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Secondhand exposure from vaping marijuana: Concentrations, emissions, and exposures determined using both research-grade and low-cost monitors

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ABSTRACT

A popular method of inhaling marijuana is by heating marijuana liquid (vaping). We study exhaled aerosol within experimental rooms in two inhabited homes and determine peak concentrations, decay and removal rates, and source emissions. These parameters allow a simple exposure model to be developed. The experimental approach was to measure particle concentrations from one or multiple puffs of marijuana liquid within the experimental rooms. Commercial cartridges containing marijuana liquid of varying CBD:THC ratios (2:1, 7:1, 8:1, and 18:1) were compared. $PM_{2.5}$ concentrations were measured continuously by optical monitors (SidePak and PurpleAir monitors) and by mass measurements (Piezobalances). The mass measurements in a subsample were verified using gravimetric (pump-filter) methods. Air exchange rates were measured using tracer gases. Calibration factors (CFs) were developed for the SidePak and Piezobalance using gravimetric analysis of their response to the aerosol produced by vaping. These CFs were 0.97 (SE 0.04) for the Piezobalances and 0.44 (SE 0.04) for the SidePaks. Comparisons with these instruments suggested a median CF for PurpleAir monitors of 3. This CF is based upon an alternative methodology for calculating $PM_{2.5}$ based on the particle numbers in three size categories from 0.3 to 2.5 μm. Two preheating periods of about 3 and 12 s were adopted before a 3-s inhalation. The longer heating period produced an increase in the source strength from 3.0 (SE 0.3) to 8.8 (SE 0.3) mg/puff. $PM_{2.5}$ removal rates were 0.38 (SE 0.04) h^{-1} for the SidePaks and 0.30 (SE 0.03) h^{-1} for the PurpleAir monitors. An 8-day experiment with a single puff each day from a marijuana liquid cartridge showed elevated concentrations in the small experimental room for the next 9 h. Mean concentrations during these hours were 63 $\mu g/m^3$, compared to 4.5 $\mu g/m^3$ at other times. A simple exposure model was developed and applied to several scenarios of low and high expected exposures.

1. Introduction

Vaping is a term relating to heating a liquid and inhaling the "vapor" (actually an aerosol) produced. Vaping first became popular as a means of inhaling tobacco without combusting it. Electronic cigarettes (e-cigarettes) consisting of a battery, heating coil, and liquid reservoir (tank or cartridge) usually containing nicotine were developed and went through several "generations" of modification. The third generation consists normally of a vape pen, holder containing the battery and heating oil, and a liquid cartridge with or without nicotine. The liquid consists of glycerin (vegetable glycerin, or "VG") and ethylene glycol ("EG") typically in amounts of 30–70%. A third liquid (presumably water) is also included at about 1/3 of the total amount. Some terpenes for taste and odor and nicotine may also be included. The vaper heats the cartridge for a few seconds (typically <10), inhales the aerosol and exhales it into the room or ambient air.

Many studies of secondhand exposure to e-cigarette aerosol have been published. Long (2014) determined that exhaled e-cigarette aerosol composition was greater than 99.9% water and glycerin (about 75% water, 25% glycerin). Previous studies considering exposure to e-cigarette aerosol exhaled by < 10 human subjects include Schripp et al. (2013); Czogala et al. (2014); Ruprecht et al. (2014, 2017); Ballbè et al. (2014); Bertholon et al. (2013); and Saffari et al. (2014). A later study used 13 smokers in a large room and employed several monitors to measure the proximity effect (Zhao et al., 2017). A study of e-cigarette emissions showed the importance of e-cig brand, type, flavor additives, user puffing pattern (duration and frequency), and voltage on physico-chemical properties of emissions (Zhao et al., 2018). Other

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studies considering passive vaping include Geiss et al. (2015); Grana et al. (2014); Hess et al. (2016); Maloney et al. (2016); Martuzevicius et al. (2018); McAuley et al. (2012); and O'Connell et al. (2015). Useful studies of the "topography" of vaping e-cigarettes (frequency of inhalation, amount of vapor inhaled, length of time the vapor is inhaled and exhaled, etc.) have been provided by Robinson et al. (2015); Dautzenberg and Bricard (2015); Hitchman et al. (2015); Talih et al. (2015); and Public Health England (2016).

Recently, vaporization of marijuana has emerged as a popular method of delivering marijuana. This method heats marijuana liquid to the point of vaporization, avoiding combustion. The marijuana is thus delivered without the accompanying products of combustion. Shortly after this method was introduced, Earleywine and Van Dam (2010) reported on four subjects who smoked marijuana and agreed to switch to vaping for a short period. All four refused to return to smoking marijuana at the end of the experiment. Eight years later, these early adopters of vaping have been joined by millions of persons worldwide. For example, 3.8%, 10.5%, and 13.8% of about 25 million US high school students reported vaping marijuana in 2016, 2017, and 2018, respectively (US CDC, 2018). Abrams et al. (2007) showed that vaping marijuana produced similar levels of THC in blood as smoking marijuana cigarettes, without the increase in carbon monoxide (CO) in exhaled breath associated with combustion.

