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The effect of filter vent blocking and smoking topography on carbon monoxide levels in smokers

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Abstract

Two studies were conducted to examine the effect of filter vent blocking and smoking topography on carbon monoxide (CO) levels in smokers. In Study 1, 12 participants smoked two types of cigarettes (Marlboro® Light and Carlton® 100) under two types of blocking conditions (unblocked and half-blocked) while using a smoking topography device. Participants were restricted to 8 puffs, separated by 45 s. Significant main effects of CO boost for cigarette type and blocking condition replicated previous findings. A significant increase in CO boost for the Marlboro® Light blocked condition is a novel finding for this best-selling brand. That result and the finding that topography measures did not predict CO boost made us question the reliability of CO boost. In Study 2, we examined the reliability of CO boost by recruiting 12 participants to smoke three unblocked Carlton® 100 cigarettes in one session and three half-blocked in another. CO boost was significantly greater for the blocked sessions compared to the unblocked and CO boost did not differ within session, thus supporting the reliability of the measure. When participants do not switch brands within a session, smoking topography measures are predictive of CO boost.

Keywords: Smoking; Nicotine; Topography; Carbon monoxide; Filter vents; Blocking

Ultra-light cigarette brands yield between 1 and 5 mg tar when tested by the Federal Trade Commission method, less than tar yields for light (6–15 mg tar) and regular (>15 mg tar) cigarette brands (Federal Trade Commission (FTC), 2000). One of the ways ultra-light and light brands produce low nicotine, tar and carbon monoxide (CO) yields during FTC standardized testing is by means of filter ventilation holes that dilute the smoke (Kozlowski et al., 2000). Blocking the filter ventilation holes has been shown to increase nicotine, tar and CO yields under machine-smoked conditions for both ultra-light and light cigarettes (Rickert et al., 1983). A similar effect has been observed in human behavioral smoking studies using ultra-light cigarettes, but not when smoking light cigarettes (Sweeney and Kozlowski, 1998; Sweeney et al., 1999).

In naturalistic environments, blocked filter ventilation holes have been observed in both ultra-light and light cigarette smoking, in approximately 45–58% of several populations (Kozlowski et al., 1982, 1988; Baker and Lewis, 2001). During experimental conditions with human smokers, highly ventilated ultra-light tar cigarettes have produced CO boosts 2.1–8.7 times greater in completely blocked condition compared to the unblocked condition (Zacny et al., 1986; Kozlowski et al., 1996b; Sweeney and Kozlowski, 1998). Smaller but significant effects (1.85–2.5 times) have been reported when fingers or lips were used to partially occlude filter vents in ultra-light tar cigarettes (Kozlowski et al., 1996b; Sweeney and Kozlowski, 1998; Sweeney et al., 1999). Behavioral studies have reported no significant difference in CO boost between unblocked and blocked conditions for light cigarettes (e.g., Sweeney and Kozlowski, 1998; Sweeney et al., 1999).

There are several potential reasons why blocking filter vents on light cigarettes produces a greater CO boost in machine-smoking but not during behavioral studies. The procedures for

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the human studies controlled for number of puffs, puff duration, time between puffs, and time between cigarettes. The machine-smoked study additionally controlled for puff volume. Puff volume has been found to be positively correlated with CO boost in directed smoking of a preferred cigarette brand (Zacny et al., 1987).

Additionally, smokers typically alter their puffing patterns when changing to cigarettes with a different level of tar and nicotine (Herning et al., 1981), suggesting that smokers readily adjust puffing parameters as a result of cigarette type and tar and nicotine levels. This altering of puffing behavior is referred to as compensation (Kozlowski et al., 2000) and is facilitated by cigarettes that produce low nicotine, tar and CO during standardized testing but contain elastic design features that can be manipulated by smokers to extract more nicotine, tar and CO than labeled. Compensatory smoking behavior and cigarette design features allow smokers to adjust nicotine delivery and, subsequently, tar and CO delivery, as desired. Differences in puffing behavior may be the source of individual differences in CO boost observed in smoking studies (e.g., Sweeney et al., 1999; Kozlowski et al., 1996b). Based on the discrepancy between machine-smoked results and actual exposure to tar and nicotine, many have recommended abandoning the current standard testing method procedure (WHO Framework, 2002; Jarvis et al., 2001).

In the present report two studies were designed to determine the effect of filter vent blocking on smoking behavior and the delivery of CO. The overall aim was to identify the source of individual differences in smoking behavior that account for the wide range of CO levels reported in previous studies (e.g., Sweeney and Kozlowski, 1998; Kozlowski et al., 1996b; Zacny et al., 1986). Results from this study may help to better understand the relationship between individual differences in smoking behavior, specifically filter vent blocking and smoking topography, and how these variations affect harm exposure. We hypothesize that in addition to replicating the effect of filter vent blocking, puff volume will predict CO boost, such that as puff volume increases, CO boost will increase as well.

1. Study 1

Study 1 employed a smoking topography equipment to determine the effect of puff volume on CO exposure in ultra-light tar and light cigarettes. The current study was designed to replicate previous findings (e.g., Sweeney and Kozlowski, 1998) that filter vent blocking causes a greater CO boost in highly ventilated, ultra-light tar cigarettes but not for less ventilated, light cigarettes, while measuring smoking topography. A repeated measures design was used to compare CO boost in light and ultra-light cigarettes in both filter vent blocked and unblocked conditions.

