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E-cigarette Solvent Ratio and Device Power Influence Ambient Air Particulate Matter

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Abstract

Objectives: Electronic cigarette (ECIG)-generated aerosol contains particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$). Particles of this size may be injurious to the health of those who inhale them. Few studies have assessed the relationship between ECIG aerosol $PM_{2.5}$ and ECIG liquid ingredients or ECIG device power.

Methods: Two studies were conducted in which participants generated aerosols with ECIGs: in one, ECIG liquids contained various vegetable glycerin/propylene glycol ratios and in the other, ECIG devices varied by electrical power output.

Results: Results indicate that, in general, $PM_{2.5}$ increases as the ratio of vegetable glycerin to propylene glycol increases, or as device power increases.

Conclusions: Regulating ECIG $PM_{2.5}$ emissions to protect non-users requires an understanding of all the factors that influence these emissions.

Keywords

electronic cigarette; particulate matter; $PM_{2.5}$; propylene glycol; vegetable glycerin; device power

Electronic cigarettes (ECIGs) contain a liquid usually composed of nicotine and solvents such as propylene glycol (PG) and vegetable glycerin (VG). This liquid is heated into an

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Human Subjects Approval Statement
The studies described here were approved by Virginia Commonwealth University's (VCU's) institutional review board (IRB).

Conflict of Interest Disclosure Statement
Dr. Eissenberg is a paid consultant in litigation against the tobacco industry and also the electronic cigarette industry and is named on one patent for a device that measures the puffing behavior of electronic cigarette users and on another patent for a smartphone app that determines electronic cigarette device and liquid characteristics. The other authors have no conflicts of interest to disclose.

inhalable aerosol by a coil attached to a battery.[1] Although ECIGs emit fewer toxicants compared to combustible cigarettes, ECIG aerosol contains toxicants such as volatile carbonyls and metals[2–4] that have been linked to cardiovascular disease and cancer.[5,6]

The content of ECIG aerosols depends on liquid and/or device characteristics.[7,8] Liquid solvent ratio (ie, the ratio of PG to VG) influences particulate matter size and mass within the generated aerosol. For example, at a given power output, mainstream ECIG aerosols generated from liquids that have more VG have greater particle size and a smaller mass (Total Particulate Matter; TPM) relative to aerosols generated with liquids that have more PG.[9] Further, mainstream particulate matter production may vary across different ECIGs, which may be due to differences in power output of these devices.[10] Indeed, ECIG device power is known to increase the toxicant content of mainstream ECIG aerosols.[3,11,12]

Tobacco cigarette smoke is known to be a health risk for smokers who inhale it voluntarily and also for non-smokers who are exposed to it and inhale it involuntarily.[13,14] Environmental tobacco smoke (ETS; also known as "second-hand smoke") contains many pollutants that have been linked to a variety of diseases.[15,16] ETS particles usually have a diameter of less than 2.5 μm (fine particulate matter, abbreviated as $PM_{2.5}$). Particles less than 2.5 μm in diameter are clinically important because they can reach human pulmonary alveoli and may result in respiratory inflammation and oxidative stress.[17,18] A variety of studies measuring $PM_{2.5}$ concentrations (in micrograms per cubic meter, or $\mu g/m^3$) in settings in which tobacco smoking is allowed have been conducted. For example, in a study examining $PM_{2.5}$ concentrations in waterpipe cafés, mean $PM_{2.5}$ concentrations were 374 $\mu g/m^3$;[19] in a study of hospitality venues, mean $PM_{2.5}$ concentrations were 324 $\mu g/m^3$;[20] and in a study of restaurants and bars in Greece, mean $PM_{2.5}$ concentrations were 268 $\mu g/m^3$.[21]

Similarly, ECIG aerosol is likely a health risk for users who inhale it voluntarily[22,23] and also may be a health risk to non-users who are exposed to the aerosol and who may inhale it involuntarily.[24] $PM_{2.5}$ concentrations have been measured at locations where ECIGs are being used; at an event held for ECIG users, average $PM_{2.5}$ concentrations were 607.12 $\mu g/m^3$.[25] Finally, under controlled settings, exhaled ECIG aerosol (PM_1 was measured) may increase as power settings increase.[26] Clearly more work is needed to understand the health effects associated with involuntary inhalation of ECIG aerosols. Few studies have systematically examined the effect of liquid composition (ie, PG/VG ratio) and device power on $PM_{2.5}$ concentrations detected in secondhand ECIG aerosol. One first step involves investigating how common ECIG features influence the exposure of non-users to $PM_{2.5}$. Here, we look at how PG/VG ratio (Study 1) or ECIG device power (Study 2) influence $PM_{2.5}$ exposure.

