JUUL 'new technology' pods exhibit greater electrical power and nicotine output than previous devices

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ABSTRACT
In 2019, JUUL Labs began marketing in the European Union 'new technology' pods that incorporated a new wick that it claimed provided 'more satisfaction'. In this study, we compared design and materials of construction, electrical characteristics, liquid composition and nicotine and carbonyl emissions of new technology JUUL pods to their predecessors. Consistent with manufacturer's claims, we found that the new pods incorporated a different wicking material. However, we also found that the new pod design resulted in 50% greater nicotine emissions per puff than its predecessor, despite exhibiting unchanged liquid composition, device geometry and heating coil resistance. We found that when connected to the new technology pods, the JUUL power unit delivered a more consistent voltage to the heating coil. This behaviour suggests that the new coil-wick system resulted in better surface contact between the liquid and the temperature-regulated heating coil. Total carbonyl emissions did not differ across pod generations. That nicotine yields can be greatly altered with a simple substitution of wick material underscores the fragility of regulatory approaches that centre on product design rather than product performance specifications.

INTRODUCTION
Electronic cigarettes (e-cigarettes) heat and vaporise a nicotine-containing liquid to produce an aerosol that when inhaled can deliver nicotine to the bloodstream and the brain.[1] E-cigarette use is increasing globally and industry analysts estimate that sales will increase by a compounded annual growth rate of 20% over the period 2019–2023.[2] The popularity of e-cigarettes, particularly among youth and young adults,[3–5] has caused concerns about the potential role of e-cigarettes in initiating dependence. It is well established that nicotine is the drug that causes dependence in tobacco products.[6] Therefore, in an effort to make e-cigarettes 'less addictive and appealing to youth', some jurisdictions have mandated or are considering mandating a limit on nicotine concentration[7 8] in e-cigarette liquids, so that e-cigarettes deliver no more nicotine than combustible cigarettes.[7] However, it has been shown that as a standalone regulation, limiting nicotine liquid concentration does not constrain nicotine emissions because the latter depends on multiple variables in combination, including device power and design, liquid composition and user puffing behaviour.[9]

E-cigarettes typically employ a wick to convey liquid from a reservoir to an electrical heating coil that is powered whenever the user draws a puff (figures 1 and 2). In 2019, JUUL Labs, the manufacturer of the popular JUUL device, announced that it changed the wick material in its newly released 'new technology' pods, providing 'a more satisfying vapor experience… [and] …more consistency puff-to-puff… with the potential to deliver more nicotine'.[10] Apart from monitoring developments of a brand that has captured the largest share of e-cigarette sales in the USA if not the world, this product update provided the opportunity to examine how a design variable that has heretofore received no regulatory attention—namely wick design—may influence nicotine emissions. In this study, we compared device design, electrical characteristics, including voltage versus time during a puff, liquid composition, and aerosol emissions (nicotine and carbonyl compounds (CCs)) of new and previous generation JUUL pods.

METHODS
We analysed and compared the heating coil dimensions, wick characteristics, electrical features, liquid composition and aerosol emissions of new (Golden Tobacco, 18 mg/mL) and previous technology brand-new (unused) JUUL pods (Golden Tobacco, 20 mg/mL) that were procured from the UK in July 2020. Liquid composition and aerosol emissions measurements were repeated five times with each product, using a new pod each time. Electrical measurements were repeated in triplicate, using a new pod for each measurement. The same fully-charged JUUL power unit was used for all measurements to ensure that any observed differences were due solely to changes in pod design.

Several variables were assessed in relation to electrical power features of the new and previous technology pods, including maximum puff duration, electrical resistance and resistivity, the electrical voltage delivered during a puff, and computed power. The maximum puff duration (second) was measured as the time elapsed from puff commencement before the JUUL device automatically cut power, as in Talih *et al*.[11] The electrical resistance (Ω) was measured using a standard laboratory Ohm-meter connected at the pod leads. The electrical resistivity (ρ, Ωm) was calculated according to $\rho = \text{resistance} \times \frac{A}{\text{coil length}}$, where A is the wire cross-sectional area and is computed as $A = \pi \times \frac{\text{wire diameter}^2}{4}$. The heating coil wire diameter and wire length were measured using a calliper after disassembling the device (figure 1B).