1.1. Materials and method

1.1.1. Participants

Twelve eligible participants (eight males) responded to advertisements placed on bulletin boards of a large university campus. Minimum eligibility requirements were: 1) 18 years of age; 2) currently smoking 10 cigarettes daily; 3) daily smoking for at least 3 years; 4) self-report inhaling when smoking; and 5) reporting usual brand as non-mentholated. Participants received US$10.00 for completing the single experimental session.

1.1.2. Cigarettes

Marlboro® Light 100 HP (hard pack) (10 mg tar, 0.8 mg nicotine, 13 mg CO) under standard testing conditions (FTC, 2000) and Carlton® 100 HP cigarettes (1 mg tar, 0.1 mg nicotine, 1 mg CO under standard testing conditions) (FTC, 2000) were used in this study. Ventilation testing procedures (Kozlowski et al., 1997a,b) of the unused cigarettes from this study found that the unblocked Carlton® 100 HP cigarettes were 83.8% ventilated and the half-blocked Carlton® 100 HP cigarettes were 47% ventilated. The Marlboro® Light 100 cigarette was 29.4% ventilated and 14% ventilated when half-blocked. Ultra-light cigarettes with half of the filter vents blocked had more ventilation than unblocked light cigarettes.

1.1.3. Procedure

Participants were screened for eligibility, scheduled for an appointment and instructed not to smoke for 1 h prior to attending the session. Upon arrival, participants were seated in the laboratory, had the study and equipment explained to them, and informed consent was obtained. Participants smoked one cigarette in each of four conditions: unblocked light, half-blocked light, unblocked ultra-light, and half-blocked ultra-light. Unblocked light refers to a Marlboro® Light 100 with none of the vents blocked. Half-blocked light refers to a Marlboro® Light 100 with half of the filter vents occluded by a piece of Scotch Magic® Tape transparent tape that was one-half the length of the cigarette circumference. Unblocked ultra-light tar refers to a Carlton® 100 HP cigarette with none of the filter vents blocked and half-blocked ultra-light means half of the filter vents on a Carlton® 100 HP were covered with transparent tape. The experiment was a single 2-h-and-15-min session where participants smoked one cigarette from each of the four conditions, balanced orthogonally to counter potential order effects.

Participants were instructed to take a total of eight puffs, each 45 s apart, not including a lighting puff. There was a 20-min period between each cigarette, timed from when the cigarette was extinguished to the lighting of the next cigarette. The investigator instructed the participants when to light the cigarette and when to take a puff on the cigarette. Sessions began between 13:00 and 17:00 hours. The University Institutional Review Board approved the study protocol.

1.1.4. Measurement procedure

1.1.4.1. Participant characteristics. Demographic information (e.g., age, gender, and race), smoking history, nicotine dependence and cigarette brand preference were collected at baseline. The Heaviness of Smoking Index (HSI; Kozlowski et al., 1994) was used to assess nicotine dependence. Greater HSI scores reflect greater nicotine dependence. HSI is a two-item subset of the Fagerstrom Test of Nicotine Dependence (FTND) and has shown significant positive correlation between the two measures (Kozlowski et al., 1994).

1.1.4.2. Carbon monoxide measure. CO was measured 4 min prior to smoking by taking two breath samples and then averaging these values for a pre-cigarette CO level. Two CO breath samples were then taken 4 min after each cigarette and averaged to determine post-cigarette CO level. Post-cigarette CO average minus pre-cigarette CO average determined CO boost. In order to obtain consistent readings, participants were instructed to inhale deeply, then exhale, inhale again, place nose clips on their nostrils, then hold their breath for 15 s. After 15 s, participants were instructed to exhale for as long as possible (Ahijevych et al., 2004; Sweeney and Kozlowski, 1998). The highest CO reading (in parts per million (ppm), displayed by the CO breath sample device (Vitalograph, Lenexa, KS) was recorded.

1.1.4.3. Smoking topography. Cigarettes were smoked using the CReSS® (Clinical Research Support System) smoking topography machine (Plowshare, Baltimore, MD), calibrated as per the manufacturer's instructions. This device works by placing a cigarette in a flowmeter mouthpiece, while the participant puffs on the cigarette through the proximal end of the sterilized mouthpiece. A pressure transducer attached to the mouthpiece measures pressure changes that occur during inhalation. The pressure changes are amplified, digitized and sampled at 1000 Hz. CReSS® software converts the signal to airflow (ml/s) in real time (s) and from this provides number of puffs taken on the cigarette, puff volume, puff duration, maximum flow, and interpuff interval (time between puffs).

1.1.4.4. Subjective measures. After each cigarette, participants were asked to rate the cigarette they had just smoked on 14 characteristics on a visual analog scale (VAS). The characteristics were strength, harshness, heat, draw, taste (bad/good), satisfaction, burn rate, taste (mildness), too mild, harshness of smoke, after taste, staleness, strength of smoke, and smoke smell (pleasantness). Participants were instructed to place a vertical line along a 100-mm line that had anchor terms at either end for each rating characteristic. The VAS items have been used in similar research (Sweeney et al., 1999; Zacny et al., 1986) and by the tobacco industry (www.pmdocs.com, Bates #: 2022259048).

1.1.5. Data analysis

Descriptive statistics were used to characterize the participants and their cigarette brands. Correlations for continuous measures or unpaired t-tests for nominal measures were used to determine associations of descriptive statistics with the initial CO measure and the outcome measure, CO boost. Primary analyses for CO boost and smoking topography measures were analyzed in a 2×2 (blocking condition by cigarette type) repeated measures analyses of variance (ANOVA). When warranted by significant interaction effects, post-hoc analyses were used to compare specific conditions using an adjusted Bonferroni alpha to conservatively control for type I errors ($\alpha = 0.05/4 = .0125$). Subjective ratings were considered as secondary analyses and exploratory and all 14 subjective ratings were analyzed in a manner identical to those for the primary analyses.

