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Puffing Behavior During the Smoking of a Single Cigarette in a Naturalistic Environment

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KOLONEN, S., J. TUOMISTO, P. PUUSTINEN AND M. M. AIRAKSINEN. *Puffing behavior during the smoking of a single cigarette in a naturalistic environment.* PHARMACOL BIOCHEM BEHAV 41(4) 701-706, 1992.—The 36 participants in this study were habitual low-yield cigarette smokers, medium-yield cigarette smokers, and switchers from medium- to low-yield cigarettes. All participants smoked both low- (0.4 mg) and medium-nicotine (0.9 mg) cigarettes during the study. Puffing indices were recorded during the first two cigarettes, after an overnight abstinence of smoking, by a portable flowmeter processor unit in a naturalistic environment. The puff volumes per cigarette and per day were significantly lower while switching to higher-yield cigarettes, mainly due to a decrease in the number of puffs and longer interpuff intervals, but also due to a decline in puff duration and flow rate. However, the downregulation by puff volume was incomplete, at most two thirds, as calculated by machine smoking yields. Within the course of smoking a single cigarette, the flow rate was quite stable, puff duration and puff volume decreased toward the end of the cigarette, and interpuff interval was longest during the middle of the cigarette. Total puff volumes per cigarette were similar in the first two cigarettes of the day after an overnight abstinence of smoking, with no significant differences in other puff parameters. Diurnal cotinine excretion revealed that nicotine titration in switching situations was very accurate among switchers and medium-yield cigarette smokers, but not among the low-yield cigarette smokers, and so called oversmoking was found with the higher-nicotine brand. Preferred cigarette type had little effect on the puffing patterns of smokers in single cigarettes.

Smoking Nicotine Cotinine Single cigarette Puff-by-puff analysis Naturalistic environment

PUFFING behavior of smokers is sensitive to alterations in nicotine availability. It is also influenced by psychological factors related to the ordinary smoking situation. In several studies that have been mainly carried out in the laboratory, puffing parameters have been expressed as mean values per cigarette (25). Furthermore, in comparative studies some puff parameters in the laboratory have been found to differ significantly from those obtained surreptitiously in a naturalistic setting by less obstructive observational measurements (7,23). Only a few studies have utilized a portable measuring device in a naturalistic environment. It has been indicated that situational factors, such as time of day (20), setting (environmental factors), and set (mental state) may be involved in the control of smoking topography (12). However, as far as we know, no other reports have been published on puffing behavior for single cigarettes under "natural" conditions. Laboratory studies have shown that during the course of smoking a single cigarette puff volume falls (1,9,10,14,19,28) while puff duration decreases (1,6,10,21,22,28) or remains stable (9). In addition, the initial interpuff interval increases (1,6,10), then decreases again toward the end of the cigarette while the pressure drop along the cigarette remains fairly constant (10,19).

The present study was conducted to examine details of smoking topography in single cigarettes of low and medium nicotine/tar yields by a portable recording device. The novel aspect in this study was that a puff-by-puff analysis was performed in a naturalistic environment in three smoking groups with different smoking histories. Special focus was put on the possible differences in puff parameters between the first two cigarettes after overnight abstinence. Also, some correlations between the various puff parameters were estimated.

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METHODS

Subjects

For the puff-by-puff analysis, the smoking behavior data in young smokers (17) was reanalyzed. Volunteers, 36 smoking students, were divided into three groups according to their smoking histories, disclosed by a questionnaire (Table 1). The main criterion of acceptance was habituation, which was classified on the basis of nicotine and tar yields according to machine smoking: low yield, nicotine ≤ 0.6 mg, tar ≤ 9.9 mg; and medium yield, nicotine 0.7–1.2 mg, tar 10–15 mg per cigarette. The first group consisted of 18 subjects who had always smoked low-yield cigarettes, the second group consisted of 10 smokers of medium-yield cigarettes, and the third group of 8 smokers who had switched from medium- to low-yield cigarettes (switchers) 2.8 ± 1.3 years (range 1–5) ago. Smoking times were, on the average, 3.9, 9.4, and 5.7 years, respectively. Written informed consent was obtained after the nature of the procedures had been explained.

