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Meta-Analysis

Actual use puffing topography and mouth level exposure to aerosol and nicotine for an evolving series of electronic nicotine delivery systems

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ABSTRACT

Electronic nicotine delivery systems (ENDS) have evolved substantially in the past 10 years from disposable “cig-a-likes” to rechargeable devices with refillable tanks or disposable cartridges. It is less clear whether users’ puffing behaviour and exposure to aerosol emissions has similarly altered. Here we evaluate changes in the puffing topography and mouth level exposure (MLE) of users to aerosol and nicotine for a series of commercially available ENDS. In five separate consumer studies conducted from 2014 to 2019, eight Vuse ENDS including cig-a-likes, tanks, pen- and pod-style e-cigarettes were evaluated among ENDS users (total n=221) for puff duration, puff volume, inter-puff interval and MLE to aerosol and nicotine. Puff volumes varied two-fold (35.7-84.8 ml) with the lowest volumes for early ENDS and highest volumes for more recent pod style and tank systems. The variation in puff duration across the devices was smaller (1.70-2.39 s), especially for the five most recent devices (2.13-2.39 s). MLE to aerosol (1.9-6.4 mg/puff) tended to increase with evolution of the ENDS. MLE to nicotine, which depends on the nicotine concentration of the e-liquid as well as device design, was also highest for more recent devices. These data indicate that evolving device characteristics, such as more powerful batteries and aerosolisation technology, influence user puffing topography and the values obtained from one product might not apply to others. Continuing to evaluate ENDS consumer behaviour is important to understand further the factors that affect users’ puffing topography and nicotine uptake from these products.

Keywords: ENDS, MLE, Aerosol, Vuse

INTRODUCTION

The electronic nicotine delivery system (ENDS), or electronic cigarette (‘e-cigarette’), was originally designed as an aid to quit smoking by providing nicotine in an inhalable form but without the toxicants present in tobacco smoke.[1] Multiple studies have confirmed that ENDS aerosol contains significantly fewer, and generally substantially lower levels of the harmful and potentially harmful constituents (HPHCs) that are present in tobacco smoke.[2-4] As a result, many health bodies now support ENDS use as an alternative to conventional smoking as part of a tobacco harm reduction strategy, which aims to encourage smokers who will not otherwise quit to switch to a less harmful product.[5-8]

Although a reduction in toxicants in ENDS aerosol relative to cigarette smoke has been established, actual exposure to HPHCs is influenced by the way in which the ENDS device is used, including puff duration, volume and frequency.[9] Consumer use behaviour studies can provide an understanding of puffing topography and potential nicotine uptake, as well as variability or unique patterns of usage among types of ENDS and users.[10-14] Such studies can also inform machine-based protocols for testing aerosol emissions, which is central to regulating ENDS.[9]

Since first products were marketed, ENDS have continuously evolved from one-piece cig-a-likes and refillable tanks to pen- and pod-type modular devices with disposable cartridges. Initial studies of puffing topography demonstrated that users of cig-a-likes had puff durations, inter-puff intervals and puff volumes similar to the CORESTA-recommended machine-puffing protocol for monitoring HPHC emissions (3, 30 and 55 mL, respectively), while tank-style ENDS products had much higher puff volumes.[15-18] Subsequent studies have focused on the effects of user characteristics and nicotine strength on these parameters.[11,13,14,19-22] However, relatively few studies have directly compared puffing topography among later-generation ENDS/ estimated MLE to nicotine.[10-12,23] Furthermore, recent study documented wide variations in puff duration and puff volume among 24 individuals using their own-choice e-cigarettes in natural environment; therefore, it is important to characterise these parameters for wide range of product types.[19]

In the past few years, the range of ENDS available has greatly increased, leading to substantial heterogeneity among commercially available products. Battery capacity and power have also increased, which is likely to influence user behaviour.[10,24] This study describes 'actual use, puffing topography and MLE to aerosol and nicotine for a single ENDS brand (Vuse, BAT, London, UK) as it has evolved from cig-a-like and early pen-type devices to refillable tanks and pod-type devices. Using an observational approach, data gathered across five separated studies in the past 8 years were evaluated to assess trends and patterns across eight iterations of Vuse products in order to inform our understanding of the factors that affect puffing topography.

