



Effect of variable power levels on the yield of total aerosol mass and formation of aldehydes in e-cigarette aerosols

I.G. Gillman ^{a,*}, K.A. Kistler ^b, E.W. Stewart ^a, A.R. Paolantonio ^a

^a Enthalpy Analytical Inc., Durham, NC 27713, USA

^b Department of Chemistry, The Pennsylvania State University, Brandywine Campus, Media, PA 19063, USA

ARTICLE INFO

Article history:

Received 23 April 2015

Received in revised form

28 December 2015

Accepted 28 December 2015

Available online 29 December 2015

Keywords:

Toxicology

Electronic nicotine delivery systems

Electronic-cigarettes

2,4-DNPH derivatives of aldehydes

Liquid chromatography

Chemical composition

Formaldehyde

Acetaldehyde

Acrolein

ABSTRACT

The study objective was to determine the effect of variable power applied to the atomizer of refillable tank based e-cigarette (EC) devices. Five different devices were evaluated, each at four power levels. Aerosol yield results are reported for each set of 25 EC puffs, as mass/puff, and normalized for the power applied to the coil, in mass/watt. The range of aerosol produced on a per puff basis ranged from 1.5 to 28 mg, and, normalized for power applied to the coil, ranged from 0.27 to 1.1 mg/watt. Aerosol samples were also analyzed for the production of formaldehyde, acetaldehyde, and acrolein, as DNPH derivatives, at each power level. When reported on mass basis, three of the devices showed an increase in total aldehyde yield with increasing power applied to the coil, while two of the devices showed the opposite trend. The mass of formaldehyde, acetaldehyde, and acrolein produced per gram of total aerosol produced ranged from 0.01 to 7.3 mg/g, 0.006 to 5.8 mg/g, and <0.003 to 0.78 mg/g, respectively. These results were used to estimate daily exposure to formaldehyde, acetaldehyde, and acrolein from EC aerosols from specific devices, and were compared to estimated exposure from consumption of cigarettes, to occupational and workplace limits, and to previously reported results from other researchers.

© 2015 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Electronic cigarettes (ECs) are becoming increasingly popular, with millions of users both in the US and in Europe (Pearson et al., 2012; Regan et al., 2013; Vardavas et al., 2014) and are often used as a replacement for combustible cigarette usage (Barbeau et al., 2013). Aldehydes including formaldehyde, acetaldehyde, and acrolein are known to form during heating of mixtures of glycerol (GLY) and propylene glycol (PG) (Flora et al., 2015; Lauterbach and Spencer, 2015; Ohta et al., 2011; Paschke et al., 2014; Uchiyama et al., 2013), the most common solvent formulation for EC liquids. These aldehydes are of concern since formaldehyde is classified by the International Agency for Research of Cancer (IARC) as a human carcinogen (Group 1) and acetaldehyde is classified as possibly carcinogenic to humans (Group 2B) (IARC, 2012). Acrolein causes irritation of the nasal cavity and damages the lining of the lung (USEPA, 2003). Glycerol has been shown to produce these three

aldehydes due to thermal decomposition (pyrolysis) in temperature-dependent amounts (Paine et al., 2007), with small amounts of acrolein being formed in some ionic environments at 350 °C, and all three aldehydes being formed at 600 °C. The pathway for this pyrolysis is shown in Fig. 1, and it involves a free-radical dehydration of glycerol to form 3-hydroxyl-1-propen-1-ol, which tautomerizes to 3-hydroxypropionaldehyde. This then loses another water in a free-radical mechanism to form acrolein. At higher temperatures 3-hydroxypropionaldehyde can convert to formaldehyde and acetaldehyde, by way of a retro-aldol reaction, which easily cleaves the C2–C3 bond at >400 °C.

Because of these known decomposition products, one of the main concerns related to EC use is the inhalation of aldehydes contained in EC aerosol. Studies on relatively lower power, prefilled disposable devices have found that formaldehyde, acetaldehyde, and acrolein are produced at levels far lower in comparison to tobacco cigarette smoke (Bekki et al., 2014; Cheng, 2014; Goniewicz et al., 2014; Lauterbach and Spencer, 2015). However, recent studies on higher powered, refillable tank systems have found that these devices may produce levels of aldehydes exceeding the levels found in mainstream cigarette smoke (Jensen et al., 2015; Kosmider et al., 2014). To date, however, there has not been a systematic

* Corresponding author. Enthalpy Analytical Inc., 800 Capitola Dr. Suite 1, Durham, NC 27713, USA.

E-mail address: gene.gillman@enthalpy.com (I.G. Gillman).

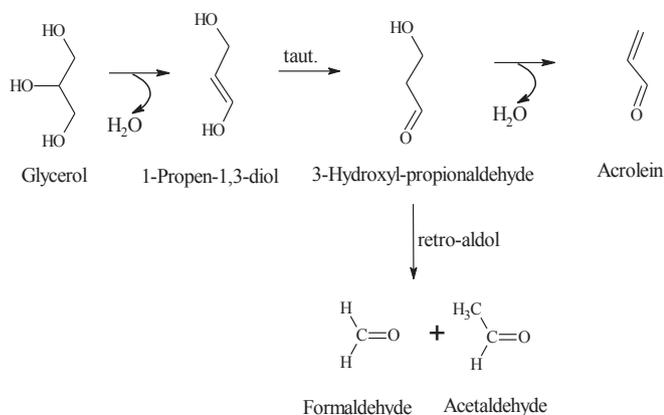


Fig. 1. The pyrolytic reactions of glycerol to produce formaldehyde, acetaldehyde and acrolein. Radical intermediates for steps involving loss of water are omitted for simplicity.

study on the formation of aldehydes in EC aerosol using a variety of devices and power levels.

It should be noted that PG can also decompose thermally, to propionaldehyde (Dai et al., 2004), however, in order to better compare to the previous studies mentioned above, which only reported formaldehyde, acetaldehyde and acrolein production, and to focus more on device dependence of their formation, we did not analyze for propionaldehyde in this study. Such analysis, as well as dependence on EC liquid solvent composition, is planned for future studies.

2. Methods

2.1. EC devices

In this study, five refillable “tank” based EC were studied:

- Device 1: Single top coil, 2.8 Ω ,
- Device 2: Single bottom coil, 2.7 Ω ,
- Device 3: Dual bottom coil, 2.8 Ω ,
- Device 4: Single bottom coil, 2.2 Ω , and
- Device 5: Single bottom coil, 0.72 Ω .

