Electrical features, liquid composition and toxicant emissions from 'pod-mod'-like disposable electronic cigarettes

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ABSTRACT

Introduction Use of flavoured pod-mod-like disposable electronic cigarettes (e-cigarettes) has grown rapidly, particularly among cost-sensitive youth and young adults. To date, little is known about their design characteristics and toxicant emissions. In this study, we analysed the electrical and chemical characteristics and nicotine and pulmonary toxicant emission profiles of five commonly available flavoured disposable e-cigarettes and compared these data with those of a JUUL, a cartridge-based e-cigarette device that pod-mod-like disposables emulate in size and shape.

Methods Device construction, electrical power and liquid composition were determined. Machine-generated aerosol emissions including particulate matter, nicotine, carbonyl compounds and heavy metals were also measured. Liquid and aerosol composition were measured by high-performance liquid chromatography, gas chromatography-mass spectrometry/flame ionisation detection, and inductively coupled plasma mass spectrometry.

Results We found that unlike JUUL, disposable devices did not incorporate a microcontroller to regulate electrical power to the heating coil. Quality of construction varied widely. Disposable e-cigarette power ranged between 5 and 9 W and liquid nicotine concentration ranged between 53 and 85 mg/mL (~95% in the protonated form). In 15 puffs, total nicotine yield for the disposables ranged between 1.6 and 6.7 mg, total carbonyls ranged between 28 and 138 µg, and total metals ranged between 1084 and 5804 ng. JUUL emissions were near the floors of all of these ranges.

Conclusions Disposable e-cigarettes are designed with high nicotine concentration liquids and are capable of emitting much higher nicotine and carbonyl species relative to rechargeable look-alike e-cigarettes. These differences are likely due to the lower quality in construction, unreliable labelling and lack of temperature control regulation that limits the power during operation. From a public health perspective, regulating these devices is important to limit user exposure to carbonyls and nicotine, particularly because these devices are popular with youth and young adults.

INTRODUCTION

Electronic cigarettes (e-cigarettes) are devices that use an electrical heater to heat and aerosolise a liquid for user inhalation.[1] E-cigarette use has increased in popularity in recent years among adults[2–6] and youth.[7–11] In 2017, there was a large jump in the use of 'pod-mod' devices, with one product, JUUL, capturing the greatest market share in this product class.[12] Some authorities have considered or implemented policies to prevent youth uptake and use of these products. For example, in February 2020, the US Food and Drug Administration (FDA) issued a ban on flavoured 'cartridge-based' e-cigarettes other than tobacco or menthol-flavoured products.[13] However, flavoured disposable e-cigarettes that resemble pod-mod e-cigarettes have been recently introduced to the market (eg, Puff Bars). While these products resemble in appearance pod-based systems like the JUUL, these disposable e-cigarettes are not refillable; they are also cheaper, are sometimes labelled as containing high concentrations of salt-based nicotine (up to 7% nicotine content), and often feature vibrant colours and youth-appealing flavours.[14]

While some disposable e-cigarettes recently were ordered off the market by the FDA, including the popular Puff Bar,[15] many pod-mod-like disposable e-cigarettes are still available for purchase from brick and mortar and online retailers. For example, while the Puff Bar manufacturers no longer sell devices on their website, Puff Bar products can still be found on other online vape shops.[16–18] Importantly, despite the popularity of pod-mod-like disposable e-cigarettes, little is known about the design, toxicant emission profiles, or how disposable pod-mod-like e-cigarettes may impact health or cause and maintain dependence. The purpose of this study was to examine device characteristics, liquid composition and toxicant emissions from pod-mod-like disposable e-cigarettes. The toxicant emissions examined included nicotine, carbonyl species and heavy metals.

Carbonyl species are a product of the thermal decomposition of glycerol and propylene glycol, the primary constituents of e-cigarette liquids and are a class of chemicals thought to be responsible for the preponderance of non-cancer pulmonary disease in smokers.[19] Heavy metals in e-cigarette aerosols are thought to be leached from the e-cigarette core assembly or other sources of contamination, and can include species that are associated with cancer and other adverse health effects.[20]

METHODS

We analysed and compared the construction, electrical characteristics, liquid composition and aerosol emissions of five disposable e-cigarettes and one JUUL (Classic Tobacco, 5% nicotine) product procured from the USA in 2020: Ezzy Oval (berry cool and mango lychee flavours), Hyde (cherry lemonade), SEA (mint) and Puff Bar (banana ice). These devices were identified as popular disposable e-cigarette devices by participants in an ongoing study.