Regression analyses controlling for cigarette type, blocking condition and any descriptive statistics found to be significantly associated with initial CO or CO boost were used to examine the effect of smoking topography on CO boost.

Sample size was calculated using NCSS PASS (Kaysville, Utah) software using effect sizes based on previous CO boost and smoking topography data in our laboratory. A sample size of 12, alpha = .05, effect sizes greater than 0.6, and correlation across time points set to $r = .75$ indicates power >90%. Analyses were performed using Statview (SAS Institute, Cary, NC) and Stata (StataCorp LP, College Station, TX).

1.2. Results

1.2.1. Descriptive statistics

All participants completed the study. Six participants reported their usual brand smoked as Marlboro® Lights (King HP: 11 mg tar, 0.8 mg nicotine, 12 mg CO, FTC, 2000); four participants reported usually smoking Camel® Lights (King HP: 11 mg tar, 0.8 mg nicotine, 11 mg CO, FTC, 2000); and one each reported usually smoking Marlboro® Mediums (King HP: 12 mg tar, 0.9 mg nicotine, 12 mg CO, FTC, 2000) and Marlboro® Red (100 HP: 15 mg tar, 1.1 mg nicotine, 14 mg CO, FTC, 2000).

The average age of the participants was 21.6 (SD = 4.5; range 18–35) and they reported having been daily smokers for 5.4 years (SD = 4.5; range 3–19). Participants smoked on average 17.5 cigarettes per day (SD = 12.5; range 10–50). Their mean time until the first cigarette of the day was 59 min (SD = 62; range 1–240). Their mean heaviness of smoking index (HSI; Kozlowski et al., 1994), a measure of nicotine addiction based on cigarettes per day and time until the first cigarette, was 1.9 (SD = 1.2; range 1–5; possible range 0–6). There were no significant associations between descriptive statistics and initial CO level or CO boost.

One participant had an initial CO level nearly three standard deviations greater than the sample mean. When he was excluded all associations between descriptive statistics and outcome measure were not significant ($ps > .3$). This participant did not produce significantly different CO boosts and therefore was included in all analyses.

1.2.2. CO baseline

Baseline CO levels taken at the beginning of the experimental session prior to smoking ranged from 3–50 ppm, with a mean of 17.0 (SD = 12.1). Baseline CO measures were not significantly correlated with CO boost or smoking topography measures from the first cigarette. CO levels steadily increased for each participant but were always lower than the post-CO levels measured from the prior smoking condition. Pairs of CO measures before and after the cigarette never differed by more than 1 ppm. Time of session was not associated with baseline CO level.

1.2.3. Outcome measure: CO boost

CO boost for the unblocked light cigarette was 4.5 ppm (SD = 1.8) and 6.8 ppm (SD = 1.5) for the half-blocked light cigarette. The unblocked ultra-light tar cigarette had a mean CO boost of 0.9 ppm (SD = 0.4); while the half-blocked ultra-light tar cigarette had a mean CO boost of 3.4 ppm (SD = 1.0). Both main effects were statistically significant ($p < .0001$), as ultra-light cigarettes produced a lower CO boost than the light cigarettes and blocking half of the filter vents produced a greater CO boost than in the unblocked conditions. The interaction effect was not significant, a finding that is different than what has been reported by previous research (refer to Fig. 1A).

1.2.4. Smoking topography measures

1.2.4.1. Puff volume. Mean values appear in Table 1. Analyses indicate both the cigarette type ($p = .01$) and blocking ($p < .01$) main effects were statistically significant. The cigarette type by blocking interaction was also statistically significant ($p < .01$). Post-hoc analyses indicate statistically significant differences between the unblocked ultra-light cigarette and each of the three other conditions (ps < .01, refer to Fig. 1B).

1.2.4.2. Puff duration. Mean values appear in Table 1. Analyses indicate main effects of cigarette type ($p < .05$) and blocking ($p < .05$) were statistically significant. Participants took longer puffs on the ultra-light cigarettes compared to the light cigarettes and longer puffs on unblocked cigarettes compared to blocked cigarettes. The interaction effect was also significant ($p < .05$), indicating differences in puff duration between the two ultra-light tar cigarettes greater than the differences in puff duration between the two light cigarettes.

