Nicotine in Tobacco Product Aerosols: 'it's Deja Vu All over Again'

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Nicotine in tobacco product aerosols: 'It's déjà vu all over again'

Anna K Duell,1 James F Pankow,1,2 David H Peyton1

ABSTRACT
Introduction The distribution of nicotine among its free-base (fb) and protonated forms in aerosolised nicotine affects inhalatability. It has been manipulated in tobacco smoke and now in electronic cigarettes by the use of acids to de-freebase nicotine and form 'nicotine salts'.

Methods Measurements on electronic cigarette fluids (e-liquids) were carried out to determine (1) the fraction of nicotine in the free-base form (αfb) and (2) the levels of organic acid(s) and nicotine. Samples included JUUL ‘pods’, ‘look-a-like/knock-off’ pods and some bottled ‘nicotine salt’ and ‘non-salt’ e-liquids.

Results αfb = 0.12 ± 0.01 at 40°C (≈ 37°C) for 10 JUUL products, which contain benzoic acid; nicotine protonation is extensive but incomplete.

Discussion First-generation e-liquids have αfb ≈ 1. At cigarette-like total nicotine concentration (Nicfb) values of ~60 mg/mL, e-liquid aerosol droplets with αfb ≈ 1 are harsh upon inhalation. The design evolution for e-liquids has parallelled that for smoked tobacco, giving a ‘déjà vu’ trajectory for αfb. For 17th-century ‘air-cured’ tobacco, αfb in the smoke particles was likely ≥ 0.5. The product αfb in the smoke particles was high. ‘Flue-curing’ retains higher levels of leaf sugars, which are precursors for organic acids in tobacco smoke, resulting in αfb ≈ 0.2 and lowered harshness. Some tobacco cigarette formulations/designs have been adjusted to restore some nicotine sensory ‘kick/impact’ with αfb ≈ 0.1, as for Marlboro. Overall, for tobacco smoke, the de-freebaseing trajectory was αfb ≈ 0.5 → ~0.1 for e-cigarettes. For JUUL, the result has been, perhaps, an optimised, flavoured nicotine delivery system. The design evolution for e-cigarettes has made them more effective as substitutes to get smokers off combustibles. However, this evolution has likely made e-cigarette products vastly more addictive for never-smokers.

INTRODUCTION
Nicotine can exist in a free-base (fb) form and in two protonated forms (figure 1). For electronic cigarette fluids (e-liquids) and the aerosolised droplets created therefrom, both the total nicotine concentration (Nic) and the fraction of nicotine in the free-base form (αfb) can vary.1 Fb nicotine is volatile and gaseous fb nicotine is directly sensible. Protonated nicotine is not volatile and so has been referred to in the tobacco industry as ‘bound nicotine’.2 First-generation e-liquids were simply fb nicotine dissolved in a mix of propylene glycol (PG) and/or glycerol (GL), with αfb = 1, and Nicfb in the range of 6–24 mg/mL. In comparison, in the droplets making up tobacco smoke particulate matter (PM), Nicfb values are typically much higher (~60 mg/mL).3 Electronic cigarette (e-cigarette) aerosols with high values of the product αfbNicfb can be expected to be harsh upon inhalation, as with αfb = 1 and Nicfb = 60 mg/mL. Non-harsh cigarette-like nicotine levels in aerosolised e-liquids therefore require αfb < < 1. This can be achieved by the addition of an acid to the PG/GL/nicotine mix, for example, benzoic acid, as in the JUUL product line.

Given the large market share quickly achieved by JUUL4 5 and its youth-oriented e-cigarette demographic,6 the goal of this work was to determine αfb values and acid levels in the e-liquids from JUUL and look-a-like/knock-off product competitors, available as of October 2018, and thereby characterise the use of acid additives to moderate fb nicotine delivery, and thus harshness, while maintaining high total nicotine delivery. The measured αfb values were compared with those for first-generation e-cigarette products. The first-generation e-cigarette → JUUL trajectory is compared with that for the smoke aerosol from colonial-era air-cured tobacco → flue-cured tobacco (1850s forward) → the modern Marlboro cigarette. The measurements were carried out by application of 1H NMR spectroscopy (hereafter, NMR).1 8 9 As outlined by Duell et al.,1 NMR is a method that allows the reliable determination of αfb values in e-liquids without any alteration of the sample, for example, without water addition, which changes nicotine protonation chemistry. The e-liquid results are examined in the context of the acid+nicotine first protonation equilibrium constant.

Nicotine protonation and αfb
Predicting the extent of nicotine protonation (including αfb) in any solution requires knowledge of the governing acid/base concentrations and their medium-dependent equilibrium constants. Fully protonated nicotine carries two protons (figure 1) with acidity constants KaNicH+ (=Kac) and Ka NicH2+ (=Kab). Measurement of Ka values in tobacco smoke and e-liquids is very difficult but relatively easy in water. In water, reported values at 25°C are pKaNicH+ = 8.01 and pKaNicH2+ = 3.10.11 At 37°C, the values are 7.65 and 2.77, respectively.12 In water, pH≤ 4 is required for significant (≥10%) NicH2+. When conditions are such that there is not an equivalent excess of acid over nicotine (so that total molar-based concentration of monoprotic acid (Caa) total molar-based concentration of nicotine (Cac) is ≤ 1), or the protonating acid is weak for the medium, NicH2+ can be neglected and the dominant protonation of fb nicotine (Nic) occurs according to

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The protonated form may not be negligible for all e-liquids, including some non-JUUL high-acid brands examined experimentally. Each bracketed term in equations (1) and (2) is a molar concentration (not a chemical activity) so that $K_{oa,1}^{NicH^+}$ and all the other $K$ values herein are constant-medium type equilibrium constants, analogous to 'K values as discussed by Fankow,13 and dependent on the nature of the particular solution medium.