Measurements

Analysis of puffing parameters (puff duration, flow rate of smoke, single puff volume, puff volume per cigarette and per day, interpuff interval, and number of puffs) was performed by a microcomputer-assisted system (24). The measurement system was based on the Bernoulli equation, which states that the pressure difference is proportional to the square of flow. The measuring device contained a portable microcomputer programmed by the extended version of Microsoft Basic, with a microcassette unit and an IBM-compatible personal computer. Subjects smoked cigarettes through a holder with an orifice flowmeter that measured pressure difference as an analog signal by a differential-type transducer. Then, the signal was changed to digital by an analog-digital converter. After smoking a cigarette, the puff data was automatically taped on the microcassette. Data were transmitted from cassette to the hard disc through an RS-232C interface. The measuring devices were calibrated with a syringe (60 ml) before and after measurements on the test days. All subjects became familiar with the device on the day before the first test day.

Urine samples were collected over 24 h and subjects started the test day by emptying their bladder at 8:00 a.m. Samples were stored at −20°C until analyzed. Cotinine in urine was analyzed by the HPLC method previously described (16) with minor modifications in the extraction procedure.

Study Procedure

Volunteers were tested in three 1-week smoking blocks. Subjects smoked their preferred brand, with no limits, for the first week, the second week low-yield cigarettes (nicotine 0.4 mg, tar 5.0 mg), and the third week medium-yield cigarettes (nicotine 0.9, tar 15.0 mg). According to instructions given at the beginning of the study, volunteers were permitted to smoke ad lib, but only those cigarettes selected for that week. Puffing indices were recorded on the last day of every test week. Puff parameters in single cigarettes were investigated puff by puff only in the first two low- and medium-yield cigarettes smoked after an overnight abstinence (8–11 h). The average interval between these two "morning" cigarettes was 73 min.

Data Analysis

Calculations and statistical analyses were performed with the Stats+ microcomputer program (StatSoft™, StatSoft, Inc.). Differences between groups were analyzed by repeated-measures analysis of variance (ANOVA) with posthoc comparisons by the Scheffè multiple comparison test. The differences in puff parameters within the three groups in the course of the two morning cigarettes were also examined using the nonparametric Friedman two-way ANOVA by ranks followed with multiple comparisons between puffs. Linear association between puff volume and other puff parameters in the different portions of cigarette was estimated by the Pearson's correlation coefficient with an indication of significance level. Specific comparisons between the preferred brand of subjects and the test brands are not given in the text since the brands used by different individuals had different nicotine/tar yields.

RESULTS

Daily Puff Volume and Cotinine Excretion

When different groups smoked the same type of cigarette, there were no significant differences although switchers

TABLE 1

SOME CHARACTERISTICS OF THE 36 STUDY SUBJECTS GROUPED INTO THREE GROUPS ACCORDING TO THEIR PREFERRED KIND OF CIGARETTES ASCERTAINED BY THE QUESTIONNAIRE

	Smoker Groups by Smoking History*		
	L-Y Smokers (n = 18)	Switchers (n = 8)	M-Y Smokers (n = 10)
Men/women	5/13	3/5	3/7
Age (years)	22 ± 2.6	27.4 ± 6.9	23.4 ± 2.2
Smoking years	3.9 ± 1.7	9.4 ± 6.9	5.7 ± 3.1
No. of cigarettes per day	12.3 ± 6.8	15.9 ± 8.8	10.9 ± 3.7
Preferred Cigarette Brand			
Tar (mg/cig.)	6.3 ± 3.0	7.1 ± 1.7	14.2 ± 1.5
Nicotine (mg/cig.)	0.4 ± 0.2	0.5 ± 0.1	0.9 ± 0.2
CO (mg/cig.)	5.5 ± 2.8	6.5 ± 2.1	10.9 ± 1.9

Data are mean ± SD. L-Y and M-Y, low- and medium-yield (tar/nicotine) cigarette.