All samples were commercial “tank” products (Hare, 2015) and were used according to the manufacturer's instructions. They all have similar functional parts: a tank which holds the liquid, a resistive heating wire (“coil”) to which voltage is applied to generate heat and aerosolize the liquid, a “wick” which can be silica string (Devices 1–3), poly-fill (Device 4) or cotton (Device 5), that transports the liquid in the tank to the coil, a mouth piece for inhalation, and a threaded connector to attach to and receive current from the power source. Device 1 was a CE4 “top-coil” tank-style (Vision, Shenzhen, China). Three separate devices were used in this study, and from the same manufacturer, all virtually identical save for some variations in coil resistance. The three devices used in this study were determined to have coil resistance of 2.2, 2.8 and 3.4 Ω (average was 2.8 Ω , with standard deviation of 0.5 Ω). In this device, the liquid is held inside a tank, and silica strings acting as wicks descend from a ceramic cup containing the coil into the liquid, which is fed to the coil through the wicks. “CE4” refers to the general design, using a ceramic coil cup, fourth version of this type of tank system. Air flow travels up through a center tube to under the coil, and then to the mouth. Adequate wetting of any EC coil depends on the ability of the wick to feed the liquid as fast as the coil vaporizes it. It should be noted that this style of atomizer is

largely out of favor now in the vaping community, due to the difficulty of wicking with some liquids, and the propensity for dry-puff to occur. It should also be noted that this was the atomizer style chosen recently by previous researchers who reported high aldehyde and acrolein content of EC aerosol using 5 V or more (Jensen et al., 2015). Device 2 was a Protank 1 (KangerTech, Shenzhen, China) with a replaceable 2.7 Ω bottom single-coil-head. A single tank and three separate coils were used in this study. In this device the liquid is held in a tank and gravity fed to the coil, which is positioned at the bottom of the tank, through short silica wicking threads which the coil is wrapped around and oriented horizontally if the tank is held tip-up. It was expected that this design would allow more consistent wetting of the coil compared to Device 1. Device 3 was a Gladius (Innokin, Shenzhen, China) bottom coil tank system with a replaceable dual-coil-head and a total resistance of 2.8 Ω . A single tank and three unique coil-heads were used in this study. The overall design with respect to liquid feed is very similar to the Protank, but here there are two coils in parallel, at 5.6 Ω each, each wrapped horizontally around short silica wicks, stacked vertically on top of each other and across the central air-flow, which travels through a center tube to the mouth. The two coils in parallel have the effect of spreading the heat out evenly over the coils, compared to one coil when the same wattage is applied, assuming total resistance and all other factors are identical. Device 4 was bottom single coil Nautilus (Aspire USA, Kent, WA) with 2.2 Ω resistance. The overall design is visually similar to the Protank, but the replaceable coil-head is larger and the coil is vertically oriented, longer and of thicker gauge, and in contact with more wicking material (poly-fill). A single tank and three unique coil-heads were used in this study. Device 5 was a SubTank (KangerTech) with a 0.72 Ω bottom-coil-head. Since wattage is inversely proportional to coil resistance, reducing coil resistance will increase the wattage for a given battery voltage proportionally, allowing very high wattage from typical 3.7 V Li-ion batteries. The coil is vertically oriented, similar to the Nautilus coil-head, but the wicking material is cotton. A single atomizer was used with each device. In all cases, samples were collected from lowest power to highest power levels. All tanks were maintained at a minimum of 50% of the maximum liquid level. Where adjustment was possible for a device, airflow was set to maximum. Detailed images for the devices used in this study are available online (Google, 2015) and schematics of example top coil and bottom coil devices are given in supplemental materials Appendix A.

2.2. Sample collection

Puffing of devices was carried out using either a Cerulean SM450 (Milton Keynes, UK) or a KC Automation KC-5 (Richmond, VA) analytical smoking machine. The smoking regime was a puff every 30 s with 4-s duration and a volume of 55 mL collected using a “square” wave profile (Farsalinos et al., 2013). All devices were automatically activated at the start of each puff using an air power linear actuator attached to the battery. The button on each device was depressed during each puff. All devices were puffed with the tank held in a horizontal orientation. Between each puff block, devices were removed from the smoking machine to record the weight change. During the weighing process the devices were transported in a vertical orientation to allow for liquid equilibration. A puff block consisting of 25 puffs was performed and collected for each device and condition in duplicate, and this was repeated twice more with different units of the same device, three times total. Thus, each device and condition was averaged over 6 trials ($N = 6$). Batteries were fully charged before use, and the weight of each device was measured before and after each puff block. Devices were allowed to rest for least ten minutes between

puff blocks.

Samples generated for Devices 1–4 were collected using an Innokin iTaste VV4 battery (Shenzhen, China) as the power source, with samples collected at 3.8, 4.2, 4.6, and 5.0 V. Samples for Device 5 were collected using a DNA 40 power supply (Evolv, Ashtabula, OH) with samples collected at 10, 15, 20, and 25 W. Total resistance for all devices was measured using an Extech milliohm meter, P/N 380560 (Nashua, NH) prior to analysis and, for Devices 1–4, with power supply voltage, was used to calculate wattage. Voltages delivered were assumed to be the same as displayed by the power supply.

The liquid used for all samples was 48% (wt/wt) propylene glycol (PG), CAS # 57-55-6, USP grade, The Flavor Apprentice (Circle Scotts Valley, CA); and glycerin (GLY), CAS # 56-81-5, USP grade, Essential Depot (Sebring, FL); with 2% nicotine, CAS# 54-11-5, Sigma Aldrich (St. Louis, MO).

2.3. Chemical analysis

All methods used for this study were validated for linearity, recovery, precision, and limits of detection in the EC sample matrix prior to analyses. Method validation details are given in Appendix B.