Essentially all passive exposure to marijuana smoke from vaping is from exhaled breath since there is no sidestream smoke. The aerosol emerging from exhaled breath will be different in many respects from the inhaled aerosol, due to lung deposition, humidification, growth, and coagulation, so it is important to test exposure under real-world conditions using human vapers. One recent study has focused on indoor air concentrations of particles due to various indoor sources, including both marijuana and tobacco smokers (Klepeis et al., 2017). This study included 193 persons, of whom about 22% and 15% smoked tobacco and marijuana, respectively. It may be the first study to look at passive exposure to marijuana from human smokers in their own homes. The authors found that nonsmokers exposed to persons smoking either tobacco or marijuana cigarettes had roughly twice the exposure to fine particles as nonexposed nonsmokers. The Dylos monitors used in this study were not calibrated by comparison to gravimetric levels, so the investigators could not estimate $PM_{2.5}$ exposures or source strengths.

Exposure models depend on the vaping "topography" including frequency of use, depth or time of inhalation, and time retained in the lungs. McClure et al. (2012) studied 20 heavy users who were allowed to smoke marijuana cigarettes freely over 4 days. On average, they smoked 12 (SD 5) cigarettes per 9-h day, taking 13 (SD 4) puffs from each cigarette. The volume per puff ranged from 51 to 61 ml. A second study of 98 Dutch adolescents found that they smoked an average of 2.5 (SD 1.7) joints per day of use, and 21 days of use per month (van der Pol et al., 2014).

Another required parameter in an exposure model is the air exchange rate. Chan et al. (2005) used leakage information to show that rates in the US vary in log-normal fashion from about 0.1 to 2 h^{-1}. The rate is affected by the indoor-outdoor temperature difference and by wind direction and speed (Sherman and Modera, 1984). One of the strongest effects on air exchange rates is window-opening behavior (Howard-Reed et al., 2002). The volume of the home is another necessary parameter, statistics for which can be obtained for the US from the US Census Bureau (2010).

Although these previous studies are useful in developing exposure models, we believe that no studies have sufficiently characterized the two crucial ingredients of such models: source strengths and decay rates of real-world aerosols from vaping marijuana liquids by human subjects. In this study, we use more than 100 controlled experiments involving human vapers in rooms within inhabited homes to provide information on source strengths and decay rates, from which models of exposure can be built.

2. Objectives

The main objective of the study was to measure, under real-world conditions, the two main parameters affecting secondhand $PM_{2.5}$ exposure to marijuana aerosol from vaping: the source strength and removal rate from the air. The source strength is the mass of $PM_{2.5}$ emitted (mg/puff) and is generalizable to other locations and situations. The removal rate for nonvolatile particles not subject to coagulation is the deposition rate k (h^{-1}). In the case of vaping marijuana, the deposition rate may be augmented by evaporation, so the removal rate = k + evaporation rate (h^{-1}).

In carrying out this objective, we evaluated the calibration factors (CFs) for the 3 p.m. instruments measuring vaping aerosol. For the SidePak and Piezobalance monitors, the CFs were determined directly using gravimetric techniques (Zhao et al., 2020). Since the PurpleAir monitors in this study were collocated with the SidePak monitors, the CF for them was determined by direct comparison with the SidePak readings.

A secondary objective was to compare the performance of a low-cost monitor (PurpleAir) to research-grade instruments (SidePak and Piezobalance). If the low-cost monitor performed sufficiently well, it could be adopted in future studies of exposure. It offers the opportunity of a much broader sample of homes and participants. It is able to monitor continuously with no maintenance. In the case of PurpleAir, there is also an existing network on the internet that can be sampled at will by a researcher.

3. Methods and materials

Three main particle monitor types were used in the study: an optical monitor with a $PM_{2.5}$ impactor (the SidePak™, three instruments) (TSI Inc, Shoreview, MN, Model AM510); a monitor employing a piezoelectric crystal (the Piezobalance, two instruments) (TSI, Model 3511), also with a $PM_{2.5}$ impactor; and a low-cost optical monitor (two instruments) providing estimates of PM_1, $PM_{2.5}$ and PM_{10} (PurpleAir™ Model PA-II, PurpleAir.com).

