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Effects of Puff Number and Puff Spacing on Carbon Monoxide Exposure From Commercial Brand Cigarettes[1]

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WEINHOLD, L. L. AND M. L. STITZER. *Effects of puff number and puff spacing on carbon monoxide exposure from commercial brand cigarettes.* PHARMACOL BIOCHEM BEHAV **33**(4) 853–858, 1989.—Six chronic smokers of mid- to high-carbon monoxide (CO) yield cigarettes smoked ultralow- (1.6 mg CO), low- (5.9 mg CO) and high- (14.3 mg CO) yield commercial cigarettes under controlled smoking conditions in which either puff number or puff spacing was manipulated. CO exposure (pre- to postsmoking increments) was directly related to the number of puffs taken for all cigarette yields. CO exposure from the high- and low-yield cigarettes was equivalent when the number of puffs taken from the low-yield cigarettes was increased by 50% (from 8 to 12 puffs). In contrast, CO exposure from ultralow-yield cigarettes was still marginally lower than exposure from high-yield cigarettes after a 4-fold increase in puff number (8 to 32 puffs). Puff spacing did not affect biological exposure to CO. The study showed that the number of puffs taken during smoking can clearly affect biological exposure to CO, but that compensation for lowered yield using increased puffs is much more difficult when ultralow- as compared with low or "light"-yield cigarettes are smoked.

Carbon monoxide Cigarettes Cigarette smokers Smoking topography

TO reduce the health hazards of cigarette smoking, some chronic smokers have adopted the strategy of, I'd rather switch [brands] than fight [the habit]. Results from the Federal Trade Commission's report (4) of main stream smoke constituents delivered by commercial cigarettes indicated that consumers have a broad range of tar, nicotine and carbon monoxide deliveries from which to select a preferred brand. The relationship between main stream cigarette smoke carbon monoxide (CO) delivery and biological exposure to CO has been intensively studied, but requires further clarification.

In general, basal body burden breath CO (i.e., afternoon levels not immediately postsmoking) have shown little relationship to CO deliveries of smokers' usual brands (5, 6, 11) or experimenter-initiated brand switching (12). When differences are seen, it is generally because ultralow-yield cigarettes result in reduced biological exposure to CO (2,10).

The poor observed relationship between CO delivery and CO exposure has been attributed by most authors to changes in smoking behaviors such as number of cigarettes smoked per day (11), hole blocking of the filter vents by mouth or fingers (8); and number, size and frequency of puffs taken (12). Recent studies from our laboratory, for example, showed that subjects smoked more cigarettes per day and also took larger and more closely spaced puffs when assigned to smoke low-yield as compared to higher-yield cigarettes (5).

The current studies were conducted to further clarify how smoking behaviors can influence biological exposure to CO from commercial brand cigarettes. The studies took an experimental, rather than a naturalistic, approach and manipulated smoking parameters in order to determine the effects of these behavioral manipulations on biological exposure. Experiment 1 examined the effects of puff number while Experiment 2 examined the effects of puff spacing on biological exposure as determined by postsmoking CO increments.

EXPERIMENT 1: PUFF NUMBER

The purpose of this study was to assess the effect of puff number on biological exposure to CO from cigarettes with a wide range of CO delivery characteristics. Using puff number as a means to vary smoke dose, we determined a puff number dose-effect function for several different commercial brand cigarettes. In addition, we were interested in determining how many puffs a smoker would have to take to equate CO exposure from cigarettes with very different CO yield characteristics. Data from a previous controlled smoking experiment (13) suggested that postsmoking CO increments from high-yield (approximately 15

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mg CO delivery) and low-yield (approximately 6 mg CO delivery) cigarettes could be equated with a small (e.g., 50%) increase in smoke dose from the low-yield cigarettes but that a much larger dose increment (e.g., 300%) would be needed to achieve equivalent CO exposure from the ultralow-yield (approximately 1.5 mg CO delivery) cigarettes as compared with high-yield cigarettes. Thus, puff parameters were selected for the present study both to determine the effects of several comparable puff doses across three cigarette yield conditions and also to test the more specific hypothesis derived from the previous experiment concerning puff doses that would yield equivalent biological exposure for cigarettes with a wide range of yield characteristics.

