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Original Investigation

Variability Among Electronic Cigarettes in the Pressure Drop, Airflow Rate, and Aerosol Production

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Abstract

Introduction: This study investigated the performance of electronic cigarettes (e-cigarettes), compared different models within a brand, compared identical copies of the same model within a brand, and examined performance using different protocols.

Methods: Airflow rate required to generate aerosol, pressure drop across e-cigarettes, and aerosol density were examined using three different protocols.

Results: First 10 puff protocol: The airflow rate required to produce aerosol and aerosol density varied among brands, while pressure drop varied among brands and between the same model within a brand. Total air hole area correlated with pressure drop for some brands. Smoke-out protocol: E-cigarettes within a brand generally performed similarly when puffed to exhaustion; however, there was considerable variation between brands in pressure drop, airflow rate required to produce aerosol, and the total number of puffs produced. With this protocol, aerosol density varied significantly between puffs and gradually declined. Consecutive trial protocol: Two copies of one model were subjected to 11 puffs in three consecutive trials with breaks between trials. One copy performed similarly in each trial, while the second copy of the same model produced little aerosol during the third trial. The different performance properties of the two units were attributed to the atomizers.

Conclusion: There was significant variability between and within brands in the airflow rate required to produce aerosol, pressure drop, length of time cartridges lasted, and production of aerosol. Variation in performance properties within brands suggests a need for better quality control during e-cigarette manufacture.

Introduction

Electronic cigarettes (e-cigarettes) or electronic nicotine delivery systems deliver nicotine to users without burning tobacco. The anatomy of various models of e-cigarettes has been described previously (Trtchounian & Talbot, 2010). Puffing on an e-cigarette activates a heating device that aerosolizes cartridge fluid which is in turn delivered to the user (Flouris & Oikonomou, 2010; Pauly, Li, & Barry, 2007; Wollscheid & Kremzner, 2009). E-cigarette products vary in their cartridge contents and may have different humectants (e.g., propylene glycol, glycerin), flavorings, and various concentrations of nicotine. E-cigarettes are sold worldwide and are readily available over the Internet and in shopping malls in the United States. They are sometimes advertised to be safer than tobacco-containing products since they do not produce the many chemicals found in mainstream and sidestream cigarette smoke (Cahn & Siegel, 2010; Laugesen, 2008). E-cigarettes, unlike nicotine replacement therapies such as patches and gum, are not regulated by the Food and Drug Administration (FDA) as medical devices, and little is known about their safety, quality control, aerosol delivery, and long-term health effects.

The FDA questioned e-cigarette quality control and safety after finding: (a) low levels of carcinogens in cartridges, (b) concentrations of nicotine in cartridges were not always consistent with labeling, and (c) diethylene glycol (a toxicant) in one cartridge (Westenberger, 2009). In contrast, a study supported by an e-cigarette manufacturer concluded these products are safe since carcinogen levels are low and the aerosol contains fewer chemicals than tobacco-containing cigarette smoke (Laugesen, 2008). Poor labeling and packaging of e-cigarettes, leakiness of the cartridges, confusing nomenclature for nicotine concentrations, defective parts and safety features, errors in filling orders, insufficient warnings on packaging, incomplete instruction manuals, and misleading advertisements have also raised concern about their safety and usage (Trtchounian & Talbot, 2010).

Three human studies found low levels of nicotine in the blood of e-cigarette users raising questions about their effectiveness as nicotine delivery devices (Bullen et al., 2010; Eissenberg, 2010; Vansickel, Cobb, Weaver, & Eissenberg, 2010). This could be related to the relatively low delivery of nicotine per puff (Laugesen, 2008) or nonuniform production of aerosol (Trtchounian, Williams, & Talbot, 2010). These observations notwithstanding, there are numerous testimonials on the Internet endorsing e-cigarettes, and a recent survey suggests that e-cigarettes can help users of tobacco-containing cigarettes quit smoking (Etter, 2010).

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We previously found that performance properties of e-cigarettes are quite variable (Trtchounian et al., 2010). When compared with tobacco-containing cigarettes, some e-cigarette brands required significantly stronger airflow to produce aerosol and most had significantly higher pressure drop. All brands examined previously produced aerosol which varied in density from puff to puff, suggesting nicotine delivery is not uniform.

The current study, which follows-up on our prior work, investigated additional brands of e-cigarettes, compared different models within a brand, compared identical copies of the same model, and examined e-cigarette performance using three different protocols. We have found significant variability in the performance of e-cigarettes from brand to brand and between models within a brand.