The JUUL wick material was assessed using thermogravimetric analysis coupled to Fourier

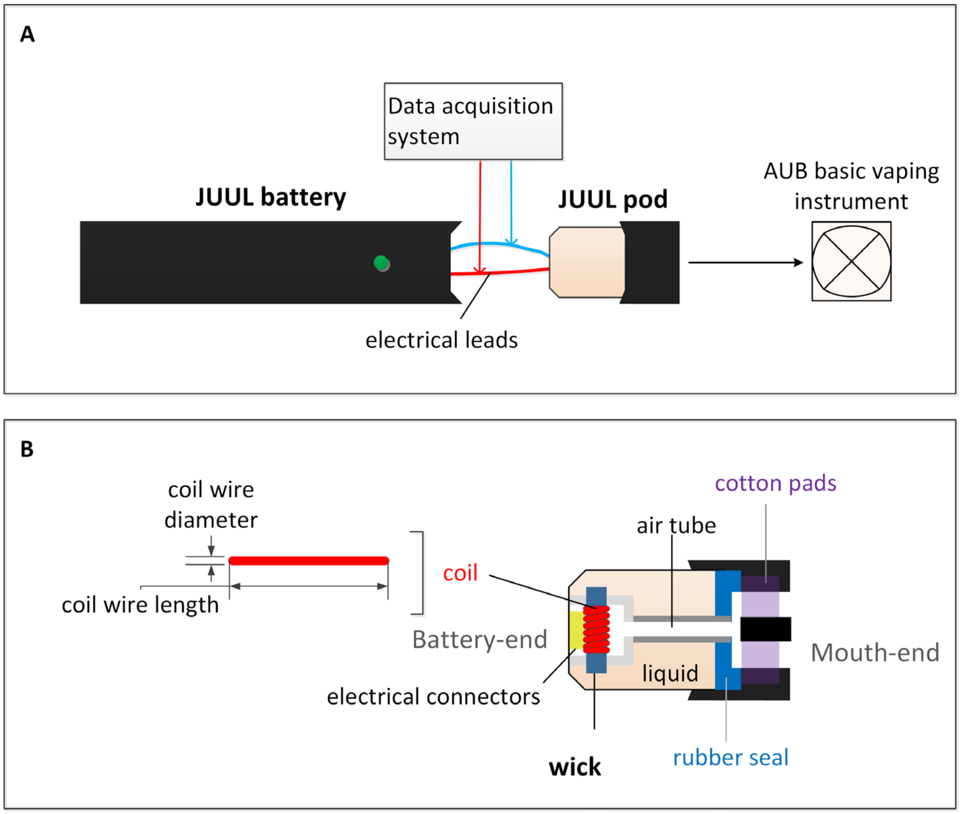

Figure 1 (A) Schematic of the set-up used to measure the voltage delivered to the JUUL pod during a puff. (B) Schematic of a JUUL pod. AUB: American University of Beirut.

transform infrared spectroscopy (TGA/FTIR; TGA: NETZSCH TG 209 F1 Libra; FTIR: Bruker Tensor 27). The TGA analysis was done under air atmosphere and a thermal programme that ranged from 30°C to 1000°C with a ramping of 10°C/min.

For electrical output characterisation, the JUUL battery unit was disassembled and connected to the JUUL pods via electrical leads of negligible resistance. A single 10 s puff at a flow rate of 1 L/min was drawn while the voltage signal across the pod terminals was sampled using a data acquisition device (NI USB-6003) at a rate of 74 kHz (figure 1A). Three 10 s puffs were drawn with each pod, with 2 min between each puff to allow the system to cool.

Liquid nicotine concentration and form were measured using a liquid–liquid extraction method and gas chromatography–mass spectrometry (GC–MS), as in El-Hellani, El-Hage.[12] The pH was measured by diluting the liquid with deionised water to prepare an aqueous extract of 600 µg/mL of nicotine concentration in a final volume of 6 mL. The pH of this extract was measured by a pH-metre (Starter 3100 OHAUS).