Net protonation reaction

In a liquid medium (eg, the PG/GL matrix and water), the acid dissociation reaction of an acid, HA (eg, benzoic acid and acetic acid), is

$$ HA = H^+ + A^- $$

The overall reaction for monoprotonation of Nic by HA is given by equations (1) + (3), so that

$$ HA + Nic = A^- + NicH^+ $$

and

$$ K_{oa,1}^{HA/Nic} = \frac{[HA][A^-]}{[HA][Nic]} = K_{oa,1}^{HA/Nic} $$

$K_{oa,1}$ is dimensionless because both the forward and backward reactions are bimolecular: any molar and the nicotine methyl resonance, respectively. The average was so that $\alpha_a = (C_{Nic} - x) / C_{Nic}$. Because the reaction is bimolecular and $K_{oa,1}$ is dimensionless, for any mass concentration of total nicotine, we can set $C_{Nic} = 1$ and $C_{HA} = C_{HA/CNic}$. Then $\alpha_a = 1 - x$, and

$$ K_{oa,1} = \frac{(1-\alpha_a)^2}{C_{Nic}^2 (1+\alpha_a) \alpha_a} $$

When $K_{oa,1}$ and $C_{HA/CNic}$ are known, then equation (6) can be solved for $\alpha_a$ either numerically or by the quadratic equation. For the latter, $a = K_{oa,1} - 1$, $b = (K_{oa,1} C_{HA}/C_{Nic} - K_{oa,1} + 2)$, and $c = -1$; the root $\alpha_a = \left\{ -b + \sqrt{b^2 - 4ac} \right\} / (2a)$ is chosen so that $\alpha_a > 0$. Cases involving $K_{oa,1} = 1$ are not second order ($a=0$), and so reduce to $\alpha_a = 1/(1+C_{HA/CNic})$. When protonation is favoured, the reliability of equations (5-6) will decrease for $C_{HA/CNic} > 1$ due to an increasing importance of NicH$^2+$. For the special case of $C_{HA/CNic} = 1$, then

$$ K_{oa,1} = \frac{(1-\alpha_a)^2}{\alpha_a^2} $$

$$ \alpha_a = \frac{1}{1+\sqrt{K_{oa,1}}} $$

LABORATORY METHODS

NMR determinations of $\alpha_a$, nicotine and acid concentrations

JUUL e-liquid ‘pods’ were purchased from JUUL. Other pod brands (ZOOR, SMPO, Myle, ZiiP and Eon Smoke) and bottles of e-liquids (Fuzion Vapor) were purchased from online suppliers. Bottles of ‘nicotine salt’ e-liquids (Salt Bae50 and Pacha Mama Salts) were purchased from a vape shop in Portland, Oregon. Glacial acetic acid was obtained from Mallinckrodt Chemicals (Staines-upon-Thames, England). Terbutylamine (98%) was obtained from Sigma-Aldrich (St. Louis, Missouri, USA). DMSO-d$_6$, D 99.9%, was obtained from Cambridge Isotope Laboratories (Andover, Massachusetts, USA). Precision coxial NMR inserts (WGS-5BL-SP and WGS-5BL) and precision NMR tubes (535-PP-7) were purchased from Wilmad (Vineland, New Jersey, USA).

Monoprotonated and fb nicotine standards, which were used to calculate the fb nicotine fraction in each sample, were prepared by adding acetic acid or terbutylamine to the e-liquids until the limiting NMR chemical shifts were achieved. In the present study, standards were prepared using the following commercial e-liquids: ‘Mango’-flavoured JUUL, ‘Apple’-flavoured ZOOR, ‘Cafe’-flavoured ZOOR and ‘Blue Raspberry Lemonade’-flavoured Salt Bae50. In our previous work, standards were prepared from nicotine-containing PG/GL samples rather than actual commercial e-liquids, resulting in small differences in the $\alpha_a$ values reported here. Various commercial e-liquid standards were prepared because dissimilarities in the e-liquid compositions (such as the presence of benzoic acid or levulinic acid) can result in slightly different limiting chemical shifts for the monoprotonated and fb nicotine reference samples. Appropriate reference samples were matched to the tested commercial e-liquids by using the most similar compositions as determined by analysis of $^1$H NMR spectra. In particular, this was executed by matching samples and reference standards containing the same primary acid(s) (if present), that is, benzoic acid or levulinic acid. Details for the references used for each sample can be found in online supplementary table S1. $\alpha_a$ was calculated using the difference between the chemical shifts of two aromatic nicotine protons and the nicotine methyl resonance, respectively. The average was