METHOD

Subjects

Two female (H.W.I., L.P.O.) and four male (H.M.C., J.O.X., R.H.I., W.E.V.) chronic smokers of commercial cigarettes delivering from middle to high CO yields served in the experiment. Mean age of the subjects was 37.0 years (range, 28–47). Subjects smoked cigarettes for 19.33 mean years (range, 10–25) at the recent mean rate of 34.17 cigarettes per day (range, 25–50). Data from the Federal Trade Commission (4) revealed that the commercial brands smoked by subjects delivered the following mean values of smoke constituents per cigarette: 13.75 mg carbon monoxide, 0.98 mg nicotine and 14.88 mg tar. Subjects were recruited by newspaper advertisements and paid $5.00 per hour for participation in the experiment.

Cigarettes

Subjects smoked ultralow- (Carlton), low- (Vantage Ultra-Lights) and high- (Camel filter) yield cigarettes during daily smoking sessions. FTC-determined (4) yields were: tar (1.3, 4.7, 15.6 mg), nicotine (0.11, 0.43, 1.07 mg) and carbon monoxide (1.6, 5.9, 14.3 mg), respectively. Cigarettes were stored under refrigeration and maintained at room temperature 15 min prior to smoking sessions.

Procedure

Subjects were seated in an enclosed, well-ventilated room containing a television set and topography equipment. Cigarettes were lit with a puffer device. Smoking trials were sequenced so that at least 25 min elapsed between puffs of previous and subsequent trials.

Each subject participated in 27 smoking trials with three trials per session day. To facilitate consistent baseline CO levels, subjects were requested to smoke a consistent number of cigarettes prior to arriving at the laboratory and to refrain from smoking 30 min preceding daily smoking sessions. Subjects also abstained from smoking during the intertrial-intervals which were at least 25 min.

Smoke dose was manipulated by using the following nine puff number/cigarette yield conditions: 8, 16, 24, 32 puffs from ultralow-, 8, 12, 16 puffs from low- and 8, 16 puffs from high-CO yield cigarettes. The nine conditions were repeated three times as per random design. With the exception of the last 4 puffs of the 12 puff condition, each cigarette provided 8 puffs of smoke.

Puff onset was controlled by verbal cues delivered at 45-sec intervals. Biofeedback from the computer was used to obtain 50-ml puff volume and 25 percent vital capacity postpuff inhalation volume. The Apple IIe computer feedback system has been described in previous reports (13,14). Briefly, puffing topography was monitored by a portable flowmeter cigarette holder and respiratory activity was monitored by two plethysmograph belts connected to the Respitrace Calibrator (Respitrace Corp). The Apple IIe computer recorded data based on input received from the portable flowmeter and the Respitrace. Biofeedback for puff volume and inhalation volume was provided by the Apple computer which summed volume measures in real time and emitted a beep when preset parameters were approached. The flowmeter-Apple IIe system was calibrated daily via syringe and subjects were calibrated to the Respitrace-Apple IIe system prior to each trial by rebreathing into 800 ml capacity spirobags.

Smoking Behavior Measures

Puff-respiratory cycles were recorded in real time from puff onset (initial negative oral pressure applied to the flowmeter cigarette holder) through exhalation of smoke from the lungs. During each puff-respiratory cycle, the following puffing behaviors were recorded: 1) *puff number*—number of puff onsets, 2) *interpuff interval*—time from each puff offset (end of negative oral pressure applied to the flowmeter cigarette holder) to next puff onset, and 3) *puff volume*—integrated differential pressure signal from puff onset through puff offset. The following respiratory behaviors were recorded during each puff-respiratory cycle: 1) *inhalation duration*—time elapsed from puff offset to peak amplitude of Respitrace signal, 2) *inhalation volume*—calibrated value of Respitrace output during inhalation duration, and 3) *lung exposure duration*—time elapsed from inhalation onset through appearance of the minimum amplitude of Respitrace signal concomitant with exhalation offset. Exhalation duration and exhalation volume were recorded but were not included in the data analysis.

Increments in Biological Exposure to Carbon Monoxide (CO)

Two expired end-air CO samples were obtained from each subject immediately preceding and two min following the last puff of each smoking trial. Subjects invoked a forced exhalation-inhalation cycle, breath-held for 20 sec and exhaled into two one-liter bags. The second one-liter bag, which contained expired air in proximity to the alveoli, was analyzed for CO content using an Ecolyzer 2000 (Energetics Science, Elmsford, NY). The efficacy of this standardized procedure for breath CO collection and measurement was recently reconfirmed (7).