*Groups are formed by the preferred cigarette type smoked. Switchers have changed their cigarette brand from medium- to low-yield cigarette.

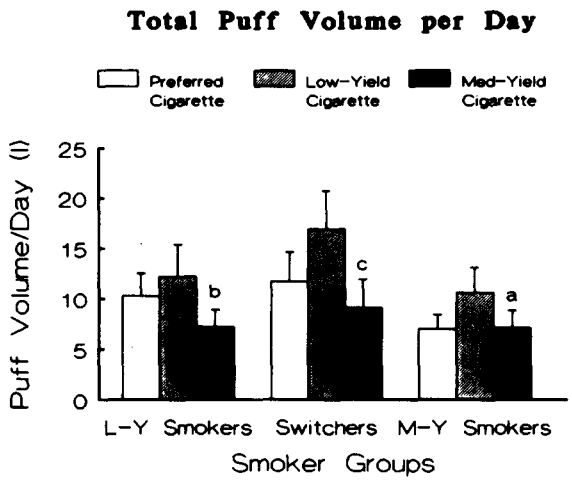

FIG. 1. Total puff volume per day with preferred, low-yield, and medium-yield cigarettes in the different smoking groups. Mean ± SE; 18 low-yield cigarette (L-Y) smokers, 8 switchers, and 10 medium-yield cigarette (M-Y) smokers. a, $p < 0.05$; b, $p < 0.01$; c, $p < 0.001$ between low- and medium-yield cigarettes (Friedman ANOVA).

tended to have higher volumes. All groups had the highest puff volumes per day while smoking low-yield and the lowest volumes while smoking medium-yield test cigarettes (Fig. 1). When switching from low- to medium-yield brands, habitual low-yield cigarette smokers decreased their daily volumes, on the average, by 41% ($\chi^2 = 7.60$, $p < 0.01$ by the Friedman ANOVA), switchers decreased by 46% ($\chi^2 = 12.25$, $p < 0.001$), and medium-yield cigarette smokers decreased by 38% ($\chi^2 = 3.43$, $p < 0.05$).

The results showed that within the groups there were no significant differences between the brands in cotinine excretion. In the low-yield smokers, daily cotinine excretion averaged (±SE) 1.47 ± 0.20 mg with their preferred brand, 1.28 ± 0.21 mg after the low-yield cigarettes, and 1.83 ± 0.30 mg after the medium-yield cigarettes; in the switchers, 2.21 ± 0.35, 2.65 ± 0.56, and 2.68 ± 0.45 mg; and in the medium-yield cigarette smokers 2.19 ± 0.45, 2.06 ± 0.42, and 2.15 ± 0.38 mg, respectively. A significant difference was found only between low-yield cigarette smokers and switchers when they smoked the low-yield brand ($\chi^2 = 4.35$, $p < 0.05$). No significant correlation was found between daily puff volume and urinary cotinine excretion in any of the groups.

Cigarette consumption did not differ according to nicotine yields in the test cigarettes. The low-yield smokers smoked 9.1 of their preferred cigarettes. 9.0 low- and 9.6 medium-yield cigarettes per day; switchers 14.9, 15.8, and 14.2; and medium-yield smokers 9.3, 8.3, and 8.7 cigarettes, respectively. However, subjects in every group decreased the number of cigarettes during device smoking ($p < 0.06$) on the average 23.2%.