Nicotine and carbonyl compound (CC) emissions were measured by drawing 15 4 s puffs at 1 L/min flow rate using the American University of Beirut Aerosol Lab Vaping Instrument. The aerosol exiting the e-cigarette was trapped on a fibreglass filter (Gelman Type A/E 47 mm). Total particulate matter (TPM)

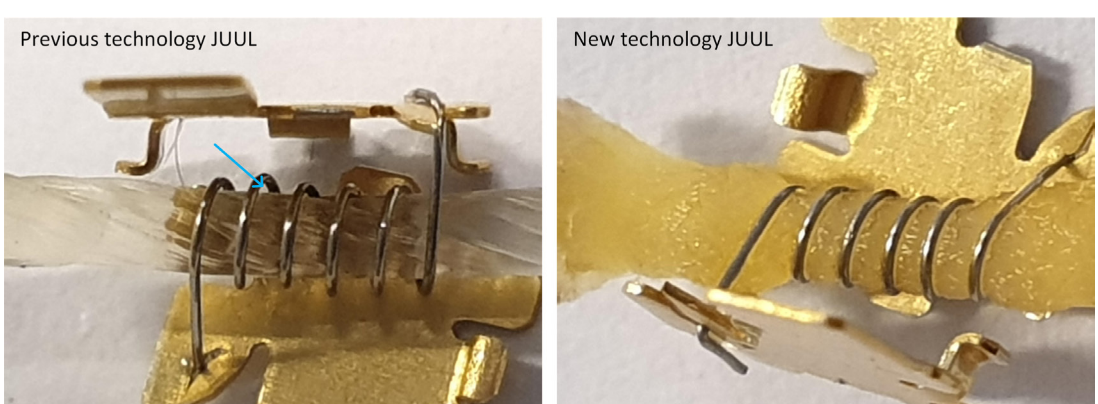

Figure 2 Images of the wick assemblies of the new and previous technology JUUL pods. The blue arrow indicates an air gap between the coil and wick. Air gaps were found in both of the prior technology pods that were disassembled, and in neither of the new technology pods. The thicker cotton wick appears to fit more tightly in the coil than the prior technology silica wick.

Table 1 Comparison of device geometry, electrical characteristics, liquid composition and nicotine, and carbonyl emissions, mean (SD), of new and old technology JUUL pods procured in the UK in July 2020

	JUUL	'new technology' JUUL
Coil dimensions		
Coil wire diameter (mm)	0.13	0.13
Coil wire length (mm)	26.8	26
Number of coils	1	1
Electrical characteristics		
Max puff duration (s)	5.9	5.9
Pod resistance (Ω)	1.7	1.7
Computed resistivity (Ωm)	8.4×10^{-7}	8.67×10^{-7}
Voltage (V)	1–2.5	2.5–2.8
Computed power range (W)	0.6–3.7	3.6–4.5
Liquid composition		
Nominal nicotine content (mg/mL)	20	18
Measured nicotine content (mg/mL)	18.33 (1.55)	18.18 (0.45)
% Protonated	91.97 (3.57)	92.45 (3.23)
pH	6.59 (0.14)	6.19 (0.11)*
% Propylene glycol	26.2 (0.45)	27.6 (0.55)*
% Vegetable glycerin	73.8 (0.45)	72.4 (0.55)*
Emissions in 15 puffs		
Total particulate matter (mg)	41.66 (3.99)	59.7 (14.02)*
Nicotine (mg)	0.47 (0.1)	0.73 (0.18)*
Carbonyl compounds (µg)		
Formaldehyde	0.6 (0.27)	0.29 (0.03)
Acetaldehyde	0.96 (0.19)	0.79 (0.05)
Acetone	4.13 (0.39)	4.63 (0.19)*
Acrolein	ND	ND
Propionaldehyde	0.04 (0.03)	0.03 (0.02)
Crotonaldehyde	0.03 (0.05)	0.11 (0.06)
Methacrolein	0.49 (0.08)	0.6 (0.07)
Butyraldehyde	ND	ND
Valeraldehyde	0.29 (0.1)	0.33 (0.07)
Glyoxal	ND	ND
Methylglyoxal	0.86 (0.51)	0.95 (0.06)
Total carbonyls	7.41 (1.23)	7.73 (0.26)

*Represents a significant difference between the new and previous technology JUUL pods (p<0.05).

was determined gravimetrically by weighing the filter pads presampling and post sampling. Nicotine in the filter was determined by GC–MS.[13] CCs were trapped on 2,4-dinitrophenylhydrazine cartridges, eluted with 90/10 (vol/vol) ethanol/acetonitrile, and quantified by high-performance liquid chromatography ultraviolet, as in El-Hellani *et al*.[13] The species analysed, and the limit of detection and limit of quantitation were, respectively, as follows (µg/mL): 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.