1.2.4.3. Puff velocity. Mean values appear in Table 1. Analyses indicate a statistically significant main effect for

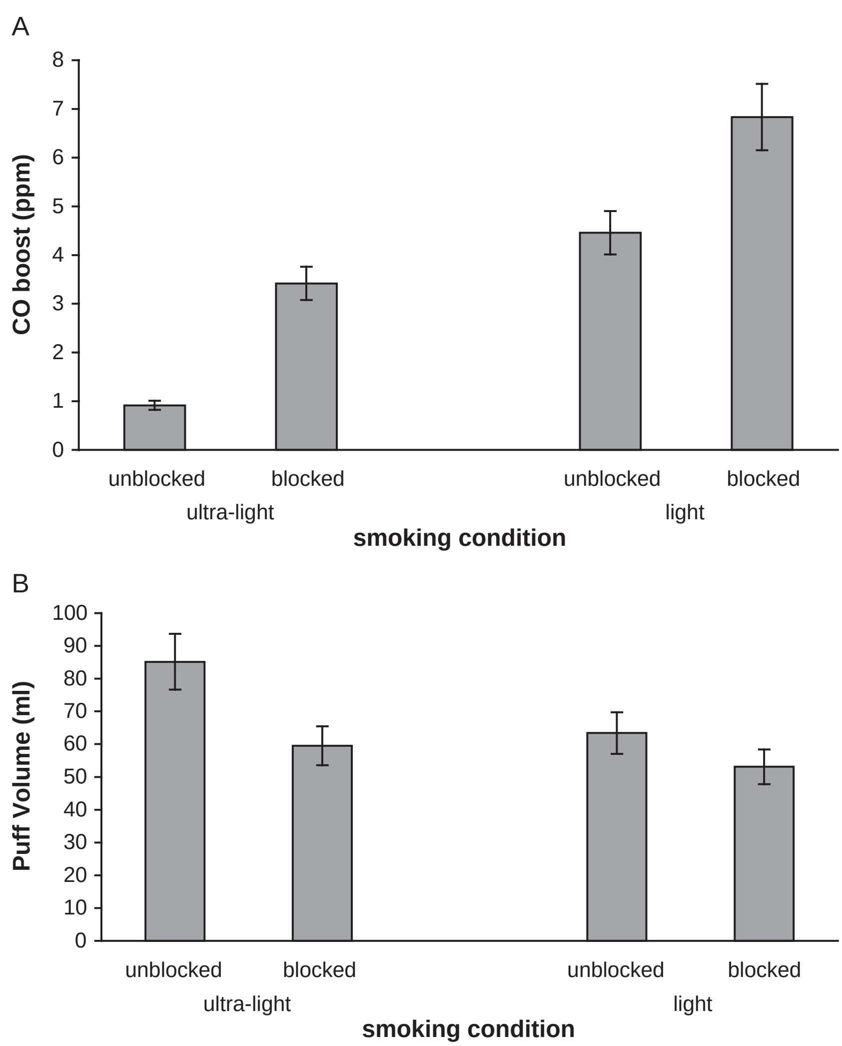

Fig. 1. A. Study 1. The effect of cigarette type and filter vent blocking condition on CO boost. Values are CO boost (in parts per million) reported as mean ± standard deviation. Significant main effects indicate blocking increased CO boost for both cigarette types. Light cigarettes had greater CO boost than ultra-light cigarettes. B. Study 1. The effect of cigarette type and filter vent blocking condition on puff volume. Values are average puff volume (in milliliters) reported as mean ± standard deviation. Puff volume for unblocked ultra-light was significantly larger than puff volume for the three other conditions.

Table 1
CO boost, smoking topography measures and subjective ratings data from Study 1 and Study 2

	Study 1				Study 2					
	Light		1 mg tar		Unblocked			Blocked		
	Unblocked	Blocked	Unblocked	Block	1	2	3	1	2	3
Biochemical measure										
CO boost (ppm)	4.5 (0.5)	6.8 (0.4)	0.9 (0.1)	3.4 (0.3)	2.4 (0.4)	2.5 (0.3)	2.9 (0.2)	4.6 (0.5)	4.3 (0.4)	5.0 (0.4)
Smoking topography measures										
Mean puff volume (ml)	63.4 (8.4)	53.1 (5.3)	85.1 (10.9)	59.5 (5.6)	79.5 (4.1)	85.8 (5.0)	86.5 (4.5)	67.1 (3.2)	70.5 (3.7)	65.8 (2.9)
Puff duration (s)	1.6 (0.2)	1.4 (0.2)	2.0 (0.3)	1.7 (0.2)	1.8 (0.1)	1.9 (0.1)	1.9 (0.1)	1.9 (0.1)	1.7 (0.1)	1.7 (0.1)
Puff velocity (ml/s)	42.5 (3.2)	39.0 (3.0)	44.5 (2.8)	37.7 (2.7)	61.0 (3.5)	62.0 (2.9)	63.6 (2.5)	52.3 (1.5)	57.5 (2.5)	54.4 (2.0)
Subjective ratings										
Strength: (very weak/very strong)	46.6 (5.5)	53.6 (5.5)	26.3 (5.9)	40.4 (4.8)	19.7 (4.1)	18.9 (3.7)	21.9 (5.0)	29.3 (4.4)	41.3 (6.8)	38.0 (7.7)
Harshness: (very mild/very harsh)	31.9 (5.3)	47.9 (6.0)	34.3 (8.3)	47.8 (8.0)	32.9 (8.3)	31.1 (8.6)	29.8 (7.6)	34.1 (5.9)	44.7 (9.3)	43.3 (9.8)
Heat: (no heat/very hot)	25.2 (4.1)	30.2 (5.0)	20.6 (5.0)	31.4 (5.6)	13.8 (4.4)	14.9 (4.3)	13.5 (3.5)	16.1 (5.9)	19.8 (4.6)	18.6 (4.6)
Draw: (easy/difficult)	18.4 (2.5)	22.0 (5.0)	53.3 (9.7)	32.9 (5.8)	38.1 (8.5)	40.4 (8.9)	49.2 (8.0)	30.7 (6.5)	34.1 (6.3)	33.0 (5.5)
Taste: (very bad/very good)	58.9 (6.3)	57.3 (8.0)	32.3 (4.2)	40.1 (5.1)	41.9 (3.7)	44.2 (5.4)	44.3 (6.1)	37.3 (4.6)	45.3 (4.6)	41.6 (4.9)
Satisfaction from smoking: (unsatisfying/satisfying)	55.3 (6.3)	54.4 (6.0)	29.9 (5.3)	44.6 (5.4)	38.8 (8.3)	35.8 (7.9)	37.4 (8.0)	44.0 (4.7)	51.4 (7.6)	40.4 (8.2)
(Burned/did not burn) too fast in too few puffs	58.9 (8.0)	66.3 (5.9)	46.3 (8.4)	43.3 (5.6)	47.9 (5.9)	41.6 (6.2)	42.5 (6.7)	51.2 (6.7)	48.7 (7.4)	45.4 (8.5)
Mild taste/no mild taste	29.2 (3.7)	39.3 (5.6)	35.7 (6.7)	36.2 (5.1)	30.6 (7.3)	29.6 (7.6)	31.5 (7.5)	35.9 (8.5)	45.7 (9.1)	43.0 (8.8)
It (was/was not) too mild for me	62.6 (8.1)	65.3 (5.7)	41.3 (8.5)	42.3 (7.2)	36.4 (9.5)	32.3 (9.0)	35.8 (10.2)	48.8 (9.9)	57.6 (10.3)	53.1 (10.8)
Smoke (seemed/did not seem) harsh	71.9 (6.7)	68.3 (5.7)	63.5 (8.4)	56.4 (6.0)	69.0 (8.4)	56.4 (9.3)	53.3 (8.5)	52.6 (8.1)	54.3 (6.8)	51.3 (7.8)
(Did not leave/left) a good aftertaste in my mouth	54.4 (5.5)	49.6 (6.6)	38.78 (5.5)	35.9 (5.3)	4.03 (7.2)	41.5 (7.3)	47.5 (6.7)	37.3 (5.5)	43.1 (6.3)	43.3 (7.3)
Somehow it (seemed/did not seem) stale	80.4 (4.2)	78.5 (4.7)	56.9 (8.45)	59.7 (7.8)	50.7 (7.3)	61.56 (8.6)	59.9 (9.1)	56.6 (5.5)	56.6 (7.2)	57.4 (7.5)
Smoke seemed (very weak/very strong)	46.0 (4.2)	54.8 (5.7)	28.0 (5.9)	42.8 (4.3)	22.1 (4.6)	23.8 (5.5)	25.6 (6.8)	32.9 (5.6)	36.4 (5.5)	42.1 (6.1)
Smoke smell: (unpleasant/pleasant)	59.3 (5.4)	59.7 (5.6)	53.8 (4.2)	49.4 (4.3)	57.9 (3.8)	60.4 (5.1)	59.2 (4.6)	58.0 (5.1)	53.2 (5.0)	57.4 (4.7)