The Piezobalance is manufactured by Kanomax, Inc. Japan, and has previously been licensed for sale in the US by TSI Inc., Shoreview, MN. Piezobalances used in this study included models from both Kanomax USA Inc. (Andover NJ, Model 3511), and TSI, Model 8510. For the Piezobalances used in this study, a special connector has been added by the factory, which allows the 1-min average frequency counts to be output to a computer where they can be logged. The instrument employs a vibrating quartz crystal exposed to a steady flow rate (1 L/min) that has passed through a $PM_{2.5}$ impactor. As the exposed crystal collects particles, its frequency changes due to the piezoelectric principle, and within a certain frequency range the change in frequency is proportional to the amount of material collected on the exposed crystal. The frequency change during each measured time interval is then multiplied by the factory-set calibration factor to give an estimate of the amount of mass collected during the time interval.

The SidePak is an optical particle monitor. It uses a laser to sense particles as they pass through a chamber. The scattered light is collected and calculated as a volume determined by applying Mie scattering formulae. The SidePak is calibrated at the factory using ISO 12103-1 Test Dust (formerly Arizona Test Dust; specific gravity 2.6). As with all optical monitors, it is recommended that the particular aerosol mixture being studied be analyzed using gravimetric methods, so that a calibration factor can be determined for that aerosol. For example, the calibration factor for the SidePak has been found to be about 0.32 for tobacco smoke (Dacunto et al., 2013). We have been able to determine a calibration factor for the marijuana aerosol produced by vaping (discussed below).

The PurpleAir instruments use a laser of ~650 nm wavelength to sort particles into one of six size categories (0.3–0.5 μm, 0.5–1 μm, 1–2.5 μm, 2.5–5 μm, 5–10 μm and >10 μm). There are two lasers in each monitor,

providing the opportunity to detect departures from normal operation and calculate internal precision. The monitors have a small inaudible fan to counter "starvation" of air at the face of the monitor. They operate off line current and have no battery. Every 80 s (after May 2019: 2 min) they upload observations directly to the Web. The monitors provide the number per deciliter of particles in each of the six categories. Also, they provide two data series, identified as CF1 and CF ATM for PM_1, $PM_{2.5}$, and PM_{10}. The manufacturer of the sensor (PMS 5003) is a Chinese company (plantower.com). The company does not provide details on the calibration aerosol used, such as the density, or any correction factors employed in calculating PM_1, $PM_{2.5}$ or PM_{10}. Therefore, we chose not to use the CF1 or CF ATM data series provided by Plantower. Instead we adopted a standard method for determining $PM_{2.5}$ from the particle numbers provided for the three size categories up to 2.5 μm. We chose an intermediate particle diameter within each category to represent all particles in the category, calculated the resulting particle volume, and determined a reference mass by adopting a density of 1 g cm^{-3}. This approach succeeded in improving the limit of detection (LOD) from about 2 μg/m^3 using the CF1 or ATM to ~1 μg/m^3 (Wallace, 2020).

The calibration factors (CF) for the Piezobalance and SidePak response to vaping marijuana were studied using gravimetric procedures by Zhao et al. (2020). The Piezobalance CF was 0.97 (SE 0.04, $n = 8$). The SidePak CF was 0.44 (SE 0.4, $n = 8$).

A carbon monoxide monitor (Langan Instruments, Model T15) was employed to estimate the air exchange rate of each of the two experimental rooms. A known amount of carbon monoxide was released using a flow rate regulator attached to a 107-liter cylinder containing 10% CO (GasCo). The air exchange rate was determined as the negative slope of the background-corrected logarithm of the CO concentration. A correction was made for the temperature based on observations of the variation of the Langan monitor readings with temperature.

3.1. Study design and experimental conditions

Tests were carried out between May 21, 2018 and May 25, 2019. Each test was conducted in a room in a home. Two rooms were used, one in Santa Rosa (30 m^3) and one in Redwood City (43 m^3). Rooms were sealed off from the remainder of the home. The HVAC system was off and floor registers sealed. Usually no fan was employed. In some experiments, one or two table fans were employed to test the effect of a fan on measured decay rates. Two Piezobalances, two PurpleAir monitors, and 2–3 SidePaks were employed for each experiment. They were situated at two well-separated locations at heights between 0.9 and 1 m. A single Langan electrochemical device was set at a central location in the room to monitor CO. CO was released using the cylinder discussed above. A target peak concentration above 5 ppm was set. Background $PM_{2.5}$ concentrations were collected for 5–10 min before the experimenter took one or more puffs of the heated marijuana oil. A battery-operated device (AbsoluteXtracts, abx.org) was used to vaporize marijuana oil from a 500 ml cartridge (Care by Design, cbd.org). Oils with different CBD/THC ratios were tested: 18:1 ($n = 56$); 8:1 (9); 7:1 (17); and 2:1 (41). The amount of CBD and THC was listed for each cartridge. For example, the 8:1 CBD/THC ratio included 336 mg (67.2%) CBD and 40 mg (8%) THC. The missing 124 ml liquid was not identified. The other formulations also included about 2/3 marijuana liquid and 1/3 unidentified liquid. Only one person at each location was the vaper. He sat or stood at a location roughly equidistant from the two locations for the instruments. After completing the protocol for heating the cartridge (see below), the experimenter left the room.

