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Electronic cigarette solutions and resultant aerosol profiles

Jason S. Herrington [a,*], Colton Myers [b]

[a] Restek Corporation, 110 Benner Circle, Bellefonte, PA 16823, United States
[b] Juniata College, 1700 Moore Street, Huntingdon, PA 16652, United States

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ABSTRACT

Electronic cigarettes (e-cigarettes) are growing in popularity exponentially. Despite their ever-growing acceptance, their aerosol has not been fully characterized. The current study focused on evaluating e-cigarette solutions and their resultant aerosol for potential differences. A simple sampling device was developed to draw e-cigarette aerosol into a multi-sorbent thermal desorption (TD) tube, which was then thermally extracted and analyzed via a gas chromatography (GC) mass spectrometry (GC–MS) method. This novel application provided detectable levels of over one hundred fifteen volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) from a single 40 mL puff. The aerosol profiles from four commercially available e-cigarettes were compared to their respective solution profiles with the same GC–MS method. Solution profiles produced upwards of sixty four unidentified and identified (some only tentatively) constituents and aerosol profiles produced upwards of eighty two compounds. Results demonstrated distinct analyte profiles between liquid and aerosol samples. Most notably, formaldehyde, acetaldehyde, acrolein, and siloxanes were found in the aerosol profiles; however, these compounds were never present in the solutions. These results implicate the aerosolization process in the formation of compounds not found in solutions; have potential implications for human health; and stress the need for an emphasis on electronic cigarette aerosol testing.

1. Introduction

Electronic cigarettes (e-cigarettes) do not burn tobacco, rather they produce an aerosol (without flame or smoke) from a battery-powered, metal, heating element and liquid-containing cartridge [1]. The liquid typically consists of humectants (propylene glycol (1,2-propanediol) and/or glycerin), flavorings, and nicotine [2]. When an e-cigarette's power source is activated, the heating element aerosolizes the liquid to form a mist, which the end user then may inhale (often referred to as "vape") [3]. The smoke-like aerosol imitates tobacco smoke visually and replicates the burning sensation in the throat and lungs (often referred to as "throat hit"). These similarities with conventional tobacco smoke, combined with the same hand-to-mouth behaviors, have contributed to the rapid adaptation of electronic cigarettes [4–6]. Despite their increasing use on a global scale [3], relatively little is known about the e-cigarette chemical components. The majority of studies have focused on nicotine content and specific target compounds (e.g., nitrosamines) that are anticipated to be in e-cigarette liquid (e-juice) [7]. More importantly, relatively little is known about the chemical composition of the aerosol, which is ultimately what end users are exposed to [7,8].

Only a few researchers (e.g., Goniewicz et al. [7], Kosmider [9], McAuley et al. [10], Schober et al. [8], and Uchiyama et al. [11]) have attempted to characterize electronic cigarette (EC) aerosol. Goniewicz et al. [7], Kosmider et al. [9], McAuley et al. [10], and Uchiyama et al. [11] all utilized smoking machines to generate and directly collect EC aerosol. Goniewicz et al. utilized solid adsorbent tubes for fifteen carbonyl compounds (aldehydes and ketones) and twelve volatile organic compounds (VOCs); and methanol impingers for two nitrosamines and sixteen heavy metals [7]. Kosmider et al. [9] and Uchiyama et al. [11] utilized 2,4-dinitrophenylhyrdrazine (DNPH) coated silica cartridges to capture and analyze twelve and six carbonyls, respectively. McAuley et al. [10] utilized thermal desorption (TD) tubes for five VOCs; DNPH coated cartridges for three carbonyls; quartz fiber filters treated with ground XAD-4 resin for seventeen polycyclic aromatic hydrocarbons (PAHs); and Teflon coated fiber filters for four nitrosamines. Schober et al. attempted to characterize the particulate matter (PM), particle number concentrations (PNC), VOCs, PAHs, carbonyls, and metals with the use of a "café-like" scenario [8]. The "café-like" scenario may have represented both primary EC aerosol constituents (i.e., directly emitted from the ECs) and secondary EC components, which resulted from atmospheric reactions

* Corresponding author.
E-mail address: jason.herrington@restek.com (J.S. Herrington).

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of the primary EC compounds and/or reactions with café surfaces (e.g., study participants, chairs, tables, etc.).

