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ORIGINAL INVESTIGATION

Disposable Electronic Cigarettes and Electronic Hookahs: Evaluation of Performance

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ABSTRACT

Introduction: The purpose of this study was to characterize the performance of disposable button-activated and disposable airflow-activated electronic cigarettes (EC) and electronic hookahs (EH).

Methods: The airflow rate required to produce aerosol, pressure drop, and the aerosol absorbance at 420 nm were measured during smoke-outs of 9 disposable products. Three units of each product were tested in these experiments.

Results: The airflow rates required to produce aerosol and the aerosol absorbances were lower for button-activated models (3 mL/s; 0.41–0.55 absorbance) than for airflow-activated models (7–17 mL/s; 0.48–0.84 absorbance). Pressure drop was also lower across button-activated products (range = 6–12 mm H₂O) than airflow-activated products (range = 15–67 mm H₂O). For 25 of 27 units tested, airflow did not have to be increased during smoke-out to maintain aerosol production, unlike earlier generation models. Two brands had uniform performance characteristics for all parameters, while 3 had at least 1 product that did not function normally. While button-activated models lasted 200 puffs or less and EH airflow-activated models often lasted 400 puffs, none of the models produced as many puffs as advertised. Puff number was limited by battery life, which was shorter in button-activated models.

Conclusion: The performance of disposable products was differentiated mainly by the way the aerosol was produced (button vs. airflow-activated) rather than by product type (EC vs. EH). Users need to take harder drags on airflow-activated models. Performance varied within models and battery life limited the number of puffs. Data suggest quality control in manufacturing varies among brands.

INTRODUCTION

Electronic cigarettes (EC) are nicotine delivery devices that may be safer than conventional cigarettes since they do not burn tobacco and therefore produce fewer chemicals (Goniewicz, Knysak, et al., 2013). Disposable EC, which are nonrefillable and discarded after use, are a relatively new entry into the EC market. Models and brands of disposable EC vary with respect to flavors, nicotine concentration, puff count, and price. The most popular flavors are tobacco and menthol, with nicotine concentrations usually ranging from 0 to 24 mg/mL, and puff counts advertised to be 400 or more per EC. Disposable EC come in two styles, button-activated, which require pressing a button to activate the battery during puffing, and airflow-activated, which have an airflow sensor that activates the battery during puffing. Disposable EC are widely available for purchase in convenience stores, retail outlets, such as Target and Walmart, smoke shops, and over the Internet, and are therefore poised to become a major contributor to EC sales. The FDA has not issued any regulation on performance, manufacturing,

or quality control for these devices since they are not treated as medical devices.

Disposable electronic hookahs (EH) are another new type of nicotine delivery device that share many physical characteristics with disposable EC. However, EH differ from disposable EC in several ways. EH are marketed toward conventional hookah users seeking a healthier alternative or a convenient portable device. The range of nicotine concentrations in disposable EH (0–12 mg/mL) is lower than in EC (0–24 mg/mL), and the flavor selections for EH are more representative of those found in hookah bars. EH are commonly sold in smoke shops and on the Internet, and like EC, are not regulated by the FDA.

Many EC studies are surveys of users (reviewed by McCarthy, 2013) or inquiries into health effects (Bahl et al., 2012; Behar et al., 2014; Hua, Alfi, & Talbot, 2013; McCauley, Markin, & Hosmer, 2012; Pepper & Brewer, 2013; Williams, Villarreal, et al., 2013; Vardavas et al., 2012). The performance properties of nondisposable cartridge and cartomizer style EC are highly variable both between and within products (Goniewicz, Kuma, Gawron, Knysak, & Kosmider, 2013;

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Trtchounian & Talbot, 2010; Trtchounian, Williams, & Talbot, 2010). Disposable EC and EH products are relatively new, and there is no information available on their performance characteristics. The purpose of this study was to evaluate and compare the performance of disposable button-activated and airflow-activated EC and EH. Specific parameters that were evaluated included the airflow rate required to activate aerosol production in disposable products, pressure drop during puffing, puff count, and aerosol absorbance.