2.4. Determination of formaldehyde, acetaldehyde, and acrolein as dinitrophenylhydrazine derivatives

The procedure followed was based on the HPLC carbonyl compound analysis method for mainstream cigarette smoke by CORESTA (Paris, France) (CORESTA, 2014), with the following modifications. Aerosol samples were collected in 35 mL of 2,4-dinitrophenylhydrazine (DNPH) trapping solution using a single glass impinger and coarse fritted impinger inserts (Prism Research Glass, Raleigh, NC). The samples were collected directly in a DNPH trapping solution; a 5 mL aliquot was then quenched with 0.250 mL of pyridine. An Agilent Model 1100 High Performance Liquid Chromatograph (Santa Clara, CA, USA) was equipped with an Agilent Model 1100 Ultraviolet (UV) Detector operating at 365 nm and a Waters Xterra C18 3.0 × 250 mm column (Billerica, MA) for the analyses. The limit of detection was 0.015 µg/mL for all aldehyde compounds. The materials used for the HPLC analysis were: deionized water, Millipore (Billerica, MA); phosphoric acid (H₃PO₄), CAS # 7664-38-285, 85%, Sigma–Aldrich; DNPH, CAS# 119-26-6, 50% in water, TCI America (Portland, OR); acetonitrile, CAS #75-05-8, Fisher (Waltham, MA); tetrahydrofuran, CAS #109-99-9, Fisher; isopropanol, CAS #67-63-0, distilled-in-glass, Fisher; pyridine, CAS #110-86-1, Aldehyde-Ketone-DNPH TO-11A Calibration Mix, P/N 270407, Sigma–Aldrich.

DNPH trapping solution was prepared by adding 2.0 g of DNPH (50%) to 500 mL of acetonitrile and 40 mL of 10% H₃PO₄. This was brought to a final volume of 1 L with deionized water. It should be noted that while it is possible for aldehydes to form hydrates, acetals and hemiacetals in EC liquid or in the heating process, through various dynamic and rapid solution equilibria with water, PG or GLY (Funderburk et al., 1978), because addition of DNPH leads to very stable dinitro-phenylhydrazone carbonyl derivatives, this effectively drives all of these equilibria in the direction of the carbonyl form of the aldehydes, resulting in eventual trapping of all forms of these aldehydes as the hydrazone derivative, and thus rendering this derivative method unable to distinguish between the carbonyl form of these aldehydes and their hydrate, acetal or hemiacetal forms (García-Alonso et al., 2006). It should, however, be noted that collection of air samples using DNPH media is a well-established method to determine occupational and ambient exposure to aldehydes (USEPA, 1999) without speciation of hydrates, acetals and

hemiacetals forms.

3. Results

The mass of aerosol produced from each device varied depending on the amount of power that was applied to the atomizer. The five devices tested in the study produced between 38 mg to over 692 mg of aerosol in 25 puffs, in the range of 5.2–25 W, as shown in Table 1. Data for all replicates are given in supplemental materials Appendix C. Since yield depends on the total number of puffs, results are also presented in mg of aerosol per puff, which ranged from 1.5 to 28 mg/puff over the same range of power. It was also found that devices 2–5 produced more aerosol mass as increasing power was applied to the atomizer. In contrast, the highest power level for Device 1, 9.2 W, produced less aerosol mass than produced at 7.8 W. Since the aerosol yield varied by device and power level, the calculation of total aerosol mass per puff divided by power applied to the coil ((mg per puff)/(watt)) is also given in Table 1. Reporting the results in these units allows for a direct comparison of aerosol yield independent of coil resistance. The mass of aerosol produced per puff/watt ranged from 0.27 to 1.1

Table 1
Aerosol yield by device and power level. Average values are boldfaced. Standard deviation (SD) for each average is given below the average value.

	Volts	Ohms	Watts	mg (25 puffs)	mg/puff	(mg/puff)/watt
Device 1: Single top coil						
Average	3.8	2.8	5.3	103	4.1	0.78
SD	NA	0.5	1.0	28	1.1	0.26
Average	4.2	2.8	6.5	155	6.2	0.95
SD	NA	0.5	1.3	36	1.4	0.29
Average	4.6	2.8	7.8	185	7.4	0.95
SD	NA	0.5	1.5	51	2.0	0.32
Average	5.0	2.8	9.2	176	7.1	0.77
SD	NA	0.5	1.8	38	1.5	0.22
Device 2: Single bottom coil						
Average	3.8	2.6	5.2	95	3.8	0.72
SD	NA	0.3	0.1	24	1.0	0.18
Average	4.2	2.6	6.4	134	5.4	0.84
SD	NA	0.3	0.1	27	1.1	0.17
Average	4.6	2.6	7.7	162	6.5	0.85
SD	NA	0.3	0.1	39	1.6	0.20
Average	5.0	2.6	9.0	193	7.7	0.85
SD	NA	0.3	0.2	45	1.8	0.20
Device 3: Dual bottom coil						
Average	3.8	2.8	5.6	38	1.5	0.27
SD	NA	0.1	0.7	16	0.6	0.12
Average	4.2	2.8	6.9	98	3.9	0.57
SD	NA	0.1	0.9	8	0.3	0.05
Average	4.6	2.8	8.2	137	5.5	0.66
SD	NA	0.1	1.1	6	0.2	0.03
Average	5.0	2.8	9.7	173	6.9	0.71
SD	NA	0.1	1.3	8	0.3	0.03
Device 4: Single bottom coil						
Average	3.8	2.8	7.3	57	2.3	0.31
SD	NA	0.1	0.5	12	0.5	0.07
Average	4.2	2.8	8.9	108	4.3	0.49
SD	NA	0.1	0.7	26	1.0	0.12
Average	4.6	2.8	10.6	167	6.7	0.63
SD	NA	0.1	0.8	36	1.5	0.14
Average	5.0	2.8	12.6	234	9.4	0.75
SD	NA	0.1	0.9	26	1.0	0.08
Device 5: Single bottom coil						
Average	2.6	0.7	10.0	187	7.5	0.75
SD	NA	NA	NA	14	0.5	0.05
Average	3.2	0.7	15.0	385	15	1.0
SD	NA	NA	NA	33	1.3	0.1
Average	3.7	0.7	20.0	543	22	1.1
SD	NA	NA	NA	34	1.4	0.1
Average	4.2	0.7	25.0	692	28	1.1
SD	NA	NA	NA	149	5.9	0.24

(mg/puff)/(watt).