Values presented are mean ± standard error.

the blocking condition ($p<.001$). Unblocked cigarettes had significantly greater puff velocities than both blocked cigarettes.

1.2.5. Subjective measures

Strength, draw, taste (bad/good), satisfaction, burn, too mild, staleness, smoke weakness and pleasantness of smoke smell differed significantly by cigarette type (ps $<.05$), such that the light brand cigarette was rated as: stronger, an easier draw, better tasting, more satisfying, not burning too fast, not being too mild, tasting less stale, having stronger and more pleasant smelling smoke. The blocked cigarettes were rated as significantly stronger, having more heat, being more harsh, and producing stronger smoke than the unblocked cigarettes (ps $<.05$). A significant interaction effect was observed for draw ($p<.05$). The blocked light was rated as having a more difficult draw than the unblocked light and the blocked ultra-light was rated as having an easier draw than the unblocked ultra-light. Values for these subjective measures are presented in Table 1.

1.2.6. Smoking topography as a predictor of CO boost

Regression analysis controlling for cigarette type and blocking condition was used for analysis of topographic predictors of CO boost. None of the smoking topography measures were significant predictors of CO boost, although puff velocity approached significance ($p=.06$).

1.3. Discussion

This study was designed to replicate prior research on the effect of filter vent blocking in highly ventilated ultra-light tar cigarettes and less ventilated light cigarettes. The novelty of the current study was using a device that would measure smoking topography in an attempt to identify the source of individual differences in CO boost. CO boost had varied greatly in previous research that had not measured topography. Number of puffs and time between puffs was held constant in our study and we hypothesized that puff volume might explain why some participants produce larger CO boosts than others. However, it appears that under directed smoking conditions, puff volume, puff duration, or puff velocity do not predict individual differences in CO boost.

There are several reasons why we may not have found a significant relationship between smoking topography measures and CO boost. Perhaps there may not be a relationship between these measures. However this seems unlikely based on existing evidence (see Lee et al., 2003; Eissenberg et al., 1999; USDHHS, 1988). Second, the topography mouthpiece may have compromised the relationship between smoking topography measures and CO boost. This too seems unlikely (Lee et al., 2003). Another possible explanation is the novelty of the cigarettes to the participants. Smokers have been shown to smoke lower tar and nicotine cigarettes differently than their usual brand (Zacny and Stitzer, 1988;

Herning et al., 1983; Benowitz et al., 1983). Six participants who enrolled in this study typically smoked Marlboro® Lights. The Marlboro® Light smokers took significantly smaller volume ($p = .048$), greater velocity ($p < .01$), and shorter-duration ($p < .01$) puffs than those whose usual brand was not Marlboro® Light. However, usual Marlboro® smokers did not differ from non-Marlboro® Light smokers in CO boost, either when considering all cigarettes smoked or the Marlboro® cigarettes only. Lastly, the constraints of the protocol (i.e., 8 puffs, 45 s apart, not smoking own brand of cigarettes) may have altered participants' normal smoking behavior in such a way that participants smoked differently than during naturalistic smoking.