The aforementioned studies were not without their limitations/shortcomings. Most notably, all of the aforementioned studies utilized very target analyte specific (e.g., DNPH-coated solid sorbents for a few carbonyls) methods and/or relatively small target lists; and therefore may have overlooked other important aerosol constituents. Furthermore, with the exception of the Schober et al. study, it appeared that none of these studies evaluated the raw e-juice in conjunction with the aerosol to verify that the aerosolization process was responsible for the generation of the observed aerosol compounds, as opposed to the compounds simply being present in the liquid. Although this may have relatively little impact from a human health perspective, this is a significant data gap. The following study was executed to evaluate for difference between electronic cigarette solutions and their respective aerosols with an open-ended analytical approach (i.e., not target analyte specific). The analytical techniques, obstacles, solutions, results, and implications are discussed.

2. Experimental

2.1. Electronic cigarettes and solutions

Four commercially available electronic cigarettes (Table S1) were chosen from the "Best E-Cigarettes of 2014," which is a top 10 list of e-cigarettes as viewed by "experts and users." These four chosen e-cigarettes also routinely appeared on other web-based review sites as "top 10" performers." In addition, these four brands were readily obtained from local stores. All four e-cigarettes were "1st generation" cigarettes (i.e., generally mimicking the size and look of regular cigarettes) and contained solutions of propylene glycol and glycerin.

2.2. Solution analysis

The following analytical system was used for the qualitative determination of compounds found in the electronic cigarette solutions: an Agilent 7890B GC coupled with an Agilent 5977A MS detector. The GC-MS parameters are presented in Table 1. In order to provide representative results, solutions were extracted from the same e-cigarette utilized for the aerosol experiment. Solutions were obtained post aerosol sampling, as the e-cigarettes were permanently destroyed while disassembling for solution extraction.

2.3. Aerosol compounds

Electronic cigarette aerosol was analyzed for nicotine and compounds by trapping the aerosol on thermal desorption tubes. It is important to note that e-cigarette emissions contain compounds both in gas and liquid droplet phase (i.e., the "vapor" is technically an aerosol). It was expected that the thermal TD tubes collected the total aerosol emitted from the e-cigarettes. Goniewicz et al. and other researchers used smoking machines (e.g., Teague TE-2, Borgwaldt RM20S) to generate and collect e-cigarette aerosols; however, access to such an apparatus was not available for this study. Therefore, in order to provide reproducible and quantitative results, a simple sampling device (Fig. 1) was adapted from a 50 mL gas-tight syringe. The syringe was used to draw 40 mL of aerosol in ~4 s from the e-cigarettes across a stainless steel thermal desorption tube packed with Tenax TA, Carbograph 1TD, and Carboxen 1003 (Restek Corporation, Bellefonte, PA, USA). This tube was chosen based on the optimized combination of three sorbents to screen for VOCs in the C_{2-3} range up to SVOCs in the C_{30-32} range. Although this method was manual, a ~4 s puff was utilized, as suggested based on Farsalinos et al.'s observations on e-cigarette topography [12]. In addition to the single puff sample, a 10-puff sample was also taken in order to mimic a smoking regime. This sample was taken by manually drawing ten 4 s puffs separated by 10 s intervals between puffs. The desorption tube was then transferred to the following analytical system for determining the VOCs and SVOCs directly emitted from an e-cigarette: a Markes UNITY™ paired with an Agilent 7890B GC coupled with an Agilent 5977A MS detector. The UNITY™ and GC–MS parameters are presented in Table S2 and Table 1, respectively.

The aerosol concentrations of selected VOCs were calculated from a five-point calibration curve generated by analyzing a series of volumes of a 10.0 ppb_v primary gas standard. The 10.0 ppb_v primary gas standard was generated by injecting 180 mL of a 1.00 ppm_v seventy five component TO-15 + NJ mix (Restek Corporation, Bellefonte, PA, USA) and 180 mL of a 1.00 ppm_v fifty seven ozone precursor mixture/PAMS (Restek Corporation, Bellefonte, PA, USA) into an evacuated 6-liter SilcoCan® air monitoring canister (Restek Corporation, Bellefonte, PA, USA) and pressurizing the canister to 30 psig with 50% RH nitrogen. Ochiai et al. [13] determined 50% RH to be optimal for stability. The standard was allowed to age for 7 days. The aforementioned standard afforded positive

Table 1
Analytical system and parameters utilized for determination of electronic cigarette solutions and aerosol compounds. The "Injection" parameters were not utilized for aerosol analysis, as the thermal desorption system injected directly on column.