$$ K_{oa,1} = \frac{(C_{HA} - x)}{(C_{Nic} - x)} $$


Figure 1 Top: the distribution of nicotine in vape and tobacco aerosols primarily involves two forms; centre: NicH$^+$ (monoprotonated), which is non-volatile; and right: free-base (fb) nicotine, which is volatile. The fraction of the fb ($\alpha_a$) depends on the acid/base conditions. In water at 25°C, $pK_{oa,1}$=8.01. Bottom: so-called ‘nicotine salts’ in electronic cigarettes liquids are formed by adding an organic acid (benzoic acid is depicted here) to the formulation, producing a lower $\alpha_a$ that depends on the ratio of acid:nicotine, as well as temperature and solvent conditions.
Table 1  Listed versus measured nicotine contents, molar acid/nicotine ratios and free-base fraction ($\alpha_{fb}$) for a selection of JUUL pod liquids, ‘look-alike/knock-off’ pod liquids, and bottled e-liquids (additional details can be found in online supplementary table S-1).

<table>
<thead>
<tr>
<th>Brand ‘flavour’</th>
<th>Nicotine wt%* (listed/measured)</th>
<th>Nic $n_{c_a}$ (mg/mL) (measured)</th>
<th>Acid†</th>
<th>Molar acid/nicotine ratio ($C_{acid}/C_{nic}$)</th>
<th>$\alpha_{fb}$‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUUL ‘pods’ (5% nicotine by wt.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JUUL ‘Cool Mint’/JUUL(8) group</td>
<td>5.045.1</td>
<td>60</td>
<td>BA</td>
<td>0.97</td>
<td>0.13</td>
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<tr>
<td>JUUL ‘Classic Menthol’/JUUL(8) group</td>
<td>5.045.9</td>
<td>58</td>
<td>BA</td>
<td>0.98</td>
<td>0.13</td>
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<tr>
<td>JUUL ‘Crème Brûlée’/JUUL(8) group</td>
<td>5.05.1</td>
<td>60</td>
<td>BA</td>
<td>0.97</td>
<td>0.12</td>
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<tr>
<td>JUUL ‘Fruit Medley’/JUUL(8) group</td>
<td>5.050.0</td>
<td>59</td>
<td>BA</td>
<td>0.99</td>
<td>0.12</td>
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<td>JUUL ‘Cool Cucumber’/JUUL(8) group</td>
<td>5.050.0</td>
<td>59</td>
<td>BA</td>
<td>1.00</td>
<td>0.11</td>
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<tr>
<td>JUUL ‘Classic Tobacco’/JUUL(8) group</td>
<td>5.050.0</td>
<td>59</td>
<td>BA</td>
<td>1.00</td>
<td>0.11</td>
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<tr>
<td>JUUL ‘Virginia Tobacco’/JUUL(8) group</td>
<td>5.05.1</td>
<td>60</td>
<td>BA</td>
<td>1.00</td>
<td>0.11</td>
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<td>JUUL ‘Mango’/JUUL(8) group</td>
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<td>62</td>
<td>BA</td>
<td>0.99</td>
<td>0.09</td>
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<td>JUUL ‘pods’ (3% nicotine by weight)</td>
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<tr>
<td>JUUL ‘Virginia Tobacco’/JUUL(2) group</td>
<td>3.03.0</td>
<td>35</td>
<td>BA</td>
<td>0.94</td>
<td>0.14</td>
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<tr>
<td>JUUL ‘Mint’/JUUL(2) group</td>
<td>3.03.0</td>
<td>35</td>
<td>BA</td>
<td>1.04</td>
<td>0.11</td>
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Other ‘nicotine salt’ formulation ‘pods’

<table>
<thead>
<tr>
<th>Brand</th>
<th>Nicotine wt%* (listed/measured)</th>
<th>Nic $n_{c_a}$ (mg/mL) (measured)</th>
<th>Acid†</th>
<th>Molar acid/nicotine ratio ($C_{acid}/C_{nic}$)</th>
<th>$\alpha_{fb}$‡</th>
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<tr>
<td>EM</td>
<td>6.040.0</td>
<td>47</td>
<td>BA</td>
<td>3.43</td>
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<tr>
<td>SS</td>
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<td>51</td>
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<td>1.02</td>
<td>0.09</td>
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<tr>
<td>ZIC</td>
<td>5.033</td>
<td>38</td>
<td>BA</td>
<td>4.03</td>
<td>0.015</td>
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<tr>
<td>ZIM</td>
<td>5.035</td>
<td>41</td>
<td>BA</td>
<td>3.71</td>
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<tr>
<td>FF</td>
<td>5.023.3</td>
<td>27</td>
<td>BA</td>
<td>0.76</td>
<td>0.15</td>
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<tr>
<td>ZA</td>
<td>5.045.5</td>
<td>53</td>
<td>LA</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>ZMI</td>
<td>5.044.4</td>
<td>52</td>
<td>LA</td>
<td>0.29</td>
<td>0.17</td>
</tr>
<tr>
<td>ZC</td>
<td>5.048.8</td>
<td>57</td>
<td>LA</td>
<td>0.25</td>
<td>0.14</td>
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</table>