Vital Capacity

Vital capacity measures were obtained to grossly assess the respiratory status of each research subject and to determine 25 percent vital capacity for inhalation volume values employed during the experiment. Vital capacity was determined by instructing subjects to invoke a forced exhalation-inhalation cycle, thereafter exhaling into a water spirometer. The process was repeated three times and the average value was the vital capacity measure for each subject.

Data Analysis

Data for the 8 and 16 puff conditions were analyzed by $3 \times 2 \times 3$ (Yield × Puff Number × Session) ANOVAs with repeated measures on all factors. Session signifies order of presentation across the three replications. Data for the 3 puff number conditions expected to yield equivalent CO increments were analyzed in 3×3 (Dose × Session) ANOVAs with repeated measures on both factors. Dose conditions entered were ultralow-, 32 puffs; low-, 12 puffs; and high-CO yield, 8 puffs. Specific

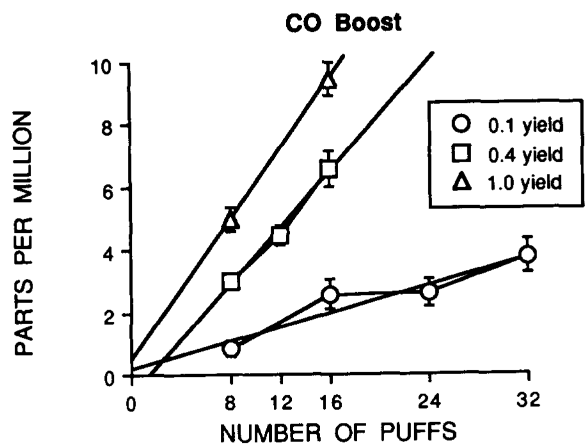

FIG. 1. Breath CO increments ppm (pre- minus postsmoking) following different numbers of consecutive puffs from ultralow- (1.6 mg CO/cigarette), low- (5.9 mg CO/cigarette) and high- (14.3 mg CO/cigarette) yield commercial brand cigarettes.

between-condition comparisons were made using Tukey's post hoc tests.

RESULTS

Increments in Biological Exposure to CO

Average presmoking CO levels were quite similar across the 9 experimental conditions, ranging from 30.3 (±1.3 SEM) to 33.7 (±2.3 SEM) ppm for 18 observations at each condition. Dose effect curves for CO increments obtained following the nine yield/puff number conditions are shown in Fig. 1. Subjects who inhaled 8, 16, 24 and 32 puffs from ultralow-yield cigarettes achieved mean CO increments of 1.00, 2.56, 2.61 and 3.78 ppm, respectively. Inhalation of 8, 12 and 16 puffs from low-yield cigarettes by subjects resulted in mean CO increments of 3.00, 4.44 and 6.56 ppm, respectively. Eight and 16 puffs inhaled from high-yield cigarettes by subjects resulted in mean CO increments of 4.94 and 9.44 ppm, respectively.

When CO increments were compared for the three cigarette yields (ultralow-, low- and high-CO yields) after 8 and 16 puffs, a significant effect of Yield, $F(2,10)=62.26$, $p<0.01$, Puff Number, $F(1,5)=64.32$, $p<0.01$, and Puff Number × Yield Interaction, $F(2,10)=6.82$, $p<0.01$, were obtained. Within each yield, CO increments after 8 versus 16 puffs were significantly different for cigarette delivering both high- (14.3 mg) and low- (5.9 mg) CO yields ($Q>9.30$, $ps<0.01$) and marginally significant for ultralow cigarettes that delivered only 1.6 mg CO ($Q=4.30$, $p<0.06$).

Z-tests (3) were used to compare beta weights, which correspond to slopes of regression lines fit to the puff number/CO boost curves for each cigarette type. Beta weights were 0.49, 0.66 and 0.77 for the ultralow-, low-, and high-yield cigarette conditions, respectively. The regression function slope for the ultralow-yield cigarette was significantly lower than slopes for both the low-yield ($Z=2.38$, $p<0.003$) or high-yield ($Z=3.26$, $p<0.002$) cigarettes. Slopes for the low-yield and high-yield cigarettes were not significantly different from each other ($Z=0.95$, $p>0.05$).

When CO increments were compared for ultralow-, 32 puffs; low- 12 puffs; and high-, 8 puff conditions, a significant Dose effect was obtained, $F(2,10)=4.91$, $p<0.05$. Post hoc comparisons revealed that CO increments were not different after 8 puffs from the high-yield cigarettes (4.94 ppm) versus 12 puffs from the low-yield cigarettes (4.44 ppm), ($Q=1.89$, $p>0.05$). However, CO increments after 32 puffs from the ultralow-yield cigarettes (3.78 ppm) was still slightly lower than the CO increments obtained after 8 puffs from the high-yield cigarettes ($Q=4.94$, $p<0.05$).