Agilent 7890B/5977A GC–MS parameters	
Column	Rtx-VMS, 30 m, 0.25 mm ID, 1.40 μm (Restek Corporation, Bellefonte, PA, USA)
Injection	Diluted (2:1) electronic cigarette liquid
Inj. vol.	1.0 μL split (10:1)
Liner	Sky 4 mm precision liner w/wool (Restek Corporation, Bellefonte, PA, USA)
Inj. temp.	250 °C
Purge flow	3 mL/min
Oven	35 °C (hold 1 min) to 250 °C at 11 °C/min (hold 4 min)
Carrier gas	He, constant flow
Flow rate	2.0 mL/min
Linear velocity	51.15 cm/s
Detector	MS
Mode	Scan
Transfer line temp.	250 °C
Analyzer type	Single quadrupole
Source temp.	230 °C
Quad temp.	150 °C
Electron energy	70 eV
Tune type	BFB
Ionization mode	EI
Acquisition range	15–550 amu
Rate	5.2 scans/s

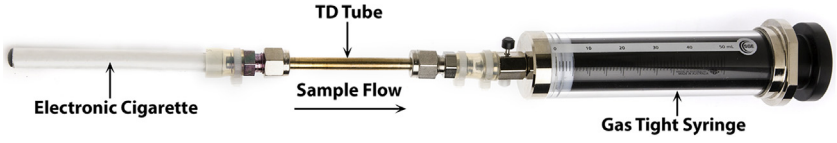

Fig. 1. Gas tight syringe sampling apparatus for quantitatively drawing electronic cigarette aerosol into a thermal desorption tube.

compound identification for one hundred fifteen unique VOCs and SVOCs from retention time and mass spectral matching.

2.4. Blanks

The thermal desorption system was operated with helium carrier gas for desorbing the thermal desorption tubes and the focusing trap during ballistic heating for analyte injection on the head of the analytical column. The combination of helium gas (devoid of oxygen) and elevated temperatures may have established conditions which facilitated the pyrolysis of propylene glycol and/or glycerin. The pyrolysis of propylene glycol and glycerin has been demonstrated to produce formaldehyde, acetaldehyde, and acrolein. Therefore, the following experiments were conducted to evaluate any compound contributions from the TD–GC–MS process itself: empty stainless steel tubes (i.e., no sorbents) and packed thermal desorption tubes (i.e., multi-bed sorbents) were injected with 1 μL aliquots of the electronic cigarette solutions and run through the TD–GC–MS analysis. In addition, the air drawn through the electronic cigarettes during sampling came from the laboratory. Due to the ubiquitous nature of VOCs such as formaldehyde and benzene, it was imperative to determine the background contributions of VOCs to the aerosol analysis. Therefore, 40 mL samples of the laboratory air were periodically collected with thermal desorption tubes and analyzed with the same TD–GC–MS method.

3. Results and discussion

3.1. E-cigarette solution compounds

As shown in Fig. S1 and Table S3, GC–MS analysis of electronic cigarette solutions revealed numerous compounds in addition to the vendor listed propylene glycol, glycerin, and nicotine. Vendor A's solution had sixty four unidentified and identified (some only tentatively) constituents flagged. Compounds were deemed "identified" when verified with an external standard (100% Match Quality and ±0.05 min of expected Retention Time); and compounds were deemed "tentatively identified" when the mass spectral quality was 80% or greater according to the NIST 2011 database [14]. Several pyrazines were tentatively identified, which is consistent with manufacturer added flavorings. For example, acetylpyrazine, which was tentatively identified, is a flavoring well known for producing "nutty" flavors/aromas. In addition, several pyridines were identified, which is consistent with the tobacco-derived nicotine. For example, 3-(3,4-dihydro-2H-pyrrol-5-yl)-pyridine(myosmine) was also tentatively identified and this compound is an alkaloid found in tobacco [15]. It was outside the scope of the current work and space constraints to discuss the solution profiles (as shown in Fig. S1 and Table S3 for Vendor A) for all four commercially available electronic cigarettes. However, there was a consistent trend of approximately sixty to seventy compounds (unidentified and identified) being observed in each solution, only varying by several constituents throughout. From the four e-cigarette solutions evaluated in the current study, there appeared to be a very distinct compound pattern (i.e., signature), which may help in future characterization studies. It is important to note that almost half (thirty six) of the compounds observed in vendor A' e-cigarette solution were unidentified and therefore future work should focus on identifying these compounds. All of the aforementioned indicate that electronic cigarette solutions are more complex than manufacturers indicate, and this is a significant data gap that needs to be addressed.