MATERIALS AND METHODS

Disposable EC and EH

Disposable EC were purchased from local retailers, drug stores (Walgreens), and on the Internet. The following EC were evaluated: BluCig (Lorillard Inc.), NJOY King (NJOY), Square 82 (PHD Marketing, Inc.), and V2 Cig (VMR Products LLC.). Disposable EH were purchased from local smoke shops and from Internet vendors. The following brands of EH were used: Starbuzz (PHD Marketing, Inc.), this device is actually labeled as an EC, but Starbuzz is a hookah-specific brand, Imperial Hookah (Imperial Smoke), Luxury Lites (Luxury Lites), Smooth (Smooth Cigs), and Tsunami (Tsunami Electronic Cigarette). All products were stored at room temperature. At least five copies of each EC and EH model were purchased to ensure that direct comparisons could be made between identical models within a brand. All brands were purchased as single units except for V2 Cigs, which were purchased in packages of 3 or 10.

Evaluation of EC and EH Performance Using a Smoking Machine

All disposable EC and EH were evaluated using a smoking machine consisting of a University of Kentucky puffer box (Knoll & Talbot, 1998), which took a 4.3-s puff every minute, a peristaltic pump, which provided airflow to activate the device, and a water manometer for measuring pressure drop across the device during each puff. Components were connected with Tygon tubing using the set up method described and illustrated previously (Trtchounian et al., 2010). A 4.3-s puff was used as this was previously shown to be the average puff duration for EC users (Hua, Yip, & Talbot, 2013).

Disposable EC and EH Smoke-Outs

The performance of each disposable EC and EH was evaluated using the smoking machine. The lowest airflow rate required to generate aerosol was used for each smoke-out experiment. Airflow rate and pressure drop were measured and recorded for each puff. To obtain a qualitative measure of emissions, the absorbance of the aerosol was measured at 420 nm in a Bausch and Lomb spectrophotometer for the first and every 10th puff, as described previously (Trtchounian et al., 2010). Airflow rate remained constant unless aerosol absorbance dropped below 0.05 absorbance units, in which case, the airflow rate was increased to produce aerosol. To examine how performance properties (airflow rate, pressure drop, and aerosol absorbance) varied over prolonged use, disposable EC and EH were puffed at 1-min intervals until no aerosol was produced or the batteries died. Batteries were considered dead when the LED at the

end of the product blinked rapidly indicating a low battery and aerosol production ceased, or when three consecutive puffs had absorbances below 0.05 units. For this study, the latter criterion was never observed. Three smoke-out experiments were conducted with each brand of EC and EH, and a new EC or EH was used each time.

RESULTS

Appearance of EC and EH

The nine products used in this study are shown in Figure 1. Only one of the brands (NJOY) resembled a conventional cigarette with respect to weight, size, and color. Other models were longer and heavier than conventional cigarettes. The EC designs were conservative, while both the names and colors of the EH were more exotic.

Disposable EC Smoke-Outs

Pressure Drop, Airflow Required for Activation, and Puff Number

There was a correlation between the mode of activation and pressure drop/airflow rate/total puff number (Figure 2 and Table 1). Button-activated models consistently required lower airflow rates to activate, had lower pressure drops, and produced fewer total puffs than airflow-activated models. The button-activated model, Square 82, consistently operated at a low airflow rate (3 mL/s), had a low pressure drop (6 ± 4 mm H₂O), and did not produce more than 150 puffs (Figure 2A). In contrast, the airflow-activated models, BluCig, NJOY King, and V2 Cigs, required higher airflow rates to activate (range = 7–15 mL/s), had high pressure drops (range = 39–67 mm H₂O), and produced 171–331 puffs during smoke-out (Figure 2C, E, and G).

When comparing within groups, the pressure drop for the three individual BluCig units oscillated (Figure 2C). At different points in the smoke-out, the pressure drop spiked, plateaued, and then dropped again. All three BluCig units required the same airflow rate in the beginning, but within 20 puffs required an increase in airflow rate to sustain aerosol production. The three BluCig trials all lasted over 300 puffs (Table 1). Each NJOY King disposable EC unit required a different airflow rate, had different pressure drops, and lasted for a different number of puffs (usually not longer than 200 puffs) (Figure 2E). V2 Cigs units were similar in performance, except for one unit that produced more puffs than the other two (Figure 2G). None of the V2 Cigs units lasted for 400 puffs, as advertised (Table 1).

Aerosol Absorbance

For the button-activated Square 82, the low initial aerosol absorbance was followed by an interesting increase in absorbance that peaked at about 50 puffs for all units, then decreased, and in two of the three Square 82 products eventually reached zero (Figure 2B).