METHODS

General Procedure

Study 1 and Study 2 were both IRB-approved clinical laboratory studies conducted at Virginia Commonwealth University with the goal of investigating factors that might influence plasma nicotine concentration, subjective effects, puff topography (all reported elsewhere), and ambient air $PM_{2.5}$ (reported here).

Study 1.—This study (described in[27]) involved 4 Latin-square ordered sessions that differed by liquid PG:VG ratio: 100:0, 55:45, 20:80, and 2:98. ECIG experienced participants (29 men, 1 woman) with a mean age of 26.9 years (SD=7.1), reported using ≥ 1 ml of ECIG liquid daily (mean=6.3 ml; SD=5.7) and reported using their ECIG ≥ 3 months (mean=16.6 months; SD=12.3). All participants completed two 10-puff use bouts with an "eGo" style (3.3 V) battery with a 1.5 ohm (Ω), dual-coil, 510 "cartomizer" (7.3 W; SmokeTech; Shenzhen, China) filled with ~1 mL of tobacco flavored ECIG liquid containing 18 mg/ml of nicotine.

Study 2.—This study (described in[28]) involved 6 Latin-square ordered sessions that differed by device power (15 W or 45 W) and liquid nicotine concentration (0, 3, or 6 mg; all 50:50 PG/VG). Cigarette-smoking participants (8 men, 2 women), with a mean age of 35.3 years (SD=10.2), reported smoking 16.4 cigarettes/day (SD=4.9). Most participants (9/10) reported ever using an ECIG, and when asked to estimate how many times they had ever used an ECIG, 5 indicated less than 5 times, and 4 indicated 6–10 times. All participants completed one 10-puff use bout and then a 90-minute *ad libitum* use period with a Kangertech Cupti ECIG filled with ~3 ml of tobacco or menthol flavored liquid.

Both studies were conducted in windowless rooms of approximately 578–612 cubic square feet, with a typical HVAC system (heat or air conditioning on, but no exhaust fan). Room doors were typically closed before and during product use.

Outcome Measures

During each session particulate matter was measured using a personal aerosol monitor (TSI Model AM510 SidePak; Study 1), or either an AM510 or AM520 SidePak personal aerosol monitor (Study 2; Shoreview, Minnesota, USA). For each session the aerosol monitor was set to a one-minute log interval measurement of $PM_{2.5}$ (60 one-second consecutive measurements averaged) and was zero-calibrated using a filter and a lubrication process referenced by the manufacturer (as in[19,29]). Similar technology and methods have been used to measure $PM_{2.5}$ in ambient air associated with tobacco cigarettes,[29] waterpipe,[19] and ECIGs.[25]

Data Preparation and Data Analysis

For all $PM_{2.5}$ data, a calibration factor of 0.32 was applied (as in[25];[29]). For each of the 4 sessions of Study 1, $PM_{2.5}$ data were averaged to produce a single value for the 30 min period before a 10-puff directed bout and the 5 min period of the first 10-puff bout. Because the data were not normally distributed, they were analyzed using a non-parametric Friedman test of differences among repeated measures, with post-hoc testing using Wilcoxon signed ranks tests. For non-orthogonal comparisons, a Bonferroni correction was used. For each of the 6 sessions of Study 2, $PM_{2.5}$ data were averaged for the 30 min before the start of the 10-puff bout and the 5 min period of the 10-puff bout. These data also were not normally distributed and were analyzed as in Study 1.