'Vuse' was previously branded under 'Vype' (pre-April 2021). All products were branded under 'Vype' at the time of the studies.

Evolution of Vuse ENDS

Vuse devices have developed from reload, 2-piece "cig-a-like" marketed in 2013, through eBox, rechargeable battery device with a refillable e-liquid tank marketed in 2016, to the iSwitch and ePod, a closed pod system. These products, categorised by their construction (2/3 piece), activation (button/puff), heating mechanism (coil and wick or blade) and specification, are summarized in Table 1; however, puffing topography data on Reload, ePen2 and Raptor have been published elsewhere, and these systems are not considered further.[12,16]

Table 1: Details of commercially available Vuse[a] ENDS since 2013.

Year[b]	Device name	System type	No. of Components	Component parts	Heating mechanism	Activation
2013	Vuse Reload	Closed	2	Cig-a-like, device + cartomiser	Coil + wick	Puff
2014	Vuse eStick	Closed	2	Cig-a-like, device + cartomiser	Coil + wick	Puff
2015	Vuse ePen	Closed	2	Pen-type device + cartridge	Coil + wick	Button
2015	Vuse iFuse	Closed	3	Pen-type device, cartridge + mouthpiece	Coil + wick	Button
2016	Vuse ePen2	Closed	2	Pen-type device + cartridge	Coil + wick	Button
2016	Vuse eTank	Open	3	Battery unit, clearomiser (refillable tank) + mouthpiece	Coil + wick	Button
2016	Vuse eBox	Open	3	Battery unit, clearomiser (refillable tank) + mouthpiece	Coil + wick	Button
2017	Vuse Raptor	Closed	2	Capsule-type device + cartridge	"PureTech" blade	Button
2018	Vuse ePen3	Closed	2	Pen-type device + cartridge	Coil + wick	Button
2018	Vuse iSwitch	Closed	2	Capsule-type device + cartridge	"PureTech" blade	Button
2019	Vuse ePod	Closed	2	Pod-type device + cartridge	Ceramic Coil + wick	Puff

[a]Previously branded as Vype. [b]Year of first commercial availability.

Among the ENDS, iFuse, a hybrid e-cigarette launched in Romania in 2015, was the only one containing tobacco. It had the same design as ePen1, but the disposable e-liquid cartomiser contained a segment of tobacco at the top of the cartomiser. When a puff was taken, the e-liquid aerosol passed through the tobacco segment, releasing volatile tobacco flavour components.[25]

METHODS

Study design

The puffing topography data were collected in five separate studies conducted among ENDS users in the

United Kingdom and Romania from 2014 to 2019. Study A was conducted internally at BAT (Southampton, UK); Studies B–E were conducted at a central location within the indicated town/city (Table 2) with participant recruitment managed by an external marketing agency. In each study, participants attended the study location, where they were asked to vape the respective study products through an SA7 puffing topography device. All studies followed appropriate governance and were approved and carried out in accordance with the ethical principles outlined in the Declaration of Helsinki and other relevant guidelines. All participants were adult ENDS users and provided written informed consent prior to enrolment. They were compensated for their time spent during the study.

Table 2: Details of the five puffing topography studies.

