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RESEARCH ARTICLE

Comparison of the effects of e-cigarette vapor and cigarette smoke on indoor air quality

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Abstract

Context: Electronic cigarettes (e-cigarettes) have earned considerable attention recently as an alternative to smoking tobacco, but uncertainties about their impact on health and indoor air quality have resulted in proposals for bans on indoor e-cigarette use.

Objective: To assess potential health impacts relating to the use of e-cigarettes, a series of studies were conducted using e-cigarettes and standard tobacco cigarettes.

Methods and materials: Four different high nicotine e-liquids were vaporized in two sets of experiments by generic 2-piece e-cigarettes to collect emissions and assess indoor air concentrations of common tobacco smoke by products. Tobacco cigarette smoke tests were conducted for comparison.

Results: Comparisons of pollutant concentrations were made between e-cigarette vapor and tobacco smoke samples. Pollutants included VOCs, carbonyls, PAHs, nicotine, TSNAs, and glycols. From these results, risk analyses were conducted based on dilution into a 40 m^3 room and standard toxicological data. Non-cancer risk analysis revealed "No Significant Risk" of harm to human health for vapor samples from e-liquids (A-D). In contrast, for tobacco smoke most findings markedly exceeded risk limits indicating a condition of "Significant Risk" of harm to human health. With regard to cancer risk analysis, no vapor sample from e-liquids A-D exceeded the risk limit for either children or adults. The tobacco smoke sample approached the risk limits for adult exposure.

Conclusions: For all byproducts measured, electronic cigarettes produce very small exposures relative to tobacco cigarettes. The study indicates no apparent risk to human health from e-cigarette emissions based on the compounds analyzed.

Keywords: E-cigarette, e-cig, ecigarette, ecig, emissions, vaping, nicotine vaporizer, SHS, secondhand vapor, SHV, eliquid, e-liquid, vapor, TSNA, VOC, PAH, DEG, PG, carbonyl, glycerine, cancer risk, risk estimate, exposure assessment, tobacco smoke, risk assessment, toxicity, indoor air quality, inhalation

Introduction

Introduced in the United States in 2007, electronic cigarettes (e-cigarettes) have quickly become a popular substitute for traditional tobacco cigarettes (Ayers et al., 2011). This substitution appears to be due to health concerns of smokers, increased cost of tobacco cigarettes, and indoor smoking restrictions (Etter & Bullen, 2011). A number of surveys and studies have shown that a substantial number of smokers significantly reduce tobacco use and/or transition completely from tobacco cigarettes to electronic cigarettes. (Bullen et al., 2010; Etter, 2010; Etter & Bullen, 2011; Foulds et al., 2011; McQueen et al., 2011; Polosa et al., 2011; Siegel et al., 2011). Currently, there are only two states that have a statewide ban on e-cigarette use in places where smoking is prohibited. However, dozens of municipalities and counties have discussed and/or introduced pending legislation that would ban the use of e-cigarettes where smoking is prohibited. Prior studies have examined e-cigarettes and e-liquids using

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Gas Chromatography/Mass Spectrometry (GC/MS) to assess the nature and concentrations of pollutants generated from e-cigarettes with different e-liquids (FDA, 2009; Laugesen et al., 2008; Trehy et al., 2011; Lauterbach et al., 2012). Although studies have provided information on the pollutants that could be generated from the vapors, there are no peer reviewed studies that assessed the impact of these air pollutants on overall indoor air quality and exposures.

Experimental methods

Setup

An e-cigarette comes in either two pieces or three pieces and uses a battery that is activated either manually or pneumatically to heat a metal coil (atomizer) that vaporizes the e-liquid in a cartridge (Figure 1). Three piece e-cigarettes have a cartridge which holds the e-liquid to be vaporized, a heating element called an atomizer and a battery to activate the heating element. In two piece e-cigarettes the atomizer and cartridge are combined and called a cartomizer. Two sets of measurements (phases I and II) were made using standard, pneumatic pressure-activated, two-piece e-cigarettes.