In contrast to the button-activated model, most of the airflow-activated disposable EC produced higher levels of aerosol initially (Figure 2D, F, and H). Aerosol absorbance from all three airflow-activated models decreased gradually with use. Aerosol production was similar for the three BluCig units in spite of the erratic pressure drop data. BluCig also lasted the



Figure 1. Disposable EC and EH models used in this study. From left to right brands are: Square 82, BluCig, NJOY King, V2 Cigs, Imperial Hookah, Luxury Lites, Starbuzz, Smooth, and Tsunami.

longest of the three brands of EC, but produced less dense aerosol than the other brands (Figure 2D). The three NJOY King products all performed differently with respect to aerosol production (Figure 2F). Two had similar densities but lasted a different number of puffs. The V2 Cigs all produced similar amounts of aerosol throughout the smoke-out period but differed in the number of puffs produced (Figure 2H).

Battery Life

Since these devices were not rechargeable, the batteries of all units died during the course of the smoke-out, and aerosol production stopped. Battery death often occurred before aerosol production declined to zero, that is before the product ran out of fluid. Examples of this can be seen with the NJOY products that were still producing aerosol of reasonable absorbance when the battery died and aerosol production stopped abruptly.

Disposable EH Smoke-Outs

Pressure Drop, Airflow Required for Activation, and Puff Number

EH smoke-out data are summarized in Figure 3 and Table 1. Button-activated models (Imperial Hookah, Luxury Lites, Starbuzz) consistently worked at an airflow rate of 3 mL/s, had pressure drop values that were generally less than 12 mm H₂O, and had average puff counts less than 182 (Figures 3A, C, and E). Except for one button-activated product (Starbuzz), airflow rate did not have to be increased to continue producing aerosol during the smoke-out period. The pressure drop, in general, remained low over time for all button-activated EH models (Figure 3A, C, and E).

Airflow-activated EH models (Smooth and Tsunami) consistently operated at an airflow rate of 15 mL/s or greater, had pressure drop values around 50 mm H₂O, and generally lasted over 400 puffs (Figure 3D and E). Pressure drop was similar among units within a brand, and airflow rate did not have to be increased to maintain aerosol production during the smoke-out.

Aerosol Absorbance

For button-activated models, aerosol absorbance, oscillated during the smoke-out and was similar within brands for the three products from Imperial Hookah and Luxury Lites (Figure 3B and D). One unit from Starbuzz had declining aerosol production between puffs 10–50 but was reactivated by increasing the airflow rate at puff 60. Button-activated models (Figure 3B, D, and F) had initial absorbance values around 0.5, while airflow-activated models had denser aerosol with absorbances between 0.8 and 1.0 (Figure 3H and J). For Smooth and Tsunami, absorbance oscillated, and each unit within brands performed similarly, except for one Tsunami product which had oscillating absorbances and produced fewer puffs, and may have had manufacturing flaws (Figure 3J).

Battery Life

As was observed with the EC, battery life varied between brands and all batteries died during the smoke-out at which time aerosol production ceased.

DISCUSSION

We have compared the performance of four brands of disposable EC and five brands of disposable EH, and within each