Two protocols for heating the cartridges were adopted to study the effect of different heating times on the amount of vapor produced. Protocol I ($n = 105$) consisted of heating the oil for 3 s by pressing the power button on the vaping pen and then inhaling for three additional seconds while still pressing the power button. Protocol II ($n = 19$) involved heating for 12 s before the 3-s inhale, a total of 15 s of heating compared to 6 s in Protocol I.

Source strengths (emissions in mg per puff) were calculated as follows. Since the initial peaks registered by the monitors occurred under conditions of poorly-mixed air, the true estimated peak concentration assuming perfect mixing was determined by calculating decay rates after good mixing (<0.1 relative standard deviation across instruments) was attained (Ott, 2007). The line of best fit could then be extended "backward" in time to the time of the puff. The estimated concentration at this time would be the best estimate of the concentration if perfect instantaneous mixing had occurred. This estimated peak concentration was then multiplied by the room volume to provide an estimate of the source strength (mg/puff). Decay rates were determined by regressing the logarithms of the background-corrected concentrations over time. These rates reflect the effects of all particle dynamics on a given day, which include the deposition rates on room surfaces, the air exchange rate, condensation/evaporation of volatile substances, and coagulation). These mechanisms are also affected by environmental conditions including air flow rates in the room, temperature, and humidity. Removal rates were determined by subtracting the air exchange rates from the measured decay rates. Decays were followed for multiple hours.

3.1.1. 8-Day exposure study

Over an 8-day period, a study of 24-h exposure was carried out using the PurpleAir monitors. Each day, a single puff of marijuana fluid (2:1 CBD/THC ratio, Care by Design) was exhaled into this 30 m^3 room following Protocol II (high heat). The door was closed during the 6 h following the puff, and open after that. Air exchange rates were measured by releasing a 10% mixture of CO into the room just prior to vaping and calculating the decline of the background-and temperature-corrected CO concentrations.

3.1.2. Quality assurance

Prior to the study and during it at intervals, two of the main monitors (SidePak and Piezobalance) were zeroed, their impactors were cleaned and regreased, and flow rates checked. Since at least 2 monitors of each type were collocated, the agreement within each type could be determined, as well as the relative bias and precision (Figures S1, S2 and S3). For the two PurpleAir monitors at each location, there were two independent lasers within each monitor, so each monitor could be checked for internal agreement, and they could also be checked against each other.

4. Funding source

This study was supported in part by a grant awarded to Stanford University to study secondhand exposure to marijuana: Agreement #28IR-0062 sponsored by the University of California Office of the President; Tobacco Related-Disease Research Program (TRDRP).

4.1. Ethical considerations

As part of that grant, the Stanford Institutional Review Board (IRB) gave approval to the authors to carry out human experimentation. Since no human subjects were recruited for the experiments presented in this paper, telephone contact was made with a member of the IRB to obtain his opinion on whether IRB coverage of the authors was needed by the IRB. His advice was that IRB review is not required if the researchers doing the study are the only human subjects. In addition, the research is not medical, since its focus is on evaluating measurement methods and applying mathematical approaches to a class of indoor air pollutants, not on health impacts for humans. Finally, the emissions of every experiment were produced by a subset of the authors, who were experienced in inhaling both nicotine and marijuana smoke, and no persons were present in the room during the air pollutant decay periods. No other individuals participated in the smoking or vaping activities, nor were any persons other than the authors exposed to the aerosols produced.

4.2. Role of funding source

The funding source had no involvement in the study design, collection, analysis, or interpretation of data, writing or editing of the report, or the decision to seek publication.

5. Results

124 tests were performed (see Table S1 in Supplementary Information for a complete list of the dates, marijuana liquids with CBD:THC ratios, whether table fans were used, number of puffs, inhalation protocols, and source strengths for the 3 p.m. instruments employed). Although multiple different formulations of the marijuana liquids were employed, there was no significant difference shown in the main parameters (source strengths and decay rates) so all results were combined.

5.1. Source strengths

The source strengths for the high-heat Protocol II are about 3 times those for the low-heat Protocol I (Table 1). These values of 3–9 mg/puff may be compared to measured values on the order of 1.4 mg/puff for a tobacco cigarette (Özkaynak et al., 1996). The 3 instruments show fairly similar means, medians, and ranges, with no instrument significantly different from any other. The low-cost PurpleAir instrument also shows equally good coefficient of variation (CV), as the two higher-cost instruments. Table 1 suggests that both the research-grade (SidePak) and low-cost (PurpleAir) optical air monitors can reasonably be used to determine the source strengths of marijuana vaping when applying suitable calibration factors to each monitor.