Study	Date	Location	Re-cruiting agency	Sample size	Study product	Nic. mg/ ml	Device settings	Flavour[a]	Inclusion criteria
A	2014	Southampton, UK	Internal	7	eStick	35[b]	Fixed	BT	Male users of eStick; aged 21-65 years
B	2016	Enfield, UK	TNS, Kantar Group	53	eTank	12	Fixed	BT / DC	Solus daily e-cigarette users; vaping for at least 1 month; aged 21-64 years
					eBox	6	Fixed/ variable	BT / DC	
C	2016	Bucharest, Romania	ISRA	59	ePen1	18	Fixed	GT	iFuse users aged 21-64 years
					iFuse	18		U	
D	2019	Gosport, UK	SMS	60	ePen3	18	Fixed	WB	Daily e-cigarette users; vaping 12 mg/ml nicotine or higher; vaping for at least 6 months; aged 21-64 years
					iSwitch	5		FB	
E	2019	Gosport, UK	SMS	58	ePod	0/18	Fixed	MW	Daily e-cigarette users; vaping 12 mg/ml nicotine or higher; vaping for at least 6 months; aged 21-64 years

[a]BT-Blended tobacco; DC-Dark cherry; GT-Golden tobacco; U-unflavoured; WB-Wild berries; FB-Forest berries; MW-Mango Wonder. [b]This study conducted prior to the introduction of UK regulations on maximum nicotine concentration of 20 mg/ml (2016).

Study participants

In Study A, a preliminary study conducted internally at BAT (Southampton), adult eStick users aged 21-65 years were recruited. In studies B-E, approximately 50-60 adult daily e-cigarette users aged 21-64 years were recruited via a third-party market research agency. In all studies, the inclusion criteria were general good health and regular use of e-cigarettes or a specific brand of e-cigarette (Table 2). Women who were pregnant or breastfeeding were excluded. Eligible participants were briefed on the study protocol and provided written informed consent prior to participation in any study procedures. Participants were free to withdraw from the study at any time and received pro-rata reimbursement to compensate for their time taken to participate in research.

Study products

Eight products were evaluated in the five studies, with nicotine concentrations ranging from 0 to 35 mg/ml. All devices were provided fully charged with a fresh cartridge containing e-liquid of fixed flavour and nicotine strength (Supplementary table 1). In Study B, participants were offered a choice of blended tobacco and dark cherry flavoured e-liquid to use throughout the study; in addition, participants used the eBox under both fixed settings (8.0 W, airflow open) and user-customized settings. In Study E, ePod was used with both nicotine-free and 18-mg nicotine cartridges.

The 35 mg/ml nicotine product was included in study A, which was conducted prior to the introduction of UK regulations on maximum nicotine concentration of 20 mg/ml (2016). All other products contained nicotine up to and including 18mg/ml.

Puffing topography measurements

Puffing topography measurements, including puff volume, puff duration, puff interval and number of puffs, were recorded by using a Smoking Analyser 7 (SA7), a bespoke portable puffing topography device originally developed for use with conventional cigarettes, but subsequently modified for use with ENDS.[12,16,26]

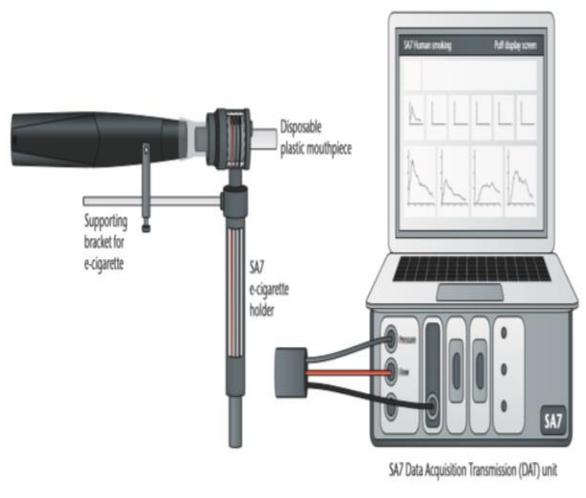

Figure 1: Schematic diagram of the SA7 puffing topography device with modified product holder, DAT unit and laptop computer.