3.2. E-cigarette aerosol

As shown in Fig. 2 and Table 2, the simple sampling device (Fig. 1) was able to successfully draw electronic cigarette aerosol into a thermal desorption tube and provide detectable levels of VOCs and SVOCs from a single 40 mL puff. Unless noted otherwise, all discussion herein is in reference to a single 40 mL puff, which was chosen for the two following reasons: (1) a single 40 mL puff provided detectable levels of VOCs and SVOCs, while minimizing potential interferences/overloading of propylene glycol and glycerin; (2) a single 40 mL puff on the selected 1st generation e-cigarettes (i.e., operating at ~3.3 V) avoids the "dry puff" phenomenon reported by others [16].

Vendor A's aerosol had eighty two unidentified and identified (some only tentatively) compounds in addition to propylene glycol, glycerin, and nicotine, which is consistent with the previous solution observations. However, there were eighteen additional compounds observed over the solution study. It was outside the scope of the current work and space constraints to discuss aerosol profiles (as shown in Fig. 2 and Table 2 for vendor A) for all four commercially available e-cigarettes; however, there was a consistent trend of more compounds being observed in the aerosol over their respective solution. In addition, it is important to note that although there were only eighteen additional compounds flagged in the aerosol over the solution, the aerosol and solution profiles differed by more than eighteen compounds (i.e., the other sixty four compounds were not an identical match between liquid and aerosol). All of the aforementioned implicate the aerosolization process in generating an aerosol which differs from the parent solution.

Of particular interest was the presence of formaldehyde, acetaldehyde, propylene oxide, acrolein, propanal, acetone, hexane, xylenes, styrene, benzaldehyde and several siloxanes in the electronic cigarette aerosol. Due to space constraints, it is not possible to discuss the implications of all of the aforementioned compounds. The hazardous air pollutants (HAPs) formaldehyde, acetaldehyde, and acrolein were found in the aerosol of all four commercially available e-cigarettes; however, these compounds were not present in the solutions, blanks, and laboratory air. The current observation of these three carbonyls in the aerosol was consistent with Goniewicz et al.'s [7] and Kosmider et al.'s [9] observations. The current observations are significant for the two following reasons: (1) all three of these carbonyls are acutely toxic; in addition, formaldehyde is a known human carcinogen [17] and acetaldehyde is a probable human carcinogen [18]; (2) these compounds were confirmed in the current work not to be present in the e-juice, which indicates they were generated solely from the aerosolization process and/or from the e-cigarette materials. This is consistent with the fact that pyrolysis of propylene glycol and glycerin results in the formation of formaldehyde, acetaldehyde, and acrolein [19]. Identification of siloxanes is also consistent with the fact that polysiloxanes are often used as plastic additives and the majority of the 1st generation e-cigarettes, like those evaluated in this study, are made with plastic bodies. All of the aforementioned have profound implications for how e-cigarettes should be evaluated, especially when considering the fact that the e-cigarette aerosol is ultimately what end users are exposed to.

To expound upon this further, acrolein was not found in the electronic cigarette solutions or background air. However, acrolein was found in the aerosol from all four of the e-cigarettes evaluated in the current study. The acrolein concentrations ranged from 1.5 to 6.7 ppm_v (corrected for TD–GC–MS pyrolysis (to be discussed later)) per 40 mL puff (0.003–0.015 μg/mL), which is comparable to the 0.004 μg/mL as Goniewicz et al. reported [7]. Assuming 40 mL per puff and 400–500 puffs per e-cigarette (values suggested by several e-cigarette manufacturers), each e-cigarette would generate ~20 to 230 μg of acrolein. These e-cigarette acrolein emissions appear to be on par with what has previously been reported for conventional tobacco cigarettes (3–220 μg of acrolein/cigarette) [19]. However, although the acrolein emissions per cigarette are