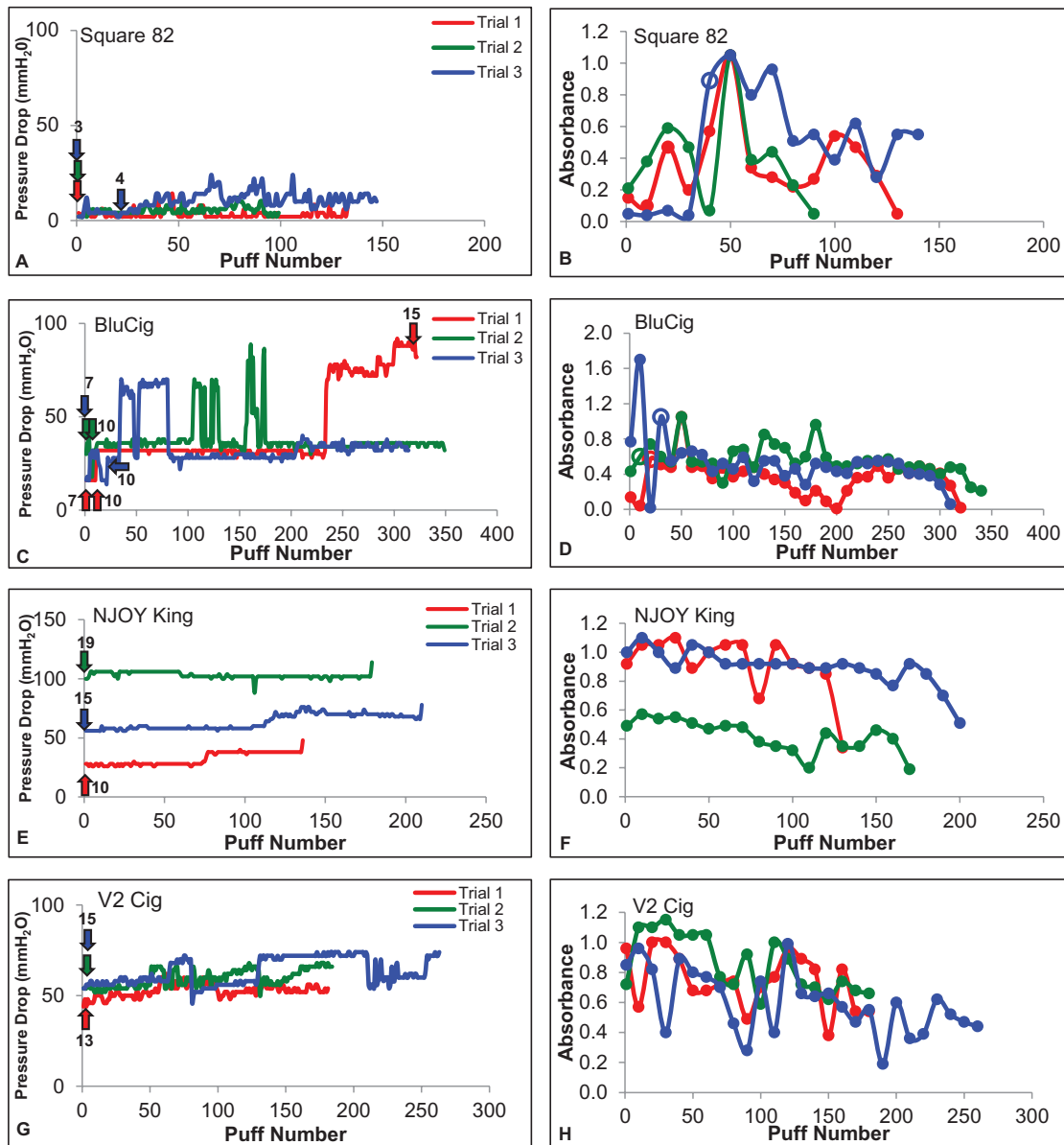


Figure 2. Smoke-out results for four brands of disposable EC. (A and B) Button-activated models. (C–H) Airflow-activated models. (A, C, E, and G) Pressure drop is plotted versus puff number for four brands of disposable EC. Arrows in A, C, E, and G indicate starting airflow rate (mL/s) and increases in airflow rate that were needed to continue aerosol production. (B, D, F, and H) Aerosol absorbance is plotted versus puff number for the same four brands of disposable EC. Open circles indicate puffs where airflow rate was increased to maintain aerosol production. Three different disposable units are shown for each brand.

product type, we compared button-activated and airflow-activated models. Significant variation was found among products and in some cases within brands. The main discriminator in performance was whether the unit was button or airflow-activated. Button-activated models consistently had lower pressure drops, airflow rates, absorbances, and puff numbers. Battery life, which limited puff number, was highly variable among brands and was much shorter in button-activated units.

Button-activation appeared to have an advantage in that it reduced the airflow required for aerosol production, thereby reducing the strength of the drag required to produce aerosol. The higher pressure drops in air flow-activated EC and EH models may be due to the air flow sensor itself which could provide a physical barrier to airflow. Also, the airflow sensors

may vary in their sensitivity to airflow as the range (7–17 mL/s) for this parameter was quite large.

Pressure drop and airflow rates varied between and, in some cases, within brands, with NJOY being the most variable of the products we tested. Each BluCig unit had spikes in pressure drop at different times during smoke-out, a feature that was not observed with other brands in this or prior studies (Trtchounian & Talbot, 2010; Williams & Talbot, 2011). The airflow rate and pressure drop variations are likely due to inconsistencies in manufacturing of these products, as discussed previously (Trtchounian & Talbot, 2010; Williams & Talbot, 2011).