The SA7 comprises a data acquisition and transmission (DAT) unit, a product holder and a laptop computer, controlling operation of the device and collection of puffing topography data in real time on a puff-by-puff basis (Figure 1). Two unidirectional pressure transducers within the DAT unit are connected to either side of the stainless-steel orifice (diameter 2 mm) of the product holder. When a puff is taken on an ENDS device placed in the holder, the transducers measure the change in pressure across the orifice, which is proportional to the square of the flow rate and allows calculation of puff volume. To ensure accurate measurements, the puffing topography device was calibrated daily for pressure and flow.[26]

In all studies, e-cigarette devices were weighed before and after each session. In studies A, B and C, participants were asked to use the study products through the SA7 as they normally would, taking puffs ad libitum for 40, 15 and 20 min, respectively. In studies D and E, participants were asked to take a fixed number of puffs (n=10) in their usual way. The duration of product use from the first puff until the last puff was also recorded in each topography session.

MLE

MLE to aerosol was estimated by device mass loss (DML), which has been previously shown to be highly correlated with aerosol collected mass (r^2=0.991).[12] DML was determined from the difference in device mass before and after each topography session. MLE to nicotine was estimated from the DML using the %w/w of nicotine in the e-liquid formulation (Supplementary Table 1).

Data analysis

Data were analysed using Minitab version 19 statistical analysis software (Minitab, Coventry, UK). Categorical data were reported as number (percentage) and continuous data as mean ± standard deviation (SD). Data for study B were analysed for significant differences between products and flavours at 5% significance level (α) using a mixed effect linear model with subject as random effect, product and flavour as fixed effect. Data for study E were analysed for significant differences between nicotine level (0mg/ml and 18mg/ml) using a paired t-test at the 5% significance level (α).

RESULTS

Study participants

Table 3 shows the demographics of the participants who completed the puffing topography studies (n=221 in total). Although the studies were conducted separately over 5-6 years, the participants in each were regular e-cigarette users (iFuse users in Study C) or dual users of cigarettes and e-cigarettes in order to reduce variations in puffing topography due to differences in use between e-cigarette-naïve smokers and established e-cigarette users.[13,14,20]

Table 3: Demographic characteristics of the study participants.

Characteristic	Study A, (n=7)[a] (%)	Study B, (n=53) (%)	Study C, (n=57) (%)	Study D, (n=52)[b] (%)	Study E, (n=52) (%)
Gender					
Male	7 (100)	24 (45)	31 (54)	27 (52)	27 (52)
Female		29 (55)	26 (46)	25 (48)	25 (48)
Age range, (years)	21-65	21-64	21-64	21-64	21-64
Age group, (years)					
21-24		6 (11)	11 (19)	8 (15)	8 (15)
25-29		4 (8)	13 (23)	7 (13)	9 (17)
30-34		19 (36)	16 (28)	5 (10)	8 (15)
35-44		11 (21)	13 (23)	10 (19)	14 (27)
45-54		9 (17)	2 (4)	11 (21)	13 (25)
55-65		4 (8)	2 (4)	3 (6)	0 (0)
User type					
Solus		53 (100)	0 (0)	26 (50)	26 (50)
Dual		N/A	57 (100)	18 (35)	26 (50)

[a] Study A was a preliminary study conducted internally at BAT. [b] Age and user type not available for eight participants.

Puffing topography and MLE

Overall trends

Puffing topography data for the eight study products, used with nicotine-containing e-liquid under fixed device settings, are summarized by type of ENDS in Table 4. Across the eight products, puff volumes varied twofold, ranging from 35.7 to 84.8 ml. The lowest volumes were observed for early pen-type devices ePen1 and iFuse (35.7 and 37.1 ml, respectively), while the highest volumes were observed for more recent devices, including the tank-style eBox, ePen3 and iSwitch (84.0–84.4. 79.8, and 84.8 ml, respectively).

Puff duration also varied substantially across the ENDS (1.70-2.39 s). Overall, puff durations were lowest for the early versions of pen-type devices (ePen1, 1.70 s; iFuse, 1.81 s), while the highest puff duration was observed for the iSwitch (2.39 s). All other devices had a puff duration in the range 2.1-2.3 s.