Nicotine salt bottled e-liquids

<table>
<thead>
<tr>
<th>Brand</th>
<th>Nicotine wt%* (listed/measured)</th>
<th>Nic $n_{c_a}$ (mg/mL) (measured)</th>
<th>Acid†</th>
<th>Molar acid/nicotine ratio ($C_{acid}/C_{nic}$)</th>
<th>$\alpha_{fb}$‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuji-50</td>
<td>4.24.2</td>
<td>50</td>
<td>U</td>
<td>U</td>
<td>0.08</td>
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<tr>
<td>BRL-50</td>
<td>4.24.1</td>
<td>49</td>
<td>U</td>
<td>U</td>
<td>0.08</td>
</tr>
<tr>
<td>Fuji-25</td>
<td>2.12.0</td>
<td>24</td>
<td>U</td>
<td>U</td>
<td>0.02</td>
</tr>
<tr>
<td>BRL-25</td>
<td>2.12.1</td>
<td>25</td>
<td>U</td>
<td>U</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Non-‘salt’ bottled e-liquids

<table>
<thead>
<tr>
<th>Brand</th>
<th>Nicotine wt%* (listed/measured)</th>
<th>Nic $n_{c_a}$ (mg/mL) (measured)</th>
<th>Acid†</th>
<th>Molar acid/nicotine ratio ($C_{acid}/C_{nic}$)</th>
<th>$\alpha_{fb}$‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er-24</td>
<td>2.01.0</td>
<td>12</td>
<td>–</td>
<td>U</td>
<td>0.98</td>
</tr>
<tr>
<td>RvC-24</td>
<td>2.02.8</td>
<td>33</td>
<td>U</td>
<td>U</td>
<td>0.70</td>
</tr>
<tr>
<td>UB-24</td>
<td>2.00.9</td>
<td>11</td>
<td>U</td>
<td>U</td>
<td>0.84</td>
</tr>
<tr>
<td>Er-6</td>
<td>0.50.5</td>
<td>5</td>
<td>–</td>
<td>U</td>
<td>0.96</td>
</tr>
<tr>
<td>UBP-6</td>
<td>0.50.4</td>
<td>5</td>
<td>U</td>
<td>U</td>
<td>0.53</td>
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<tr>
<td>UB-6</td>
<td>0.50.4</td>
<td>5</td>
<td>U</td>
<td>U</td>
<td>0.43</td>
</tr>
<tr>
<td>RvC-6</td>
<td>0.50.5</td>
<td>6</td>
<td>U</td>
<td>U</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Calculated by integrating 1H NMR resonances for nicotine relative to propylene glycol and glycerol resonances in each e-liquid and obtaining the mole per cent values, which were then converted into wt% values.
†These values do not reflect the variable presence of water, accounting for water affecting nicotine mg/mL by less than ~10%.
‡Different chemical shift references were used based on composition. The value presented is that for the average at 40°C. For details, see the Methods section.
§Only one $\alpha_{fb}$ value was obtained by 1H NMR due to either resonance overlap or peak broadening.
¶Incomplete characterisation of the acid content.

Concentric tube samples containing each e-liquid were prepared for $\alpha_{fb}$ analyses per previous methods, and samples containing a single drop of each e-liquid in 500 µL of DMSO-6, were used for composition analysis, owing to the better shim that can be achieved with a lower sample concentration. A 600 MHz NMR spectrometer was used to execute zg30 4H experiments using parameters reported previously and heteronuclear single quantum coherence spectroscopy (HSQC) experiments, as needed. Thus, each e-liquid sample was placed in a precision coaxial NMR insert and the lock solvent, DMSO-6, was placed in the outer 5 mm NMR tube. 1H NMR experiments were conducted using a TXI (“Triple Resonance”) probe and at 40°C in order to increase the molecular tumbling rate, improving the shim. Sixteen scans were collected using the zg30 pulse sequence; a relaxation delay (D1) of 3 s between each scan was used; the size of the real spectrum (TD) was 65 536 data points; and the spectral width (SW) was 15 ppm, with the transmitter frequency offset (O1P) set to 6 ppm, giving a total experiment time of 2 min per sample.

Spectra for composition determinations were assessed using integration analysis. After phasing and baseline correction, the chemical components (eg, PG, GL, nicotine, and benzoate or levulinate) were analysed using the resonance(s) with the least overlap. The resulting integrations were used to calculate the mole percent of each component, which was then used to calculate the weight percents (wt%). Other details about the calculation of $\alpha_{fb}$ have been reported previously, except with a modification to the $fb$ and monoprotonated nicotine standards used as described above.
RESULTS

Protonation in e-liquids

Table 1 lists the measured (by $^1$H NMR) versus manufacturer-listed nicotine concentrations and the measured $a_n$ values (online supplementary figure S-3 visually depicts the data in a bar chart). The e-liquids tested included those for JUUL pods, other look-a-like/knock-off pods, bottled nicotine salt e-liquids and early-generation (ie, non-salt) bottled e-liquids. The agreement between the listed and actual nicotine contents varied among brands; in this work, the measured values were used; online supplementary figure S-1 illustrates the differences among the e-liquids. Table 1 also gives $C_{HA}/C_{nic}$; the acids were fully identifiable by NMR for the first 14 e-liquids, and the presence of at least one acid was identified for the first 18 e-liquids. $C_{HA}/C_{nic}$ values varied widely among the brands (see also online supplementary figure S-2). Online supplementary figure S-5 is a comparison of the $^1$H NMR spectra for two e-liquids with differing ratios of benzoic acid relative to nicotine; for one, $C_{HA}/C_{nic}=−1$, and for the other, $C_{HA}/C_{nic}=−4$.