Outcome variables, including liquid composition and aerosol emissions, were summarised as mean (SD). Outcome variables were compared between the new and old technology JUUL pods using independent sample t-tests with an alpha level of 0.05 to determine significance.

RESULTS

Heater coil dimensions, electrical characteristics, liquid composition and toxicant emission results of new and old technology JUUL pods are summarised in table 1.

New and previous technology JUUL pods were indistinguishable by all design measures, except for the coil-wick assembly. Both JUUL pods featured a metallic heating coil that was wrapped around a wick. Magnified images show that the previous technology JUUL wick is made of strands of bundled twisted threads, similar in appearance to OEM silica wicks sold for e-cigarette construction. Also apparent from the figure is that segments of the heating coil windings are not in direct contact with the silica wick. In contrast, the new technology JUUL wick is made of cotton fibres, tightly wound by the coil (figure 2). The coil wire diameter (0.13 mm) and length (26–27 mm) were the same across the two devices. Both pods had 1.7 Ω resistance heating coils, and a computed resistivity of ($8.4–8.7\times10^{-7}$ Ωm), which is near that of nichrome ($1–1.5\times10^{-6}$ Ωm).[14 15]

The TGA analysis of the new technology JUUL wick exhibited a mass loss profile and chromatogram consistent with previously reported data on cotton (online supplemental material). In contrast, the prior generation JUUL wick showed no signs of degradation within the 1000°C limit of the instrument, indicating that the material was not cotton.

When the device was activated, the voltage delivered to the new technology JUUL coil remained near its initial value whereas the voltage dropped precipitously during a puff for the previous technology pods (figure 3). As a result, the computed average power for the new technology JUUL pods was more than double that of the previous generation pods (4.3 W vs 1.6

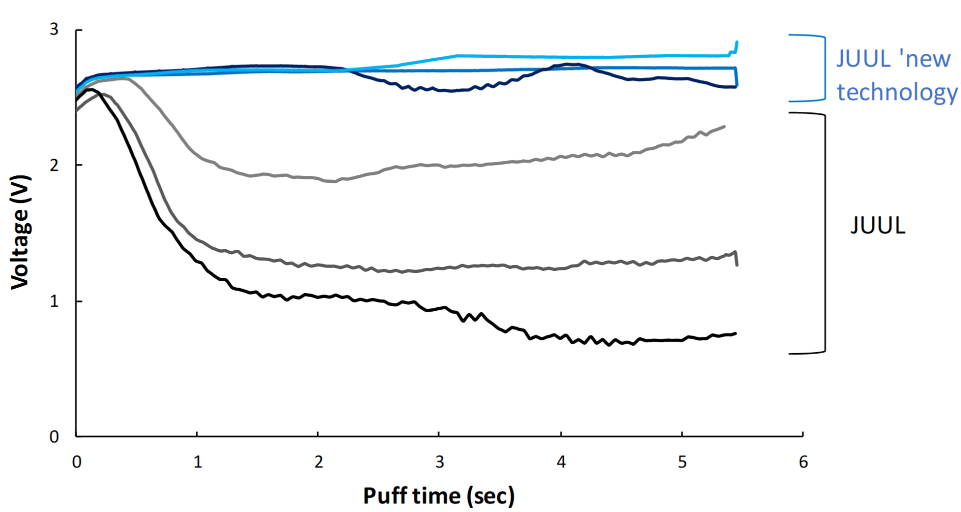

Figure 3 Average voltage for three puffs for three new and three old technology JUUL pods puffed using the same JUUL battery.

W). In addition, interpod variability in power was significantly greater for the previous generation technology ($p<0.05$). With both pods, the battery unit automatically terminated the power to the coil when the puff duration exceeded 5.9 s.

As shown in table 1, the composition of the liquids across both generations did not differ significantly, except that the pH was slightly lower for the new technology JUUL pod (6.2 vs 6.6) and that the propylene glycol to vegetable glycerin ratio was slightly greater for the new technology pod (28/72 vs 26/74).