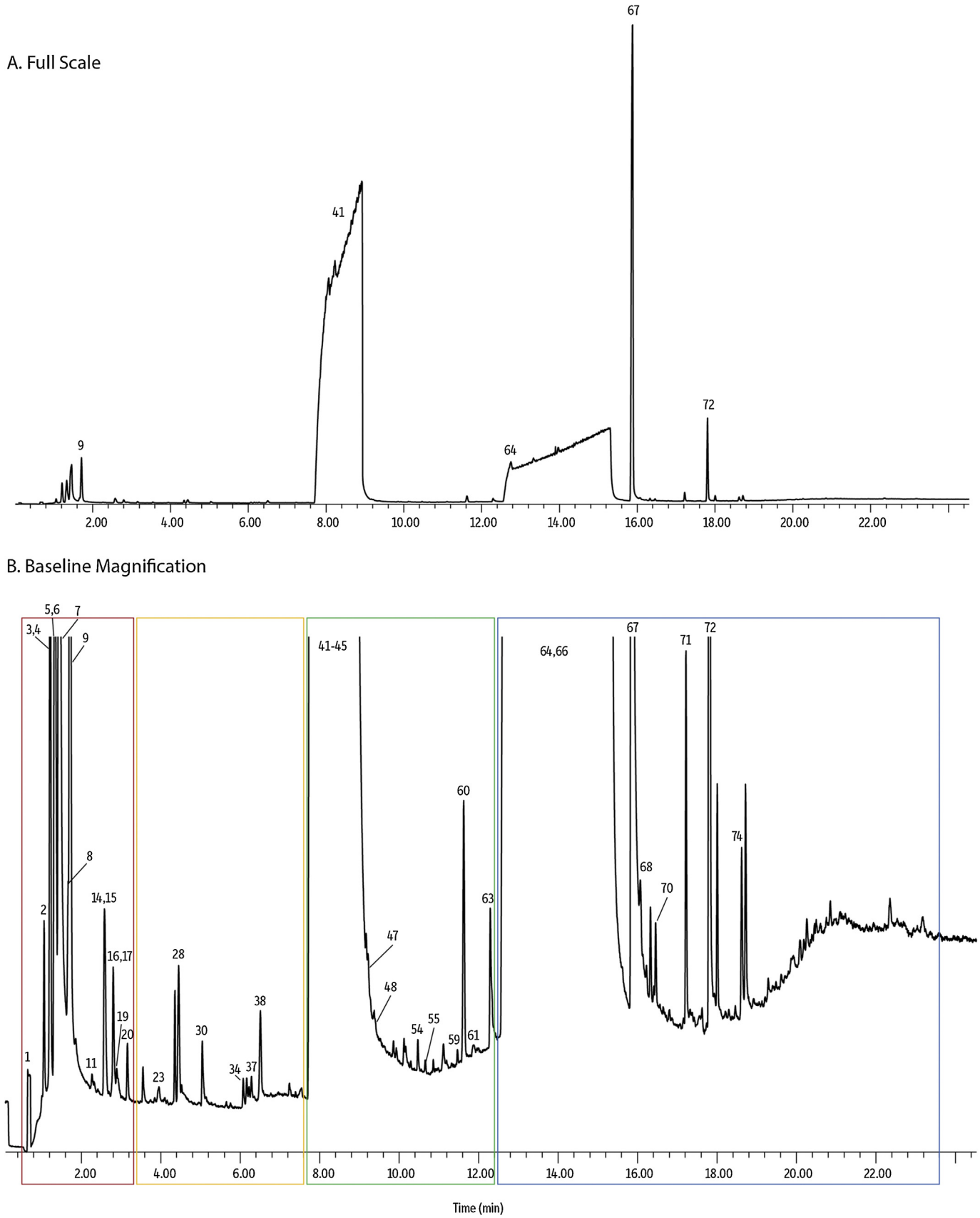

Fig. 2. Total Ion Chromatogram (TIC) of a single 40 mL puff of electronic cigarette aerosol collected on a thermal desorption tube and analyzed via GC–MS (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.).

Table 2
Electronic cigarette aerosol compounds identified in a single 40 mL puff with thermal desorption. A compound was deemed "identified" when verified with an external standard (100% Match Quality and ±0.05 min of expected Retention Time); and compounds were deemed "tentatively identified" when the mass spectral quality was 80% or greater according to the NIST 2011 database [14]. "Blank" represents a 40 mL sample of laboratory air. "Region" is the colored section on Fig. 2 where the compound may be found.