A fully charged and tested battery was used for each sample collected. Twelve new cartomizers were filled to capacity with 1.8 mL of e-liquid each from four different-liquid bottles labeled A, B, C and D (three samples from each bottle) using sterile 18 gauge syringes. The four popular e-liquid brands were tobacco flavored and extra high nicotine strength, the highest commonly used level of nicotine (24 mg/mL or 26 mg/mL depending on manufacturer). The same liquid samples were used for both phase I and II. All four liquids and actual tobacco cigarettes (Marlboro Red) were used in both phases. Each brand was studied in triplicate in phase I. In phase II, the e-liquids were repeated three times, but the cigarettes were only duplicated due to some filter cassettes being damaged during shipping. During both phase I and phase II, blank samples were collected using the same setup as for the actual tests without any cigarette or e-cigarette in the smoking machine. These samples were to assess any baseline gaseous species that may be present as a result of off-gassing from the polyethylene bag. No off-gassing from the bag was evident based on the low values obtained from the analyses of the blank samples (Table 1).

Figure 2 shows the experimental setup. Polyethylene glove bags (37″ L × 37″ W × 25″ H; Glas-Col, Terre Haute, IN) were used for collection. Around one hundred and ten liters of commercial zero air were introduced as the dilution air. A Single Cigarette Smoking Machine meeting FTC and ISO requirements as suggested by Lauterbach et al. (2012) (SCSM; CH Technology, Westwood, NJ) was connected to the bag. The e-cigarettes and tobacco cigarettes were connected to the smoking machine to simulate the smoking. Although studies have shown slightly increased levels of some VOCs analyzed in this study in the exhaled breath of nonsmokers (Wallace & Pellizzari, 1995; Gordon et al., 2002), these studies suggest such emissions are likely due to environmental factors such as exposure to gasoline or environmental tobacco smoke (ETS). Schripp et al. (2012) measured VOC levels of exhaled vapor or smoke from an e-cigarette user and cigarette smoker respectively and their results were comparable to our findings. Based on these results, the authors make the assumption that although there may have been lower levels of some compounds assessed in e-cigarette vapor if the vapor had first been inhaled and partially absorbed by the e-cigarette user, it is unlikely there would be significantly higher levels of most of the compounds tested for.

For each e-cigarette trial, 50 puffs of 50 mL per puff (4 s/puff, every 30 s) were used. For the tobacco cigarettes, the puff lasted 2 s with the smoke volume as 35 mL as per the Federal Trade Commission (FTC) protocol (Bradford et al., 1936; Ogg, 1964; International Standards Organization [ISO], 2000). The increased duration of puff for the e-cigarettes was based on direct

Table 1. Phase I and II pollutants sampled for and media for sampling.

Pollutant	Filter type/coating	Method of analysis
Nicotine	Na_2SO_4	GC/NPD
TSNAs	Teflon	GC/MS
PAHs	XAD	GC/MS
PG	XAD	GC/MS
DEG	XAD	GC/MS
VOCs	Multisorbent Tubes	HS-GC/MS
Carbonyls	Quartz Filter	HPLC-UV

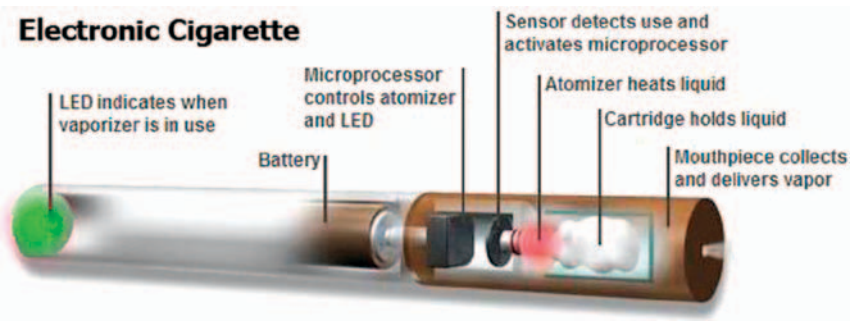

Figure 1. Image of cross section of e-cigarette components.