Materials and Methods

E-cigarettes

E-cigarette starter kits with refill cartridges were purchased through the Internet or from a local retailer. The following e-cigarettes were used: (a) Liberty Stix with tobacco flavored cartridges (labeled 16 mg of nicotine; classic three-piece model; Liberty Stix, LLC, Cleveland, OH), (b) Crown Seven Hydro Imperial with USA blend flavor (labeled 16 mg of nicotine; two-piece cartomizer model; Crown Seven Shop, Scottsdale, AZ), (c) Smoking Everywhere Platinum with tobacco flavor (labeled16 mg of nicotine; two-piece cartomizer model; Smoking Everywhere, Sunrise, FL), and (d) VapCigs with menthol flavor (high strength; classic three-piece model; local retailer, Norco, CA). Liberty Stix were used in our prior study (Trtchounian et al., 2010) and were chosen, so direct comparisons could be made between two different copies of the same model within a brand. Crown Seven Hydro Imperial and Smoking Everywhere Platinum were chosen to study atomized cartridges (cartomizers), in which the atomizer and cartridge are combined. VapCigs and their brand-specific cartridges were studied, in contrast to our prior study in which we were sold generic cartridges for use with VapCigs. E-cigarettes and cartridges were stored at room temperature.

One Liberty Stix and one VapCigs e-cigarette from our prior study (Trtchounian et al., 2010) were included in the current study. The original purchases are designated Liberty Stix #1 and VapCigs #1, while the purchases used only in this study are designated Liberty Stix #2 and VapCigs #2.

Set Up of Machine for Puffing E-cigarettes

The performance of e-cigarettes was evaluated as described previously (Trtchounian et al., 2010). A puffer box (University of Kentucky, Lexington, KY) was connected to a U-shaped water manometer and MasterFlex peristaltic pump (Barnart Company, Barrington, IL, Model #7520-00) via Cole Parmer MasterFlex Tygon tubing. The puffer box drew 2.2-second puffs at 1-min intervals. The water manometer measured pressure drop (mm H_2O) across the cigarette during each puff. Airflow was controlled manually by adjusting revolutions per minute (rpm) on the peristaltic pump. Airflow rate was determined by measuring rpm with a Sorvall tachometer and multiplying this value by a conversion factor supplied by the pump manufacturer. Before use, tubing connections were sealed with Parafilm and the peristaltic pump was warmed up for 15 min at a speed of 530 rpms.

General Protocol for Testing E-cigarettes

Fresh cartridges and fully charged batteries were used in all experiments. The lowest airflow rate that allowed aerosol to be produced was determined for each brand and used to begin each experiment. Pump speed was 0 rpm (no airflow) until a puff was taken at which time it was increased to the lowest speed that produced sufficient airflow to generate aerosol. To simulate the behavior of an active user, speed was reduced to 0 rpm between puffs. Pump speed remained constant unless aerosol density dropped below 0.05 absorbance units in which case pump speed was increased by one interval on the pump dial to enable aerosol production. During each puff, pressure drop across the e-cigarette was recorded. Aerosol density was measured at 420 nm in a Bausch & Lomb spectrophotometer (Rochester, NY).

First 10 Puff Experiment

The performance of Liberty Stix #2, VapCigs #2, Crown Seven Hydro Imperial, and Smoking Everywhere Platinum was compared during the first 10 puffs using the above protocol. Each e-cigarette was puffed 10 times at the lowest airflow rate that produced aerosol. Pressure drop and airflow were recorded for each puff. Aerosol density was recorded for every other puff. Experiments were performed three times using each brand.

Air Hole Area

To measure air hole area at the tip of the battery and between the battery and atomizer, each e-cigarette was fully assembled, and images of air holes were taken using a Nikon SMZ 800 Stereoscope (Nikon, Japan) equipped with a Digital Sight DS Fi1 camera (Nikon, Japan). NIS Elements AR software (Nikon, Japan) was used to compute the area of each air hole.

Smoke-Out Experiments

To determine how airflow rate, pressure drop, and aerosol density changed during prolonged use, e-cigarettes (VapCigs #2, Smoking Everywhere Platinum, and Crown Seven Hydro Imperial) were puffed continually until cartridges were exhausted. Cartridges were considered exhausted when pump speed reached its maximum and/or three consecutive puffs had densities below 0.05 absorbance units. Pressure drop and airflow rate was recorded for every puff, and aerosol density was recorded every tenth puff. Airflow rate was increased by increasing pump speed by one interval on the pump dial whenever aerosol density dropped below 0.05 absorbance units or until pump speed reached its maximum (850 rpms). Three experiments were performed with each brand of e-cigarette.

Eleven-Puff Repetitive Trials

Liberty Stix #1 and #2 were used to determine if performance varies within the same model from one brand. For each e-cigarette, 3 consecutive 11-puff trials were performed. The first and second trials were separated by 30 min, while the second and third trials were separated by 11 days. For each trial, two experiments with different fresh cartridges were performed. Pressure drop and aerosol density were recorded at constant airflow during the first 10 puffs. To determine if e-cigarettes produce aerosol at a lower airflow rate after warming up, pump speed was reduced

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one interval on the peristaltic pump dial during 11th puff, and then pressure drop and aerosol density were recorded.