The calculated source strengths for the PurpleAir and SidePak instruments agreed well, with a slope of nearly 1 and an R^2 value of 99% (Fig. 1).

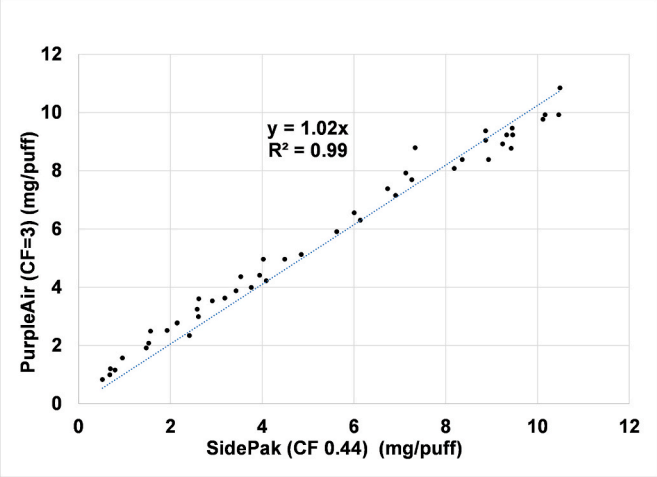

Fig. 1. $PM_{2.5}$ source strengths as determined by two independent methods: PurpleAir and SidePak monitors ($n = 42$).

5.2. Decay rates, air exchange rates, and removal rates

5.2.1. Decay rates

Decay rates were measured for all experiments. The measured decay rates for the SidePak and PurpleAir monitors include air exchange rates a and deposition rates k, as well as other possible losses or gains due to evaporation, condensation, and coagulation: decay rate $= a + k + other$. If we subtract the observed air exchange rate from the observed decay rate, we are left with a term we call the "removal rate", which is the sum of the deposition rate k and all other gain/loss mechanisms. The measured "decay rates" for the Piezobalance are actually the rates of mass accumulation on the crystal, and are affected by the evaporation from the crystal as well as the losses of the airborne fraction ($a + k + evap + other$).

The SidePak and PurpleAir decay rates were consistently maintained at a constant slope over the entire time following a single puff of the heated marijuana liquid—a time that extended from 1 to 8 h. The R^2 values for these regressions were very high at an average R^2 of 98%. However, the "decay rates" for the Piezobalance (which are actually the rates of mass accumulation on the crystal) were typically constant for only 1–2 h, before accelerating toward zero due to evaporation from the crystal surface. An example of the differing behavior of the SidePak and Piezobalance decay rates is provided in Fig. 2. This is the record of a single experiment carried out in the Santa Rosa experimental room. The

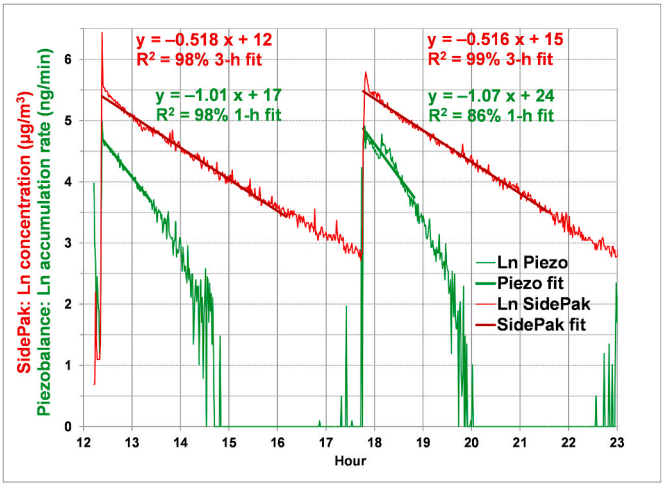

Fig. 2. Calculation of "true peaks" and decay rates for an experiment with a single puff of a vape pen with marijuana-containing liquid (repeated about 5 h later). The "true peaks" are calculated by fitting a line (thick lines) to the decay rates after they have achieved stability and extending the line backward in time to the time of the puff. This is the predicted concentration if perfect instantaneous mixing had occurred. The decay rates are stable for the SidePak (red) but not for the Piezobalance (green). The Piezobalance shows increasing rates due to evaporation from the crystal. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Source strengths (mg/puff) for low and high heating protocols for three instruments.