For the disposable e-cigarettes, power (W) was calculated from battery voltage (V) and electrical resistance (Ω) measured using a standard laboratory multimetre. Because the JUUL device incorporates a variable voltage temperature control system that continuously adjusts voltage during each puff, we computed average power for JUUL by sampling the voltage continuously using a data acquisition system, as described in Talih *et al*.[21]

Propylene glycol and vegetable glycerin in the liquid were measured by gas chromatography-flame ionisation detector as in El-Hellani *et al*.[22] Liquid nicotine concentration and form were measured using a liquid–liquid extraction method and gas chromatography-mass spectrometry (GC-MS), as in El-Hellani *et al*.[23] Liquid pH was measured using a Starter 3100 OHAUS pH-metre.

Nicotine, carbonyl compounds and metals in the aerosol were measured by drawing 15 4-second puffs at 1 L/min flow rate (similar to that of an experienced e-cigarette user)[24] using the AUB Aerosol Lab Vaping Instrument,[22] for all devices except the Ezzy Oval which required a minimum flow rate of 1.2 L/min to trigger activation. The aerosol exiting the e-cigarette was split into two parallel flow streams, with each stream drawn through a 47 mm quartz filter (Pall Type A/E) for nicotine and metal analysis, respectively. One filter was followed by a 2,4-Dinitrophenylhydrazine (DNPH) cartridge (Sigma-Aldrich/LpDNPH H30) to trap gas-phase carbonyl species. The filter dedicated for metal determinations was pre-washed in a 1% nitric oxide solution and air-dried prior to sampling.

Total particulate matter (TPM) was determined gravimetrically by weighing the filter pads pre-sampling and post-sampling. Nicotine was determined by soaking the filters in an ethyl-acetate solvent and analysing the solution by GC-MS, as in El-Hellani *et al*.[22]

Carbonyl compounds trapped and derivatised on the DNPH cartridges were eluted with 90/10 (vol/vol) ethanol/acetonitrile and quantified by high-performance liquid chromatography ultraviolet, as in El-Hellani *et al*.[22] The species analysed, and the limit of detection and limit of quantitation were, respectively, as follows (µg): formaldehyde, 0.002 and 0.007; acetaldehyde, 0.004 and 0.012; acetone, 0.001 and 0.004; acrolein, 0.003 and 0.012; propionaldehyde, 0.008 and 0.028; benzaldehyde 0.009 and 0.029; valeraldehyde, 0.002 and 0.007; glyoxal, 0.014 and 0.047; and methylglyoxal, 0.027 and 0.091.

Metals were analysed by digesting the filter in 4 mL of nitric acid and 2 mL of hydrogen peroxide at 200°C for 20 min. The obtained solution was diluted in 10 mL of deionised water prior to analysis by inductively coupled plasma mass spectrometry. Blank filters were digested in the same manner as the sampled filters for background subtraction. Spiked blank filters of 5 ppb and 50 ppb standard solutions were used to estimate the accuracy, precision and ruggedness of the method. The species analysed and the limits of detection were as follows (ng): antimony 5, chromium 5, iron 500, nickel 5, copper 5, arsenic 5, cadmium 5, tin 50, manganese 5, molybdenum 5, selenium 5, strontium 5, thallium 5, and tungsten 5.

Liquid composition and toxicant emissions were determined in triplicate for each device. Outcome variables, including device characteristics and toxicant yields, were summarised as mean (SD). Outcome variables were compared between each of the disposable e-cigarettes and the JUUL device using independent sample t-tests with an alpha level of 0.05 to determine significance.

RESULTS

All pod-mod-like disposables had a single heating coil that was wrapped around a silica (SEA and Hyde) or cotton (Ezzy Oval and Puff Bar) wick. The coil and wick were enclosed in a textile sheath that was covered by a liquid-soaked polyfill material (online supplemental figure S1 and S2). This basic architecture is the same as that of first-generation 'cigalike' e-cigarettes and cartomisers.[25] Unlike JUUL, none of the disposable devices contained a microcontroller circuit, and all showed discolouration of the wick where it contacts the heating coil, indicating corrosion.

Electrical characteristics, liquid composition and toxicant emission results are shown in table 1. Mean battery voltage ranged narrowly from 3.74 to 3.92 V. With the exception of the SEA, all devices had similar coil resistances (1.64–1.91 ohms vs SEA 2.78 ohms).