Three consecutive trials were performed with Liberty Stix #1 (battery #1, atomizer #1) and Liberty Stix #2 (battery #2, atomizer #2) using the above protocol. For the third and fourth experiment, the batteries and atomizers from the two Liberty Stix e-cigarettes were interchanged, and the hybrid e-cigarettes were tested (Liberty Stix battery #1 atomizer #2, Liberty Stix battery #2 atomizer #1).

Results

First 10 Puffs

The purpose of this experiment was to quantify airflow rate, pressure drop, and aerosol density during the first 10 puffs across various brands (Figure 1). Ten puffs were used to mimic the number of puffs a smoker of tobacco-containing cigarettes would take during a single usage. E-cigarettes produce aerosol when airflow rate is sufficient to activate the atomizer, which

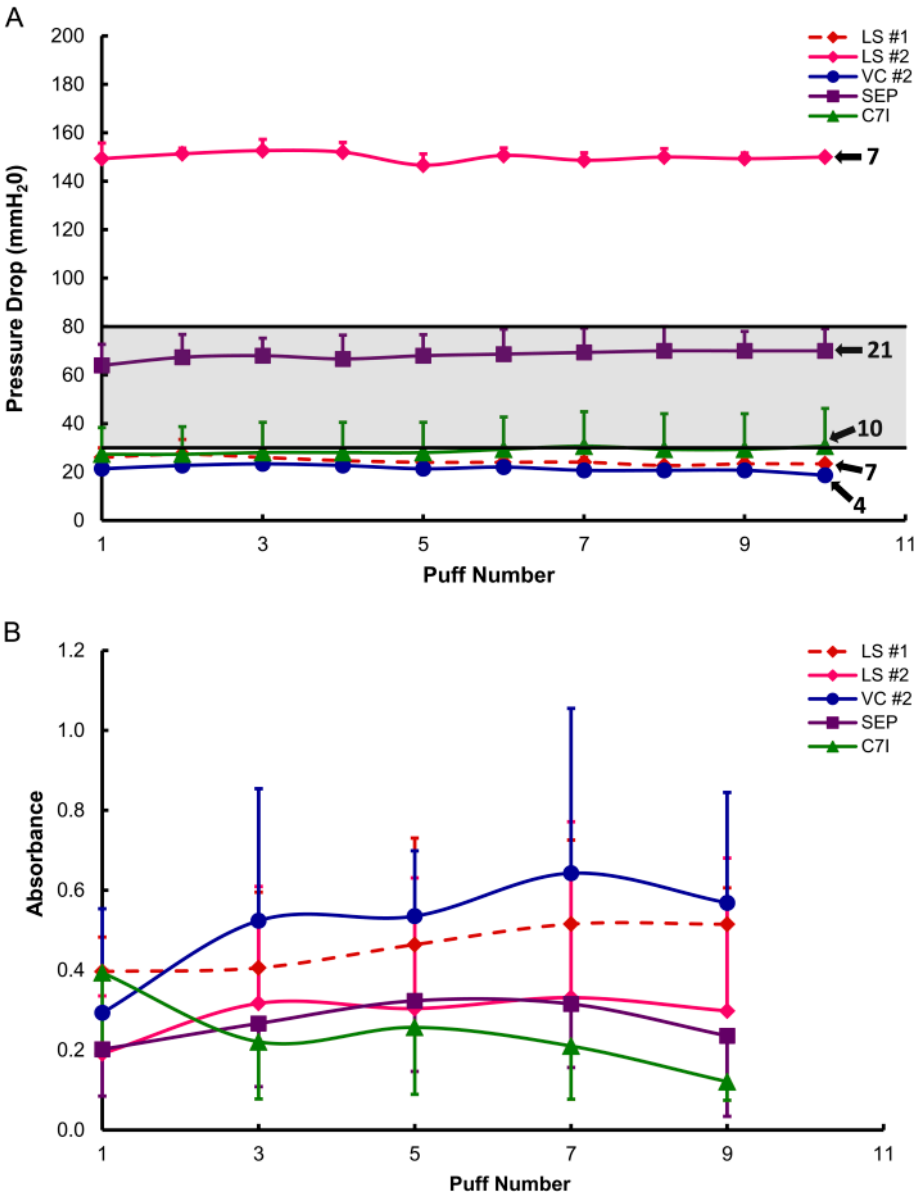


Figure 1. For the first 10 puff protocol, pressure drop, flow rate, and aerosol density remained relatively constant for a given e-cigarette but varied among brands. The shaded area shows the pressure drop range found previously for tobacco-containing cigarettes (Trtchounian et al., 2010). Average pressure drop (mm of H_2O) across e-cigarettes (A) was measured with a manometer during the first 10 puffs. The airflow rate needed to produce aerosol is indicated in ml/s by an arrow for each brand. Aerosol density (B) during the first 9 puffs varied between brands and between the same model of Liberty Stix (#1 and #2) but remained relatively constant over 9 puffs for a given brand. Liberty Stix #1 was used in a prior study (Trtchounian et al., 2010) and is included here for comparison. Each point is the mean ± *SD* of three experiments.