	n	Mean	Median	Min	Max	SD	SE	CV
Protocol I (low heat)								
Sidepak (CF 0.44)	23	3.00	2.92	0.52	6.13	1.50	0.31	0.1
Piezobalance	23	2.38	2.35	0.36	5.12	1.18	0.25	0.1
PurpleAir (CF 3)	23	3.45	3.42	0.80	6.10	1.42	0.30	0.09
Protocol II (high heat)								
Sidepak (CF 0.44)	19	8.77	8.94	6.74	10.48	1.22	0.28	0.03
Piezobalance	19	7.51	7.84	5.60	10.00	1.42	0.33	0.04
PurpleAir (CF 3)	19	8.86	8.92	7.16	10.84	0.95	0.22	0.02

experimenter took a single puff from the vape pen with an 8:1 CBD/THC ratio at around 12:20 p.m. and then stepped out of the room. For the next 5 h, the aerosol was allowed to decay undisturbed. At around 5:40 p.m., the experiment was repeated. As can be seen, following an initial "false peak" due to unmixed air conditions, the SidePak (red observations) decay rate settles down to a single value of about 0.52 h^{-1} for the 5 h. That value is the negative slope of the best-fit line (thick red line). The line can be extended backward in time to the time of the puff. The intersection of that line and the time of the puff is the "true peak" that would have occurred under instantaneous perfect mixing. From the graph, the peak was about exp (5.4) or 221 μg/m^3. In the second experiment, the decay rates were virtually identical (0.518 h^{-1} and 0.516 h^{-1}). The "true peaks" were also similar (exp(5.4) and exp(5.5)) or 221 and 245 μg/m^3.

The Piezobalance (green) also shows similar peaks for the two experiments, and similar decay rates (for the first hour) following each puff. However, after the first hour, the decay rates increase (steeper slope) and eventually the "concentration" (actually a mass accumulation rate in ng/min) goes to zero (and, in fact, goes to negative values as material evaporates from the crystal surface). Therefore, for the Piezobalance throughout all experiments, the decay rates were only calculated for the first 20 min following a puff. This behavior is expected for volatile particles collected on the crystal undergoing evaporation, and can result in overestimating the actual aerosol decay rates (Table 2).

Decay rates are strongly affected by air movement. The use of a table fan approximately doubled the decay rates for both the SidePak and the Piezobalance (Table S2). The use of two fans led to a further increase that was not, however, statistically significant.

For building models of indoor exposure, it is important to measure a and k separately. The mean air exchange rate was 0.128 (SE 0.008) h^{-1} (Table S3).

5.2.2. Removal rates and air exchange rates

$PM_{2.5}$ removal rates for the SidePaks and PurpleAir monitors are determined by subtracting the measured air exchange rates a from the decay rates ($a + k + other$). The mean removal rates were 0.38 (SE 0.04) h^{-1} for the Sidepak and 0.30 (SE 0.03) h^{-1} for the PurpleAir monitors (n = 29; Table 2). Table S3 The monitors showed good correlation (R^2 = 88%) but also showed that the PurpleAir removal rates are consistently a little lower than those for the SidePak monitors. However, a t-test showed the difference was not statistically significant ($p = 0.12$).

6. Exposure

6.1. 8-Day secondhand exposure experiment

Data from the 8-day exposure experiment were examined to identify the time of elevated concentrations. Concentrations were considered "elevated" if they were associated with the time of vaping and were higher than typical concentrations during non-vaping periods (Fig. S4). The elevated periods had a mean concentration of 62.9 μg/m^3 and lasted about 9 h each day (Table 3). The background concentration for $PM_{2.5}$ was 4.5 μg/m^3. The 24-h average $PM_{2.5}$ concentration was 26.5 μg/m^3 and may be compared to the 24-h average outdoor standard of 35 μg/m^3.

Table 2
$PM_{2.5}$ removal rates (h^{-1}) for the SidePak and PurpleAir monitors.

Statistic	SidePak	PurpleAir
Valid n	29	29
Mean	0.38	0.30
Std.Dev.	0.20	0.19
Std. Err.	0.04	0.03
Minimum	0.11	0.06
10th Percentile	0.15	0.07
Lower quartile	0.23	0.17
Geometric mean	0.33	0.24
Median	0.37	0.28
Upper quartile	0.51	0.40
90th Percentile	0.63	0.54
Maximum	0.91	0.84

6.2. Exposure model

Modeling $PM_{2.5}$ exposure in the experimental room over the time of elevated concentrations requires only 3 inputs: source strength, decay rate, and time of the puff. The PurpleAir monitors were used for this study since they are able to run for multiple days without requiring any attention from the experimenters. The average peak concentration was 226 μg/m^3 (source strength of 6.7 mg/puff divided by the volume of 30 m^3); the observed decay rates were represented by the median value of 0.399 h^{-1}; and the times of the puff were taken from the data. This results in an equation for the logarithm of the concentration C during the time of the peaks:

$$\text{Ln } C = S/V - (a+\text{k})t \ (0 < t < 9\text{h})$$

$$\text{Ln } C = 5.41–0.399t$$

where S is the source strength, V the volume of the room, and t is measured in hours, starting at the time of the puff. The decay rate is a+k, where a is the air exchange rate (h^{-1}) and k is the deposition rate (h^{-1}).