The amount of each aldehyde compound, as the DNPH adduct, was determined by passing the aerosol through an impinger containing DNPH trapping solution. The summary results for each device at each of four power levels are given in Table 2 on a per puff basis ($\mu\text{g}/\text{puff}$). Data for all replicates are given in Appendix C. The amount of formaldehyde, acetaldehyde, and acrolein produced per puff ranged from 0.05 to 51 μg , 0.03–40.7 μg and <0.02–5.5 μg respectively. To account for the large differences in total aerosol yield between devices and power levels, the amount of each compound was divided by aerosol mass in a puff block of 25 puffs, to yield mg/g values for each compound. These results are presented in Table 3. The mass of formaldehyde, acetaldehyde, and acrolein produced per gram of total aerosol produced ranged from 0.01 to 7.3 mg/g, 0.006–5.8 mg/g, and <0.002–0.78 mg/g, respectively.

To estimate daily exposure to aldehydes, as the DNPH derivatives, from the devices in this study, we based our calculations on an average daily consumption of 3 mL of EC liquid, which is the reported average usage amount for experienced users of EC devices (Farsalinos et al., 2014), assuming a density close to 1 g/mL, this corresponds to an average daily consumption of approximately 3 g.

For this calculation, amounts in $\mu\text{g}/\text{mg}$ were converted to mg/g and multiplied by 3. The values are given in Table 4. The amount of formaldehyde, acetaldehyde, and acrolein that would be produced per 3 g of e-liquid consumed ranged from 0.04 to 22 mg, 0.02–17 mg, and <0.003–2.4 mg, respectively. The sum of all compounds was also calculated and ranged from 0.06 to 41 mg.

4. Discussion

The results show the amount of aerosol produced from heating the e-liquid varies depending on the device and power. Every device, with the exception of Device 1 at 9.2 W, produced more aerosol with an increasing amount of power applied to the coil. To normalize for the range of power used, yield results are also presented as the mg/puff of aerosol produced per watt of power applied to the coil (mg/watt) in Table 1. Results are presented as the mg/watt production, which enables a direct comparison of the efficiency of each atomizer to convert power into aerosol formation.

Surprisingly, the devices had unique aerosol yield profiles under the test conditions in this study. Device 1 gave a decrease in mg/watt output at the highest power level applied to the atomizer, while Device 2 gave a relatively constant mg/watt output over the

Table 2

Aldehydes produced by device and power level on a per puff basis. Average values are boldfaced. Standard deviation (SD) for each average is given below the average value.

	Power Watts	Aerosol mass mg/puff	Formaldehyde $\mu\text{g}/\text{puff}$	Acetaldehyde $\mu\text{g}/\text{puff}$	Acrolein $\mu\text{g}/\text{puff}$
Device 1: Single top coil					
Average	5.3	4.1	8.5	6.9	0.23
SD	1.0	1.1	8.9	7.4	0.23
Average	6.5	6.2	21	17	0.47
SD	1.3	1.4	16	14	0.53
Average	7.8	7.4	32	25	1.0
SD	1.5	2.0	12	11	0.45
Average	9.2	7.1	51	41	5.5
SD	1.8	1.5	31	25	9.0
Device 2: Single bottom coil					
Average	5.2	3.8	0.25	0.06	<0.02
SD	0.1	1.0	0.22	0.03	NA
Average	6.4	5.4	1.5	0.33	0.11
SD	0.1	1.1	0.83	0.14	0.05
Average	7.7	6.5	8.0	2.6	0.70
SD	0.1	1.6	5.0	2.0	0.52
Average	9.0	7.7	17	8.3	2.0
SD	0.2	1.8	19	10	2.3
Device 3: Dual bottom coil					
Average	5.6	1.5	0.07	0.04	<0.02
SD	0.7	0.6	0.04	0.02	NA
Average	6.9	3.9	0.07	0.06	<0.02
SD	0.9	0.3	0.04	0.02	NA
Average	8.2	5.5	0.05	0.03	0.08
SD	1.1	0.2	0.01	0.02	0.03
Average	9.7	6.9	0.59	0.53	0.23
SD	1.3	0.3	0.52	0.33	0.08
Device 4: Single bottom coil					
Average	7.3	2.3	0.13	0.05	<0.02
SD	0.5	0.5	0.08	0.02	NA
Average	8.9	4.3	0.28	0.06	<0.02
SD	0.7	1.0	0.33	0.01	NA
Average	11	6.7	0.14	0.05	<0.02
SD	0.8	1.5	0.14	0.02	NA
Average	13	9.4	0.21	0.06	<0.02
SD	0.9	1.0	0.11	0.03	NA
Device 5: Single bottom coil					
Average	10	7.5	0.13	0.08	<0.02
SD	NA	0.5	0.08	0.06	NA
Average	15	15	0.21	0.16	<0.02
SD	NA	1.3	0.06	0.07	NA
Average	20	22	0.31	0.15	<0.02
SD	NA	1.4	0.07	0.04	NA
Average	25	28	0.34	0.16	<0.02
SD	NA	5.9	0.08	0.08	NA

Table 3
Aldehydes produced by device and power level on a per gram of aerosol basis. Average values are boldfaced. Standard deviation (SD) for each average is given below the average value.

	Power Watts	Formaldehyde mg/gram	Acetaldehyde mg/gram	Acrolein mg/gram
Device 1: Single top coil				
Average	5.3	2.1	1.7	0.05
SD	1.0	2.2	1.9	0.06
Average	6.5	3.3	2.7	0.08
SD	1.3	2.7	2.4	0.09
Average	7.8	4.3	3.4	0.14
SD	1.5	2.0	1.7	0.07
Average	9.2	7.3	5.8	0.78
SD	1.8	4.7	3.8	1.28
Device 2: Single bottom coil				
Average	5.2	0.07	0.02	<0.01
SD	0.1	0.06	0.01	NA
Average	6.4	0.28	0.06	0.02
SD	0.1	0.16	0.03	0.01
Average	7.7	1.2	0.40	0.11
SD	0.1	0.82	0.33	0.09
Average	9.0	2.2	1.1	0.26
SD	0.2	2.5	1.3	0.30
Device 3: Dual bottom coil				
Average	5.6	0.04	0.03	<0.02
SD	0.7	0.03	0.02	NA
Average	6.9	0.02	0.01	<0.02
SD	0.9	0.01	0.01	NA
Average	8.2	0.03	0.02	0.05
SD	1.1	0.04	0.02	0.06
Average	9.7	0.08	0.08	0.03
SD	1.3	0.08	0.05	0.01
Device 4: Single bottom coil				
Average	7.3	0.06	0.02	<0.01
SD	0.5	0.04	0.01	NA
Average	8.9	0.06	0.01	<0.006
SD	0.7	0.08	0.005	NA
Average	11	0.02	0.008	<0.004
SD	0.8	0.02	0.004	NA
Average	13	0.02	0.006	<0.003
SD	0.9	0.01	0.003	NA
Device 5: Single bottom coil				
Average	10	0.017	0.011	<0.003
SD	NA	0.011	0.009	NA
Average	15	0.014	0.010	<0.002
SD	NA	0.004	0.005	NA
Average	20	0.014	0.007	<0.002
SD	NA	0.003	0.002	NA
Average	25	0.012	0.006	<0.002
SD	NA	0.004	0.003	NA