Among studies of ad libitum puffing (A, B and C), inter-puff interval was largest for the cig-a-like (55.0 s), possibly because the high nicotine content in this ENDS (35 mg/ml) meant that the user did not need to draw so frequently. The other ENDS had similar inter-puff intervals, ranging from 30.3 to 38.5 s. The short inter-puff interval observed for ePen3, iSwitch and ePod (Studies D and E) reflects the study design, where the participants were asked to take a fixed number of puffs rather than puffing ad libitum during the study. MLE to aerosol, determined by dividing the amount of e-liquid used (determined from DML) by the number of puffs, ranged from 1.9 to 6.4 mg/puff. There was a general trend of increasing MLE to aerosol as the ENDS have evolved, especially within the pod-style closed systems (Table 4). The highest value was observed for the iSwitch (6.4 mg/puff). MLE to nicotine, which depends on the nicotine strength of the e-liquid as well as on device parameters, ranged from 0.02 mg/puff (eBox; 6 mg/ml nicotine) and 0.03 mg/puff (ePen1/iFuse, 18 mg/ml) to 0.08 mg/puff (ePod, 18 mg/ml). The early cig-a-like ENDS had high MLE to nicotine due to the high nicotine strength of the e-liquid (35 mg/ml).

Individual study findings

Study A (2014) was a preliminary study to determine user puffing topography for an early ENDS device. The mean puff volume (51.9±11.8 mL), puff duration (2.29±0.64 s) and puff interval (55.0±22.9) of the cig-a-like device were close to the CORESTA-recommended machine-puffing parameters subsequently established in 2015.[17] The device had low battery power and the MLE to aerosol (2.0 mg/puff) was at the low end of the recorded MLE (range 1.9-6.4 mg/puff). However, MLE to nicotine was high (0.07 mg/puff) because the nicotine strength was 35 mg/ml. EU and UK regulations subsequently introduced have now fixed the maximum concentration of nicotine as 20 mg/ml.[27]

In study B (2016)-a comparison of puffing topography between two commercially available tank-style ENDS, eTank and eBox-participants were given a choice between two flavoured e-liquids (Vuse dark cherry and Vuse Blended Tobacco) to use for the duration of the study. Participants also used the eBox twice, once under fixed device settings (8W, with airflow fully open) and once under variable (user-customized) settings. User selection of device settings had little effect on the topography parameters and MLE values recorded for the eBox (Table 5).

Of the 53 participants, 36 (68%) chose the dark cherry flavour, while 17 (32%) chose the blended tobacco flavour (Table 6). There was no statistically significant difference between dark cherry and blended tobacco flavour e-liquids across any of the puffing parameters measured (Table 6). The sample sizes were small, but these observations suggest that e-liquid flavour may have little, if any, influence on the way in which a user puffs on the ENDS device.

Table 4: Puffing topography parameters by type of ENDS device.[a]

Product	Nicotine (mg/ml)	Sample size	Puff no.[b]	Session (min)	Puff vol. (mL)	Puff duration (s)	Puff interval (s)	MLE aerosol (mg/puff)	MLE nicotine (mg/puff)
Cig-a-like									
eStick	35	7	43.7±20.9	33.1±5.5	51.9±11.8	2.29±0.64	55.0±22.9	2.0±1.0	0.07±0.03
Tank									
eTank	12	53	28.5±22.6	13.0±3.0	59.5±23.4	2.30±0.86	37.4±23.1	3.3±1.7	0.04±0.02
eBox	6	53	31.4±20.5	13.7±1.6	84.0±46.3	2.32±0.87	38.5±35.4	3.9±2.0	0.02±0.01
Pen/Pod									
ePen1	18	57	53.6±34.2	18.4±1.5	35.7±14.5	1.70±0.78	32.2±28.7	1.9±1.0	0.03±0.02
iFuse	18	57	54.9±34.9	18.3±1.4	37.1±14.5	1.81±0.72	30.3±23.9	1.9±1.0	0.03±0.02
ePen3	18	52	9.9±0.7	1.7±0.7	79.8±48.9	2.13±1.00	8.9±4.4	4.4±2.9	0.07±0.05
iSwitch	5	52	9.9±0.5	1.7±0.7	84.8±48.7	2.39±1.18	9.1±4.2	6.4±4.1	0.03±0.0
ePod	18	52	10.1±0.3	1.9±1.0	49.4±20.6	2.29±0.99	10.3±6.2	4.9±2.9	0.08±0.05