Effects of Smoking History and Deprivation

The difference in parameters between the two morning cigarettes after overnight abstinence (number of puffs, puff volume, and total puff volume per cigarette) were negligible in groups of smokers with different smoking history when the same cigarette brand was smoked (Table 2). However, when the brand was changed to medium-yield cigarettes total puff volume per cigarette was significantly lowered. Among the low-yield cigarette smokers, the decrease after switching in the first morning cigarette was 42% [$F(1,33) = 14.46$] and in the second cigarette 38% [$F(1,33) = 5.91$]; among the switchers, 38% [$F(1,14) = 14.46$] and 32% [$F(1,14) = 16.23$]; and among the medium-yield cigarette smokers 20% (not significant) and 44% [$F(1,18) = 10.03$], respectively.

The difference in total puff volume per cigarette between brands in the low-yield cigarette smokers was due to the smaller number of puffs (downregulated by 24.6%) and a 20% lower puff volume. In the switchers' group, the number of puffs decreased slightly, but puff volume fell by 32% ($p < 0.05$). Medium-yield cigarette smokers decreased puff volume by 23.4%, but the number of puffs fell only in the second morning cigarette (23.7%, Table 2).

Puffing Topography in Single Cigarettes

Puff duration tended to be shorter in the last puffs of the cigarette (Fig. 2). This was seen with both medium- and low-yield cigarettes. However, the change was statistically sig-

TABLE 2

MEAN VALUES OF SOME PUFF PARAMETERS OF THE FIRST TWO LOW- AND MEDIUM-YIELD CIGARETTES SMOKED IN THE NATURALISTIC SMOKING CONDITIONS

	Number of Puffs		Puff Volume (ml)		Puff Volume/Cigarette (ml)	
Group	L-Y Cigarette	M-Y Cigarette	L-Y Cigarette	M-Y Cigarette	L-Y Cigarette	M-Y Cigarette
L-Y Smokers						
1st Cig.	18.4 ± 1.0*	13.5 ± 0.9	66.9 ± 8.3	52.5 ± 6.9	1198 ± 144†	694 ± 98
2nd Cig.	18.6 ± 0.8†	14.4 ± 0.8	70.3 ± 9.1	57.3 ± 8.0	1292 ± 165†	799 ± 113
Switchers						
1st Cig.	18.4 ± 1.8	16.8 ± 1.4	61.3 ± 9.9‡	41.4 ± 3.7	1025 ± 27†	694 ± 83
2nd Cig.	17.6 ± 1.8	14.4 ± 1.3	64.4 ± 9.9	43.8 ± 3.7	1038 ± 66†	632 ± 76
M-Y Smokers						
1st Cig.	13.9 ± 1.6	14.4 ± 2.0	86.0 ± 9.7	66.0 ± 12.1	1088 ± 106	872 ± 152
2nd Cig.	16.9 ± 2.4	12.1 ± 1.7	84.7 ± 12.4	64.6 ± 13.1	1283 ± 135†	716 ± 117

Mean ± SE reported. L-Y and M-Y, low- and medium-yield (tar/nicotine) cigarettes.

*$p < 0.001$, †$p < 0.01$, ‡$p < 0.05$, between cigarette brands (ANOVA). No significant differences between the first and second cigarette in the puff indices.

nificant ($p < 0.01$) only in the low-yield cigarette smokers both with low-yield (first cigarette, $\chi^2 = 12.33$, and second cigarette, $\chi^2 = 9.33$) and medium-yield cigarettes (first cigarette, $\chi^2 = 10.41$, and second cigarette, $\chi^2 = 9.56$).

The flow rate along the cigarette was stable in every group with both brands. Also, the puff interval varied during the course of the cigarette, being shortest in the beginning and at the end of cigarette. Regardless, the only significant difference (first cigarette, $\chi^2 = 6.78$, second cigarette, $\chi^2 = 8.11$, $p < 0.05$) was seen in low-yield cigarette smokers (Fig. 2).

The fall in puff volume was most significant among the low-yield cigarette smokers with both brands and cigarettes (χ^2 ranged from 9.29–15.65, $p < 0.01$), but was also seen among the other groups (Fig. 3). Puff volumes in the different portions of a single cigarette were significantly ($p < 0.001$) related to puff duration ($r = 0.70$–0.88) and to flow rate ($r = 0.56$–0.76, Table 3). Poor and mostly negative correlation was found between puff volume and puff interval.