A novel finding was that CO boost was significantly different between the unblocked and partially blocked Marlboro® Light conditions. This finding had not been previously reported in human smoking studies, which reported that filter vent blocking had no effect on CO boost in light cigarettes. On average, CO boost was 2.37 ppm greater for the partially blocked light condition compared to the unblocked condition (paired t, $p < .001$). The range of differences between the two conditions (blocked–unblocked) was -0.5 to 4.0 ppm, suggesting large individual differences in CO boost; but these individual differences in CO boost were not predicted by smoking topography measures.

This study is the first to demonstrate a significant effect on CO boost by blocking filter vents on light cigarettes and further demonstrates large differences between individuals in CO boost, even when smoking identical cigarettes and controlling for number of puffs and time between puffs. For this reason, we felt it important to determine the reliability of the CO boost measure.

2. Study 2

The novel finding with light cigarettes and the absence of association between smoking topography measures and CO levels brought the reliability of CO boost into question. The primary purpose of Study 2 was to determine if CO boost is a reliable measure when assessing smoke exposure in filter vent blocking studies. The ultra-light cigarettes have consistently demonstrated CO increases when blocking vents and therefore was the only cigarette used in Study 2.

2.1. Materials and method

2.1.1. Participants

Twelve participants (7 males) were recruited through flyers posted throughout the community or who had participated in previous studies and agreed to future contact. To be eligible, participants had to: 1) be 18 years of age or older; 2) currently smoking at least 10 cigarettes a day; 3) be smoking for a minimum of 5 years; 4) be not currently trying to quit smoking; 5) report inhaling when they smoke; and 6) smoke non-mentholated cigarettes. Participants received US$25.00 for completing the study.

2.1.2. Cigarettes

Carlton® 100 HP cigarettes (1.0mg tar, 0.1mg nicotine, 1mg CO, FTC, 2000) were used throughout the study. These cigarettes and vent blocking technique are identical to the procedures in Study 1.

2.1.3. Procedure

Procedures were similar to those followed in Study 1. Participants were screened and those eligible were asked not to smoke for 1 h prior to the session. Upon entering the smoking laboratory, participants were seated, had the experiment and equipment explained to them, and informed consent was obtained. An initial CO breath test was collected.

During each session participants smoked three cigarettes, either all unblocked or all partially blocked. Both researcher and participant were blinded to the blocking manipulation until the conclusion of session two. Two CO measures were taken 4 min before and after smoking to assess CO boost. Participants were instructed when to take each of the 8 puffs spaced 45 s apart. There was a 20-min period between the last puff of the preceding cigarette and the lighting puff of each subsequent cigarette. Puff volume, puff duration and puff velocity were free to vary and were measured with the CReSS smoking apparatus.

Session two procedures were the same as session one, with the exception that the alternate blocking condition was used. Each session lasted about 90 min in this study, which was approved by the University Institutional Review Board.

2.1.4. Measurement procedure

Participant characteristics, CO, smoking topography and subjective measures were collected in identical fashion to the protocol of Study 1.

2.1.5. Data analysis

Descriptive statistics were used to characterize the participant population and their cigarette brands. Correlations for continuous measures or unpaired t-tests for nominal measures were used to determine associations of descriptive statistics with the initial CO measure and the outcome measure, CO boost. Primary analyses were to investigate the effects of vent blocking and order on CO boost and smoking topography and were assessed using a 2×3 repeated measures analysis of variance (ANOVA). Vent blocking conditions were unblocked and half-blocked. Order refers to cigarette one, two and three during each session. When warranted, post-hoc analyses were used to compare specific conditions using an adjusted Bonferroni alpha to conservatively control for type I errors ($\alpha = 0.05/6 = 0.0083$). Secondary analyses of the 14 subjective ratings were considered exploratory and were analyzed with an identical approach used for the primary analyses. Intraclass correlation coefficients were calculated for puff volume, puff velocity, puff duration, and CO boost to determine the reliability of these items. Maximum puff velocity was not included in this analysis because it only occurs at a discrete instant during a puff and therefore assessing reliability for it does not seem warranted. Regression analyses controlling for cigarette type, blocking condition and any descriptive statistics found to be significantly associated with initial CO level were used to examine the effect of smoking topography variables on CO boost. Power analyses were performed identically to that described in Study 1. Analyses were performed using Statview (SAS Institute, Cary, NC) and Stata (StataCorp LP, College Station, TX).

2.2. Results

2.2.1. Descriptive statistics

All participants completed the study. Two participants reported that their usual brand was Marlboro® Light (King HP: 11 mg tar, 0.8 mg nicotine, 12 mg CO, FTC, 2000); two usually smoked Camel® Lights (King HP: 11 mg tar, 0.8 mg nicotine, 11 mg CO, FTC, 2000); two usually smoked Parliament® Light (100 SP: 12 mg tar, 1.0 mg nicotine, 14 mg CO, FTC, 2000); one usually smoked Camel® Regular 100 SP (soft pack): (17 mg tar, 1.2 mg nicotine, 17 mg CO, FTC, 2000); one usually smoked Carnival® Regular (FTC data not available); one usually smoked Camel® Ultra-Light (100 HP: 5.0 mg tar, 0.5 mg nicotine, 7.0 mg CO, FTC, 2000); one usually smoked USA® Ultra-Light (FTC data not available), and 2 smoked various Light brands.

The average age of the participants was 41.6 (SD = 15.3; range 20–68) and they reported having been daily smokers for 21.5 years (SD = 16.5; range 5–49). Participants smoked on average 19.4 cigarettes per day (SD = 9.5; range 10–40). Their average FTND nicotine dependence score was 4.0 (SD = 2.6; range 0–8). Their mean heaviness of smoking index (HSI) was 2.7 (SD = 1.8; range 0–5). The two nicotine dependence measures were positively correlated ($r = .93$, $p = .0001$).