[a]Data are mean ± SD of two replicates per participant per product except for eStick and eBox (one replicate per participant). [b] In studies A, B and C, puffing was ad libitum for up to 40 min (A), 5 min (B) or 20 min (C); in studies D and E, participants were asked to take 10 puffs.

Table 5: Comparison of puffing topography and MLE between user-customized and fixed device settings for eBox (Study B).

Product	Device settings	Puff number	Session (min)[a]	Puff interval (s)	Puff volume (mL)	Puff duration (s)	MLE aerosol (mg/puff)	MLE nicotine (mg/puff)
eBox	User-customized	28.4±15.7	13.2±1.9	37.7±26.1	84.4±43.1	2.35±0.94	4.1±3.3	0.02±0.02
eBox	Fixed	31.4±20.5	13.7±1.6	38.5±35.4	84.0±46.3	2.32±0.87	3.9±2.0	0.02±0.01

[a]Ad lib for up to 15 min.

Table 6: Comparison of puffing topography parameters between flavours for the eTank and the eBox (Study B)[a].

Product	Sample size	Puff no.		Puff interval (s)		Puff volume (mL)		Puff duration (s)		MLE to aerosol (mg/puff)		MLE to nicotine (mg/puff)	
		Value	P	Value	P	Value	P	Value	P	Value	P	Value	P
eTank													
BT	17	27.1±17.4	0.999	32.0±19.5	0.934	53.8±14.4	0.974	2.08±0.59	0.818	3.2±1.6	1.000	0.03±0.02	0.989
DC	36	29.2±24.8		40.0±24.5		62.2±26.4		2.40±0.96		3.3±1.8		0.04±0.02	
eBox-V													
BT	17	30.0±19.1	0.999	31.5±15.6	0.885	65.2±14.9	0.122	2.02±0.56	0.439	2.9±1.7	0.144	0.02±0.01	0.251
DC	36	27.7±14.1		40.6±29.5		93.5±48.9		2.50±1.04		4.7±3.7		0.03±0.02	
eBox-F													
BT	17	35.1±22.8	0.939	29.2±16.2	0.571	65.8±19.9	0.161	2.06±0.73	0.655	2.8±1.2	0.214	0.01±0.01	0.334
DC	36	29.7±19.4		43.0±41.0		92.6±52.6		2.45±0.91		4.4±2.1		0.02±0.01	

Abbreviations: BT-Blended tobacco; DC-Dark cherry; V-Variable settings (user-customised); F, Fixed settings (8W airflow fully open). [a] Significant differences determined at 5% significance level (α) using a mixed effect linear model with subjects as random effect, products and flavours as fixed effect.

Table 7: Comparison of puffing topography parameters between 0 mg and 18 mg ePod (Study E)[a].