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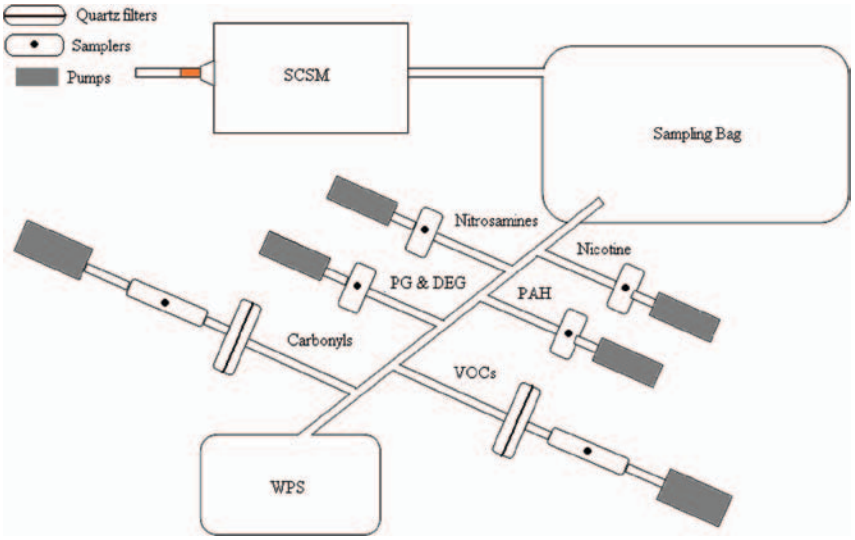

Figure 2. Illustration of the setup for capturing the pollutants after the vapor or smoke was released from the smoking machine.

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observation of e-cigarette use at a gathering for e-cigarette users where puff length average was found to be 4 s. Longer puff duration was also used by Lauterbach et al. (2012). This study was a target compound analysis of tobacco smoke-specific pollutants. Six different types of pollutants were sampled: Nicotine, tobacco specific nitrosamines (TSNAs) (N'-nitrosonornicotine (NNN), N'nitrosoanatabine (NAT), N'nitrosanabasine (NAB), and 4-(methylnitrosamino-1-(3-pyridyl)-1-butanone(NNK)), polyaromatic hydrocarbon's (PAHs), glycols (propylene glycol/PG and diethylene glycol/DEG), volatile organic compounds (VOCs) and carbonyls (i.e. formaldehyde, acrolein, acetaldehyde). The flow rates through these samplers were 265 mL/min, 250 mL/min, 235 mL/min, 250 mL/min, 180 mL/min and 200 mL/min, respectively. For the first four species, filter cassettes were prepared by a certified laboratory according to the protocol described by Hammond et al. (1987). The glycol sampler used an XAD-4 impregnated quartz filter using a procedure similar to that described by Lewtas et al. (2001). A 47 mm quartz filter (Pall, Quartz 47 mm, 2 μm pore size, USA) was placed in front of the sampling tube for VOCs and carbonyls to remove particles. The filter was replaced for each trial. Preconditioned thermal desorption tubes (SUPELCO, USA) were used to collect VOC samples. Sorbent tubes (catalog #226-119; SKC, Eighty Four, PA) and the filters in ChemDisk Personal Samplers (Assay Technology, USA) were used for carbonyl collection in the two phases, respectively. The latter impregnated filters were used for phase II as prior to beginning phase II there was a shortage of the sorbent tubes used in phase I. The sorbent tubes and impregnated filters used 2,4-dinitrophenylhydrazine (DNPH) to collect carbonyls for an EPA TO-11 type analysis. Each species had its own sampling pump. A Wide Range Particle Spectrometer (WPS) (Model 1000 XP, MSP Corporation, Shoreview, MN) was used to measure particle number size distributions. The WPS is designed to sample particle ranges from 10 nm to 10 um. The total WPS flow rate was 1 LPM of which 0.3 LPM was for the differential mobility analyzer (DMA) aerosol flow and 0.7 LPM was for the laser particle spectrometer (LPS) aerosol flow. The sampling bag was changed after each trial. In addition, the smoking machine was cleaned with ethanol to prevent any cross contamination between the samples.

After sampling, the cassettes used for nicotine, nitrosamines (NNN, NAT, NAB, NNK), polyaromatic hydrocarbons (PAHs), propylene glycol (PG) and diethylene glycol (DEG) samples were packed in dry ice for shipment to the laboratory for analysis.