Nicotine dependence score (FTND) was significantly correlated with initial CO level at session one ($r = .73$, $p < .01$) and session two ($r = .65$, $p < .05$). All other associations between CO and descriptive statistics were not significant ($p\text{s} > .2$).

2.2.2. CO baseline

Baseline CO levels taken at the beginning of each session averaged 20.3 ppm (SD = 11.3) and did not differ between session day, blocking condition, or by participant between sessions ($p\text{s} > .7$). Baseline CO measures were not significantly correlated with CO boost or smoking topography associated with the first cigarette in either session. CO levels generally increased during the sessions. Sessions began between 15:00 and 18:00 and time of session was not associated with baseline CO level.

2.2.3. Outcome measure: CO boost

CO boost for the unblocked condition was 2.4 (SD = 1.3), 2.5 (SD = 1.2), and 2.9 ppm (SD = 0.7) for cigarette one, two, and three, respectively. CO boost for the blocked condition was 4.6 (SD = 1.8), 4.3 (SD = 1.2), and 5.0 ppm (SE = 1.3) for cigarette one, two, and three, respectively. Repeated measures ANOVA indicate a significant effect of blocking condition ($F = 77.64$, $p < .0001$), but no significant order effect (refer to Fig. 2A).

2.2.4. Smoking topography measures

2.2.4.1. Puff volume.

Mean values appear in Table 1. Repeated measures ANOVA indicate a significant effect of blocking condition on puff volume, such that participants took larger puff volumes during the unblocked session ($F = 29.682$, $p < .001$). Additionally, an effect approaching significance was observed for order ($F = 3.291$, $p = .056$). Post-hoc analyses indicate a near-significance increase in puff volume between time point one and two for both blocking conditions ($p = .0187$; refer to Fig. 2B).

2.2.4.1.1. Puff velocity. Mean values appear in Table 1. Repeated measures ANOVA indicate a significant main effect of blocking condition ($F = 12.46$, $p < .01$).

2.2.4.1.2. Puff duration. Mean values appear in Table 1. Repeated measures ANOVA indicate a significant main effect of blocking condition ($F = 8.62$, $p < .05$).

2.2.5. Subjective measures

There was a significant main effect of blocking condition for ratings of strength ($F = 18.7$, $p < .01$) and smoke weakness ($F = 11.3$, $p < .01$), such that the unblocked cigarettes were rated as not as strong as the blocked cigarettes and the smoke from the unblocked cigarettes seemed weaker than the smoke from the blocked cigarettes. Additionally, there was a marginally significant effect of cigarette mildness ($p = .053$), such that the unblocked cigarettes were rated milder than the blocked cigarettes (refer to Table 1).

2.2.6. Intraclass correlation of smoking topography measures and CO boost

Participants' smoking topography measures appeared to be consistent over time. All intraclass correlation coefficients (ICC) were in the fair-to-good (0.4 > ICC < 0.75) or excellent (ICC > 0.75) range and were significant ($p\text{s} < .01$). ICCs for unblocked and blocked CO boost were less consistent. All data are reported in Table 2.

2.2.7. Smoking topography as a predictor of CO boost

Regression analysis controlling for blocking condition, order and nicotine dependence score was used for analysis of topography predictors of CO boost. Puff volume was a significant predictor of CO boost (beta = 0.03, $p < .01$, $r^2 = 0.59$), as was puff duration (beta = 0.65, $p < .05$, $r^2 = 0.58$). Puff velocity showed a trend toward a significant relationship with CO boost (beta = 0.03, $p = .10$, $r^2 = 0.54$). Larger puff volume and longer puff duration were positively associated with greater CO boost.

2.3. Discussion

This study provides additional support that blocking half of the filter vents on ultra-light cigarettes significantly increases