The result of applying these average values to each peak is shown in Fig. 3 (green lines). The simplified model has only 2 parameters rather than 16 for the source strengths and decay rates. The model's mean $PM_{2.5}$ exposure during the 9-h elevated period is 60.0 μg/m^3 compared to the observed value of 62.9 μg/m^3.

Given the observed source strengths and decay rates, a model of exposure can be created by choosing the puff frequency, removal and air exchange rates, and volume of the room or house. For an average-sized new home of 450 m^3, a typical air exchange rate of 0.5 h^{-1}, a removal rate for $PM_{2.5}$ of 0.34 h^{-1}, and a source strength of 4 mg/puff, we find an average exposure of less than 1 μg/m^3 for a puff frequency of one per day (Fig. 4a) or about 25 μg/m^3 for a frequency of 1 per hour for 16 h/day (Fig. 4b). For a worst-case scenario for a small unventilated room of 30 m^3 volume, an air exchange rate of 0.1 h^{-1}, a removal rate of 0.1 h^{-1}, and a high source strength of 7 mg/puff, we find an average exposure of 53 μg/m^3 for a puff frequency of one per day (Fig. S5).

7. Discussion

The four main monitors (SidePak, PurpleAir, pump-filter, and Piezobalance) used in this study had complementary strengths and weaknesses. Both optical monitors (SidePaks and PurpleAir) were able to count particles and estimate particle volumes. However, the resulting PM mass could not be determined from these two monitors without the use of a calibration factor. The mass could be determined both from the pump-filter and Piezobalance results. However, evaporation may be an important process and could only be determined from the Piezobalance. On the other hand, because evaporation from the Piezobalance presumably started soon after aerosol collection, only the early measurements by the Piezobalance could be used to estimate mass. In terms of 24-h average indoor concentrations, only the PurpleAir monitors could be operated continuously for so long, with the other monitors needing considerable downtime for maintenance.

Two results from this study are required for building indoor air quality and exposure models: source strengths and removal rates.

7.1. Source strengths

The source strengths shown by the SidePak and PurpleAir monitors ranged from 3 to 8.8 mg/puff. This is roughly 2–6 times that of tobacco cigarettes on a per-puff basis. Longer heating periods and correspondingly higher temperatures produced significantly higher source

Table 3
$PM_{2.5}$ concentrations (μg/m^3) during background, elevated concentrations, and 24-h average for a frequency of one puff per day.

Event	time (h)	Mean	Std.Dev.	Std.Err.	Lower quartile	Median	Upper quartile
Background	15.0	4.5	2.5	0.0	2.7	4.0	5.5
High concentrations	9.0	62.9	64.7	1.1	13.9	30.8	98.6
All day	24	26.5	48.8	0.5	3.5	5.9	18.3

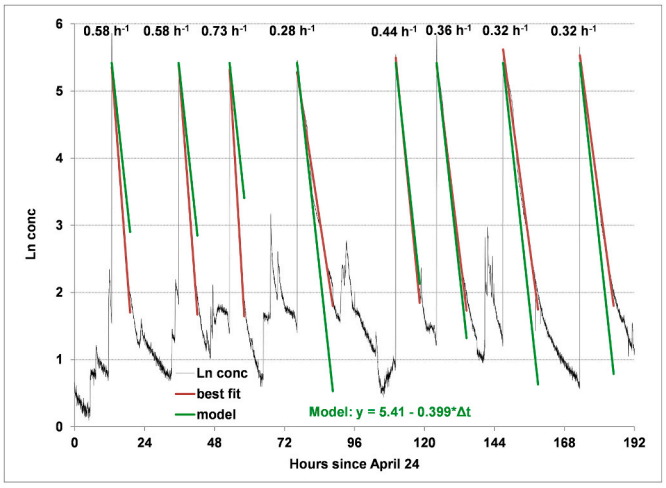

Fig. 3. The natural logarithms of the observed $PM_{2.5}$ concentrations during the 8-day study are shown in black. The best-fit decay rates (red lines) are provided at the top of the figure. The model approximates each peak using the natural logarithm of the observed mean of the peak concentrations (226 μg/m^3) and the median decay rate (0.399 h^{-1}) (green lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