Analysis

VOCs and carbonyls

VOCs

VOC samples were stored in a freezer at –20°C before analysis. The concentrations of the VOC species were determined using a modified EPA Method TO-17 procedure (USEPA, 1999a). Using an Entech Model 5400 (Entech Instruments, Simi Valley, CA), the samples were individual thermally desorbed into silonized bottles. Conventional thermal desorption provides only one opportunity to make the measurement. However, by desorption into the equivalent of a canister, a second analysis can be performed if there are problems with the initial analytical run. The partial contents of the bottle were introduced to a cryogenic preconcentrator (Model 7100A, Entech Instruments), and then flash evaporated into and analyzed with a Finnigan Gas Chromatography-Ion Trap Mass Spectrometry (GC/MS, Trace GC with Polaris Q MS, ThermoFinnnigan, San Jose, CA).

Carbonyls

Each carbonyl sample was placed into a brown glass vial to avoid any photodecomposition and was

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extracted with 1 mL of acetonitrile (ACN) for 1 h using a Standard Orbital Shaker (VWR, Model 3500, Houston, Texas). The extracts were then analyzed using the EPA TO-11HPLC/UV method (USEPA, 1999b). In brief, a 20 µL aliquot was injected to the HPLC/UV analysis system (Surveyor PDA Detector, Surveyor Autosampler, Surveyor LC Pump, Thermo Electron). A Nova-Pak C18 analytical column (3.9 × 150 mm, Waters, Milford, MA) was used for the separation of the carbonyl-DNPH derivatives. The mobile phase contains two mixed solutions: A = ACN/water 60/40 (v/v) and B = water/ACN/tetrahydrofuran 60/30/10 (v/v/v). The LC pump setup was 100% B solution for 2 min, followed by linear gradient from 100% B to 100% A in 10 min and then 100% A for another 13 min. The mobile flow rate was 1 LPM and the samples were analyzed with UV detection at 365 nm.

Blank and 1 ppm standard were run every nine samples as the quality control. The extraction efficiency was determined as 95–105% in general for the target analyses by spiking a known amount of the standard mixture (Air Monitoring Aldehyde-DNPH Mix, AccuStandard, New Haven, CT) to the sample matrix. The relative standard deviation of the 7 repeated injections of a mid-level standard was around 2–10 % for all the target compounds.

PAHs

The PAHs to be quantified were naphthalene, acenaphthylene, acenapthene, fluorine, anthracene, henanthrene, fluoranthene, pyrene, benz(a)anthracene, chrysene, retene, benzo(b)fluoranthene benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenz(a, h) anthracene, and benzo(ghi)perylene. Samples were collected on Pallflex 2500QAT Quartz fiber filters, treated with ground XAD-4 resin. Serial dilutions of the stock standard were made in dichloromethane. The standards were run with PAH samples that were extracted and reduced from filters. Samples are extracted by sonication in dichloromethane, followed by evaporation to 0.5 mL. A Hewlett Packard 6890 gas Chromatograph equipped with a 5972 Mass Selective detector was used to perform the analysis. The column used is an Agilent Technologies part #122–5562, DB-5MS fused silica capillary column with the following specifications: length 60 m, diameter 250 µm, film thickness.25 µm. The inlet temperature was 300°C. The oven conditions were 80°C, increased by 5°C/min to 300°C, hold for 20 min.

Nicotine

Samples were collected on Pallflex TX40HI20 Teflon coated fiber filters. Extraction of nicotine from treated filters was performed by liquid-liquid extraction of the filters by vortexing in NaOH and heptane. The 0.5 mL organic layer was removed from the solution and injected into the Gas Chromatograph. A Hewlett Packard 7890 Gas Chromatograph equipped with a Nitrogen Phosphorus detector was used to perform the analysis. The column used was an Agilent Technologies part #123-5012E, DB-5MS fused silica capillary column with the following specifications: length 15 m, diameter 320 µm, film thickness.25 µm. The inlet temperature was 235°C. The oven conditions were 60°C initially, hold for 4 min, increased by 10 C/min to 190°C, then 30°C/min to 225°C