Button-activated models generally produced aerosol with lower absorbance than airflow-activated brands. Square 82 was the exception in that its aerosol absorbance started

Table 1. Performance Characteristics of Disposable EC and EH

Brand	Flavor/nicotine concentration (mg/mL)	Button activated (Y/N)	Average pressure drop (mm H ₂ O)	Average absorbance	Average air flow rate (mL/s)	Average # puffs	Advertised # puffs	Cost (\$)	Cost/puff (\$)
EC									
Square 82	Original Red/18	Y	6±4	0.41±0.07	3±0	126±25	400	9	0.07
BluCig	Classic Tobacco/24	N	39±5	0.48±0.11	7±0	331±13	400	10	0.03
NJOY King	Bold/18	N	67±34	0.75±0.28	15±5	171±37	N/A	8	0.05
V2 Cigs	Red/18	N	59±5	0.73±0.13	14±1	208±47	400	10	0.05
EH									
Imperial Hookah	Blueberry Blast/6	Y	12±0	0.55±0.11	3±0	163±12	600	10	0.06
Luxury Lights	Citrus Berry/12	Y	9±5	0.41±0.14	3±0	182±19	700	10	0.05
Starbuzz	Blue Mist/12	Y	6±7	0.45±0.09	3±1	130±2	500	10	0.08
Smooth	Watermelon Punch/0	N	46±8	0.84±0.02	15±0	407±39	500	10	0.02
Tsunami	Cool Citrus Mist/12	N	54±2	0.68±0.25	17±0	395±131	800	7	0.02

Note. Y = yes; N = no; N/A = not available.