DISCUSSION

In brand-switching situations like this, smokers seem to up- or downregulate their smoke intake by changing puff volume and inhalation to maintain their usual levels of blood nicotine (25,26). The present results of diurnal cotinine excretion revealed that nicotine titration was very accurate in switchers and medium-yield cigarette smokers, but low-yield cigarette smokers seem to oversmoke when smoking stronger cigarettes. Furthermore, the daily cigarette consumption and whole-day puff volume were almost identical in habitual low- and medium-yield cigarette smokers; however, there was a clear difference in cotinine excretion when the same brand was smoked. This may be due to differences in inhalation depth in the groups. Judging from nicotine deliveries in the test cigarettes, a maximum of about two thirds of compensation within each group may be explained by changes in whole-day puff volume. These in turn can be derived from alterations in the number of puffs and individual puff volumes affected by changes in puff duration and interval. This effect has been shown in one naturalistic setting (17) and in a number of laboratory studies (3,5,13,16,27,29) where smokers altered their mean puff volume per cigarette by changing puff intensity and spacing according to the nicotine yield of the cigarette.

Puffing behavior after abstinence was very similar in the two morning cigarettes, suggesting that smokers probably do not change puffing intensity during first cigarettes very much after normal nocturnal abstinence. In an experimental study (16), it was found that smokers with medium-yield cigarettes decreased slowly the total puff volume per cigarette in the course of the day, but with low-yield cigarettes it was rather stable. It has been shown that smokers have quite a high blood level of nicotine in the morning (2), and for that reason they may not have a great need to change puffing behavior. However, in an experimental study smokers notably increased nicotine seeking after an overnight abstinence (15).

Smoking history, that is, the preferred cigarette type, may also influence changes in puffing behavior. There were some significant differences in the flow rate between the medium-yield cigarette smokers and switchers and habitual low-yield cigarette smokers. However, while this last group took more puffs per cigarette, no significant differences were found between total puff volumes with the same test brand. In a cross-sectional study (3), puff volumes per cigarette differed significantly between smokers whose usual cigarette contained