Tobacco specific nitrosamines

The four nitrosamines to be quantified were N′-nitrosoanabasine, N′-nitrosoanatabine, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, and N′-nitrosonornicotine. The samples were collected using Pallflex TX40HI20 Teflon coated fiber filters (Hammond et al., 1987). Filters are extracted by sonication in methanol, followed by evaporation to 0.5 mL. A Hewlett Packard 7890 Gas Chromatograph equipped with a Nitrogen Phosphorus detector was used to perform the analysis. The column used was an Agilent Technologies part #123-5012E, DB-5MS fused silica capillary column with the following specifications: length 15 m, diameter 320 µm, film thickness 0.25 µm. The inlet temp was 300°C. The oven conditions were 80°C initially, increased by 15°C/min to 140°C.

Glycols (DEG and PG)

Samples were collected on XAD-4 impregnated Pallflex 2500QAT Quartz fiber filters in phase I, and on XAD-4 impregnated Pallflex TX40HI20 Teflon coated fiber filters in phase II (Lewtas et al., 2001). The filters were extracted by sonication in methanol, followed by evaporation to 0.5 mL. A Hewlett Packard 6890 gas Chromatograph equipped with a 5972 Mass Selective detector was used to perform the analysis. The column used was an Agilent Technologies part #19091X-133, DB-WAX fused silica capillary column with the following specifications: length 30 m, diameter 250 µm, film thickness 0.25 µm. The inlet temperature was 250°C. The oven conditions were 70°C initially, hold for 2 min, increased by 10°C/min to 220°C.

Results

The values of the pollutant concentrations for the e-liquid vapor samples and the cigarette smoke samples are presented in the Table 2 and in more detail in the supplemental material (Tables S1–S6).

For all of the samples, average VOC concentrations measured during phases I and II were below the limit of detection with limited exceptions. Ethylbenzene, benzene, toluene, and m/p xylenes (BTEX) were above detection limits. Their measured concentrations were orders of magnitude higher in tobacco smoke relative to the e-liquid vapor. The latter 3 compounds were measured by Schripp et al. (2012) and the results were comparable. For most carbonyls, concentrations were found to be low for both phases I and II for samples A-D, with some exceptions, such as acetone, formaldehyde, and acetaldehyde. These 3 carbonyls, however, were orders of magnitude higher in tobacco smoke relative to e-liquid vapor. Findings

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Table 2. Summary of the average concentrations (ng/L) of sampled pollutant during phase I and II.

	Vapor Sample A		Vapor Sample B		Vapor Sample C		Vapor Sample D		Blank E		Cigarette Smoke F	
	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II	Phase I	Phase II
VOCs	18.0	139.2	76.0	178.7	115.5	137.7	317.5	45.7	112.0	64.0	3566.3	6185.3
Carbonyls	797.7	345.0	1112.0	376.3	809.3	357.5	973.7	360.5	1648.8	327.4	31865.2	11357.3
PAHs	4.25	1.83	0.30	0.93	3.05	0.55	0.18	0.75	N/F	0.65	2.69	2.67
Nicotine	905	1705	725	2144	538	8770	6794	5904	N/F	N/F	5039	48050
TSNAs	N/F		18		18		15				121	
PG	2668	2254	37,785	56,133	120,000	54,993	77,390	88,365	1339	196	3,185	260
DEG	N/F	N/F	3	N/F	511	N/F	143	N/F	16	N/F	13	N/F

See Tables S1–S6 in the supplemental sections for additional information on specific pollutants, measured concentrations, and limits of detection (LOD).

are consistent with Schripp et al. (2012) and Lauterbach et al. (2012). Most PAHs were below the LOD for e-cigarette vapor but were above LOD for tobacco smoke. An anomaly was found with benzo(a)pyrene as it was found at similar levels in e-cigarette vapor, tobacco smoke, and the blank sample. Lautebach et al. (2012b) found contrasting results and noted benzo(a)pyrene was below their LOD for e-cigarette vapor but more than 40 times higher in tobacco cigarette smoke. Nicotine levels were also significantly higher in cigarette smoke than in the e-liquid vapor, typically by an order of magnitude or more. This result is corroborated by Laugesen et al. (2008), Lauterbach et al. (2012), and Trehy et al. (2011). Tobacco specific nitrosamines (N′-nitrosoanabasine, N′-nitrosoanatabine, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, and N′-nitrosonornicotine) quantified in e-cigarette vapor were also typically found at lower levels than tobacco smoke. The TSNA results for phase II were not included in the summary table because significant levels of TSNAs in the blank sample and atypically low levels of TSNAs in the cigarette smoke make this data set unreliable. Previous studies (Laugesen et al., 2008; FDA, 2009: Lauterbach et al., 2012) have shown levels of these TSNAs in e-cigarette vapor to be orders of magnitude lower than in tobacco cigarettes which is similar to our findings from phase I. DEG was detected in some samples, but below toxic levels as is corroborated by FDA (2009) and Lauterbach et al. (2012). The risk analysis of all the phase I and II measured pollutants is presented in the toxicology section.