Figure 2 is a plot of measured $Nic_{tot}$ versus $a_n$. Lines of constant fb concentration as given by the product $a_n/Nic_{tot}$ plot as hyperbolas (see also the issue cover graphic for Duell et al).1 All the e-liquids with $C_{HA}/C_{nic}=1$ with benzoic acid were found to be characterised by similar $a_n$ values (0.09−0.14). As noted earlier, the inhalation harshness of a nicotine aerosol is related to the fb concentration in the aerosol liquid, as given by $a_n/Nic_{tot}$. Values for $a_n/Nic_{tot}$ can be computed from the data in table 1 (see also online supplementary figure S-4). Bookending these values, e-liquids with $C_{HA}/C_{nic}>>1$ gave $a_n$=0, and some e-liquids that were not marketed as nicotine salts gave $a_n$ values as high as 0.98.

Besides carboxylic acids (eg, benzoic acid and levulinic acid) as protonating agents, the prevalent flavour phenols vanillin and ethyl vanillin can contribute to protonation of nicotine; these two weak acids can be found at high concentrations in some e-liquids.18 Such an effect on $a_n$ may be indicated in the $a_n$ values for the ‘Roundhouse with Cream’ flavour formulations for two different $Nic_{tot}$ values, 33 and 6 mg/mL, with $a_n=0.70$ and 0.08, respectively. Assuming a constant phenol flavourant level, the lower $a_n$ for the lower nicotine-level may have been caused in part by a higher total acids:nicotione ratio.

K$_{Ha_{1}}$ determinations

Based on equation (6), values of K$_{Ha_{1}}$ were determined for benzoic acid at 40°C in 43/57 PG/GL by weight (48/52 by mol). The mixture was amended with benzoic acid and nicotine to give $C_{HA}=3.31\times10^{-4}$ mol/mL and $C_{Nic}=3.28\times10^{-4}$ mol/mL ($C_{HA}/C_{Nic}=1.01$, nicotine at 4.6 wt%). A second mixture was prepared with a PG/GL ratio of 32/68 by weight (36/46 by mol) (similar to that currently represented by JUUL) and amended with benzoic acid to give $C_{HA}=3.38\times10^{-4}$ mol/mL and nicotine at $C_{Nic}=3.30\times10^{-4}$ mol/mL ($C_{HA}/C_{Nic}=1.03$, nicotine 4.6 wt%). To investigate the effects of water on nicotine protonation, an aliquot of the second mixture was amended with water at 5% (by volume). Values of K$_{Ha_{1}}$ were also calculated for benzoic acid at 40°C based on the data for the JUUL products in table 2, with $C_{HA}/C_{Nic}=1$, as verified here by a liquid chromatography (LC) method discussed elsewhere.12

$^1$H NMR results gave slightly different $C_{HA}/C_{Nic}$ ratios (online supplementary table S-1); because NMR spectra can be subject to resonance overlap in these cases, due to the presence of flavourants, the LC-determined $C_{HA}/C_{Nic}$ ratios were used for the calculations herein.

K$_{Ha_{1}}$ values were also determined for vanillin at 40°C in 45/55 PG/GL by weight (49/51 by mol). The mixture was amended with nicotine and three levels of vanillin. The three solutions were characterised by (1) $C_{HA}=1.80\times10^{-4}$ and $C_{Nic}=3.61\times10^{-4}$ mol/mL ($C_{HA}/C_{Nic}=0.50$ (nicotine at 5.1 wt%), (2) $C_{HA}=3.67\times10^{-4}$ and $C_{Nic}=3.59\times10^{-4}$ mol/mL ($C_{HA}/C_{Nic}=1.02$ (nicotine at 5.1 wt%) and (3) $C_{HA}=5.15\times10^{-4}$ and $C_{Nic}=3.41\times10^{-4}$ mol/mL ($C_{HA}/C_{Nic}=1.51$ (nicotine at 4.9 wt%).
for vanillin may indicate some tendency to increase with an increasing $C_{HA}/C_{Nic}$ ratio; an increasingly ionic medium would be expected to favour the $HA+Nic=HA^+ + NicH^+$ reaction, due to Debye–Hückel effects.)

**JUUL aerosol PM determinations**

The average mass lost per puff, for five puffs, was 4.4 mg, which when divided by the puff volume (55 mL) results in an average aerosol PM of ~80 mg/L, or $80 \times 10^6$ µg/m$^3$. This is only slightly greater than the high end of the range for tobacco cigarettes, from 13 to $63 \times 10^6$ µg/m$^3$.