RESULTS

Study 1

All mean (SD) and median $PM_{2.5}$ values detected before and during the first ECIG use bout for the 4 experimental conditions are presented in Table 1. The Friedman test of differences among repeated measures resulted in a Chi-square value of 97.88 ($p < .001$). As Table 1 shows, Wilcoxon signed ranks tests indicated that $PM_{2.5}$ concentrations significantly increased in each condition from pre-ECIG use to during use except for the 100PG:0VG condition (Zs<−4.4; ps < .001). Across conditions, compared to 100PG:0VG, $PM_{2.5}$ concentrations during use were significantly higher in the 2PG:98VG, 20PG:80VG, and 55PG:45VG conditions (Zs<−4.0, ps < .02).

Study 2

Table 2 displays all mean (SD) and median $PM_{2.5}$ values detected before and during the 10-puff ECIG use bout for the 6 experimental conditions. The non- Friedman test of differences among repeated measures resulted in a Chi-square value of 45.73 ($p < .001$). As Table 2 shows, Wilcoxon signed-ranks tests indicated that for the 45W conditions, mean $PM_{2.5}$ concentrations significantly increased during each condition (Zs<−2.30, ps < .05). Across conditions, comparing $PM_{2.5}$ concentrations during ECIG use, significantly higher $PM_{2.5}$ concentrations were observed in the 45W_0mg than in the 15W_0mg condition, as well in the 45W_6mg compared to the 15W_6mg condition (Zs<−2.0, ps < .05).

CONCLUSIONS

Fine particulate matter ($PM_{2.5}$) was assessed before and during ECIG use in 2 studies. Results from Study 1 revealed that, during the 10-puff ECIG use bouts with the 3 liquids containing VG, significant amounts of $PM_{2.5}$ were detected in the ambient air, compared to before ECIG use. Results from Study 2 revealed that during the 10-puff use bouts with the ECIG set at 45 W, $PM_{2.5}$ concentrations were significantly higher than before ECIG use. These findings are consistent with previous work showing an increase in particulate matter ($PM_{2.5}$, PM_1, and ultra-fine particles) during times when ECIGs were used under controlled conditions.[30–32] Of note, the $PM_{2.5}$ concentrations observed in the present study are markedly lower than those detected in locations that permit the use of tobacco cigarettes,[20] waterpipe,[19] and ECIGs.[25] However, because each of these studies assessed $PM_{2.5}$ while many individuals used their respective products for upwards of 30 minutes, their results likely do not provide an adequate comparison to the present study that measured $PM_{2.5}$ from a single participant taking 10 puffs from an ECIG over 5 minutes. Thus, the important message is that even a single, brief ECIG use may involve significant increases in ambient air $PM_{2.5}$ (influenced by liquid ingredients and device power, see below), causing non-ECIG users to involuntarily inhale ECIG aerosol.

Notably, in study 1, negligible $PM_{2.5}$ concentrations were detected when participants used the 100PG:0VG liquid. Given that the SidePak personal aerosol monitor used in that study was set to detect only particles between 0.1 (or 100 nm) and 2.5 µm, these results could suggest that the majority of particles emitted from ECIGs containing liquids high in PG may be smaller than 100 nm (also referred to as ultrafine particles), although it is possible that a minimal fraction of the particles could be larger than 2.5 μm (also referred to as inhalable coarse particles).[9,33] Previous examinations in which ECIG particulate matter was assessed using equipment sensitive enough to detect ultrafine particulate matter suggest that the particles may be smaller than 100 nm (eg,[4,9,30]). In one pre-clinical examination, PG:VG ratio was varied systematically, and particulate matter was examined using equipment capable of detecting ultrafine particles. The 100PG:0VG liquid produced mainstream aerosols significantly smaller than 100 nm.[9] Thus, in the present study, use of the 100PG:0VG liquid likely resulted in users exhaling predominantly ultrafine particles that could not be detected by the Sidepak personal aerosol monitor. Further, 100PG:0VG particles have shorter evaporation timescales as compared to particles derived from VG, which can potentially lead to shrinking of particles by the time they get detected by the instrument.[9] Future examinations should be conducted to characterize the content of ECIG $PM_{2.5}$ and ultrafine particles and determine their respective effects on the user, as very small particles may be particularly harmful.[18] The results of Study 1 clearly demonstrate that $PM_{2.5}$ is present in ambient air when a human inhales and then exhales ECIG aerosol produced by heating liquid that contains VG. VG is a near ubiquitous ECIG liquid ingredient, thus any indoor venue in which ECIG use occurs likely involves exposure to $PM_{2.5}$ for any non-ECIG users present.[34]