Table 3 shows very low particle counts across all e-liquids tested. Figure 3 presents the average size distributions for all of the samples measured in the phase I experiments. Instrument problems with the WPS produced highly uncertain measurements for the phase II experiments and thus, they are not presented. The e-cigarette liquids include components like the glycols that can nucleate in the air to produce visible particles and provide the illusion of "smoke." Figure 3 shows at least two size modes are formed in the bag where there were essentially no pre-existing particles. It also shows that the particle number concentrations in the tobacco smoke are significantly higher than in the e-cigarette emissions (Figure 3). These results are in reasonable agreement with those of Schripp et al. (2012) where they diluted the emissions into a much higher volume resulting in modes with

Table 3. Total particle counts for phase I.

Sample	Mean number concentration ± SD (p/cm^3)	N (samples)
Vapor Sample A	1795 ± 2315	79
Vapor Sample A	2015 ± 2361	79
Vapor Sample A	1654 ± 2067	79
Vapor Sample B	667 ± 1873	79
Vapor Sample B	635 ± 1800	79
Vapor Sample B	2115 ± 2329	79
Vapor Sample C	2119 ± 2378	79
Vapor Sample C	2287 ± 2472	79
Vapor Sample C	2963 ± 3122	79
Vapor Sample D	994 ± 2023	79
Vapor Sample D	2019 ± 2040	79
Vapor Sample D	2057 ± 2218	79
Blank E	28 ± 35	79
Cigarette Smoke F	21810 ± 55287	79
Cigarette Smoke F	21352 ± 50414	79
Cigarette Smoke F	19906 ± 48189	79

Phase II results are not presented due to complications with the WPS.

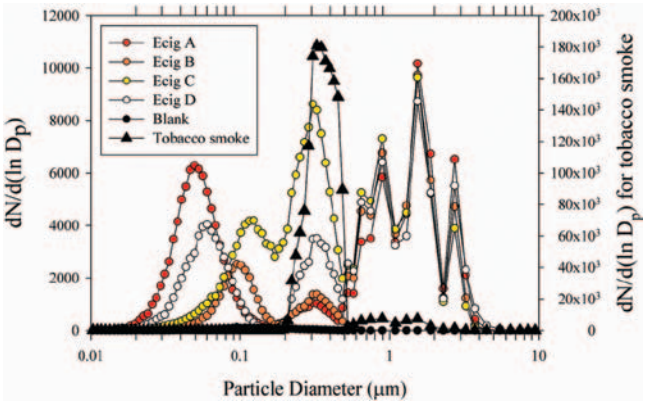

Figure 3. Overall particle number concentration (p/cm^3) and size distribution data for all vapor and smoke samples collected in phase I.

different relative proportions. The Schripp et al. (2012) measurements were measurements of the size distribution after a smoker or e-cigarette user exhaled the aerosol and only measured particles <560 nm in diameter. These distributions are similar to those observed in the present

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study. These measurements indicate that e-cigarettes do not contribute significant particulate matter mass to the indoor environment.

The cigarette smoke particle number concentration was an order of magnitude higher than the highest concentration of any e-liquid (2963 ± 3122, liquid C vs. 21,352 ± 50,414). Similar differences were found in Schripp et al. (2012). These results would be expected given the combustion of the tobacco.

