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Characteristics and toxicant emissions of JUUL electronic cigarettes

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Abstract

Introduction—JUUL is an electronic cigarette (ECIG) with a compact form factor. It is prefilled with a liquid that is advertised to contain a high concentration of nicotine salt. JUUL commands 50% of the US ECIG market share, and its wide popularity with underage users has triggered unprecedented actions by the US FDA. Apart from its nicotine salt-containing liquid and compact form, a salient advertised design feature is a control circuit that limits the heating coil temperature, presumably reducing unwanted toxicants. In this study, several tobacco-flavoured JUUL devices were reverse engineered, and their aerosol emissions were studied.

Methods—Total nicotine and its partitioning (freebase and protonated), propylene glycol/vegetable glycerin (PG/VG) ratio, and carbonyls were quantified by gas chromatography (GC) and high performance liquid chromatography (HPLC). The temperature control functionality of JUUL was investigated using a temperature-controlled bath in which the coil was submerged.

Results—The liquid nicotine concentration was found to be 69mg/mL, and the liquid and aerosol PG/VG ratio was found to be 30/70. In 15 puffs, JUUL emitted 2.05 (0.08) mg of nicotine, overwhelmingly in the protonated form. Carbonyl yields were significantly lower than those reported for combustible cigarettes, but similar to other closed-system ECIG devices. The heating coil resistance was 1.6 (0.66) Ohm, while the maximum power delivered by the JUUL device was 8.1 W. The control circuit limited the peak operating temperature to approximately 215C.

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Conclusions—JUUL emits a high-nicotine concentration aerosol predominantly in the protonated form. JUUL's nicotine-normalised formaldehyde and total aldehyde yields are lower than other previously studied ECIGs and combustible cigarettes.

INTRODUCTION

Electronic cigarettes (ECIGs) are controversial and increasingly popular devices that heat and vaporise a liquid to produce an aerosol that can deliver nicotine. In June 2015, Pax Labs launched an ultraportable ECIG device called JUUL. Resembling a universal serial bus (USB) flash drive, it is easily concealed at home and school and has proven popular among underage teens.[1] Its popularity with adolescents recently led the Food and Drug Administration (FDA) to pursue enforcement actions to stop youth use and access to JUUL. JUUL is currently one of the most popular ECIG brands in the USA; it holds the top market position in US ECIG sales revenues, accounting for approximately half the total LTS ECIG market.[2]

JUUL consists of two main components: a liquid-containing and heating coil-containing pod, and a LTSB-rechargeable battery. JUUL's product literature states that the nicotine in the pod is salt based (ie, protonated rather than free-base, FB).[3] Protonated nicotine has long been associated with greatly reduced airway irritation compared with FB nicotine,[45] and therefore may be more easily inhaled, particularly by new tobacco users.

JUUL also claims that its circuitry ensures that 'the vapour is always at, and never above, the ideal temperature.' ECIG temperature is linked to formaldehyde and other toxic carbonyl compounds (CCs) that form by thermally degradation of propylene glycol (PC) and vegetable glycerin (VC), the primary ECIG liquid constituents. Limiting the maximum temperature suggests that JUUL may emit lower CC than other ECIGs. Few industry-independent laboratories have addressed JUUL toxicant emissions. Separate reports have so far addressed JUUL nicotine content and partitioning between its FB and protonated forms,[6] nicotine yield,[78] free radicals and CC emissions.[8] The proportion of FB and protonated nicotine is thought to impact user sensory experience and aerosol inhalability.[4] In this study, we add to the limited publicly available knowledge on the JUUL device and toxicant emissions by reporting its liquid composition, its nicotine and CC emissions, and its previously unreported electronic characteristics.

METHODS

We analysed nicotine and CC emissions, liquid composition (PG/VG ratio, nicotine content and pH), electrical characteristics (maximum power and resistance) of tobacco-flavoured JUUL pods procured in January 2018 in the USA using previously described methods.[9–11] To test the advertised temperature control functionality of JUUL, we used a VG (99.0%–101.0%, CAS 56-81-5, Sigma-Aldrich) filled glass beaker placed on a hot plate (Corning PC-420D) that features a variable temperature control. The VG temperature was measured using a type-K thermocouple (error: ±2.2°C, 10th degree of precision) coupled with an HH21 microprocessor thermometer (Omega). A disassembled JUUL coil was submerged in the solution of VG and connected, using external electrical wires, to the JUUL battery unit.

The mouth end of the battery unit was connected to a digital puffing machine. When activated, the puffing machine generates a suction flow which activates the battery unit which in turn powers the submerged JUUL coil. We then systematically increased the temperature of the VG solution from 27°C to 215°C. For each temperature, the puffing machine was activated and the voltage across the coil was simultaneously monitored using a digital oscilloscope (Tektronix TBS1072B-EDU) (online supplementary figure S1).