three highest power levels. In contrast, Devices 3, 4 and 5 had an increasing mg/watt output as more power was applied to the atomizer. These results indicate that differences in the atomizer design impact their ability to efficiently produce aerosol at a given power level. The decrease in mg/watt output seen in Device 1 at higher power levels, may be due to insufficient liquid flow to the atomizer resulting in less efficient aerosol production and therefore overheating of the atomizer coil, commonly called a “dry puff” (Farsalinos et al., 2013). The efficient production of aerosol depends on an adequate supply of liquid to the coil, and maximum liquid supply would be limited by the wicking rate of wick material. Power levels that produce aerosol beyond the ability of the wick to resupply the liquid to the coil could result in overheating of the atomizer coil.

The production of aldehydes from overheating PG and GLY in EC aerosols has been previously shown by Uchiyama et al (Uchiyama et al., 2013). The devices with the lowest aerosol production in mg/watt output might be anticipated to produce more aldehydes as less efficient formation of aerosol might imply that the power supplied to the coil is converted into excess heat instead of aerosol formation. Aldehyde yields adjusted for total aerosol production

are given in Table 3. Device 1 gave the lowest average mg/watt production of all devices and also produced the highest total aldehydes per gram of aerosol produced. However, no clear trends in the mg/watt production versus aldehyde formation per gram of aerosol produced were found for Devices 2–5. Interestingly, it was found that the devices that produced the lowest aldehyde yields also had the largest increase in aerosol production in terms of mg/watt output with increasing power. For Device 4, the mg/puff per watt production increased from 0.31 mg/puff/(watt) to 0.75 mg/puff/(watt), a 142% increase in efficiency from the lowest to highest power level used in this study. The % increase, from lowest to highest power level, in mg/puff/(watt) production for Devices 1, 2, 3 and 5 was –1.3%, 18%, 163%, and 47%, respectively. Device 1 showed an actual decrease in production and also yielded the highest amount of aldehyde formation per gram of aerosol produced, and Devices 2–5 showed increases in efficiency, with Device 2 showing the least increase, but the highest aldehyde production of those four devices. These results indicate that decreased efficiency of aerosol production, in terms of mg/watt, at higher power levels might indicate overheating of the atomizer leading to elevated levels of aldehydes in the aerosol. This effect may be due to

Table 4

Daily exposure with consumption of 3 g of EC liquid per day. Average values are boldfaced. Standard deviation (SD) for each average is given below the average value.

	Power Watts	Formaldehyde mg per day	Acetaldehyde mg per day	Acrolein mg per day	Total aldehydes mg per day
Device 1: Single top coil					
Average	5.3	6.2	5.0	0.16	11
SD	1.0	6.7	5.6	0.17	8.7
Average	6.5	10	8.0	0.23	18
SD	1.3	8.1	7.1	0.26	11
Average	7.8	13	10	0.41	23
SD	1.5	6.0	5.1	0.22	7.9
Average	9.2	22	17	2.3	41
SD	1.8	14	11	3.8	18
Device 2: Single bottom coil					
Average	5.2	0.20	0.05	<0.03	0.25
SD	0.1	0.18	0.03	NA	0.19
Average	6.4	0.85	0.18	0.06	1.1
SD	0.1	0.49	0.09	0.03	0.5
Average	7.7	3.7	1.2	0.32	5.2
SD	0.1	2.5	0.98	0.26	2.7
Average	9.0	6.7	3.2	0.78	11
SD	0.2	7.5	4.0	0.90	8.5
Device 3: Dual bottom coil					
Average	5.6	0.13	0.08	<0.06	0.22
SD	0.7	0.10	0.05	NA	0.11
Average	6.9	0.05	0.04	<0.06	0.09
SD	0.9	0.03	0.02	NA	0.03
Average	8.2	0.10	0.06	0.16	0.32
SD	1.1	0.11	0.07	0.17	0.21
Average	9.7	0.25	0.23	0.10	0.58
SD	1.3	0.23	0.14	0.04	0.27
Device 4: Single bottom coil					
Average	7.3	0.17	0.07	<0.03	0.27
SD	0.5	0.11	0.03	NA	0.12
Average	8.9	0.19	0.04	<0.01	0.25
SD	0.7	0.23	0.01	NA	0.23
Average	11	0.06	0.02	<0.01	0.08
SD	0.8	0.07	0.01	NA	0.07
Average	13	0.07	0.02	<0.009	0.09
SD	0.9	0.03	0.01	NA	0.04
Device 5: Single bottom coil					
Average	10	0.05	0.03	<0.009	0.09
SD	NA	0.03	0.03	NA	0.04
Average	15	0.04	0.03	<0.003	0.08
SD	NA	0.01	0.01	NA	0.02
Average	20	0.04	0.02	<0.003	0.07
SD	NA	0.01	0.01	NA	0.01
Average	25	0.04	0.02	<0.003	0.06
SD	NA	0.01	0.01	NA	0.01

insufficient liquid supply to coil, leading to production of excess heat instead of conversion of the liquid into aerosol. From a thermodynamic stand point, formation of the aerosol and liquid decomposition can be viewed as competing pathways, and decomposition, involving bond breaking, would be in thermal competition with formation of the aerosol since both pathways would absorb available heat from the atomizer coil.

In order to put the aldehyde results in context, it might be valuable to compare our results with both occupational exposure limits and exposure results due to use of combustible tobacco cigarettes. This comparison is intended only to compare our results with other known sources of aldehyde exposure and not to assay health effect. E-cigarettes are recreational usage products, and any toxins delivered to the users would be additive to other exposure sources.