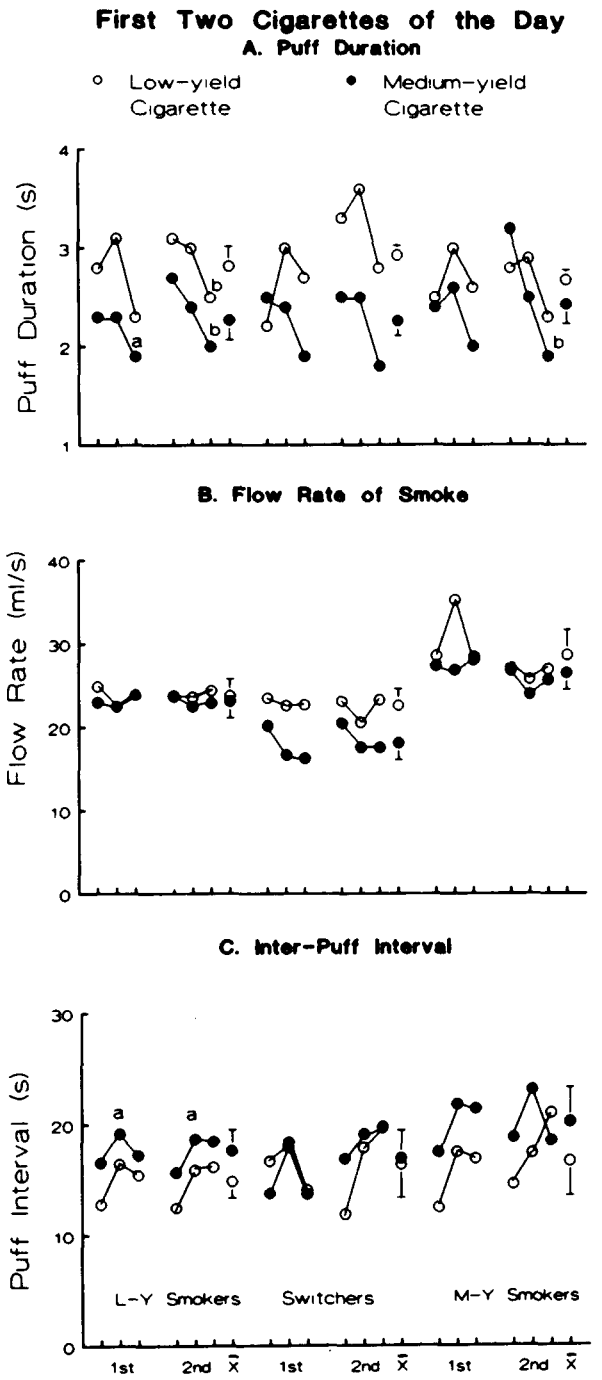

FIG. 2. Average puff duration, flow rate, and puff interval of the first, middle, and last three puffs in the first two low- and medium-yield cigarettes on the test days in natural conditions. X, mean ± SE. See Fig. 1 for numbers per group and abbreviations. a, $p < 0.05$; b, $p < 0.01$ between the first and last three puffs (puff duration) or the first and middle three puffs (puff interval) during a single cigarette (Friedman ANOVA).

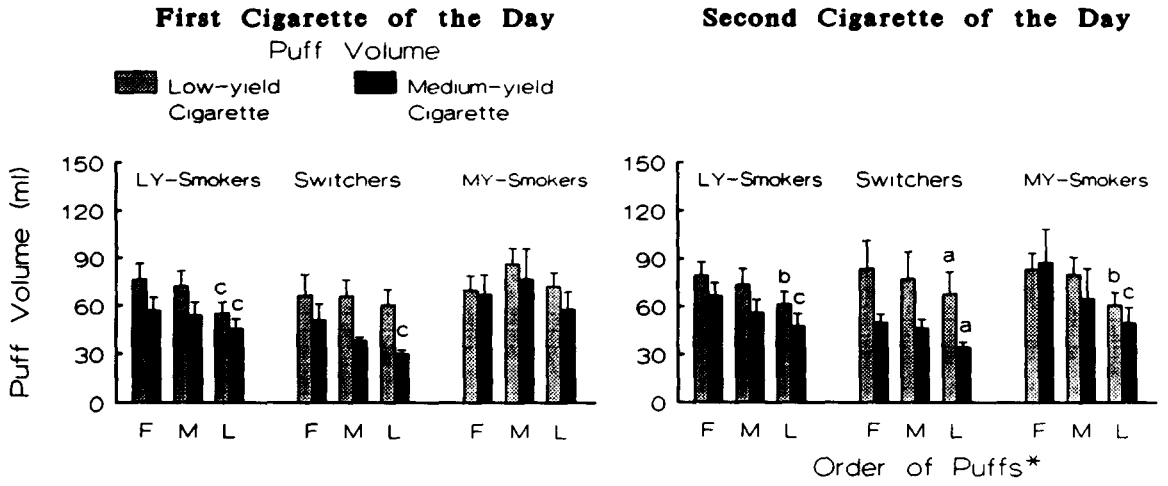

FIG. 3. Puff volume during the course of a single cigarette in natural settings. *The first three (F), middle (M), and last (L) puffs in the first two cigarettes on the test days. Mean ± SE. See Fig. 1 for numbers per group and abbreviations. a, $p < 0.05$; b, $p < 0.01$; c, $p < 0.001$ between the first and last three puffs within the groups (Friedman ANOVA).

nicotine 0.43 mg or less vs. 0.50–1.1 mg, whereas no significant difference was found between the groups smoking their preferred cigarettes with nicotine yields of 0.50–0.70, 0.71–0.90, or 0.91–1.10 mg.