The measured liquid nicotine concentration for three disposable products (Ezzy Oval *mango lychee*, Hyde and Puff Bar) was significantly greater than the labelled concentration (57–61 mg/mL vs 75–86 mg/mL). One product, the Hyde e-cigarette, exhibited much greater nicotine concentration than the others. Based on measured pH, all products had nicotine predominantly in the protonated form (94% or greater using the Henderson-Hasselbalch equation). Propylene glycol to vegetable glycerin ratio varied widely across products and ranged between 20/80 and 50/50.

Except for the SEA device, disposable products generated significantly greater TPM (65–125 mg), nicotine (3.1–6.7 mg) and total carbonyls (36–138 µg) than JUUL (37 mg of TPM, 1.7 mg of nicotine and 17.7 µg of carbonyls). Metal emissions were similar across devices, except for the Puff Bar, which generated significantly greater levels of antimony (410 ng) and nickel (310 ng) than JUUL (below detection limit and 90 ng, respectively). Total metal emissions varied widely and ranged between 1084 and 5804 ng in 15 puffs (online supplemental table S1).

DISCUSSION

This study found that disposable pod-mod-like e-cigarettes use liquids that contain high nicotine concentrations—often greater than indicated on the product labels—and can emit severalfold the nicotine of a JUUL. For example, Puff Bar, the most popular disposable product among young people in the USA,[26] emits four times the nicotine of a JUUL, predominantly in the palatable protonated (salt) form.[27] Disposable e-cigarettes also emitted greater levels of carbonyls, a class of powerful pulmonary toxicants. This finding is consistent with the finding that the disposable devices were not temperature controlled, unlike the JUUL. However, we note that previously reported values for JUUL carbonyl species emissions[21 28–30] vary considerably, and that some of the reported values are within the ranges of some of the disposable devices reported here. For example, formaldehyde emissions in 15 puffs were reported to be equal to 1.7 µg by Mallock *et al*,[28] 2 µg by Son *et al*[29] and 4 µg by Talih *et al*,[21] for roughly similar conditions. The reason for the differences in reported JUUL carbonyl emissions across studies is not known. Metal emissions varied widely across and within device. In general, we found no significant differences in metal emissions between pod-mod disposables and JUUL.

We found that the internal construction of the disposable devices indicated poor quality control in manufacturing, a

Table 1 Electrical characteristics, liquid composition and emissions for five different disposable e-cigarettes and one JUUL; average (SD)

Type	Pod-mod-like disposables					Pod system
Brand	Ezzy Oval		Hyde	Puff Bar	SEA	JUUL
Flavour	Berry cool	Mango lychee	Cherry lemonade	Banana ice	Mint	Classic tobacco
Electrical						
Voltage (V)	3.92	3.81	3.81	3.78	3.74	3.79
Resistance (Ω)	1.72	1.91	1.75	1.64	2.78	1.6
Computed power (W)	8.94	7.6	8.28	8.67	5.03	0.6-4[21]*
Liquid composition						
Labelled nicotine (% weight)	5	5	5	5	5	5
Labelled nicotine (mg/mL)†	57	57	61	57	58	59
Measured nicotine (mg/mL)	53.8 (0.7)‡	75.4 (1.39)‡	86.9 (5.52)§‡	83.4 (2.12)‡	54.3 (0.82)‡	69.8 (7.69)
Estimated % protonated	97 (3.5)	97 (1.5)§	99 (0)§	99 (0)§	98(1)§	94.3 (1.5)
pH	4.95 (0.04)§	5.21 (0.06)§	4.81 (0.05)§	5.08 (0.02)§	4.77 (0.03)§	6.14 (0.04)
PG/VG	51/49§	49/51§	19/81§	50/50§	44/56§	35/65
Emissions in 15 puffs						
TPM (mg)	108.8 (13.4)§	99.7 (10.4)§	65.1 (6.6)§	125.4 (4.6)§	45.6 (12.8)	36.8 (1.9)
Nicotine (mg)	4.07 (0.49)§	5.44 (0.49)§	3.15 (0.32)§	6.72 (0.31)§	1.67 (0.27)	1.67 (0.14)
Carbonyls (µg)						
Formaldehyde	8.53 (3.22)§	5.85 (0.6)§	1.36 (0.09)§	0.41 (0.03)	0.95 (0.15)§	0.32 (0.05)
Acetaldehyde	57.19 (27.73)	24.72 (3.85)§	5.47 (0.71)§	4.28 (0.48)§	4.56 (0.45)§	1.77 (0.11)
Acetone	37.22 (6.16)§	33.34 (1.48)§	11.91 (0.24)	23.65 (0.24)§	9.61 (0.25)§	11.86 (0.03)
Acrolein	ND	ND	ND	ND	ND	ND
Propionaldehyde	9.52 (5.55)	2.6 (0.78)	0.33 (0.16)	0.28 (0.2)	0.57 (0.12)	ND
Crotonaldehyde	3.6 (0.55)§	1.5 (0.39)§	0.94 (0.17)§	0.86 (0.07)§	0.69 (0.09)§	0.44 (0)
Methacrolein	4.8 (0.68)§	3.97 (0.52)§	1.25 (0.1)§	3.28 (0.02)§	1.02 (0.1)§	1.65 (0.02)
Butyraldehyde	0.32 (0.56)	ND	ND	ND	ND	ND
Valeraldehyde	ND	ND	ND	ND	0.21 (0.36)	0.45 (0.78)
Glyoxal	0.72 (1.24)	1.1 (0.95)	0.75 (0.65)	ND	1.52 (0.15)§	ND
Methylglyoxal	16.64 (0.56)§	4.64 (2.5)	13.37 (0.86)§	3.79 (0.63)§	8.16 (7.25)	1.2 (0.01)
Total carbonyls	138.53 (45.64)§	77.74 (9.74)§	35.37 (2.17)§	36.55 (1.43)§	27.88 (7.98)	17.69 (0.64)