For occupational exposure, the time weighted average (TWA) limits (8-h) as defined by OSHA is 0.92 mg/m³ for formaldehyde (USOSHA, 2015c), 0.25 mg/m³ for acrolein (USOSHA, 2015b), and 360 mg/m³ for acetaldehyde (USOSHA, 2015a). These TWA limits (8-h exposure) were compared to the levels of each aldehyde compound in EC aerosols. To approximate the workplace environment, the recommended short-term, light activity, respiratory rate

for a 21 to <31 year old adult of 0.012 m³/min was used to estimate total breath volume (USEPA, 2011). Using this value, within 8 h (480 min), the total volume of air inhaled is 5.8 m³ (0.012 m³/min × 480 min). Using this volume, the total amount of formaldehyde, acetaldehyde, and acrolein inhaled daily at the maximum OSHA limits would be approximately 5.3 mg, 2088 mg, and 1.5 mg, respectively.

The yield of formaldehyde, acetaldehyde, and acrolein delivered by combustible cigarettes has been estimated from the Counts et al. study on smoke yields from 44 commercial cigarettes under intense smoking conditions (Counts et al., 2005). Using these data, the exposure to formaldehyde, acetaldehyde, and acrolein from consuming a pack of combustible cigarettes is approximately 1.5–2.5 mg for formaldehyde, 10–30 mg for acetaldehyde, and 1.5–3 mg for acrolein.

As shown in Table 4, formaldehyde yields for Device 1 exceeded both the yield from combustible cigarettes (20 per day) and the OSHA limit even at the lowest power level and, at the maximum power level, produced formaldehyde almost 10 times the OSHA workplace exposure limit. This device also exceeded the acrolein yield from 20 combustible cigarettes per day and the OSHA workplace exposure limit, but only at the highest power level tested.

Device 2 also exceeded the formaldehyde yield from combustible cigarettes but again only at the highest power level tested. In contrast, the other three devices all produced aldehydes below both combustible cigarettes and the OSHA workplace exposure limit. One device, Device 5, produced less than 1% of the aldehydes delivered from 20 combustible cigarettes per day and the OSHA workplace exposure limit. Also, there was over a 750-fold difference in total aldehyde yield between Devices 1 and 5. The extreme levels of aldehydes produced by Device 1 indicate that the coil may have overheated due to lack of liquid in the wick. In this case, the excess energy would be transformed into heat and the coil temperature would exceed the evaporation point of the e-liquid (22), with heat-induced decomposition processes competing with aerosolization. At the conclusion of this study, the coil for Device 1 was examined and found to be charred, an indication of thermal decomposition. The charred coil, the observed decrease in yield in mg/watt production at the highest power level, and the elevated levels of aldehydes and acrolein, all indicate that the results for Device 1 may not represent typical usage of this device, we hypothesize, and a typical user might experience noxious dry-puff effects and discontinue use at that power setting. However, determination of dry-puffs is outside of the scope of this study since dry-puffs can only be confirmed by sensory evaluation of the aerosol by a user (Farsalinos et al., 2015).

5. Conclusion

The range of aerosol produced on a per puff basis ranged from 1.5 to 28 mg or approximately a 17-fold increase. The range of aerosol produced normalized for power applied to the coil ranged from 0.27 to 1.1 mg/watt or a 3.1-fold increase. From these results, it is clear that it is impossible to accurately estimate EC aerosol yield based on the coil resistance alone and that calculations based on power applied to the coil can only estimate the EC aerosol yield.

The trapped aerosol was also analyzed for aldehydes, as DNP derivatives, produced during EC aerosol formation. The amount of formaldehyde, acetaldehyde, and acrolein produced per puff ranged from 0.05 to 17 μg , 0.03–8.3 μg and <0.02–2.0 μg respectively. The amount of formaldehyde, acetaldehyde, and acrolein produced per gram of total aerosol produced ranged from 0.01 to 7.3 mg/g, 0.006–5.8 mg/g, and <0.003–0.78 mg/g, respectively. Our results demonstrate that the amount of aldehydes in EC aerosols varies by device and the power applied to the atomizer coil. An increase in the efficiency of aerosol production with increasing power supplied to the atomizer was correlated with lower levels of aldehydes in the EC aerosol.

Formaldehyde and acrolein yields for one device exceeded both the yield from combustible cigarettes (20 per day) and the OSHA limit at the maximum power level tested, produced formaldehyde almost 10 times the OSHA workplace exposure limit. However, three of the five devices studied yielded less formaldehyde, acetaldehyde, and acrolein than delivered by combustible cigarettes and also less than an 8-h occupation exposure limit. Our results demonstrate that large differences exist in the EC devices available in the market place, and that, depending on the device, changes in power applied to the atomizer can have dramatic, but different, impacts on both total aerosol yield and the formation of aldehyde compounds in the EC aerosol, with some devices far more capable than others of maximizing liquid aerosolization while minimizing thermal decomposition at higher power levels.

The high levels of aldehyde formation seen in Device 1 could be due, in part, to the formulation or viscosity of the test liquid used in this study. The composition of the liquid may have an impact on the rate at which liquid is transferred to the coil and also the formation of aldehydes. The purpose of this study was to compare different