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heats the cartridge fluid. Airflow rate is related to peristaltic pump speed with faster speeds representing faster airflow rates. The pump speed needed to produce aerosol varied between brands (range = 150–760 rpm) (Figure 1A, Supplementary Table 1). Little airflow (4 ml/s) was required to produce aerosol with VapCigs #2, while high airflow (21 ml/s) was needed to activate Smoking Everywhere Platinum.

The shaded area in Figure 1A shows the pressure drop range for various tobacco-containing cigarettes (Trtchounian et al., 2010). For e-cigarettes, pressure drop during puffing was uniform within a brand for the first 10 puffs, but varied among brands (Figure 1A), indicating e-cigarette brands differ in their "leakiness." The pressure drop for three brands (Crown Seven Hydro Imperial, Liberty Stix #1, and VapCigs #2) was at or slightly below the range for tobacco-containing cigarettes, while one brand (Smoking Everywhere Platinum) was within the range and one brand (Liberty Stix #2) was well above this range. Unexpectedly, the two Liberty Stix e-cigarettes (#1 and #2), which appeared identical and were the same model, had very different pressure drops. Liberty Stix #1 was examined in a prior study and had the lowest pressure drop (20 mm H_20) of any e-cigarettes used in that study (Trtchounian et al., 2010). In contrast, Liberty Stix #2 had the highest pressure drop of any e-cigarette in the current study (150 mm H_20).

Aerosol density, a measure of how effectively an e-cigarette vaporizes cartridge fluid, was measured during the first nine puffs for each brand (Figure 1B). Density varied across brands and fluctuated slightly between puffs from the same model within brands. VapCigs #2 and Liberty Stix #1 and #2 showed a slight increase in aerosol density over the first 9 puffs, while density for Smoking Everywhere Platinum remained about the same and density for Crown Seven Hydro Imperial decreased.

Air Hole Area

To determine if differences in pressure drop observed in Figure 1A were due to differences in air hole area, the size and number of the air holes/e-cigarette were quantified for each brand (Supplementary Table 1). Air holes, which were trapezoidal or rectangular, were present at the tip of most e-cigarettes and between the battery and atomizer of all e-cigarettes tested. Most brands had two air holes at the tip of their batteries and 1, 2, or 4 air holes between the battery and atomizer. The single air hole between the battery and atomizer in VapCigs #1 extended around the circumference of the e-cigarette. Total air hole area ranged from 1.8 mm^2 (Crown 7 Hydro Imperial) to 4.72 mm^2 (VapCigs #2). There was a good correlation between air hole area and pressure drop for four of eight brands (VapCigs #1 and #2, Smoking Everywhere Platinum, and Smoking Everywhere Gold).

Smoke-Out Experiments

VapCigs #2, Crown Seven Hydro Imperial, and Smoking Everywhere Platinum were puffed until cartridges were exhausted (Figure 2). When aerosol density dropped below 0.05 absorbance units, pump speed was increased to continue aerosol production. Each VapCigs cartridge lasted for a similar number of puffs (Figure 2A,B). However, aerosol density varied among cartridges and between consecutive puffs within cartridges (Figure 2B). Pressure drop varied slightly in trials #1 and #3 between puffs 75 and 235. Aerosol density oscillated during the experimental interval, and flow rate had to be increased to produce aerosol after 200 puffs. The step increases in pressure drop at the end of each trial show when airflow (pump speed) was increased. Puffing was stopped when pump speed reached its maximum or when three consecutive puffs did not produce aerosol density above 0.05 absorbance units. VapCigs #2 cartridges lasted an average of 245 ± 18 puffs. To determine if battery charge affected aerosol production, batteries were changed in three experiments when aerosol density dropped below 0.05 absorbance units (Supplementary Figure 1). In two of three trials, fresh batteries did not improve aerosol production, while in the third trial, aerosol production improved briefly when a fresh battery was used.

Each Smoking Everywhere Platinum cartomizer performed similarly with respect to pressure drop but lasted for different lengths of time (Figure 2C). Step increases in pressure drop were not observed at the end of each trial as a high pump speed was required to produce aerosol with this brand and puffing was stopped when pump speed reached its maximum. Aerosol density generally decreased with increasing puff number and was variable between cartomizers and between consecutive puffs from the same cartomizer. The average length of time that Smoking Everywhere Platinum could be used was 160 ± 66 puffs.