Disposable electronic cigarettes and electronic hookahs

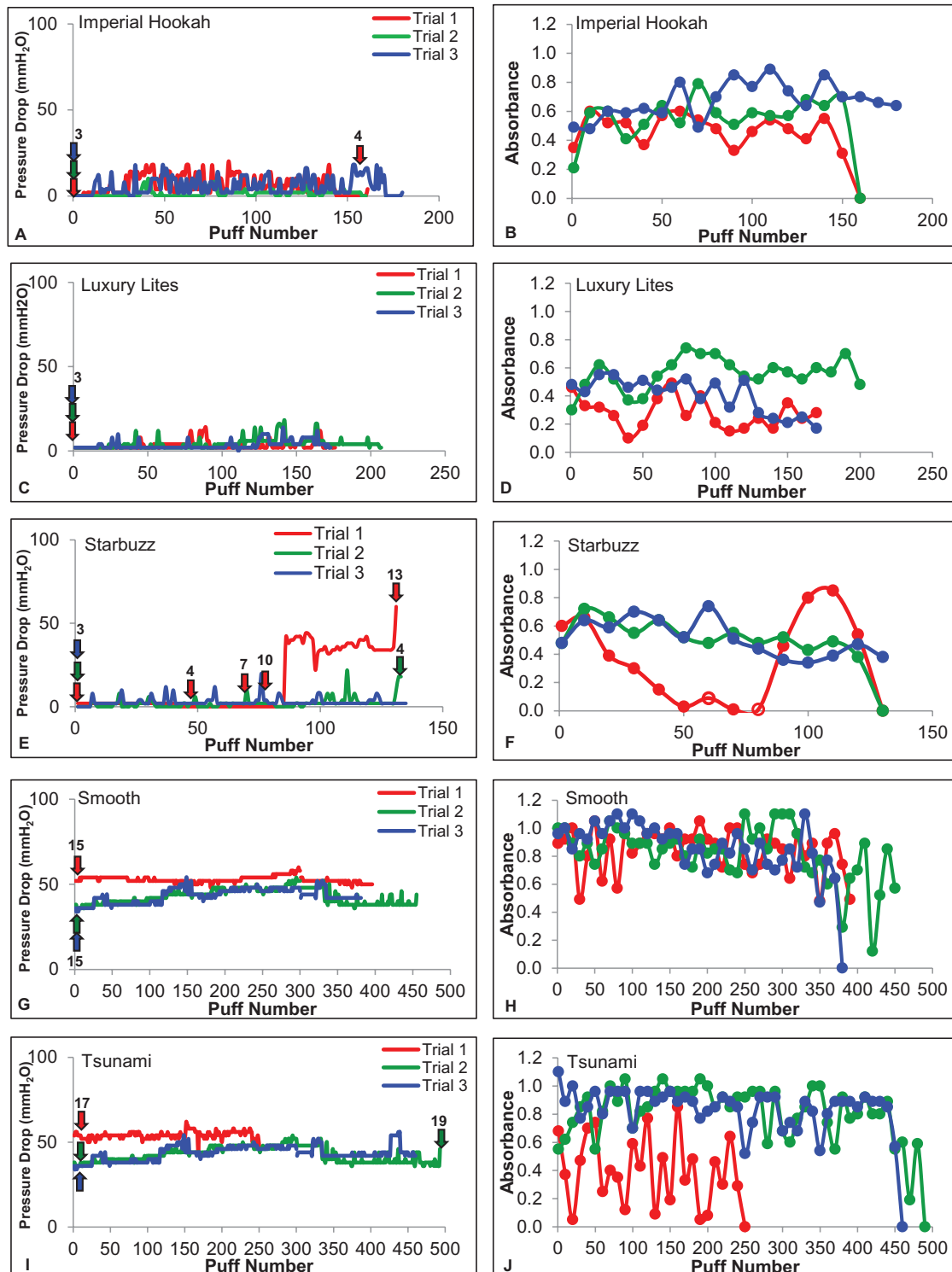


Figure 3. Smoke-out results for five brands of disposable EH. (A–F) Button-activated models. (G–J) Airflow-activated models. (A, C, E, G, and I) Pressure drop is plotted versus puff number for five brands of disposable EH. Arrows in A, C, E, G, and I indicate starting airflow rates (mL/s) and increases in airflow rate that were needed to continue aerosol production. (B, D, F, H, and J) Aerosol absorbance is plotted versus puff number for the same five brands of EH. Open circles indicate puffs where airflow rate was increased to maintain aerosol production. Three different disposable units are shown for each brand.

low, rose dramatically at about puff #50, then gradually decreased. Several products (BluCig, Smooth) were remarkable in producing similar aerosol densities over the smoke-out period, which was not observed previously with cartridge

and cartomizers models (Trtchounian et al., 2010; Williams & Talbot, 2011). Three of the products (e.g., NJOY King, Starbuzz, and Tsunami) had at least one unit with aerosol absorbance that was distinctly different than the other