**DISCUSSION**

Past was prologue: Vu – tobacco smoke

The chemistry changes during the rapid evolution of e-cigarettes closely parallel the events that occurred during the centuries-long development of smoked tobacco. The tobacco that the English colony of Jamestown in Virginia exported to England beginning in 1619 was dark, ‘air-cured’ tobacco. Air curing occurs by slow drying (6–8 weeks) in ventilated barns. Air-cured (aka ‘dark’, ‘brun’, ‘black’) tobacco generally produces tobacco smoke that is much more basic than other tobacco types. Leaf sugars, which are precursors of tobacco-smoke organic acids, are generally lost during slow air curing; it is this loss that accounts for the relatively high proportions of free base nicotine in the smoke aerosol droplets from air-cured tobacco (figure 3). Regardless of smoke basicity/acidity, most tobacco smoke nicotine is in the free-base PM, distributed among the free base and protonated nicotine forms.

Nicotine-related harshness of tobacco smoke has long been viewed as being correlated with smoke basicity, with basicity favouring PM nicotine being in the volatile and therefore sensible (harsh) free base form. Consider:

‘...The presence of unprotonated nicotine in the smoke of French cigarettes and the observation that French smokers of black tobacco inhale less frequently than smokers in England and the USA ... support our hypothesis that the pH is a determining factor in the “inhalability” of tobacco smoke.'

‘...increasing the pH ... introduces a smoke with high physiological impact and a harsh bite, which would seem to offset the advantages gained from increased nicotine.'

‘Flue-cured’ (aka ‘bright’) tobacco was developed in the 1850s after the accidental discovery that rapid drying with heat yields a bright yellow leaf that produces a noticeably milder smoke. Indeed, flue-cured tobacco remains high in leaf sugars so that the resulting smoke contains numerous organic acids. While historical measurements of ‘smoke pH’ both inside and outside the industry were indisputably flawed in absolute terms, within

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**Table 2** Values of $K_{fb,1}$ (40°C) for benzoic acid and vanillin in e-liquid formulations.

<table>
<thead>
<tr>
<th>E-liquid</th>
<th>$C_{fb}/C_{Nic}$</th>
<th>$\alpha_{fb}$</th>
<th>$K_{fb,1}$</th>
<th>Log $K_{fb,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUUL ‘Cool Mint’ (5% nicotine)</td>
<td>0.97*</td>
<td>0.13</td>
<td>58</td>
<td>1.77</td>
</tr>
<tr>
<td>JUUL ‘Classic Menthol’ (5% nicotine)</td>
<td>0.98*</td>
<td>0.13</td>
<td>53</td>
<td>1.72</td>
</tr>
<tr>
<td>JUUL ‘Creme Brûlée’ (5% nicotine)</td>
<td>0.97*</td>
<td>0.12</td>
<td>72</td>
<td>1.86</td>
</tr>
<tr>
<td>JUUL ‘Trail Mix’ (5% nicotine)</td>
<td>0.99*</td>
<td>0.12</td>
<td>59</td>
<td>1.82</td>
</tr>
<tr>
<td>JUUL ‘Cool Cucumber’ (5% nicotine)</td>
<td>1.00*</td>
<td>0.11</td>
<td>65</td>
<td>1.82</td>
</tr>
<tr>
<td>JUUL ‘Classic Tobacco’ (5% nicotine)</td>
<td>1.00*</td>
<td>0.11</td>
<td>65</td>
<td>1.82</td>
</tr>
<tr>
<td>JUUL ‘Virginia Tobacco’ (5% nicotine)</td>
<td>1.00*</td>
<td>0.11</td>
<td>65</td>
<td>1.82</td>
</tr>
<tr>
<td>JUUL ‘Mango’ (5% nicotine)</td>
<td>0.99*</td>
<td>0.09</td>
<td>115</td>
<td>2.06</td>
</tr>
<tr>
<td>JUUL ‘Virginia Tobacco’ (7% nicotine)</td>
<td>0.94*</td>
<td>0.14</td>
<td>66</td>
<td>1.82</td>
</tr>
<tr>
<td>JUUL ‘Mint’ (3% nicotine)</td>
<td>1.04*</td>
<td>0.11</td>
<td>48</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Averages for JUUL 0.99±0.03 SD 0.12±0.01 67±18 1.81±0.10

<table>
<thead>
<tr>
<th>E-liquid</th>
<th>$C_{fb}/C_{Nic}$</th>
<th>$\alpha_{fb}$</th>
<th>$K_{fb,1}$</th>
<th>Log $K_{fb,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>435/PG/GL (by wt.)+nicotine+benzoic acid (final nicotine level=4.6% w/w)</td>
<td>1.01</td>
<td>0.16</td>
<td>26</td>
<td>1.41</td>
</tr>
<tr>
<td>32/68 PG/GL (by wt.)+nicotine+benzoic acid (final nicotine level=4.6% w/w)</td>
<td>1.03</td>
<td>0.14</td>
<td>31</td>
<td>1.49</td>
</tr>
<tr>
<td>32/68 PG/GL (by wt.)+nicotine+benzoic acid+5% (by vol.) water (final nicotine level=4.5% w/w)</td>
<td>1.03</td>
<td>0.11</td>
<td>51</td>
<td>1.71</td>
</tr>
</tbody>
</table>

Averages for vanillin Ave.±1 SD 0.0089±0.0025 −2.07±0.13

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*By liquid chromatography for both nicotine and benzoic acid, using a method discussed elsewhere.15

ave, average; $C_{fb}$, total molar-based concentrations of HA; $C_{Nic}$, total molar-based concentrations of nicotine; $\alpha_{fb}$, fraction of nicotine in the free-base form; GL, glycerol; PG, propylene glycol; vol., volume; wt., weight.