Pressure drop for the three Crown Seven Hydro Imperial cartomizers varied initially but during smoke-out became similar (Figure 2E). Each cartomizer required airflow rate increases at different times. Most airflow increases occurred after 250 puffs. This brand's cartomizer lasted significantly longer than any other brand we have tested. Aerosol density was variable between and within cartomizers and declined with time (Figure 2F). For the last 100 puffs, aerosol density was low for all three cartomizers. Crown Seven Hydro Imperial e-cigarettes lasted on average 400 ± 10 puffs.

Eleven-Puff Repetitive Trials

To determine how pressure drop and aerosol density behaved during repetitive usage, e-cigarettes were used for 11 puffs followed by a 30-min break, then used for another 11 puffs followed by an 11-day break, and then used for a final 11 puffs (Figure 3). Experiments were done with two different Liberty Stix e-cigarettes (#1 and #2) which were the same model but purchased at different times. For Liberty Stix #1, pressure drop was low in all three consecutive trials (Figure 3A–C). While aerosol density fluctuated during the first nine puffs, density remained similar in each consecutive trial (Figure 3D–F). Liberty Stix #1, therefore, performed quite uniformly from trial to trial. In contrast, pressure drop was high for Liberty Stix #2 during the first two trials but dropped significantly during trial three (Figure 3G–I). The decrease in pressure drop was accompanied by a corresponding decrease in aerosol density (Figure 3J–L), indicating that Liberty Stix #2 was not functioning well by the third trial. These data show that different copies of the same model of e-cigarette performed quite differently in both individual and consecutive trials. When airflow rate (pump speed) was reduced during puff 11, aerosol was not produced by either Liberty Stix #1 or #2, indicating that warming up the e-cigarettes did not enable aerosol production at lower airflow rates.

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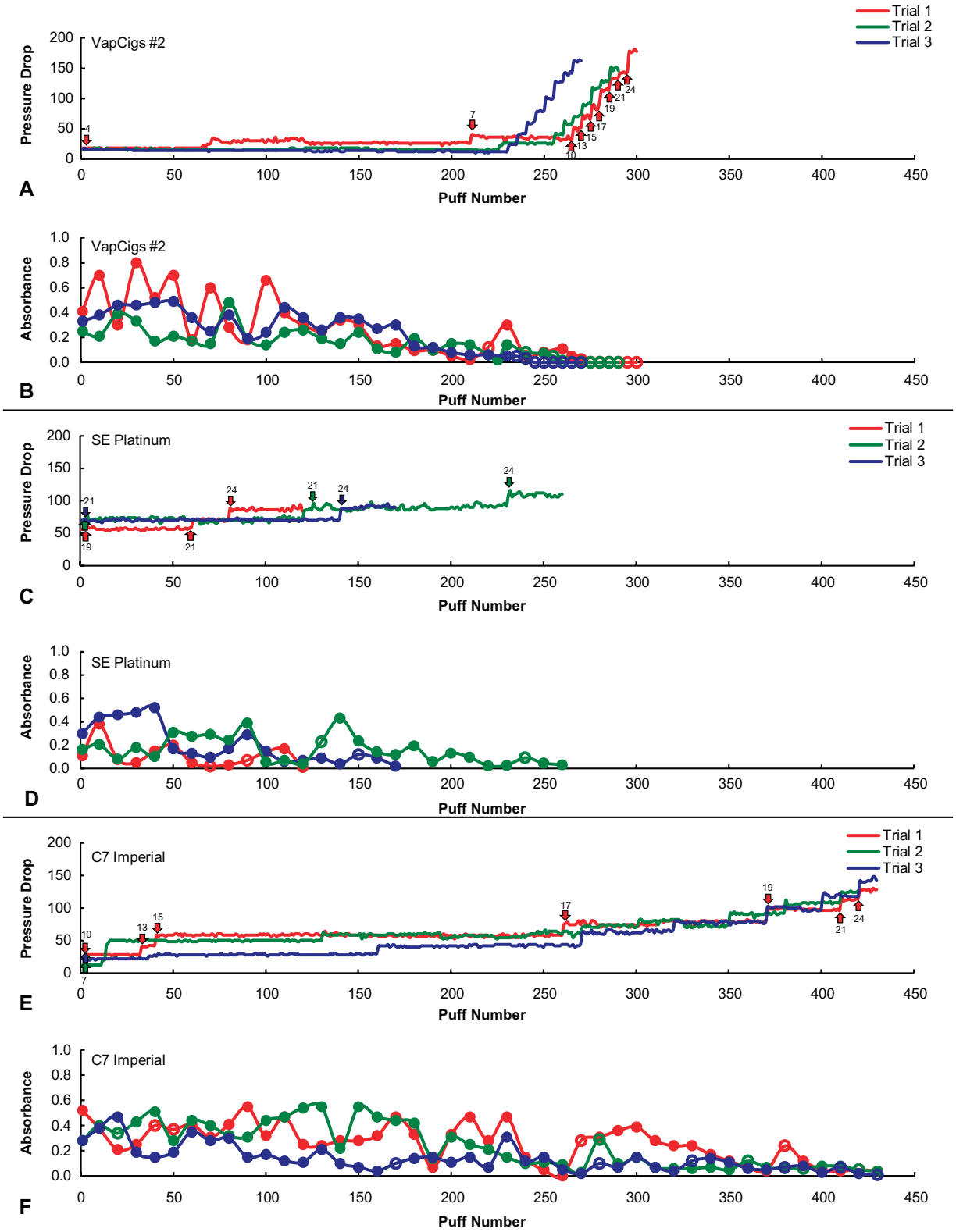