devices and power levels using a simple PG and GLY liquid formulation. Similar e-liquids are widely used both by consumers and by previous researchers. Repeating the analysis using different liquids formulations was beyond the scope of this study. However, it would be of interest for future studies to compare the results of the formulation used here with nicotine solutions using only PG, or various PG, GLY and water mixtures, including liquids that contain popular flavor compounds. There are some caveats to studying this: mixtures with a different composition or components may change the boiling point of the e-liquid and may impact the yield of EC devices, and flavor compounds themselves may have wide variance in propensity for thermal decomposition. Another interesting and important consideration for future studies would be direct measurement of the temperature of the coil during activation to better understand what coil temperatures lead to decomposition, but this was technologically beyond the scope of this study. Finally, we only measured the levels of three aldehydes, and there could be other toxic substances produced, including propionaldehyde (Dai et al., 2004) and free-radicals, which have been detected previously at low levels in EC emissions (Goel et al., 2015; Sussan et al., 2015). Since these thermal decomposition processes (pyrolysis) have been shown to involve formation of free-radical species during dehydration steps of PG and GLY on the pathway to aldehydes (Dai et al., 2004; Paine et al., 2007), it is possible that these free-radicals would be detected at levels commensurate with the amounts of aldehydes being produced. However, this also was technologically beyond the scope of this study. One also needs to consider that, in terms of actual risks from aldehyde toxicity to the user, it is very possible that when significant thermal decomposition of an EC liquid is occurring, commonly called the dry-puff phenomenon (Farsalinos et al., 2015), the aerosol produced may be quite noxious, and cause the user to discontinue use until the dry-puff issue is resolved. More quantitative analysis of actual aldehyde production under human usage conditions should be done in the future, since it is possible that a user would avoid inhalation of EC aerosols under significant thermal decomposition conditions. Also, the aldehydes present in EC aerosol have been shown by others to be a mixture of the free aldehydes along with hydrate, acetal and hemiacetal forms. The health effect due to the inhalation of this mixture of complexed aldehydes relative to free aldehydes is currently unknown and warrants further study. It is also possible that these hydrates, acetals and hemiacetals convert back to free aldehydes *in vivo* through hydrolysis, which is in principle possible under the aqueous and slightly basic conditions of the lungs (Funderburk et al., 1978), however to our knowledge this has not been studied under physiological conditions.

Funding

A portion of the equipment used in this study was provided by Innokin Technology and Evolv.

Appendix A-C. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.yrtph.2015.12.019>

Transparency document

Transparency document related to this article can be found online at <http://dx.doi.org/10.1016/j.yrtph.2015.12.019>

References

Barbeau, A.M., Burda, J., Siegel, M., 2013. Perceived efficacy of e-cigarettes versus