TABLE 1

PUFF AND RESPIRATORY MEASURES COLLAPSED ACROSS THE NINE PUFF NUMBER CONDITIONS

	Projected Values	Obtained Values*
Interpuff Interval (sec)	45	44.62 (0.9)
Puff Volume (ml)	50	51.03 (1.6)
Inhalation Volume (ml)	783†	775.63 (135.7)
Lung Exposure Duration (sec)	—‡	5.50 (1.5)
Inhalation Duration (sec)	—‡	2.19 (0.6)

*Mean (±s.d.).
†Average of 25% vital capacity for study subjects.
‡Not controlled.

Smoking Topography

Table 1 shows targeted and average obtained values for puff and respiratory behaviors that were controlled during the nine yield/puff number conditions. Statistical tests comparing smoking behaviors of subjects during the 8 and 16 puff conditions from ultralow-, low- and high-CO yield cigarettes revealed a significant Yield effect for puff volume, $F(2,10)=25.70$, $p<0.01$, and inhalation duration, $F(2,10)=5.31$, $p<0.05$. Subjects took slightly larger puff volumes (51.9 vs. 50.2 ml) and inhaled smoke more quickly (2.13 vs. 2.28 sec) from the ultralow- than from the high-CO yield cigarettes ($Q=3.69$, $p<0.05$; $Q=4.10$, $p<0.05$), respectively. There were no significant differences in smoking topography across puff number conditions.

EXPERIMENT 2: PUFF SPACING

Previous studies have reported that smokers space their puffs close together when smoking ultralow-yield as compared with higher-yield cigarettes (16). Puff spacing is at least one indicator of smoking intensity, the other indicator being puff flow rates. The purpose of this study was to determine whether puff spacing is a component of smoking that contributes to biological exposure to CO, as measured by postsmoking increments in breath CO. Thus, puff spacing was controlled at 15-, 30- or 45-sec intervals while subjects smoked cigarettes with a wide range of CO delivery characteristics.

METHOD

Subjects

Three male (J.M.C., R.H.I., W.E.V.) and three female (H.W.I., L.P.O., L.S.H.) chronic smokers of commercial cigarettes delivering from middle- to high-CO yields served in the experiment. Mean age of the subjects was 35.5 years (range, 30–47). Subjects smoked cigarettes for 20.5 mean years (range, 13–37). Data from the FTC revealed that the commercial brands smoked by subjects delivered the following mean values of smoke constituents per cigarette: 13.57 mg carbon monoxide, 0.92 mg nicotine and 13.8 mg tar. As in Experiment 1, new subjects were recruited by newspaper advertisement and paid $5.00 per hour for participation in the experiment.

Cigarettes

As in Experiment 1, subjects smoked Carlton, Vantage Ultralights and Camel Filter cigarettes during controlled smoking sessions.

Procedure

Subjects participated in nine daily laboratory smoking sessions consisting of three trials per day. As in Experiment 1, subjects were requested to smoke a consistent number of cigarettes prior to the daily session and also to abstain from smoking 30 min preceding daily smoking sessions. Puffing within trials was signaled to occur following either 15-, 30- or 45-sec interpuff intervals. The three puffing intervals were presented daily using counterbalanced design. One cigarette type, i.e., ultralow-, low- or high-yield, was smoked each day with order of exposure to cigarette yield counterbalanced across subjects. Puff volumes were controlled at: ultralow- (60 ml), low- (55 ml) and high- (50 ml) yield cigarettes. Inhalation volume was controlled and held constant at 25 percent vital capacity for all trials. Each trial consisted of eight puff-respiratory cycles.

To ensure that 8 puffs were taken from the mid-section of each cigarette, burn times preceding first puff was adjusted for the 15- and 30-sec interpuff interval conditions only. Cigarettes were allowed to burn approximately 50 and 100 sec, respectively, before smoking under the 30-sec and 15-sec IPI conditions.

Instrumentation and Measurement

Apparatus, smoking behavior measures, measurement of increments in biological exposure to carbon monoxide, vital capacity determination and subjective effects were the same as described in Experiment 1.

