination of selected chemical levels in room air and on surfaces after the use of cartridge- and tank-based e-vapor products or conventional cigarettes. Int J Environ Res Public Health. 14(9):969. doi:10.3390/ijerph14090969
Maloney JC, Thompson MK, Oldham MJ, Stiff CL, Lilly PD, Patskan GJ, Shafer KH, Sarkar MA. 2016. Insights from two industrial hygiene pilot e-cigarette passive vaping studies. J Occup Environ Hyg. 13(4):275–283. doi:10.1080/15459624.2015.1116693
Melstrom P, Koszowski B, Thanner MH, Hoh E, King B, Bunnell R, McAfee T. 2017. Measuring $PM_{2.5}$, ultrafine particles, nicotine air and wipe samples following the use of electronic cigarettes. Nicotine Tob Res. 19(9):1055–1061. doi:10.1093/ntr/ntx058
Mikheev VB, Brinkman MC, Granville CA, Gordon SM, Clark PI. 2016. Real-time measurement of electronic cigarette aerosol size distribution and metals content analysis. Nicotine Tob Res. 18(9):1895–1902. doi:10.1093/ntr/ntw128
Morris AM, Leonard SS, Fowles JR, Boots TE, Mnatsakanova A, Olgun NS, Attfield KR. 2021. Effects of e-cigarette flavoring chemicals on human macrophages and bronchial epithelial cells. Int J Environ Res Public Health. 18(21):11107. doi:10.3390/ijerph182111107
Muthumalage T, Prinz M, Ansah KO, Gerloff J, Sundar IK, Rahman I. 2017. Inflammatory and oxidative responses induced by exposure to commonly used e-cigarette flavoring chemicals and flavored e-liquids without nicotine. Front Physiol. 8:1130. doi:10.3389/fphys.2017.01130
Nguyen C, Li L, Sen CA, Ronquillo E, Zhu Y. 2019. Fine and ultrafine particles concentrations in vape shops. Atmos Environ. 211:159–169. doi:10.1016/j.atmosenv.2019.05.015
NIOSH. 1994. Method 1608: glycidol. NIOSH manual of analytical methods. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/2003-154/pdfs/1608.pdf.
NIOSH. 1996. Method 2549: volatile organic compounds (screening). NIOSH manual of analytical methods. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/2003-154/pdfs/2549.pdf.
NIOSH. 1998. Method 2551: nicotine. NIOSH manual of analytical methods. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/2003-154/pdfs/2551.pdf.
NIOSH. 2003a. Method 7303: elements by ICP. NIOSH manual of analytical methods. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/2003-154/pdfs/7303.pdf; Accessed January 11 2021.
NIOSH. 2003b. Method 9102: elements of wipes. NIOSH manual of analytical methods. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/2003-154/pdfs/9102.pdf.
NIOSH. 2016. Criteria for a recommended standard: occupational exposure to diacetyl and 2,3-pentanedione. By McKernan LT, Niemeier RT, Kreiss K, Hubbs A, Park R, Dankovic D, Dunn KH, Parker J, Fedan K, Streicher R, et al., editors. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2016-111. 97.
NIOSH. 2017a. Evaluation of chemical exposures at a vape shop. By Zwack LM, Stefaniak AB, LeBouf RF, editors. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Health Hazard Evaluation Report 2015-0107-3279. http://www.cdc.gov/niosh/hhe/reports/pdfs/2015-0107-3279.pdf.
NIOSH. 2017b. Chemical carcinogen policy. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/docs/2017-100/pdf/2017-100.pdf?id=10.26616/NIOSHPUB2017100revised.
NIOSH. 2018a. Evaluation of chemical exposures at two vape shops in Texas. By Zwack LM, Chiu S, LeBouf RF, editors. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health,

Health Hazard Evaluation Report 2016-0120-3307. http://www.cdc.gov/niosh/hhe/reports/pdfs/2016-0120-3307.pdf.

NIOSH. 2018b. Method 3900: volatile organic compounds, C1 to C10, canister method. NIOSH manual of analytical methods. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/nmam/pdf/3900.pdf.

NIOSH. 2019. Evaluation of ergonomics, chemical exposures, and ventilation at four nail salons. By Broadwater K, Chiu S, editors. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Health Hazard Evaluation Report 2015-0139-3338, https://www.cdc.gov/niosh/hhe/reports/pdfs/2015-0139-3338.pdf.

O'Connell G, Colard S, Cahours X, Pritchard JD. 2015. An assessment of indoor air quality before, during and after unrestricted use of e-cigarettes in a small room. Int J Environ Res Public Health. 12(5):4889–4907. doi:10.3390/ijerph120504889

Oldham MJ, Sehgal A, Cohen G, Chen J, Evans B, Heraldez D. 2021. Room air constituent concentrations from use of electronic nicotine delivery systems and cigarettes using different ventilation conditions. Sci Rep. 11(1):1736. doi:10.1038/s41598-021-80963-9

[OSHA] Occupational Safety and Health Administration. 2005. Method 1007: formaldehyde; [accessed 2020 Dec 13]. https://www.osha.gov/dts/sltc/methods/mdt/mdt1007/1007.pdf.