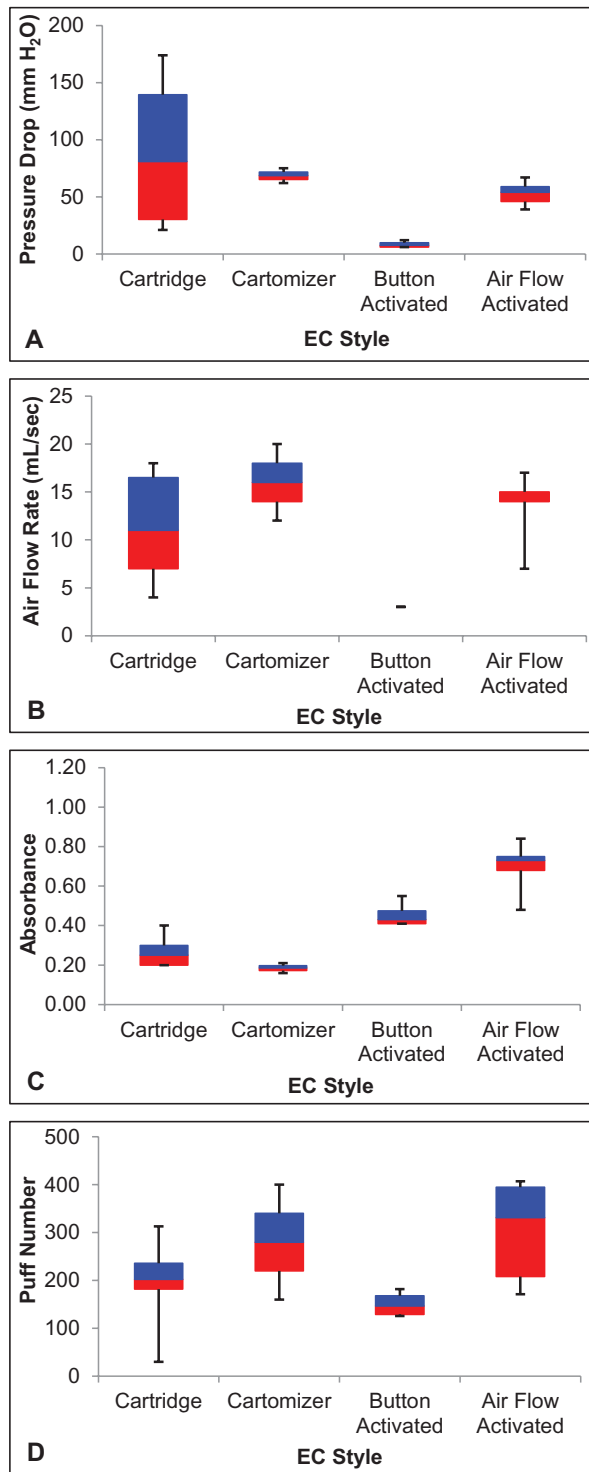


Figure 4. Comparison of performance properties across different generations of EC including EH. Four performance properties are summarized in box-whisker plots for cartridge models (Trtchounian et al., 2010), cartomizer models (Williams & Talbot, 2011), disposable button-activated models, and disposable airflow-activated models (current study). Each box shows the median, 75% percentile (blue), 25% percentile (red), and minimum and maximum values. The number of brands in each group was: six cartridge style, two cartomizer style, four button-activated disposable brands, and five airflow-activated disposable brands.

two units, presumably due to manufacturing defects in the nonconforming unit.

For all EC and EH models, the maximum number of puffs was limited, not by the fluid volume in the product, but by the life span of the battery. When batteries died, the products' LED lights flickered, and aerosol production ceased. Often aerosol production was still robust when the batteries expired. The button-activated models produced about 200 puffs in contrast to the airflow-activated models, which often produced over 300 puffs (e.g., BluCig, Smooth, and Tsunami). None of the products lasted as long as their advertisements indicated (Table 1). BluCig, which produced 331 ± 13 puffs, came closest to its advertised number (400). The decrease in puff number in the button-activated models could be a disadvantage for users.

Based on smoke-out data, the cost/puff did not exceed 10¢ for any brand (Table 1). Disposable EC and EH brands ranged from 3 to 7¢ per puff and from 2 to 8¢ per puff, respectively. The smoke-out data may over estimate the number of puffs achieved in the field since each brand was puffed at the lowest airflow rate that produced reliable aerosol. In actual use, airflow rates may be higher, which would decrease the total number of puffs and make the cost/puff higher.

EC have evolved significantly since our first performance studies (Trtchounian et al., 2010; Williams & Talbot, 2011) (Figure 4). To generalize from the data compiled across two prior studies and the current study: (a) the first generation cartridge models were generally more variable in all four performance features than later generations, (b) pressure drop and air flow activation rates were similar in all groups, except button-activated models which have the lowest values, (c) aerosol absorbance increased in the disposable models, (d) puff number is lower in button-activated models than in other models, and (e) variability is less in the button-activated models for all four parameters. In addition, the cartridge and cartomizer models of EC (not disposable) that we examined previously usually required progressive increases in airflow rate during smoke-out to maintain aerosol production (Trtchounian et al., 2010; Williams & Talbot, 2011). This would translate into harder dragging by the user as the puff number increases, unless frequent refilling is done. In contrast, the airflow rate of the disposable models in the current study generally did not need to be increased to maintain aerosol production. This may signal an improvement in design and indicates that the disposable models used in this study would tend to produce more uniform aerosol over the lifetime of the product than the earlier refillable models.

In summary, we have examined the performance of nine disposable EC and EH products. Our results show the following: (a) button-activated models require lower airflow rates (3 mL/s) for aerosol production than airflow-activated models (7–17 mL/s), (b) pressure drop was low and variable across button-activated models (6–12 mm H₂O) but always higher across airflow-activated products (30–67 mm H₂O), (c) in general, airflow did not have to be increased to maintain aerosol production during smoke-outs, unlike nondisposable cartridge and cartomizer products examined previously, (d) aerosol absorbance was, in general, higher for airflow-activated models, (e) button-activated models had shorter battery life and produced fewer puffs than airflow-activated products,

and (f) some units performed erratically and appeared to be defective.

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DECLARATION OF INTERESTS

None declared.

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