In Study 2, $PM_{2.5}$ concentrations did not increase significantly in the 15 W conditions but did increase significantly in the 45 W conditions. This contrast may be explained by the smaller volume of aerosol produced by lower-wattage devices.[10] Importantly, as nicotine concentrations in liquid are reduced, users may increase their device power to obtain more aerosol and thus more nicotine.[35] This change may cause users – and also nearby non-users – to be exposed to more particulate matter and possibly more toxicants.[36]

This study did have some limitations. First, the data presented here indicate the concentration of particles less than 2.5 μm (in micrograms per cubic meter), but not the composition of those particles (ie, whether or not the particles are toxicants). Second, our monitors were not able to measure ultrafine particles; thus, particulate matter concentrations were likely underestimated in both studies. Third, this study was not conducted under ideally controlled room conditions, although this limitation may more realistically reflect actual use in a natural environment.

Overall, results indicate that in general, as the ratio of VG/PG increases, and as device power increases, $PM_{2.5}$ exposure also increases. More work is needed to determine what other factors lead to $PM_{2.5}$ production when ECIGs are used, as well as further investigation into the physiological effects of direct and passive exposure to ECIGs. In the meantime, as $PM_{2.5}$ is dangerous to inhale, these results support the need for regulations that prevent ECIG use in indoor spaces, such as extending clean indoor air measures to include ECIG aerosol.[37]

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IMPLICATIONS FOR TOBACCO REGULATION

The use of electronic cigarettes (ECIGs) generates aerosol with fine particulate matter, and the concentration of particulate matter is influenced by device solvent ratio as well as device power. Non-users may be exposed to this fine particulate matter, which may be a health risk. Results from this study support the need for regulations that prevent ECIG use in indoor spaces, such as extending clean indoor air measures to include ECIG aerosol.

Table 1.

Study 1: Mean (SD) and Median Particulate Matter ($PM_{2.5}$ μg/m^3) for Each Study Condition.

	Pre-ECIG Use †		During ECIG Use ‡	
PG:VG Ratio	**Mean (SD)**	**Median**	**Mean (SD)**	**Median**
2:98	1.58 (1.11)	1.34	57.79 (147.11) *+	15.79
20:80	1.32 (0.63)	1.25	62.24 (86.05) *+	12.45
55:45	1.48 (0.85)	1.28	31.72 (57.77) *+	6.64
100:0	1.60 (1.26)	1.28	1.57 (1.09)	1.33

†30 minutes prior to the first 10-puff bout.

‡5 minutes during the first 10-puff bout.

*indicates significant difference from pre-ECIG use

+indicates significant difference from 100:0 PG:VG ratio

Table 2.

Study 2: Mean (SD) and Median Particulate Matter ($PM_{2.5}$ μg/m^3) for Each Study Condition.

	Pre-ECIG Use †		During ECIG Use ‡	
Condition	**Mean (SD)**	**Median**	**Mean (SD)**	**Median**
15 W 0 mg/ml	2.22 (1.35)	1.75	22.39 (55.70)	1.97
15 W 3 mg/ml	2.64 (3.89)	1.30	23.99 (63.14)	4.35
15 W 6 mg/ml	2.91 (1.16)	3.19	6.39 (7.83)	4.05
45 W 0 mg/ml	1.60 (0.84)	1.75	181.78 (311.96) *+	61.07
45 W 3 mg/ml	2.57 (1.27)	2.52	46.13 (75.39) *	6.29
45 W 6 mg/ml	4.31 (5.39)	2.85	93.36 (164.01) *+	13.47

† 30 minutes prior to the first 10-puff directed bout.

‡ 5 minutes during the 10-puff bout.

* indicates difference from pre-ECIG use

+ indicates difference from 15 W with the same liquid concentration (only tested during ECIG use).