#	Compound name	Retention time	Match quality	Aerosol	Blank*	Region
1	Nitrogen	0.685	100	x	x	Red
2	Carbon dioxide	1.063	100	x	x	Red
3	Propene	1.200	100	x		Red
4	Formaldehyde	1.227	100	x		Red
5	Sulfur dioxide	1.313	90	x		Red
6	Chloromethane	1.380	100	x		Red
7	Water	1.453	100	x	x	Red
8	Acetaldehyde	1.672	100	x		Red
9	Methanol	1.715	100	x	x	Red
10	Unidentified	1.885		x		Red
11	Ethanol	2.270	100	x		Red
12	Unidentified	2.331		x		Red
13	Propylene oxide	2.410	100	x		Red
14	2-Propenal	2.581	100	x		Red
15	Propanal	2.629	100	x		Red
16	Methylene chloride	2.770	100	x	x	Red
17	Acetone	2.843	100	x		Red
18	Unidentified	2.892		x		Red
19	Hexane	2.928	100	x		Red
20	Acetonitrile	3.160	100	x	x	Red
21	Unidentified	3.544		x		Orange
22	Unidentified	3.842		x		Orange
23	Trimethylsilanol	3.928	100	x		Orange
24	Unidentified	4.092		x		Orange
25	Unidentified	4.159		x		Orange
26	Unidentified	4.245		x		Orange
27	Unidentified	4.354		x		Orange
28	Benzene	4.452	100	x	x	Orange
29	Unidentified	4.519		x		Orange
30	Acetic acid	5.055	86	x		Orange
31	Unidentified	5.141		x		Orange
32	Unidentified	5.647		x		Orange
33	Unidentified	5.756		x		Orange
34	2-Propanone, 1-hydroxy-	6.073	80	x		Orange
35	Unidentified	6.165		x		Orange
36	Unidentified	6.220		x		Orange
37	Toluene	6.280	100	x	x	Orange
38	Cyclotrisiloxane, hexamethyl-	6.506	91	x		Orange
39	Unidentified	7.231		x		Orange
40	Unidentified	7.530		x		Orange
41	Propylene glycol	7.737	100	x		Green
42	m-Xylene	8.048	100	x		Green
43	p-Xylene	8.048	100	x		Green
44	o-Xylene	8.530	100	x		Green
45	Styrene	8.597	100	x		Green
46	Unidentified	9.158		x		Green
47	Cyclotetrasiloxane, octamethyl-	9.218	91	x		Green
48	Cyclohexene, 4-methyl-1-(1-methylethyl)-	9.371	95	x		Green
49	Unidentified	9.639		x		Green
50	Unidentified	9.852		x		Green
51	Unidentified	9.932		x		Green
52	Unidentified	10.121		x		Green
53	Unidentified	10.219		x		Green
54	Trimethylpyrazine	10.468	80	x		Green
55	Benzaldehyde	10.657	100	x		Green
56	Unidentified	10.858		x		Green
57	Unidentified	11.120		x		Green
58	Unidentified	11.187		x		Green
59	Acetylpyrazine	11.468	93	x		Green
60	Cyclopentasiloxane, decamethyl-	11.620	91	x		Green
61	Phenol	11.870	94	x		Green
62	Unidentified	12.272		x		Green
63	2-Propanol, 1,1′-oxybis-	12.333	90	x		Green
64	Glycerin	12.748	100	x		Blue
65	Unidentified	13.327		x		Blue
66	Cyclohexasiloxane, dodecamethyl-	13.979	94	x		Blue
67	Pyridine, 3-(1-methyl-2-pyrrolidinyl)-, (S)-	15.862	100	x		Blue
68	Cycloheptasiloxane, tetradecamethyl-	16.082	91	x		Blue
69	Unidentified	16.326		x		Blue
70	Unidentified	16.460		x		Blue
71	Pyridine, 3-(3,4-dihydro-2H-pyrrol-5-yl)-	17.216	94	x		Blue
72	Pyridine, 3-(1-methyl-1H-pyrrol-2-yl)-	17.807	90	x		Blue
73	Unidentified	18.002		x		Blue

Table 2 (*Continued*)

74	2,3′-Dipyridyl	18.618	94	x	Blue
75	Unidentified	18.721		x	Blue
76	Unidentified	19.294		x	Blue
77	Unidentified	19.611		x	Blue
78	Unidentified	20.093		x	Blue
79	Unidentified	20.190		x	Blue
80	Unidentified	20.269		x	Blue
81	Unidentified	20.501		x	Blue
82	Unidentified	20.855		x	Blue

[*] The levels of these compounds in e-cigarette aerosol were too close to blank and/or laboratory air concentrations to definitively state they were emitted from the e-cigarette.

comparable between e-cigarettes and conventional tobacco cigarettes; an entire e-cigarette is not consumed in one vaping session like an entire conventional tobacco cigarette is consumed one smoking session.