Product	Sample size	Puff interval (s)		Puff volume (mL)		Puff duration (s)		MLE to aerosol (mg/puff)	
		Value	P	Value	P	Value	P	Value	P
ePod									
18 mg/ml	52	10.3±6.2	0.118	49.4±20.6	<0.001	2.29±0.99	<0.001	4.9±2.9	<0.001
0 mg/ml	52	9.4±5.5		58.4±25.9		2.68±1.15		6.1±3.1	

[a]Measured under a fixed number of puffs (10 puffs). Significant differences determined by paired t-test at 5% significance level (α)

In study E (2019), puffing topography and MLE to aerosol were compared between nicotine-free and 18 mg/ml nicotine e-liquids for the ePod under a fixed number of puffs (n=10). Participants took larger puff volumes, longer puff durations, and generated more aerosol when vaping the Vuse ePod with 0 mg/ml nicotine as compared with 18 mg/ml nicotine (Table 7), suggesting that users may be puffing harder to try and achieve the same sensory effects.

DISCUSSION

With lower toxicant emissions relative to combustible cigarettes, ENDS have the potential to reduce the health risks of smoking as part of a harm reduction approach.[2,4,12] However, exposure to both nicotine and HPHCs from these devices is affected by how the consumer uses them, and thus, it is essential to characterize consumer use behaviour to obtain an overall estimate of the relative risk from these products.[28] Such data can also inform laboratory-based emissions testing by identifying the most appropriate puffing parameters for instrumental analyses.[29]

To evaluate potential patterns and trends in puffing topography, we evaluated use behaviour data collected using the same topography instrument among regular e-cigarette users for a series of ENDS as they have evolved from early cig-a-likes and refillable tanks to modular devices with disposable cartridges. Across the eight products, there were no clear trends in puff duration or puff volume, although early pen-type devices had values that were at the lower end of the observed range, probably due to their lower power output. Overall, MLE to aerosol tended to increase with more recent ENDS, again reflecting the higher power and potentially more efficient aerosolisation technology of later devices. MLE to nicotine varied with the nicotine strength of the e-liquid, but again recent devices (ePod, ePen3 and iSwitch) tended to provide higher nicotine delivery (respectively, 0.08, 0.07 and 0.03 mg/puff for 18, 18 and 5 mg/ml nicotine e-liquid). Overall, however, the nicotine delivered by any of the ENDS was considerably lower than that delivered by a typical 6-mg 'tar' cigarette (1.3±0.5 mg/stick ≈ 0.13 mg/puff).[30]

There were relatively small differences in puff duration (1.70-2.39 s) among the eight ENDS evaluated in this study, whereas puff volume varied up to twofold (35.7-84.8 mL) (Table 4). Previous studies have reported a greater range of puff durations, from 1.4 s for a recent prototype device with distiller plate technology to 4.16 s for an early tank, but have similarly noted large variations in puff volumes, ranging from 41.2 to 101.4 mL.[12,18] The lower variation in puff duration across devices has relevance to emissions analyses because puff duration, rather than puff volume, has been reported as the main driver of the amount of aerosol, and hence nicotine and HPHCs, per puff in e-cigarettes.[31,32] This is in contrast to combustible cigarettes, where puff volume is the main determinant of the amount of smoke generated as per puff.[33]

Previous studies have noted the effect of power settings on puffing topography with the higher power setting on a device with variable settings leading to shorter puff duration.[10] The eight devices assessed here varied in power from 3.6 to 12 W, but no trend in puff duration with power was observed, indicating a stronger influence of other device characteristics in puff topography. Furthermore, there were no statistically significant differences in puffing duration or volume when users selected their own device settings for the eBox tank-style device in study B (Table 5).

Flavours are an important consideration for smokers looking to switch to new category products.[34-37] This has been observed to be important to new e-cigarettes users' chances of quitting cigarette smoking. Also, users of flavoured e-liquids are more likely to quit smoking compared to tobacco flavoured e-liquid users.[36,38,39] In Study B, given the choice, majority of the smokers chose dark cherry flavoured e-liquid, compared with blended tobacco flavoured e-liquid. There was no statistically significant difference between dark cherry and blended tobacco flavour e-liquids across any of the puffing parameters measured. These observations suggest that e-liquid flavour may have little, if any, influence on the way in which a user puffs on the ENDS device.