Figure 2. Results from the smoke-out protocol showing that over time pressure drop and airflow rate increased and aerosol density decreased. (A, C, E) Pressure drop is plotted versus puff number for three brands of e-cigarettes. Three different cartridges are shown for each brand. Arrows in A, C, and E indicate increases in airflow rate (ml/s) that were needed to continue aerosol production. (B, D, F) Aerosol density (absorbance) is plotted versus puff number. Aerosol density was variable within and between brands and decreased with increasing puff number. Open circles indicate puffs where airflow (pump speed) was increased to maintain aerosol production.

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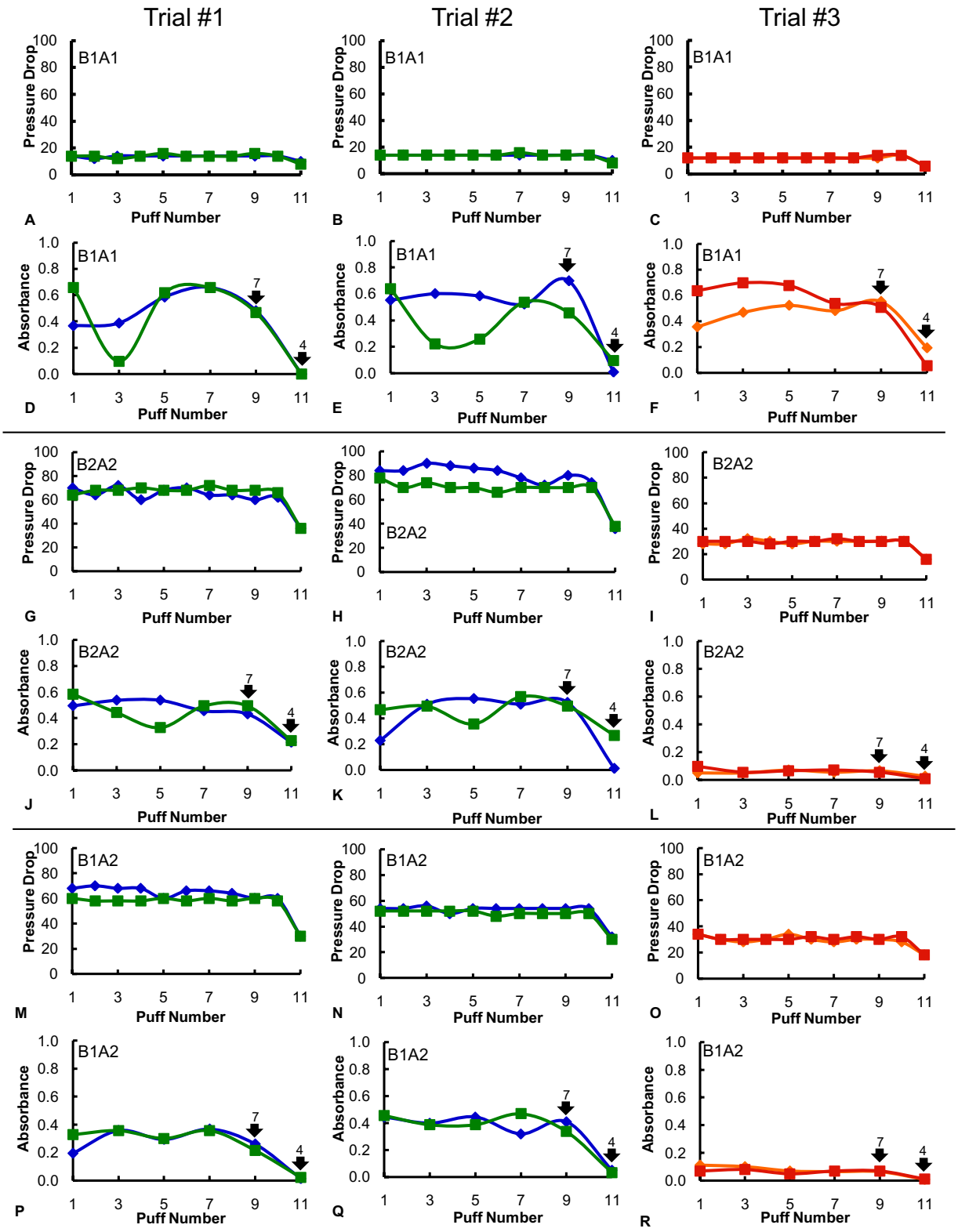