It is important to note that although not calibrated for formaldehyde (not routinely done with TD tubes due to reactions with water) and acetaldehyde, the aerosol concentrations for these two compounds appeared to be approximately the same as the acrolein concentrations observed. The observation is consistent with what Goniewicz et al. reported [7]. Couple in the fact that the e-cigarette acrolein emissions exceeded the National Institute of Occupational Safety and Health (NIOSH) short-term exposure limit (STEL; i.e., a 15-min period) of 350 ppb_v, and it is apparent why end users' experience what is often referred to as "throat hit." These three carbonyls are well known mucous membrane (including eyes, nose, and respiratory tract) irritants, and inhaling ppm_v levels of these three carbonyls will surely illicit the acute burning sensation characteristic of "throat hit."

Currently, the U.S. Food and Drug Administration (FDA) does not have any regulatory authority over electronic cigarettes. However, the FDA does acknowledge that e-cigarettes, their associated risks, nicotine levels, and any potentially harmful chemicals inhaled are "not fully studied." Therefore, the FDA has issued a proposed rule to extend their authority to include e-cigarettes [20]. Regardless of the FDA's authority (or lack thereof) over e-cigarettes it is clear from the current research, and the research of others, that the e-cigarette landscape is not fully understood. However, it appears that e-cigarettes are not without human health risks. Most importantly, and as demonstrated by the current work, when designing future e-cigarette studies investigators should strongly consider the difference between analyzing electronic cigarette solutions and analyzing electronic cigarette aerosol, as it very clear that their chemical profiles are different.

3.3. Blanks

The 1 μL aliquots of electronic cigarette solutions injected into empty stainless steel tubes (i.e., no sorbents) and analyzed via the TD–GC–MS method resulted in the formation of formaldehyde, acetaldehyde, and acrolein. However, the concentrations of these three compounds did not increase when 1 μL aliquots of the e-cigarette solutions were injected into packed thermal desorption tubes (i.e., multi-bed sorbents) and analyzed via the TD–GC–MS method. The two aforementioned observations are consistent with the hypothesis that pyrolysis of propylene glycol and/or glycerin was taking place within the TD–GC–MS system itself and not in the thermal desorption tube media (i.e., the multi-sorbent bed). However, it was unclear as to where the pyrolysis was taking place (i.e., on the focusing trap during ballistic heating versus in the heated transfer lines) within the TD–GC–MS system. Regardless, pyrolysis within the TD–GC–MS was only responsible for 14–23% of the aerosol concentrations of formaldehyde, acetaldehyde, and acrolein observed in the current study; and the degree of pyrolysis appeared to be consistent across e-cigarette brands. The aforesaid percent contributions were approximated by comparing the carbonyl/nicotine ratios obtained from the empty stainless steel tubes and packed thermal desorption tubes to the 40 mL puff samples. Coincidentally, the 1 μL aliquots of e-cigarette solutions delivered approximately the same dose of propylene glycol (128%), glycerin (80%), and nicotine (132%) as found in a 40 mL puff, which made for direct comparisons. In addition, the laboratory air was sometimes a source for certain VOCs; however, these levels (i.e., low ppb_v) were often well below the e-cigarette levels (i.e., low to mid ppm_v). Future investigators should be aware of their laboratory air concentrations and the potential pyrolysis within the TD–GC–MS system and make necessary adjustments in their reporting limits and/or background corrections. It was outside the scope of the current work; however, future work should focus on reducing pyrolysis contribution by adjusting line temperatures, heating rates, flow rates, etc.