The role of nicotine in puffing behavior is important but on the puff-by-puff level it is rather obscure. Results in this study revealed that smokers reduce puff duration and puff volume and change puff interval during the course of a single cigarette. In spite of notable intersubject variations, most volunteers showed these effects in both cigarettes. Puff volume over a single cigarette correlated best with puff duration and somewhat less with flow rate. Therefore, puff duration seemed to be the primary means of control. Our results agree with earlier laboratory studies (6,10,19,28) where smokers controlled puff volume by shortening the puff duration as the cigarette burned, probably due to deposition in the unburned cigarette and subsequential revaporization as smoking continued. The flow rate stayed rather constant during smoking, and it may well be that subjects found it simpler to control puff volume by curtailing puff duration rather than by altering flow rate (19).

Recently, Bridges et al. (3) reported that interpuff intervals appear to be the primary determinant of blood levels of smoke constituents. In the present study, interpuff intervals seem to be spaced so that the first interval is short, then longer, and short again at the end during the course of a cigarette. Short intervals between the first puffs and long puff duration may be a reflection of the nicotine crave, whereas short intervals between last puffs may be a typical maneuver for a smoker to get a final charge of nicotine just before butting the cigarette.

Also, the smoker's setting may change puffing behavior. It has been demonstrated that subjects tended to take frequent and longer puffs and to smoke more quickly in clinical and laboratory settings than in natural settings (23). Furthermore, especially in the naturalistic settings, many situational and psychological factors (set), partly related to nicotine intake, influence smoking behavior as well (12,20). However, the portable measuring device used in the previous two studies did not measure puff volume and therefore may not provide enough detailed information about puffing behavior. Also, smokers in a laboratory situation may be less distracted by companions or their activities and may simply devote more time to smoking (4,12).

In addition to nicotine and flavor (8), mechanical factors

TABLE 3

PEARSON'S PRODUCT MOMENT CORRELATION COEFFICIENT BETWEEN PUFF VOLUME AND OTHER MEASURES OF SMOKING TOPOGRAPHY WITHIN THE TWO FIRST CIGARETTES OF THE DAY

		L-Y Cigarette		M-Y Cigarette	
Puff Parameters	Order of Puff*	1st Cig.	2nd Cig	1st Cig.	2nd Cig.
Puff duration†	First	0.738	0.874	0.739	0.880
	Middle	0.800	0.705	0.849	0.765
	Last	0.801	0.871	0.719	0.700
Flow rate†	First	0.661	0.732	0.760	0.679
	Middle	0.559	0.705	0.711	0.753
	Last	0.579	0.763	0.758	0.744

*First, middle, and last three puffs.
†$p < 0.001$ with all correlation coefficients.

have been proposed to cause the decrease in puff duration and puff volume across a cigarette. First, pressure drop is one candidate responsible for the changes. This has been found to fall only slightly and the decrease is counteracted by deposition of tar in the unburned tobacco (11). Second, the elevation of smoke temperature toward the end of cigarette may result in the final puff being much smaller by volume without appreciable change in the maximum flow rate (10). In the present studies, a gradual decrease during a single cigarette was found but no specific decrease in the volume of the last puff. Furthermore, the use of the holder must inevitably distort smoking to some extent and as present measurements suggest may decrease ordinary cigarette smoking in natural conditions. While smoking low-yield cigarettes, smokers may block the ventilation holes (18), impossible to do with our device due to the design of the holder.

In conclusion, the present study showed that smokers reduce puff duration and number of puffs in the course of both cigarette brands. Puff duration also seemed to be shorter and puff number smaller with medium-yield cigarettes. Smokers downregulated puff volume identically in every smoking group when switching to the higher-yield brand but the decrease was incomplete. The difference in puff volume per cigarette was mainly based on change in puff duration and the number of puffs taken from the cigarette. The latter effect was also found clearly in puff interval.

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