Data Analysis

Data were analyzed by 3 × 3 × 3 (Yield × Interpuff Interval × Session) ANOVAs with repeated measures on all factors. Yield refers to cigarette CO delivery (i.e., ultralow—1.6 mg CO, low—5.9 mg CO and high—14.3 mg CO). Interpuff Interval (IPI) refers to time between puff offsets (i.e., 15- 30- and 45-sec interpuff intervals). Session signifies order across 3 replications of the condition. Between-condition comparisons were made using Tukey's post hoc tests.

RESULTS

Increments in Biological Exposure to CO

Average presmoking breath CO levels were quite similar across the 9 experimental conditions, ranging from 29.6 (± 1.0 SEM) to 35.9 (± 1.3 SEM) for 18 observations at each condition. CO increments obtained during the nine yield/interpuff interval smoking sessions are shown in Fig. 2. Subjects who inhaled 8 puffs from ultralow-yield cigarettes every 15, 30 and 45 sec achieved CO increments of 1.28, 1.72 and 1.22 ppm, respectively. Inhalation of 8 puffs from low-yield cigarettes every 15, 30 and 45 sec resulted in CO increments of 3.05, 3.72 and 3.50 ppm, respectively. Eight puffs inhaled from high-yield cigarettes every 15, 30 and 45 sec resulted in CO increments of 4.33, 4.39 and 4.55 ppm, respectively.

No significant IPI effect was obtained for CO increments, $F(2,10) = 2.55$, $p > 0.05$. A significant Yield effect for CO increments was obtained, $F(2,10) = 38.60$, $p < 0.01$. Subjects achieved significantly higher CO increments from both high- and low- than from ultralow-CO yield cigarettes ($Q > 8.22$, $ps < 0.01$). Higher CO increments were also achieved from high- than from low-CO yield cigarettes ($Q = 3.96$, $p < 0.05$).

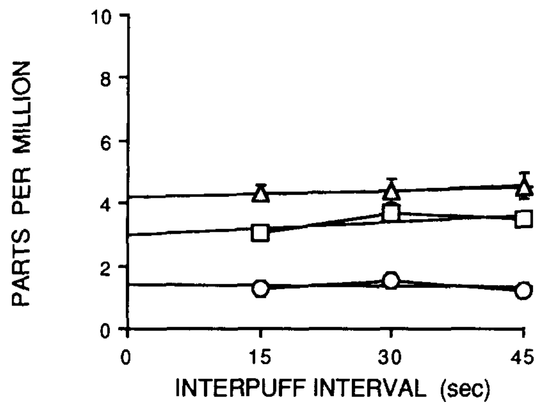

FIG. 2. Breath CO increments ppm (pre- minus postsmoking) following different intervals between consecutive puffs from ultralow- (1.6 mg CO/cigarette), low- (5.9 mg CO/cigarette) and high (14.3 mg CO/ cigarette) yield commercial brand cigarettes.

Smoking Topography

Table 2 shows targeted and average obtained values for puff and respiratory behaviors that were controlled during the 3 interpuff-interval conditions. Experimental manipulation resulted in a significant condition effect only for the interpuff interval measure, $F(2,10) = 11697.84$, $p < 0.01$. The achieved interpuff intervals during 15-, 30- and 45-sec interpuff interval conditions were significantly different from each other ($Q > 130.90$, $ps < 0.01$).

Significant Yield effects were obtained for puff volume, $F(2,10) = 238.14$, $p < 0.01$, and inhalation duration, $F(2,10) = 4.31$, $p < 0.05$. Subjects took larger puffs from the ultralow- (mean = 58.7 ml) than from both the low- (mean 54.5 ml) and high- (mean = 51.0 ml) CO yield cigarettes and larger puffs from the low than from the high-CO yield cigarettes ($Q > 16.86$, $ps < 0.01$; $Q = 13.96$, $p < 0.01$), respectively. Subjects also inhaled smoke more quickly from ultralow- (2.0 sec inhalation duration) than from both low- (2.1 sec) and high- (2.3 sec) CO yield cigarettes and from the low- than high-CO yield cigarettes ($Q = 3.96$, $p < 0.05$; $Q = 12.18$, $p < 0.01$; $Q = 8.22$, $p < 0.01$), respectively.

GENERAL DISCUSSION

The two studies reported here have shown that puff number, but not puff spacing, is an important determinant of smoke exposure as measured by postsmoking CO increments or CO boost. The magnitude of postsmoking CO boost was directly related to the number of puffs drawn and inhaled. Further, this was true across the three specific commercial brand cigarettes delivering widely different concentrations of tobacco smoke constituents (Fig. 1).