3.4. Advantages/limitations/future research

Researchers like Goniewicz et al. had access to specialized smoking machines, which enabled "realistic" smoking regimes (e.g., a 1.8 s puff with 10 s intervals between puffs). These smoking regimes may reveal more about e-cigarette aerosol and/or be more accurate and/or reproducible than the simple sampling device (Fig. 1) utilized in the current study. However, the current work is significant in that multiple puffs were not needed, because the present analytical techniques demonstrated detectability from a single 40 mL puff. In addition, the simple sampling device was found to provide very reproducible results for e-cigarette aerosol concentrations. For example, the relative standard deviation (%RSD) for nicotine aerosol concentrations was 18.5% for nine separate 40 mL puffs. This is a good %RSD considering that this variability included the variability of the e-cigarettes ability to deliver consistent puffs; the variability of the manually operated simple sampling device; and the analytical variability associated with the TD–GC–MS. It is important to note that a smoking regime of a 4 s puff with 10 s intervals between 10 puffs was executed manually with the simple sampling device (Fig. 1). The results of this 10 puff sample (Fig. S2) did reveal some early eluting compounds (i.e., identified, tentatively identified, and unidentified), which were otherwise not identified in the single puff (Fig. 2). However, the propylene glycol and glycerin peaks, which were already overloaded in the single puff sample, became so large in the 10 puff sample that most of the peaks previously identified in the single puff sample were lost due to interference with propylene glycol and glycerin. In addition, this overloading of propylene glycol and glycerin contaminated the Markes UNITY™ thermal desorption system, thereby requiring time consuming cleaning to avoid carryover. Future investigators should be aware of this. However, this degree of sensitivity suggests that the current methods may be well suited for the

easy and rapid screening of e-cigarettes. In addition, the present sampling and analytical techniques may be exploited in future e-cigarette research in conjunction with smoking machines/smoking regimes.

As previously mentioned in the discussion of the blanks results, future researchers should be aware of the potential pyrolysis conditions within the TD–GC–MS system and how that may affect their formaldehyde, acetaldehyde, and acrolein aerosol concentrations. Alternative sampling/analytical approaches (e.g., DNPH-coated solid sorbents) are available for these carbonyls, which would circumvent the pyrolysis issues; however, they come at the significant disadvantage of time-consuming solvent extractions and the inability to scan for a large number of compounds (e.g., the 82 VOCs/SVOCs observed in the current study) in a single 40 mL puff. Future TD–GC–MS work on e-cigarette aerosol should focus on optimizing the thermal desorption parameters, in order to reduce pyrolysis contributions by adjusting line temperatures, heating rates, flow rates, etc.

The current multi-sorbent sampling and analytical approach offers two distinct advantages over other analyte specific methods (e.g., DNPH-coated solid sorbents): (1) the VOCs and SVOCs were not limited to a class of compounds (e.g., carbonyls). Therefore, a variety of alkanes, alkenes, aromatics, and halogenated compounds were evaluated. Although the analytical instrumentation was calibrated with over one hundred fifteen VOCs/SVOCs, the current work was able to successfully observe numerous unidentified and tentatively identified compounds not part of the calibration standards. Future work should focus on confirming the identities of the unidentified and tentatively identified compounds flagged in the current work. The only constraint of the current approach was the limitation to hydrocarbons in the C_2–C_{32} range. However, this is a substantial improvement over other current electronic cigarette aerosol investigations; (2) derivatization and/or solvent extraction was not required. Like other studies, samples were immediately (i.e., <1 min) analyzed post-sampling, and therefore there was no need to form a "stable" carbonyl-hydrazone derivative, which then had to be solvent extracted. Overall, the current method may be well suited for the easy and rapid screening of e-cigarette aerosol for a large number of VOCs and SVOCs.

4. Conclusions

Electronic cigarette solutions contain numerous compounds in addition to the vendor listed propylene glycol, glycerin, and nicotine. E-cigarette solution profiles produced upwards of sixty four unidentified and identified (some only tentatively) compounds. A simple, yet novel sampling device was developed to draw electronic cigarette aerosol into a thermal desorption tube, which was then thermally extracted and analyzed via a GC–MS method. This approach provided detectable levels of over one hundred fifteen VOCs and SVOCs from a single 40 mL puff. E-cigarette aerosol profiles produced upwards of eighty two compounds. Notably, some of these compounds are known to be detrimental to human health and were detected in the aerosol although they were not present the e-cigarette solution. It is unequivocal that electronic cigarette solutions, and more importantly aerosol, have numerous compounds beyond the manufacturer listed propylene glycol, glycerin, and nicotine. The numerous unidentified compounds flagged in the current work may be innocuous flavor compounds or toxic impurities; therefore, it behooves the scientific community to ascertain what these compounds are. These results implicate the aerosolization process in the formation of compounds not found in solutions; have potential implications for human health; and stress the need for an emphasis on electronic cigarette aerosol testing. All of the aforementioned observations stress that electronic cigarettes have not been fully characterized.

Contributors

JSH and CM approve of this manuscript.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.chroma.2015.09.034.

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