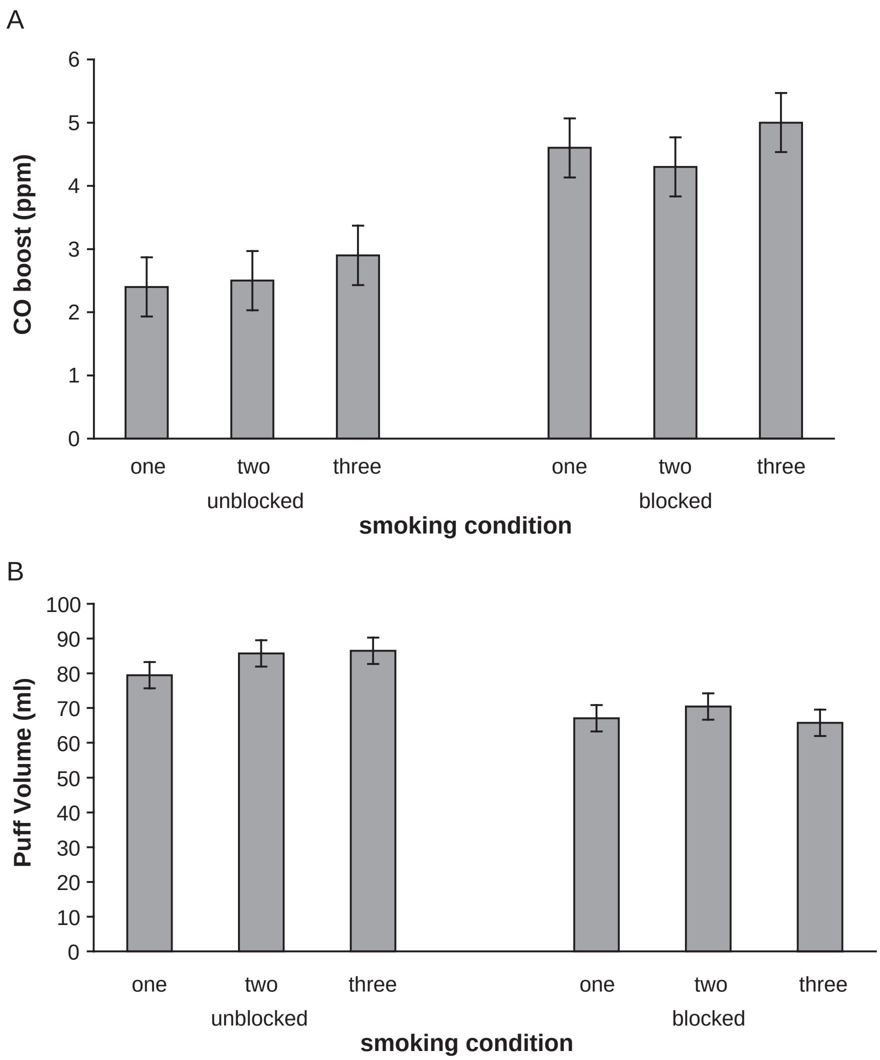

Fig. 2. A. Study 2. The effect of order and filter vent blocking condition on CO boost. Values are CO boost (in parts per million) reported as mean ± standard deviation. Significant main effect of blocking indicates greater CO boost when filter vents are blocked. B. Study 2. The effect of order and filter vent blocking condition on puff volume. Values are average puff volume (in milliliters) reported as mean ± standard deviation. Significant main effect of blocking indicates larger puff volumes in the unblocked condition.

CO levels. Additionally, this study provides support for the reliability of CO boost as a measure of relative exposure in vent blocking studies. We also demonstrate a relationship between measures of smoking topography and CO boost that has been shown elsewhere (Strasser et al., 2004; USDHHS, 1988; Zacny et al., 1986).

Table 2
Study 2

Variable	Smoking condition					
	Unblocked			Blocked		
	ICC	95% CI	*p*	ICC	95% CI	*p*
CO boost (ppm)	.22	−.12–.62	.11	.36	.05–.72	.02
Puff volume (ml)	.80	.57–.93	.001	.74	.47–.91	.001
Puff velocity (ml/s)	.52	.17–.81	.002	.60	.27–.85	.001
Puff duration (s)	.82	.60–.94	.001	.82	.60–.94	.001

Intraclass correlation coefficients with 95% confidence intervals and p-value for CO boost and smoking topography measures for unblocked and blocked smoking conditions.

Subjective ratings were consistent with Study 1, however, we speculate that we observed fewer significant rating effects due to the participant smoking the same cigarette three times consecutively and therefore contrasts were not as strong between cigarettes as observed in Study 1.

2.4. General discussion

CO boost has been used in several studies to assess differences in smoke exposure due to changes in smoking behavior (Zacny et al., 1987) and filter vent blocking (Sweeney and Kozlowski, 1998; Sweeney et al., 1999). Research by Rickert (1983) demonstrated that when light cigarettes were machine-smoked, blocking filter vents produced a relatively greater CO increase, importantly demonstrating that filter vent blocking on light cigarettes is capable of increasing smoke exposure. Subsequent behavioral studies have found not only that this same effect is not observed when participants smoke light cigarettes (Sweeney et al.,

1999) but also that the impact of filter vent blocking increasingly diminishes as the amount of filter ventilation decreases (Sweeney et al., 1999). This latter study did allow puff number to vary and participants took significantly more puffs during the unblocked smoking condition, thereby potentially allowing compensation to occur. Our protocols fixed the number of puffs, eliminating number of puffs as a potential way to compensate.

Smoking topography, as part of smoking behavior, is a more complex occurrence than machine smoking. By design, the smoking topography mouthpiece does not permit behavioral filter vent blocking. This type of restriction may affect puffing patterns in ways that are not fully understood. A naturalistic study that did not utilize the topography device but was able to replicate our findings would strengthen the external validity of our laboratory-based findings.

Smoking topography measures were not consistent predictors of smoke exposure but do appear to be associated with CO boost. Puff velocity approached significance as a predictor of CO boost in both studies ($ps < .10$) and puff volume and puff duration were significant predictors of CO boost in Study 2. These findings suggest the importance of smoking topography in smoke exposure and also hint at the complexities in understanding smoking behavior and the need for models which account for factors such as preferred cigarette brand characteristics (Scherer, 1999), tar and flavoring preferences (Schuh et al., 1996), gender (Eissenberg et al., 1999), mood and environment (Hatsukami et al., 1990; Payne et al., 1991).

Our results also support that, under controlled conditions, blocking the filter vents on Marlboro® Light cigarettes can increase CO exposure. Marlboro® Light cigarettes are currently the best selling cigarette brand in the United States. Smokers of these cigarettes are generally unaware of the filter vent holes and are misinformed about the health risks of low-tar cigarettes (Cummings et al., 2004; Kozlowski et al., 1996a). Therefore the significance of the finding that filter vent blocking increases smoke exposure of light cigarettes has potentially enormous public health implications.

We have demonstrated that CO boost is a reliable measure that can be used to assess smoke exposure in smoking behavior studies. When participants do not switch brands within a session, smoking topography measures are predictive of CO boost.

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