RESULTS

In 15 4 s puffs, the nicotine yield from JUUL was found to be equal to 2.07 (0.08) mg, the equivalent nicotine of 1–2 combustible cigarettes, overwhelmingly in the protonated form (94/6 protonated/FB). The aerosol was found to contain numerous CCs including the carcinogen formaldehyde (table 1), although at lower than combustible cigarette concentrations. The nicotine concentration of the JUUL liquid (68.6 (2.3) mg/mL) was greater than previously reported in the literature (56.2[7] and 61.6 (1.5) mg/mL[12] and advertised by the manufacturer (59 mg/mL). Accounting for the heating coil's geometry and resistance, we computed a resistivity that matched that of nichrome as the material of construction. When the temperature of the liquid exceeded approximately 215°C, the power output dropped to 0, indicating that thedevice likely regulates temperature to below the liquid boiling point (227°C for a 30/70 PG/VG liquid[9]).

DISCUSSION

JUUL emits a high-nicotine concentration aerosol. Per-puff, nicotine emissions from the JUUL are equivalent to 1–10 puffs of closed system devices previously studied.[11] Additionally, compared with previously studied ECIGs whose emissions contain predominantly FB nicotine (online supplementary figure S2), new ECIG users will likely find inhaling JUUL aerosol less aversive due to its low FB fraction. This factor may contribute to the alarming uptake of JUUL products by adolescents, while the relatively high JUUL nicotine emissions may contribute to their continued use and eventual dependence. Consistent with a device that operates at low power and limits its peak temperature, JUUL's nicotine-normalised formaldehyde and total CC yields are lower than other previously studied ECIGs and lower than combustible cigarettes (roughly by sixfold for formaldehyde, and 50-fold for total CCs) (online supplementary figure S3).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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What tgis paper adds

- JUUL is an above-Ohm device (1.6 Ohm) that modulates its power to limit its average temperature to 215°C during a puff; it can deliver up to a maximum of 8.1 W to the heating coil.
- JUUL generates a high-nicotine concentration aerosol, with the nicotine predominantly in the protonated form. The aerosol nicotine concentration and form match those of the liquid in the pod.
- JUUL propylene glycol/vegetable glycerin ratio is approximately 30/70 in both liquid and aerosol.
- JUUL carbonyl yields are significantly lower than those reported for combustible cigarettes, but similar to other closed-system electronic cigarette devices.

Table 1

Toxicant emissions and liquid composition of JUUL and other ECIGs

	Electronic cigarettes		Combustible cigarettes
	JUUL (n=3)	**Other products* (range)**	**Marlboro Red† (n=3)**
Electrical characteristics			
Maximum power (W)	8.1	5.06 (0.74)	NA
Resistance (Ω)	1.66 (0.66)	2.88 (0.29)	NA
Liguid composition			
Nicotine concentration (mg/mL)	68.6 (2.3)	7–20	NA
Freebase nicotine %	6.10 (0.11)	13–95	NA
pH	5.4 (0.6)	5.4–9.3	NA
PG/VG (% v/v)	33/67	0/100-80/20	NA
Emissions per 15 puffs or per combustible cigarette			
Total particulate matter (mg)	38.9 (1.3)	15–110	39.6 (1.23)
Nicotine (mg)	2.07 (0.08)	0.2–2	1.81 (0.11)
Freebase nicotine (%)	5.25 (0.81)	10–95	5.80 (1.7)
pH	6.12 (0.21)	NR	5.69 (0.06)
PG/VG (% v/v)	31/69	NR	NR
Carbonyl compounds (μg)			
Formaldehyde	0.56 (0.34)	1–13	3.17 (0.33)
Acetaldehyde	6.05 (0.29)	0.7–91	1059.19 (9.03)
Acetone	24.9 (2.46)	1–8	775.6 (28.42)

	Electronic cigarettes		Combustible cigarettes
	JUUL (n=3)	**Other products* (range)**	**Marlboro Red† (n=3)**
Acrolein	ND	0–1.2	0 (0)
Propionaldehyde	ND	0–12	47.89 (1.04)
Crotonaldehyde	0.85 (0.06)	0–0.7	40.42 (0.69)
Methacrolein	7.08 (0.28)	0–1.4	85.46 (3.85)
Butyraldehyde	ND	0–1.1	22.19 (2.91)
Valeraldehyde	ND	0–2.1	ND
Glyoxal	ND	NR	ND
Methylglyoxal	0.95 (0.43)	NR	ND
Total	40.4 (2.03)	NR	2033.93 (35.72)

Mean (SD).

*Data for other closed-system ECIG devices (shown for comparison) are derived from El-Hellani *et al.*[11]

†Results for Marlboro Red, purchased in Beirut in January 2018, tested using Health Canada Intense smoking regimen.

ECIG, electronic cigarette; NA, not analysed; ND, not detected; NR, not reported; PG, propylene glycol; VG, vegetable glycerin.