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**Figure 3** A visual representation of the historical changes in $\alpha_{fb}$ in tobacco smoke PM (top) in comparison to how electronic cigarette fluids and their associated aerosols have been changed (bottom). $f_c$, flue-cured; $\alpha_{fb}$, fraction of nicotine in the free-base form; M, Marlboro; Nic, nicotine; OA, organic acid; PM, particulate matter.
a given protocol (eg, the ‘pH electrode’ method), relative
comparisons have likely been meaningful, so it is relevant
that ‘smoke pH’ was found by the industry to be strongly
negatively correlated with both leaf sugar levels and leaf sugar/leaf nicotine
ratios. In 1970, Armitage and Turner\(^{29}\) wrote:

‘It is usually believed that the majority of cigarette smokers inhale
to varying degrees the smoke which they take into their mouths,
whereas the majority of cigar smokers do not…. One of the most
striking differences between cigarette and cigar smoke is the pH
of the smoke. The pH of 1929 cigarettes by the method of Grob…
was 5.35, whereas the pH of the C. I. cigar was 8.5.’\(^{29}\)

Overall, as compared with tobacco smoke from air-cured
-tobacco, for flue-cured tobacco, the fraction of the PM nicotine
in the \(fb\) form is much lower. The role of acids in converting
nicotine to a protonated, ‘salt’ form in tobacco smoke has long
been understood. In 1909, Garner\(^{23}\) wrote:

‘Apparent the only possible explanation of this pronounced
effect on the sharpness of the smoke is that in the presence of
the citric acid the nicotine enters the smoke in the form of a salt
rather than in the free state, and thereby loses its pungency
while still exerting the usual physiological effect.’\(^{23}\)

Modern measurement of \(\alpha_{fb}\) values in cigarette smoke PM
began \(-15\) years ago.\(^{30,31}\) In ‘American blend’ cigarettes, flue-
cured tobacco dominates. Thus, in measurements with tobacco
smoke PM from nine commercial brands of cigarettes sold in the
USA, Pankow \(et\ al\)\(^{12}\) reported relatively low \(\alpha_{fb}\) values, ranging
between \(-0.01\) (GPC) and \(-0.10\) (Marlboro). Two other, atyp-
cical commercial brands gave higher \(\alpha_{fb}\) values: Gauloise Brunes (relatively high in air-cured tobacco) at \(\alpha_{fb} = 0.25\) and American
Spirit/Maroon at \(\alpha_{fb} = 0.36.\)\(^{3}\) Overall, together with historical
evidence, it can be concluded that air-cured tobacco was charac-
terised by very high \(\alpha_{fb}\) values (\(\geq 0.4\) and perhaps \(\geq 0.5\)).

Figure 3 summarises the main tobacco product development
stages: (1) Aerosol PM produced from smoked tobacco products
in the early 1600s contained high levels of fb nicotine and so was
harsh on inhalation; the \(\alpha_{fb}\) in the PM was likely greater than
0.5. (2) Flue-curing allowed retention of plant acids in the leaf
during the curing process, bringing \(\alpha_{fb}\) values in smoke PM to
\(-0.01\) (very mild). (Note here that Proctor has aptly commented
that manufacturers of cigars giving high fb smoke might similarly make
their products more inhalable by adding acids, a process
that he has termed ‘de-freebasing’.\(^{27}\)) (3) For Marlboro, by using
additives and/or blend manipulation\(^{11,32}\) to accomplish a Goldi-
locks principle solution (ie, not too harsh, not too mild), \(\alpha_{fb}\) was
brought to \(-0.1\) for a tolerable/desired level of impact/shar-
ghness. Consider, by analogy, human affinity for the sensory ‘bite’
of carbonated beverages.\(^{33}\) Much has been written on the
technical efforts of Philip Morris and its competitors to understand
and provide some nicotine ‘impact’.\(^{31,32}\) Overall, the tobacco
smoke trajectory was \(\alpha_{fb} \geq 0.5 \rightarrow -0.0 \rightarrow -0.1.\)

Present: ‘Déjà Vu’ – e-cigarette aerosols
Stepanov and Fujioka\(^{12}\) were the first to consider the acid/base
chemistry of nicotine in e-liquids. Most early versions of e-ciga-
rettes used PG/GL-based fluids with total nicotine levels of
6–24 mg/mL and \(\alpha_{fb} = 1\) (nicotine+PG/GL is characterised by
\(\alpha_{fb} = 1\)).\(^{14}\) It has been verified that such e-liquids correspond-
ingly generate e-cigarette aerosol PM with \(\alpha_{fb} = 1.\)\(^{16}\) When e-
liquids including some acid and their resulting aerosol PM are
compared, total nicotine levels have been found to be similar,\(^{1,35}\)
as have the \(\alpha_{fb}\) values.\(^{3}\) Following our prior work,\(^{1}\) the product
\(\alpha_{fb} \text{ Nic}_{\text{cig}}\) can be used to compare e-liquid fb delivery values, with