Figure 3. Results from the 11-puff repetitive trial showing that Liberty Stix #1 and #2 did not perform similarly. (A–F) show data collected with Liberty Stix #1. (G–L) show data collected with Liberty Stix #2. (M–R) show data collected with a Liberty Stix hybrid consisting of battery #1 and atomizer #2. A 30-min pause was taken between trial 1 (column one) and trial 2 (column two) and an 11-day break was taken between trial 2 (column two) and trial 3 (column 3). For each set of two rows, the top row shows pressure drop and the lower row shows aerosol density. Each figure shows data from two experiments (in figures A–C, I, L, O, and R the data points on the graph overlap). All puffing was done using the lowest flow rate that would produce aerosol, except for puff #11 which was done at lower flow rate to determine if aerosol production would continue with less airflow after warming up the e-cigarette. The airflow rates (ml/s) for puffs 9 and 11 are indicted by arrows. (B = battery #1 or #2; A = atomizer #1 or #2).

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To determine if differences in performance of the two Liberty Stix e-cigarettes could be attributed to the atomizer or the battery, these components were interchanged, and experiments were repeated. When battery #2 was assembled with atomizer #1, the resulting e-cigarette did not produce aerosol, even at the maximum airflow rate (data not shown). When battery #1 and atomizer #2 were assembled, the e-cigarette performed in a manner similar to Liberty Stix #2 (Figure 3M–R). For the battery #1/atomizer #2 hybrid, pressure drop was high in the first two trials, but dropped significantly by trial #3, as was seen previously with Liberty Stix #2. The decreased pressure drop with the hybrid e-cigarette was accompanied by a decrease in aerosol density with virtually no aerosol produced during trial #3 (Figure 3R). These data show that the poor performance of Liberty Stix #2 could be attributed to the atomizer, not the battery.

Discussion

Significant variation was found among e-cigarette brands in the airflow rate required to produce aerosol, in pressure drop across e-cigarettes (manometer readings), in aerosol density, and in the manner in which e-cigarettes performed over time. Unexpectedly, two copies of the same model within a brand (Liberty Stix) performed differently. Performance characteristics of the two cartomizer e-cigarettes (Crown 7 Imperial and Smoking Everywhere Platinum) were within the range of e-cigarettes having the classical style cartridge; however, Crown 7 Imperial had the distinction of producing the most puffs/cartridge of all brands we tested. Consumers and researchers should be aware that e-cigarettes are not "one product" and that there is considerable variability among and within brands. Variation within brands (e.g., Liberty Stix) could indicate inadequate quality control in manufacture.

In our previous study, three of four e-cigarette brands required higher airflow rates to produce aerosol than eight brands of tobacco-containing cigarettes, which all produced smoke at a flow rate of 7 ml/s (Trtchounian et al., 2010). In the current study, VapCigs #2 required a lower airflow rate (4 ml/s), Liberty Stix #2 required the same rate (7 ml/s), and Crown Seven Hydro Imperial and Smoking Everywhere Platinum required higher rates (10 and 21 ml/s, respectively) to produce aerosol than tobacco-containing cigarettes. These studies together show that the airflow rate required to produce aerosol varied significantly among e-cigarette brands and was usually (four out of seven brands) higher than the airflow rate required to produce smoke from tobacco-containing cigarettes. These data support the conclusion that to effectively activate e-cigarettes, some users will need to inhale more strongly than those using tobacco-containing cigarettes. It will be important in future studies to directly compare puff volumes and inhalation strength for users of tobacco-containing cigarettes and e-cigarettes and to monitor the long-term health effects of harder inhalation.

The variations in airflow rate needed to activate aerosol production with e-cigarettes indicate that it is not practical to perform laboratory tests on e-cigarettes using the standard protocol for tobacco-containing cigarettes. E-cigarette laboratory testing will require its own standard procedure, which is yet to be developed. This finding should be considered in future research on e-cigarettes and may influence policy-making decisions regarding e-cigarettes. Additional topics that need to be addressed in future research have recently been reviewed (Etter, Bullen, Flouris, Laugesen, & Eissenberg, 2011).