- nicotine replacement therapy among successful e-cigarette users: a qualitative approach. *Addict. Sci. Clin. Pract.* 8 <http://dx.doi.org/10.1186/1940-0640-8-5>, 5–5.
- Bekki, K., Uchiyama, S., Ohta, K., Inaba, Y., Nakagome, H., Kunugita, N., 2014. Carbonyl compounds generated from electronic cigarettes. *Int. J. Environ. Res. Public Health* 11, 11192–11200. <http://dx.doi.org/10.3390/ijerph111111192>.
- Cheng, T., 2014. Chemical evaluation of electronic cigarettes. *Tob. Control* 23, ii11–ii17. <http://dx.doi.org/10.1136/tobaccocontrol-2013-051482>.
- CORESTA, 2014. CORESTA Recommended Method No. 75: Determination of Selected Carbonyls in Mainstream Cigarette Smoke by HPLC. Cooperation Centre for Scientific Research Relative to Tobacco (CORESTA). Retrieved August 11, 2015 from: http://www.coresta.org/Recommended_Methods/CRM_75.pdf.
- Counts, M.E., Morton, M.J., Laffoon, S.W., Cox, R.H., Lipowicz, P.J., 2005. Smoke composition and predicting relationships for international commercial cigarettes smoked with three machine-smoking conditions. *Regul. Toxicol. Pharmacol.* 41, 185–227. <http://dx.doi.org/10.1016/j.yrtph.2004.12.002>.
- Dai, Z., Hatano, B., Tagaya, H., 2004. Catalytic dehydration of propylene glycol with salts in near-critical water. *Appl. Catal. A Gen.* 258, 189–193. <http://dx.doi.org/10.1016/j.apcata.2003.09.001>.
- Farsalinos, K., Romagna, G., Tsiapras, D., Kyrzopoulos, S., Voudris, V., 2013. Evaluation of electronic cigarette use (Vaping) topography and estimation of liquid consumption: implications for research protocol standards definition and for public health authorities' regulation. *Int. J. Environ. Res. Public Health* 10, 2500–2514. <http://dx.doi.org/10.3390/ijerph10062500>.
- Farsalinos, K., Romagna, G., Tsiapras, D., Kyrzopoulos, S., Voudris, V., 2014. Characteristics, perceived side effects and benefits of electronic cigarette use: a worldwide survey of more than 19,000 consumers. *Int. J. Environ. Res. Public Health* 11, 4356–4373. <http://dx.doi.org/10.3390/ijerph110404356>.
- Farsalinos, K.E., Voudris, V., Poulas, K., 2015. E-cigarettes generate high levels of aldehydes only in 'dry puff' conditions. *Addiction* 110, 1352–1356. <http://dx.doi.org/10.1111/add.12942>.
- Flora, J.W., Wilkinson, C.T., Wilkinson, J., Miller, J.H., 2015. Sensitive and Selective Method for Carbonyl Determination in E-cigarette Aerosols. Presented at CORESTA Smoke Science and Product Technology. (Jeju Island, South Korea. Retrieved from:).
- Funderburk, L.H., Aldwin, L., Jencks, W.P., 1978. Mechanisms of general acid and base catalysis of the reactions of water and alcohols with formaldehyde. *J. Am. Chem. Soc.* 100, 5444–5459. <http://dx.doi.org/10.1021/ja00485a032>.
- García-Alonso, S., Pérez-Pastor, R., Sevillano-Castaño, M.L., 2006. Determination of glyoxal and methylglyoxal in atmospheric particulate matter by 2,4-dinitrophenylhydrazine derivatization. *Toxicol. Environ. Chem.* 88, 445–452. <http://dx.doi.org/10.1080/02772240600796837>.
- Goel, R., Durand, E., Trushin, N., Prokopczyk, B., Foulds, J., Elias, R.J., Richie, J.P., 2015. Highly reactive free radicals in electronic cigarette aerosols. *Chem. Res. Toxicol.* 28, 1675–1677. <http://dx.doi.org/10.1021/acs.chemrestox.5b00220>.
- Goniewicz, M.L., Knysak, J., Gawron, M., Kosmider, L., Sobczak, A., Kurek, J., Prokopowicz, A., Jablonska-Czapla, M., Rosik-Dulewska, C., Havel, C., Jacob, P., Benowitz, N., 2014. Levels of selected carcinogens and toxicants in vapour from electronic cigarettes. *Tob. Control* 23, 133–139. <http://dx.doi.org/10.1136/tobaccocontrol-2012-050859>.
- Google, 2015. Google Images. Google Search Engine. Retrieved on December, 13, 2015: <https://www.google.com/imghp> + "device name", e.g. CE4 or Kanger Protank 1.
- Hare, P.A., 2015. E-cigarette and Advanced Personal Vaporizers: Current Leading Technologies and Trends and the Importance of Materials and Design on Performance. Presented at CORESTA Smoke Science and Product Technology E-Cigarette Workshop. Jeju Island, South Korea. Retrieved December 13, 2015 from: <http://www.coresta.org/Meetings/CORESTA-Abstracts/Jeju2015-SmokeTech.pdf>.
- IARC, 2012. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: Agents Classified by the IARC Monographs, vol. 1–113. International Agency for Research on Cancer (IARC), Geneva, Switzerland. Retrieved August 15, 2015 from: <http://monographs.iarc.fr/ENG/Classification/index.php>.
- Jensen, R.P., Luo, W., Pankow, J.F., Strongin, R.M., Peyton, D.H., 2015. Hidden formaldehyde in e-cigarette aerosols. *N. Engl. J. Med.* 372, 392–394. <http://dx.doi.org/10.1056/NEJMc1413069>.
- Kosmider, L., Sobczak, A., Fik, M., Knysak, J., Zaciera, M., Kurek, J., Goniewicz, M.L., 2014. Carbonyl compounds in electronic cigarette vapors: effects of nicotine solvent and battery output voltage. *Nicotine Tob. Res.* 16, 1319–1326. <http://dx.doi.org/10.1093/ntr/ntu078>.
- Lauterbach, J.H., Spencer, A., 2015. Generation of Acetaldehyde and Other Carbonyl Compounds during Vaporization of Glycerol and Propylene Glycol during Puffing of a Popular Style of E-cigarette (Presented at Society of Toxicology National Meeting. San Diego, CA. Retrieved from:).
- Ohta, K., Uchiyama, S., Inaba, Y., Nakagome, H., Kunugita, N., 2011. Determination of carbonyl compounds generated from the electronic cigarette using coupled silica cartridges impregnated with hydroquinone and 2,4-dinitrophenylhydrazine. *Bunseki Kagaku* 60, 791–797. <http://dx.doi.org/10.2116/bunsekikagaku.60.791>.
- Paine, J.B., Pithawalla, Y.B., Naworal, J.D., Thomas Jr., C.E., 2007. Carbohydrate pyrolysis mechanisms from isotopic labeling: Part 1: the pyrolysis of glycerin: discovery of competing fragmentation mechanisms affording acetaldehyde and formaldehyde and the implications for carbohydrate pyrolysis. *J. Anal. Appl. Pyrolysis* 80, 297–311. <http://dx.doi.org/10.1016/j.jaap.2007.03.007>.
- Paschke, T., Scherer, G., Heller, W.D., 2014. Effects of ingredients on cigarette smoke composition and biological activity: a literature overview. *Beiträge zur Tabakforschung/Contrib. Tob. Res.* 20, 107–247. <http://dx.doi.org/10.2478/cttr-2013-0736>.
- Pearson, J.L., Richardson, A., Niaura, R.S., Vallone, D.M., Abrams, D.B., 2012. e-Cigarette Awareness, Use, and Harm Perceptions in US Adults. *Am. J. Public Health* 102, 1758–1766. <http://dx.doi.org/10.2105/ajph.2011.300526>.
- Regan, A.K., Promoff, G., Dube, S.R., Arrazola, R., 2013. Electronic nicotine delivery systems: adult use and awareness of the 'e-cigarette' in the USA. *Tob. Control* 22, 19–23. <http://dx.doi.org/10.1136/tobaccocontrol-2011-050044>.
- Sussan, T.E., Gajghate, S., Thimmulappa, R.K., Ma, J., Kim, J.-H., Sudini, K., Consolini, N., Cormier, S.A., Lomnicki, S., Hasan, F., Pekosz, A., Biswal, S., 2015. Exposure to electronic cigarettes impairs pulmonary anti-bacterial and antiviral defenses in a mouse model. *PLOS One* 10, 1–15. <http://dx.doi.org/10.1371/journal.pone.0116861>.
- Uchiyama, S., Ohta, K., Inaba, Y., Kunugita, N., 2013. Determination of carbonyl compounds generated from the e-cigarette using coupled silica cartridges impregnated with hydroquinone and 2,4-dinitrophenylhydrazine, followed by high-performance liquid chromatography. *Anal. Sci.* 29, 1219–1222. <http://dx.doi.org/10.2116/analsci.29.1219>.
- USEPA, 1999. Compendium of methods for the determination of toxic organic compounds in ambient air. In: Compendium Method TO-11A: Determination of Formaldehyde in Ambient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC) [Active Sampling Methodology], second ed. Center for Environmental Research Information Office of Research and Development, United States Environmental Protection Agency (USEPA), Cincinnati, OH. Retrieved August 16, 2015 from: <http://www.epa.gov/ttnamti1/files/ambient/airtox/to-11ar.pdf>.
- USEPA, 2003. Toxicological Review of Acrolein. United States Environmental Protection Agency (U.S. EPA), Washington, DC. Retrieved August 15, 2015 from: www.epa.gov/iris/toxreviews/0364tr.pdf.
- USEPA, 2011. Exposure Factors Handbook: 2011 Edition, Chapter 6: Inhalation Rates. United States Environmental Protection Agency, Washington, DC. Retrieved August 15, 2015 from: <http://www.epa.gov/ncea/efh/pdfs/efh-complete.pdf>.
- USOSHA, 2015a. Acetaldehyde. Occupational Safety & Health Administration, Washington, DC. Retrieved August 10, 2015 from: https://www.osha.gov/dts/chemicalsampling/data/CH_216300.html.
- USOSHA, 2015b. Acrolein. Occupational Safety & Health Administration, Washington, DC. Retrieved August 10, 2015 from: https://www.osha.gov/dts/chemicalsampling/data/CH_217100.html.
- USOSHA, 2015c. OSHA Fact Sheet: Formaldehyde. Occupational Safety & Health Administration, Washington, DC. Retrieved August 10, 2015 from: https://www.osha.gov/OshDoc/data_General_Facts/formaldehyde-factsheet.pdf.
- Vardavas, C.I., Filippidis, F.T., Agaku, I.T., 2014. Determinants and prevalence of e-cigarette use throughout the European Union: a secondary analysis of 26 566 youth and adults from 27 countries. *Tob. Control* 0, 1–7. <http://dx.doi.org/10.1136/tobaccocontrol-2013-051394>.