Toxicology

An expert toxicology consulting firm assessed the impacts of the measured concentrations on indoor air quality for all of the pollutants. Air quality data collected during both phases was provided to the toxicologist after being converted to estimated air concentrations using a well-mixed standard room size of 40 m^3. Indoor air quality analysis was conducted based on a dynamic system with estimated air changes per hour of 0.3. Risk analysis was conducted for all byproducts detected in vapor from e-liquids A-D, and cigarette smoke (F).

The Total Cumulative Hazard Indices (HIs) and Excess Lifetime Cancer Risks (ELCRs) values from the aforementioned Risk Analyses are presented in Supplemental Tables S7a and b & S8, respectively, for each vapor sample for e-liquids A-D and cigarette smoke (F) for phases I and II of the study. The HI and ELCR values were compared to acceptable Risk Limits of an HI of 1 for Non-Cancer Risks and an ELCR Risk Limit of 1×10^{-5} for Cancer Risks. In addition, based on individual Hazard Quotients and ELCRs, the percentage risk contributions by the individual analytes were calculated to identify either individual chemical or chemical class risk drivers and the results are presented in Supplemental Tables S7a and b and S8.

Based on the exposure assumptions listed in Tables S7a and b and S8 for child and adult subchronic, chronic, and lifetime inhalation exposures to the atmospheric concentrations of Non-Cancer and Cancer analytes detected in vapor from e-liquids A-D and cigarette smoke (F), for phases I and II of the study, the Non-Cancer Risk findings (Table S7a and b) for both subchronic and chronic exposures, revealed a condition of "No Significant Risk" of harm to human health for vapor from e-liquids A-D (i.e. no HI value >1). For the cigarette smoke, (F), phase I results, the child subchronic and chronic inhalation exposure HIs markedly exceeded the HI Risk Limit of 1 (i.e. HIs = 2 and 10, respectively). In addition, the HI value of 5 for adult chronic exposures to cigarette smoke (F) in phase I of the study also indicated a condition of "Significant Risk" of harm to human health via the inhalation route of exposure, as did the HI value of 2 for the cigarette smoke (F), phase II for chronic child exposures. It is important to note that the key risk drivers for subchronic exposures were acrolein, methacrolein and propionaldehyde and for chronic exposures, acrolein and methacrolein. In the case of acrolein and methacrolein, some degree of uncertainty may be associated with this finding, since acrolein was used as the surrogate for the methacrolein inhalation RfCs.

For child and adult exposures to carcinogens in vapor from liquids A-D and cigarette smoke (F) (Table S8) no Cumulative ELCR exceeded the Cancer Risk Limit of 1×10^{-5}, with ELCRs ranging from 1×10^{-7} to 9×10^{-10}, however for F (cigarette smoke), for phase I and phase II ELCRs adult exposures approached the ELCR risk limit of 1×10^{-5} (i.e. ELCRs of 7×10^{-6} and 1×10^{-6}, respectively). In each instance the primary risk driver was acetaldehyde. However, based on the overall findings, neither vapor from e-liquids A–D, or cigarette smoke (F) analytes posed a condition of "Significant Risk" of harm to human health via the inhalation route of exposure.

Discussion

Electronic cigarettes have earned considerable attention by local, state, and federal agencies over the last few years. Many legislators have issued warnings and/or proposed bans to prohibit the use of e-cigarettes in public places. In July 2009, the Food and Drug Administration (USFDA, 2009), issued a report (http://www.fda.gov/ForConsumers/ConsumerUpdates/ucm173401.htm) voicing several concerns, such as potential for youth addiction and possible toxicity of e-liquid. The FDA issued this report without any evidence of youth use of e-cigarettes or health impacts from the use of or exposure to emissions from an e-cigarette. In this study emissions from e-cigarette use and tobacco cigarette use were analyzed to measure levels of the chosen pollutants. Analysis of the pollutant concentrations showed that the e-cigarette vapor was found to pose significantly lower risk than cigarette smoke under the same testing conditions. Since there is no combustion with e-cigarette use, as opposed to cigarette smoking, particle counts resulting from vapor production were expected to be low as found during phase I (Table 3). These results are uncertain since they could not be replicated in phase II due to instrumental problems. For the cigarette smoke, particle concentrations were an order of magnitude higher than concentrations found for the vapor samples as shown above (Table 2). These results are similar to those of Schripp et al. (2012) and tobacco cigarette smoke particle distributions in Li and Hopke (1993).