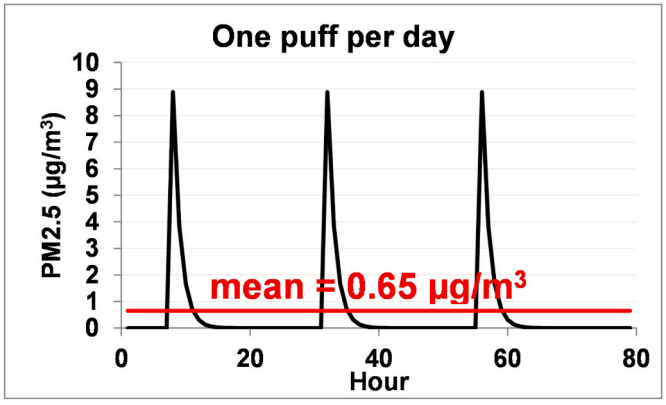

Fig. 4a. Exposure model for a 450 m^3 home with typical home tightness and average marijuana source strength, and a puff frequency of one per day.

strengths, by about a factor of 3 going from 6 to 15 s of heating time. The example from this study showed that concentrations from a single puff could be elevated for about 9 h. Wu et al. (1988) found similar results comparing tobacco and marijuana smokers, with the marijuana smokers inhaling about 3 times the amount of tar and accumulating 30% more tar in the respiratory tract. Ott et al. (submitted) used SidePaks in 60 experiments and found emission rates of 3.4–7.8 mg/puff for four sources of marijuana consumption (joint, bong, glass pipe, vaping device) compared to 2.2 mg/puff for a tobacco cigarette.

7.2. Removal rates

The PurpleAir $PM_{2.5}$ mean removal rate of 0.3 h^{-1} was slightly lower

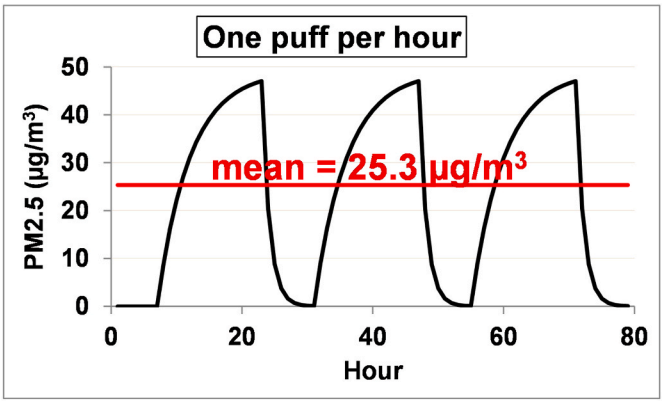

Fig. 4b. Exposure model for a 450 m^3 home with typical home tightness and average marijuana source strength, and a puff frequency of one per hour, 16 h per day.

than that for the SidePak (0.38 h^{-1}), although it was not significantly different. An important recent study by He et al. (2020) has shown that there is considerable overlap in the particle size categories reported by the Plantower sensor. For example, even monodisperse particles of 0.2 μm diameter produced a signal in the nominal 0.3–0.5 μm size category. Moreover, 1 μm particles produced their highest signal in that same 0.3–0.5 μm size category. Because of this apparent extensive mixing of particles of different sizes in the reported size categories, it may be that the PurpleAir removal rates measured in this study have been contaminated by the presence of particles that are outside the upper and/or lower boundaries, suggesting caution be exercised in using or interpreting these results.

7.3. Exposure estimates

The long period of 8–9 h of elevated exposures following a single puff of heated marijuana oil is an important consideration in estimating exposure. The 8-day exposure monitoring experiment allowed creation of a simple $PM_{2.5}$ exposure model that reflects the measured source strengths, removal rates, and air exchange rates. Together with estimates of puff frequency, home volumes and air exchange rates, these findings can be used to estimate the range of exposures likely to be experienced by vaping marijuana.

7.4. Use of low-cost PurpleAir monitors

Side-by-side comparisons of the PurpleAir monitors with research-grade instruments such as the SidePak and Piezobalance showed no essential differences in either the limit of detection or the precision of the results. The PurpleAir monitors make no noise, require no maintenance, and results are obtainable on the Web by anyone at any time. On this basis, we found no strong argument against, and several arguments for, using these monitors in future exposure and health effect studies.

CRediT authorship contribution statement

Lance Wallace: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Wayne Ott:** Methodology,

Software, Validation, Investigation, Formal analysis, Writing - review & editing. **Tongke Zhao:** Methodology, Validation, Investigation, Formal analysis, Writing - review & editing. **Kai-Chung Cheng:** Methodology, Validation, Investigation, Formal analysis, Writing - review & editing, Project administration. **Lynn Hildemann:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2020.100093.

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