Aerosol density oscillated slightly but was relatively stable for the first 9–10 puffs. Both Liberty Stix #1 and VapCigs #2 produced higher aerosol densities than the other three brands throughout the first nine puffs, suggesting they were more efficient at delivering nicotine than other brands. These two brands were also activated by the lowest flow rates.

In our earlier and current study, pressure drop, which measured the "leakiness" of e-cigarettes to air, varied among brands. Two e-cigarette brands were below, two were within, and four were above the pressure drop range of tobacco-containing brands. Unexpectedly, the two Liberty Stix units produced very different pressure drops, with Liberty #1 below and Liberty #2 above the range for tobacco-containing brands. This result suggests that either design differences existed and were not overtly apparent or differences were introduced during the manufacturing of the Liberty Stix e-cigarettes. In either case, consumers and researchers should be aware that variability can exist within a specific model of e-cigarettes.

We hypothesized that the leakiest e-cigarettes (lowest pressure drops) would have the largest air hole areas. In four cases, pressure drop correlated well with total air hole area. For example, VapCigs# 1 and #2 had large air hole areas and low pressure drops, while Smoking Everywhere Gold had smaller air hole areas and high pressure drop. However, not all brands of e-cigarettes fit the above hypothesis, suggesting other factors, perhaps related to internal design, influence pressure drop across e-cigarettes.

In the smoke-out protocol, Crown Seven Hydro Imperial lasted longest of any e-cigarette we have tested (about 400 puffs). VapCigs #2 lasted for about 250 puffs with little variation among the three cartridges. Smoking Everywhere Platinum lasted for a variable number of puffs ranging from 125 to 270 puffs. For Smoking Everywhere Platinum, cartridges in trials 1 and 3 were from the same pack, while the cartridge in trial 2 (which lasted longer) came from a different pack, suggesting that the amount of fluid/cartridge varied between packs.

Within a brand, step increases in airflow rate needed to maintain aerosol production were similar. In all three brands, aerosol density/puff oscillated, as observed previously in other brands (Trtchounian et al., 2010), and density gradually declined with usage until the cartridge was exhausted. While density trends within a brand were similar, some cartridges within a brand produced less dense aerosol overall (e.g., trial 1 for Smoking Everywhere Platinum and trial 3 for Crown Seven Hydro Imperial).

The third party VapCigs #1 cartridges in our prior study were sold by a vendor who claimed they were suitable for use with VapCigs e-cigarettes; however, their performance in the smoke-out experiment was poor (Trtchounian et al., 2010), even when the aluminum seal was manually removed from the cartridge prior to use. In the current study, the new VapCigs kit came with brand-specific cartridges which performed significantly better. These data demonstrate that cartridges are not necessarily interchangeable among brands and that vendors are not yet fully familiar with suitable replacements for specific brands.

In the final protocol, two different units of Liberty Stix were compared in consecutive trials separated by 30 min or 11 days to determine how performance is affected by breaks between use. For Liberty Stix #1, pressure drop and aerosol density were

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similar in the three consecutive trials, while Liberty Stix #2 performed similarly in the first two trials, but not produce aerosol in the third trial. A hybrid of battery #1 and atomizer #2 performed in a manner similar to Liberty Stix #2, indicating that the atomizer, not the battery, was influencing the pressure drop readings for Liberty Stix #2. The hybrid with atomizer #2 also produced very little aerosol during the third trial, as was observed with Liberty Stix #2. Thus, two Liberty Stix e-cigarettes of the same model behaved differently when a break separated 11-puff trials. These data show that not all copies of the same model within a brand behave similarly and that one copy failed to perform properly during the third consecutive trial, suggesting that manufacturing of some e-cigarettes is not be uniform.

In conclusion, the current data when combined with our prior study demonstrate variation in performance across different brands of e-cigarettes and within the same model of a specific brand. In general, e-cigarettes required higher airflow rates to produce aerosol than tobacco-containing cigarettes. Pressure drop was also highly variable among e-cigarette brands and often correlated with total air hole area. E-cigarettes lasted for a variable number of puffs, and some variation was found in models within a brand when different cartridges were used. Unexpectedly, one unit stopped producing aerosol when used for the third time in consecutive trials, and parts from the same model were not necessarily interchangeable. Consumers and researchers should be aware that e-cigarettes vary in performance across brands and within models from the same brand, that some brands will require harder inhalation to use than tobacco-containing cigarettes, and that aerosol density varies between puffs which may affect nicotine delivery. Researchers should further be aware that standard protocols used with tobacco-containing cigarettes will not necessarily work with e-cigarettes.

Supplementary Material

Supplementary Table 1 and Figure 1 can be found online at http://www.ntr.oxfordjournals.org

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Declaration of Interests

None declared.

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