*JUUL power is computed by averaging instantaneous measurements of coil voltage during puffing.
†Nicotine concentrations (mg/mL) were calculated based on the labelled concentrations and densities of propylene glycol (PG) and vegetable glycerin (VG).
‡Indicates significant difference between the measured and labelled nicotine concentrations.
§Indicates significant difference from JUUL.
ND, not detected; TPM, total particulate matter.

feature also reflected in the fact that the measured nicotine concentration was different than the advertised value by up to 1.5 times. Previous comparisons between measured and labelled nicotine concentrations have shown similar discrepancies.[31]

What this paper adds

- ⇒ Flavoured pod-mod-like disposable electronic cigarettes (e-cigarette) have become popular, particularly among youth and young adults. To date, little is known about the product features and toxicant emission profiles of these devices. We found that pod-mod-like disposables can emit high doses of nicotine and toxic carbonyl compounds relative to rechargeable pod-based e-cigarette devices like JUUL. This finding is likely due to the low quality of construction, lack of a temperature regulation system and unreliable labelling. For example, one product tested emitted more of the carcinogen formaldehyde than is typical of a combustible cigarette. We also found that the labelled nicotine concentration of pod-mod-like disposables is often misleading; the measured nicotine concentration was up to 1.5 times greater than the product label indicated.

A limitation of this study is that differences in flavours may contribute to differences in toxicant emissions across the examined devices.[32] The degree to which the varying flavours may confound the varying carbonyl emissions is unknown. In addition, we tested a small number of pod-mod-like disposable devices; other devices and brands are available in the market and may exhibit different emission profiles. Nonetheless, the data of this study indicate that there is reason for concern that this product class, whose use is prevalent with some groups,[32] may be more toxic and more addictive than similar form factor devices such as the JUUL, a product whose manufacturer is being investigated by public health authorities for its widespread uptake by youth.[33 34]

In conclusion, our results suggest that pod-mod-like disposable e-cigarettes can have low-quality construction and unreliable labelling, contain high liquid nicotine concentrations, and, relative to e-cigarette devices that are similar in appearance, exhibit elevated emissions of nicotine and non-nicotine toxicants that cause dependence and pulmonary disease in smokers. Given their high nicotine dose, appealing flavours, and popularity among youth and young adults, disposable e-cigarettes warrant scrutiny by public health authorities.

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Contributors ST, RS, ES, REH, EK, NK, AE-H, NS and AS designed the experiments. RS, REH and EK performed the experiments. ST, ES and AS analysed the data. ST, RS, ES, REH, EK, NK, AE-H, NS and AS wrote the original draft.

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Competing interests The authors declare the following competing financial interest: AS is named on a patent application for a device that measures the puffing behaviour of electronic cigarette users and is a consultant in litigation against the tobacco industry. ES is named on a patent application for a smartphone app that determines electronic cigarette device and liquid characteristics.

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