The new technology JUUL pod emitted 0.73 (0.18) mg of nicotine and 59.7 (14.02) mg of TPM in 15 puffs, significantly higher than 0.47 (0.10) mg of nicotine and 41.66 (3.99) mg of TPM for the previous generation JUUL. The two devices emitted similar levels of total carbonyls (7.4–7.7 µg in 15 puffs).

DISCUSSION

In this study, we investigated a new product release by JUUL, which was claimed to produce a more satisfying experience. We found that, as claimed, the new technology JUUL wick is made of cotton, and that the new wick design resulted in both more consistent intrapuff electrical power delivery, and approximately 50% greater nicotine and particulate matter emissions for the same operating conditions. This change might result in greater nicotine exposure and pod consumption by JUUL users. Interestingly, it appears that the entire difference in performance derived from the change in wick design, as all other variables tested were the same across the new technology and its predecessor.

The effect of JUUL wick design on nicotine emissions is consistent with previously reported findings. Mallock *et al*[16] recently reported that a modified European Union version of the JUUL product, sometimes referred to as 'Turbo', also uses a different wick and generates more aerosol and nicotine, and comparable levels of carbonyls, compared with the initial European JUUL. As all other aspects of the JUUL products were similar, the higher nicotine emissions were associated with the use of a different wick design.[16]

In this study, we also examined why a different wick design may influence JUUL aerosol emissions by sensing the JUUL voltage signal during a puff. As with a previous report,[11] we found that the voltage delivered to the prior generation JUUL pod decreases in the timespan of a puff. However, with the new wick design, we found that the voltage delivery was by comparison strikingly steady and showed little variability across pods (figure 3).

The results obtained in this study suggest that the new technology wick conveys liquid to the coil more effectively than the previous technology wick. This hypothesis stems from the fact that the JUUL power unit uses automatic feedback control to regulate power in order to attain a preset temperature (eg, below the liquid boiling point).[17] Thus, a decaying voltage signal during a puff indicates that the control unit is reducing the voltage to avoid exceeding the temperature set point, which can occur when the coil or segments of the coil run dry. The fact that the new technology exhibits no voltage drop during a puff indicates that the coil is sufficiently wetted that it can be powered at the maximum voltage continuously without risk of exceeding the set temperature. Ultimately, the greater average voltage output results in a greater amount of liquid vaporised and therefore greater nicotine emissions, per unit time or per puff. Interestingly, the greater vaporisation rate is not accompanied by a concomitant increase in carbonyl emissions, apart from a small but statistically significant increase in acetone. We note that other factors that we did not measure in this study, such as the type and concentration of the acid used to adjust the liquid pH and the composition of the flavorants, may affect user sensory experience and puffing patterns.

In conclusion, while the results of this study may be interesting to those who study e-cigarette technology, a larger question is whether product regulations aiming to limit nicotine emissions from e-cigarettes can ever succeed when regulations focus on product design specifications, such as power or nicotine concentration. A regulatory approach focusing instead on product performance specifications, for example, nicotine flux,[18] is less likely to lag behind in a race against addiction-fueled, revenue-driven product innovation.

What this paper adds

⇒ Without changing battery voltage, liquid composition or electrical resistance, JUUL's 'new technology' device emits 50% greater nicotine per puff than its predecessor due to a subtle change in the coil-wick assembly of its UK product. This design change allows JUUL to approach combustible cigarette-like nicotine emissions while employing a liquid that comports with the European Union regulations, which limit liquid nicotine concentration to 20 mg/mL. The new coil-wick design results in better vaporisation performance by improving liquid delivery to the heating coil, allowing JUUL's automatically controlled electronic circuit to deliver power more consistently during a puff. This finding shows that wick design can significantly influence nicotine emissions and highlights that e-cigarette product performance is not well constrained by regulations that focus on liquid composition in isolation of other factors. A more effective regulatory approach is one that centres on product performance specifications rather than product design specifications.

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Contributors All authors designed the experiments and wrote the original draft. RS, REH and EK performed the experiments. EK, ST, RS and AS analysed the data.

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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 paid consultant in litigation against the tobacco industry.

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