In addition to device variations, other factors are reported to affect puffing topography including nicotine content, where the lower nicotine concentration leads to longer puff durations as users self-titrate their puffing to obtain the nicotine level that they prefer.[21,22,24] Our observations in study E are consistent with previous studies. Participants vaping ePod with 0 mg/ml nicotine e-liquid took longer puffs than those using 18 mg/ml nicotine e-liquid (2.68 s vs 2.29 s), consequently generating higher puff volumes in the process (Table 7).

The results from this paper have a number of limitations. First, the puffing topography studies were conducted in different locations within and outside the United Kingdom (Table 2), and therefore recruited different subsets of the population, although all participants were regular e-cigarette users. Second, with the exception of the iFuse consumers in study C, the majority of participants, although e-cigarette users, were unlikely to be using the test product as their usual product, and therefore puffing topography may alter as an individual becomes familiar with the ENDS product.[20] Third, the studies described herein were conducted at a central location in the presence of research staff, which might have affected the natural use behaviour of the participants, especially where they were asked to use the products for only a limited number of puffs or a limited amount of time. Last, the e-liquids used in the devices varied in nicotine strength, precluding a direct comparison of MLE to nicotine and potentially influencing the puffing parameters measured.[21,22]

CONCLUSION

ENDS are continually evolving in terms of design, battery power and aerosolisation technology. The present study of user puffing topography for a series of ENDS dating back to 2014 found that puff duration, and puff volume especially, varied considerably among the different devices with no clear trends among the products. By contrast, MLE to aerosol has generally increased with evolution of the devices, reflecting the more advanced batteries and higher power settings that are now available. Recent devices also tended to show higher nicotine delivery. Collectively, the data indicate that user puffing topography differs substantially from one device to another.

No single machine puffing regime is likely to represent true human behaviour or produce emissions tightly linked to human exposure or risk, either for individual smokers or for population-level differences between device types. Even though the CORESTA recommended method no. 81 does not reflect intense use, it lays out the essential requirements necessary to generate and collect e-cigarette aerosol for analytical testing and comparison purposes.

Across the three generation of ENDS (Cig-a-like, closed and open systems) evaluated, a range of puff volume (35.7-93.5), puff duration (1.7-2.7s) and puff interval (8.9-55.0s) were observed. These parameters are broadly in-line with the CORESTA recommended method no. 81 (55 ml/3s/30s) machine puffing regime. Although puff volumes are higher than that recommended by CORESTA, this has little influence on ENDS aerosol delivery.

It is also suggested that given the choice, smokers prefer non-tobacco flavoured e-liquids, which has been an important consideration for smokers looking to switch. Similarity in puffing parameters observed in study B between dark cherry and blended tobacco flavoured e-liquids, suggests that e-liquid flavour may have little, if any, influence on the way in which a user puffs on the ENDS device.

Continuing to evaluate ENDS consumer behaviour will be important to understand further the factors that affect users' puffing topography and nicotine uptake from these products.

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SUPPLEMENTARY TABLE

Table 1: Composition of the e-liquids used in the five puffing topography studies.

Study	Device	Nicotine (mg/ml)	Nicotine (%w/w)	PG (%w/w)	VG (%w/w)	Water (%w/w)
A	**eStick1**					
	Blended tobacco	35.0	3.29	77	23	0
D	**eTank1**					
	Blended tobacco	12.0	1.07	32	50	18
	Dark cherry	12.0	1.12	70	20	10
	eBox1					
	Blended tobacco	6.0	0.53	32	50	18
	Dark cherry	6.0	0.56	70	20	10
E	**ePen1**					
	Golden tobacco	18.0	1.78	25	50	25
	iFuse1					
	Unflavoured	18.0	1.78	25	50	25
B	**ePen3**					
	Wild berries	18.0	1.62	54	36	10
	iSwitch2					
	Forest berries	5.0	0.43	36	63	1
C	**ePod1**					
	Mango wonder	0	0	47	50	0
	Mango wonder	18.0	1.59	47	48	0