Total air emission concentrations for many pollutants were found to be very low. The toxicology data shown in supplemental material (Tables S7a and b and S8) provides scientific evidence that for all pollutants sampled during this study, the endpoints of concern for assessing overall risk revealed no discernible health impacts from exposures to the vapor produced by any e-liquid used in this study. ELCR values for mainstream cigarette smoke samples were fairly low. The authors believe that this was because the measurements did not include side stream smoke in the testing environment. This lack of ETS should be taken into account for levels of all compounds measured in cigarette smoke

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in this study with respect to indoor air quality. All risk analysis findings are based on a standard room size of 40 m^3 taking into account dispersion of the pollutants and a well-mixed environment. There is no prior research that compares actual emissions data collected with an assessment of potential exposures. These findings assess only the actual emissions measured and associated risk analysis impacts, not potential adverse health impacts related to e-cigarette use.

To date, no study on e-cigarettes suggests a potential risk to bystanders of e-cigarette users. A recent study by Flouris et al. (2012) concluded that acute active and passive vaping of e-cigarettes did not influence complete blood count (CBC) indices in smokers and never smokers, respectively. In contrast, acute active and passive tobacco cigarette smoking increased the secondary proteins of acute inflammatory load for at least 1 h.

Some weaknesses of this study include not changing the tubes in consideration of the possibility of glycol adherence to Teflon tubes used for sample collection during phase I of the experiment and the WPS error during phase II of the experiment. Difficulty obtaining IRB approval in 2009 for human subject trials using previously unstudied products made use of a smoking machine necessary to conduct this study. As a result, data did not reflect real world use of e-cigarettes, where the human user is an intermediary between the vapor and the environment.

There are a number of possibilities for future research. As a result of a large data gap as to what chemical compounds and/or pollutants found in tobacco smoke are also found in vapor produced by e-cigarettes, this study was designed to assess similarities and differences between tobacco smoke and e-cigarette vapor. Constituents were then assessed based on their overall risk for potential health impacts based on measured concentrations during phase I and II. Future studies should include repeating the experiment with other flavors of e-liquid (including flavorless) to determine whether flavoring in e-liquid plays a part in levels of various pollutants, varied voltage e-cigarettes to investigate whether increased heat initiates pyrolysis or decomposition that increases the toxicity, various types of cartridges and atomizers to determine whether cartomizer filler (polyfil) affects levels of tested compounds, and additional brands of e-liquid to assess emissions from a greater variety of e-liquids. It may also be beneficial to repeat the current study using a multi-cigarette version of the smoking machine to see if higher concentrations of vapor may affect toxicity. Tobacco cigarettes produce side stream smoke continuously, but there is minimal side stream vapor with e-cigarette use. Therefore, it would be helpful to repeat the experiment with human subjects smoking or using the e-cigarette inside the testing environment for inclusion of side stream smoke for comparison to real world environment. This would also help determine the extent to which vapor components may be absorbed by the e-cigarette user, rather than being released into the ambient air (see Vansickel & Eissenberg, 2012).

Conclusions

The current study indicates that there are very low indoor air quality impacts from the use of an electronic cigarette based on the risk screening of measured emissions. It also indicates no apparent risk to human health from e-cigarette emissions based on the compounds analyzed. The authors recognize that future research assessing exposures to bystanders and users will be imperative for fully understanding the impacts from use of an electronic cigarette.

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Declaration of interest

National Vapers Club (NVC) has spent more than 3 years educating people about electronic cigarettes. This research was necessary to have more thorough information to present to scientific and political bodies who are struggling with regulation of a new product about which there is very little published scientific data. Funding was obtained by fundraising events held by NVC as well as individual donations by NVC members, and in part by e-cigarette retailers who contacted NVC to offer contributions. Although NVC funded this study, it had no control over the results. The scientists and independent contractors hired by the principal investigator were entirely responsible for collecting, analyzing and interpreting the data. Prior to data collection, no author or independent contractor who worked on this project had any financial interest in the outcome of this study. Subsequent to data collection, S. Babaian became part owner in a retail e-cigarette company.

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