JUUL products having been found to be de-freebased to \(\alpha_{fb} = 0.1.\)

Cigarette smoke PM generally contains nicotine levels that are
much higher than those in early e-liquids. Assuming unit density
for cigarette smoke PM, values of \(-54\) mg/mL for the GPC brand
and \(72\) mg/mL for Marlboro (‘red’) have been reported.\(^{3}\) If e-ciga-
rettes were to attempt cigarette-like nicotine levels along with
\(\alpha_{fb} = 1,\) then with \(\alpha_{fb} = 50–70\) mg/mL, the aerosol would be
expected to be exceedingly harsh on inhalation. Enter JUUL,
which was launched in 2015, offering its nicotine+benzoic acid
pods (5% (w/w) nicotine, \(-59\) mg/mL);\(^{1}\) table 1 (and the results
of Pankow \(et\ al\)\(^{12}\)) indicate a \(-1:1\) molar ratio of benzoic acid
to nicotine. As indicated earlier for the \(K_{\text{oa}} = 38.5\) (table 2), equation (8)
then gives \(\alpha_{fb} = 0.14\) (see therefore figure 3), so that \(\alpha_{fb} = 8.3\)
mg/mL. This is very similar to what has been found for Marlboro
cigarettes \(\alpha_{fb} = 0.10 \times 72\) mg/mL = \(7.2\) mg/mL.\(^{3}\) The trajec-
tory for e-cigarettes has then been a partial de-freebasing
according to \(\alpha_{fb} = -1 \rightarrow -0.1\) (as compared with \(\alpha_{fb} \geq 0.5 \rightarrow -0.0 \rightarrow -0.1\)
for most tobacco smoke). Thus, taken with the PM results
discussed earlier, the JUUL design characteristics provide effective
cigarette-like delivery of nicotine, including (1) high total nicotine
concentration in the liquid (Nicot, mg/mL); (2) low but not zero fb fraction
(\(\alpha_{fb}\)); (3) cigarette-like concentrations of fb nicotine in the

What this paper adds

- The chemistry of nicotine in aerosols from smoked tobacco and
electronic cigarette (e-cigarette) products underlie their parallel product developments and popularities, and therefore their abuse liabilities.

- The development over more than four centuries of smoked tobacco products (de-freebasing then partial re-freebasing) is compared with the development of e-cigarette products during the last 16 years (extensive but incomplete de-freebasing). An explanation is provided of what has been perceived by some as inconsistent that (1) tobacco companies during the mid-20th century were interested in increasing the value of the free-base nicotine fraction (by the partial re-freebasing step) in the products’ smoke aerosol particulate matter, denoted \(\alpha_{fb}\) while (2) some e-cigarette manufacturers have moved to decrease it (by the extensive but incomplete de-freebasing).

- Values of \(\alpha_{fb}\) are measured by \(^{1}H\) nuclear magnetic resonance spectroscopy for a total of 29 products, including JUUL, JUUL look-a-like/knock-off products, as well as bottles of ‘nicotine salt’ and ‘non-salt’ e-liquids.

- The overall trajectory of smoked tobacco development is discussed as having been \(\alpha_{fb} \geq 0.5 \rightarrow -0.02 \rightarrow -0.1\). A ‘Déjà Vu’ trajectory of \(\alpha_{fb} = 1 \rightarrow -0.1\) has been followed in the design of the nicotine-containing liquids used in e-cigarettes, as supported by the measurements of \(\alpha_{fb}\).

- A mathematical framework and equilibrium chemistry model are developed for understanding nicotine protonation chemistry in e-cigarette fluids in terms of \(K_{\text{oa}}\), the first overall nicotine protonation constant.

- De-freebasing has undoubtedly made e-cigarettes more effective as substitutes to get smokers off combustibles. However, as with smoked tobacco, it is likely that e-cigarettes have also been made vastly more addictive for never-smokers. The full public health implications of widely prevalent e-cigarette use will only become fully apparent perhaps a decade hence.
aerosol droplets ($e_{\text{Nic}_a}$, mg/mL); and (4) relatively low, cigarette-like PM; along with (5) optional flavours and no tobacco-smoke odour: a flavoured (at present) e-cigarette analogue of Marlboro.

The trajectory in figure 3 for smoked tobacco allowed cigarettes to become much more addictive, abused, and deadly than would have been the case if smoked tobacco remained of an air-cured type. The evolution of e-cigarettes has followed a similar overall trajectory. It is undoubtedly true that this evolution has made e-cigarettes more effective as substitutes to get smokers off combustibles. However, exactly as occurred with smoked tobacco, this evolution has made e-cigarette products vastly more addictive for never-smokers. The full public health implications of widely prevalent e-cigarette use will only become fully apparent perhaps a decade hence.

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