The study also showed that CO exposure increased much more gradually with increments in puff number for the ultralow-yield commercial cigarette employed than for the two higher-yield cigarettes (Fig. 1). This observation suggests that it would be relatively easy for smokers to equate their smoke exposure from low-yield (in the 0.4 mg nicotine delivery range) and high-yield cigarettes simply by increasing the number of puffs taken from the low-yield brand, but relatively difficult to equate exposure from

TABLE 2

PUFF AND RESPIRATORY MEASURES AVERAGED ACROSS THE YIELDS DURING CONTROLLED SMOKING SESSIONS OF 8 PUFFS EACH

Sec	Projected Values	Obtained Values* 15 Sec	30 Sec	45 sec
Interpuff Interval (sec)	15,30,45	15.50§(0.7)	30.57§(0.7)	44.94 (0.8)
Puff Volume (ml)	55	54.60 (1.6)	54.83 (1.5)	54.74 (2.0)
Inhalation Volume (ml)	788†	770.71 (150.8)	783.85 (123.8)	803.81 (163.3)
Lung Exposure Duration (sec)	—‡	5.50 (1.67)	5.55 (1.5)	5.62 (1.7)
Inhalation Duration (sec)	—‡	2.11 (0.6)	2.00 (0.6)	2.17 (0.7)

*Mean (±s.d.).
†Average of 25% vital capacity for study subjects.
‡Not controlled.
§$p<0.01$.

the ultralow-yield and high-yield cigarettes. This suggestion was confirmed in the present study. CO boosts from cigarettes delivering 6 mg versus 14 mg CO were significantly different when 8 puffs were drawn and inhaled from each cigarette type but were no longer significantly different when number of puffs from the low-yield cigarette was increased by 50%. In contrast, CO boost was still marginally, but significantly, lower for the ultralow-yield than for the high-yield smoking condition even when the number of puffs taken from ultralow-yield cigarettes was 4 times greater than the number of puffs from a high-yield cigarette (32 vs. 8 puffs). This emphasizes the magnitude of behavioral compensation required to equate exposure from ultralow- versus higher-yield brands.

In contrast to the effects of the puff number manipulation, shortening of the interpuff-interval had no effect on smoke exposure as measured by CO boost. In previous studies, it has been difficult to separately assess the role of puff spacing, since puff number and puff spacing are generally inversely related. There is some reason to believe that puffing intensity might be related to biological exposure since more intense puffing might produce greater amounts of smoke constituents, including carbon monoxide. This study has shown that puff spacing had no effect on carbon monoxide exposure. However, it is possible that puff flow rates, which constitute another dimension of smoking intensity, may influence exposure. Also, it is possible that nicotine levels might show effects that are not seen with carbon monoxide analysis alone.

A previous report from this laboratory showed discrepancies between predicted and obtained relative CO boost levels when subjects smoke commercial brand cigarettes with a wide range of CO delivery characteristics (13). As in these previous studies, CO boosts in the present study from a low-yield cigarette, delivering about 6 mg CO, were about 3 times higher than CO boosts from an ultralow-yield cigarette delivering 1.6 mg CO. However, high-yield cigarettes fell far short of producing CO boosts consistent with their package yields of 14–5 mg CO. We have previously suggested that this may reflect an inability of the respiratory system to absorb all the CO available from smoke of high-yield cigarettes during brief lung exposure times characteristic of cigarette smoking, a suggestion that is consistent with the increasing CO boosts observed during breath holding with high-yield commercial brand cigarettes (13). One result of this incomplete CO absorption is the relatively similar exposure levels seen with high-yield cigarettes as compared with cigarettes in the 0.4–0.7 mg nicotine range that are generally labeled as "lights" [e.g., (1)].

Findings from the puff number study demonstrate the effectiveness of the filter ventilation technologies used to produce ultralow-yield cigarettes and suggest that among the array of commercially available cigarettes, only ultralow-yield brands hold the potential to appreciably reduce the health hazards of cigarette smoking. However, population surveys of nicotine and CO body burden in relation to package yield suggest that smokers can defeat even the ultralow-yield brands to achieve CO exposure levels similar to those observed for smokers of high-yield brands (11,12), which we have shown requires at leat a 4-fold increase in smoke dose exposure to equate acute CO exposure. Clearly, behavioral compensation is important in terms of increased cigarettes and puffs per day. In addition, filter-vent blocking with finger tips or lips (8, 9, 15) clearly does play a key role in raising biological exposure particularly from ultralow-yield brands.

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