OSHA. 2008. Sampling and analytical methods: method 1013: acetoin and diacetyl. http://www.osha.gov/dts/sltc/methods/validated/1013/1013.html.

OSHA. 2010. Method 1016: 2,3-pentanedione. https://www.osha.gov/dts/sltc/methods/validated/1016/1016.pdf.

OSHA. 2020. Technical manual. Section III: Chapter 2: indoor air quality investigations; [accessed 2020 Dec 16]. https://www.osha.gov/dts/osta/otm/index.html.

Quinones Tavarez Z, Li D, Croft DP, Gill SR, Ossip DJ, Rahman I. 2020. The interplay between respiratory microbiota and innate immunity in flavor e-cigarette vaping induced lung dysfunction. Front Microbiol. 11:589501. doi:10.3389/fmicb.2020.589501

Rostron BL, Chang JT, Chang CM, Jackson RA, Ambrose BK. 2020. Ends flavor preference by menthol cigarette smoking status among us adults, 2018-2019. Int J Environ Res Public Health. 18(1):240. doi:10.3390/ijerph18010240

Schober W, Szendrei K, Matzen W, Osiander-Fuchs H, Heitmann D, Schettgen T, Jorres RA, Fromme H. 2014. Use of electronic cigarettes (e-cigarettes) impairs indoor air quality and increases FeNo levels of e-cigarette consumers. Int J Hyg Environ Health. 217(6):628–637. doi:10.1016/j.ijheh.2013.11.003

Sleiman M, Logue JM, Montesinos VN, Russell ML, Litter MI, Gundel LA, Destaillats H. 2016. Emissions from electronic cigarettes: key parameters affecting the release of harmful chemicals. Environ Sci Technol. 50(17):9644–9651. doi:10.1021/acs.est.6b01741

Son Y, Giovenco DP, Delnevo C, Khlystov A, Samburova V, Meng Q. 2020. Indoor air quality and passive e-cigarette aerosol exposures in vape-shops. Nicotine Tob Res. 22(10):1772–1779. doi:10.1093/ntr/ntaa094

Sussman S, Baezconde-Garbanati L, Garcia R, Barker DC, Samet JM, Leventhal A, Unger JB. 2016. Commentary: forces that drive the vape shop industry and implications for the health professions. Eval Health Prof. 39(3):379–388. doi:10.1177/0163278715586295

Tierney PA, Karpinski CD, Brown JE, Luo W, Pankow JF. 2016. Flavour chemicals in electronic cigarette fluids. Tob Control. 25(e1):e10–e15. doi:10.1136/tobaccocontrol-2014-052175

Truth Initiative. 2020. E-cigarette factsheet. Washington, DC; [accessed 2021 Feb 25]. https://truthinitiative.org/sites/default/files/media/files/2020/12/Truth_E-cigarette%20Fact%20Sheet_Dec_2020.pdf.

van Drooge BL, Marco E, Perez N, Grimalt JO. 2019. Influence of electronic cigarette vaping on the composition of indoor organic pollutants, particles, and exhaled breath of bystanders. Environ Sci Pollut Res Int. 26(5):4654–4666. doi:10.1007/s11356-018-3975-x

Wang P, Chen W, Liao J, Matsuo T, Ito K, Fowles J, Shusterman D, Mendell M, Kumagai K. 2017. A device-independent evaluation of carbonyl emissions from heated electronic cigarette solvents. PLoS One. 12(1):e0169811. doi:10.1371/journal.pone.0169811

Wang TW, Neff LN, Park-Lee E, Ren C, Cullen KA, King BA. 2020. E-cigarette use among middle and high school students—United States, 2020. MMWR Morb Mortal Wkly Rep. 69(37):1310–1312. doi:10.15585/mmwr.mm6937e1

Williams M, Bozhilov K, Ghai S, Talbot P. 2017. Elements including metals in the atomizer and aerosol of disposable electronic cigarettes and electronic hookahs. PLoS One. 12(4):e0175430. doi:10.1371/journal.pone.0175430

Williams M, Villarreal A, Bozhilov K, Lin S, Talbot P. 2013. Metal and silicate particles including nanoparticles are present in electronic cigarette cartomizer fluid and aerosol. PLoS One. 8(3):e57987. doi:10.1371/journal.pone.0057987

Vas CA, Porter A, McAdam K. 2019. Acetoin is a precursor to diacetyl in e-cigarette liquids. Food Chem Toxicol. 133:110727. doi:10.1016/j.fct.2019.110727

Zhu S-H, Zhuang Y-L, Braden K, Gamst A, Cole AG, Wolfson T, Li S. 2021. Results of the statewide 2019-20 California Student Tobacco Survey. San Diego (CA): Center for Research and Intervention in Tobacco Control (CRITC), University of California San Diego.

Zorin S, Kuylenstierna F, Thulin H. 1999. In vitro test of nicotine's permeability through human skin. Risk evaluation and safety aspects. Ann Occup Hyg. 43(6):405–413. doi:10.1016/S0003-4878(99)00030-7