METHODS & DESIGNS

Noninvasive measurement of smokers' tar and nicotine intake

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A simple device for monitoring cigarette smokers' intake of tar and nicotine is described. This device divided the mainstream smoke into two parallel paths, one containing seven parallel capillary tubes and the other containing one capillary tube; a Cambridge filter trapped the smoke passing through the path containing one tube. Analyses of both tar and nicotine trapped in the filter were performed by gravimetric and chemical methods. Calibration tests verified that a constant fraction of the tar and nicotine was retained in the apparatus over a wide range of conditions, allowing the calculation of smoke intake into the mouth. With supplementary methods for measuring the amount of smoke exhaled, the apparatus can be used to measure smoke deposition in the respiratory tract.

To assess the behavioral, pharmacologic, and health effects of cigarette smoking, it is important to measure the delivery of various smoke constituents from cigarettes. In one method of assessing smoke delivery, the Federal Trade Commission (FTC) determines the relative quantities of nicotine and "tar" (defined as the total particulate matter minus nicotine and water) delivered from commercial cigarettes that are smoked according to a standardized procedure. In this procedure, a 2-sec puff of 35 cc volume is taken once very minute until a specified butt length is reached (Federal Trade Commission, 1985). The particulate matter in the mainstream smoke is trapped in Cambridge filter pads and subsequently analyzed for tar and nicotine. However, this method of assessing smoke delivery does not necessarily reflect the amount of smoke delivered to a particular individual. Different smokers take different numbers of puffs with different volumes from cigarettes of a given brand (Herning, Jones, Benowitz, & Mines, 1983). Even the same smoker varies the manner of smoking at different times. Manipulations of cigarette deprivation, cigarette nicotine delivery, and psychological manipulations (e.g., situational stressors) affect smoking topography (Griffiths & Henningfield, 1982; Gritz, 1980; Rose, Ananda, & Jarvik, 1983).

One method of estimating actual smoke intake is to monitor each smoker's manner of puffing at a particular time. Puffing topography has been assessed with indices of puff volume, as well as by counting the number of puffs taken or measuring their durations (Gritz, Rose & Jarvik, 1983; Gust & Pickens, 1982; Herning et al., 1983). These measures give a more realistic estimate of smoke intake than that based solely on the standardized FTC analyses. However, volume measures do not always yield an accurate estimate of total nicotine and tar intake. The main reason is that the concentration of smoke particles (and hence tar and nicotine) varies as much as threefold from the first puff to the last puff of a cigarette, due to varying filtration afforded by the steadily shrinking rod of tobacco (Young, Robinson, & Rickert, 1981). Thus, taking 13 puffs from a cigarette could deliver almost twice as much smoke particulate matter as taking 10 puffs of comparable volume.

A widely used method of directly estimating smokers' intake of tar and nicotine has been to measure the amounts of these substances trapped in cigarette filters after the cigarettes have been smoked (Ashton & Watson, 1970; Rawbone, Murphy, Tate, & Kane, 1978). If a constant fraction of smoke that passes through a filter during puffing were trapped, and this filtration efficiency were known, then one could infer approximately how much smoke had been taken into the smoker's mouth by measuring the amount deposited in the filter. Unfortunately, the accuracy of this method is limited by the fact that the efficiency of a given cigarette filter is variable, depend-

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ing on the rate at which smoke is drawn through the filter. For example, at a flow rate of 40 cc/sec, a cigarette filter may retain only 70% as much smoke as it would retain at a flow rate of 10 cc/sec (Creighton & Lewis, 1978). Other factors, such as deformation of the filter in the smoker's mouth, could potentially confound this method of measurement.

Jenkins and Gayle (1984) devised a method of monitoring smoke intake that overcame these problems. This method is based on the measurement of flow with a pressure transducer and the measurement of smoke concentration with infrared light. Although this method provides an accurate measure of puff-by-puff smoke intake, the system is fairly complex and expensive. Moreover, it does not yield measurements of individual smoke constituents.

We sought to develop a simple, inexpensive method of monitoring tar and nicotine intake that would avoid the problems associated with measuring residue in cigarette butts. The basic strategy, described in detail below, was to trap a constant fraction of smoke particulates in each puff, using a set of parallel tubes in which the smoke passing through one of the tubes was diverted into a Cambridge filter pad. By using several identical tubes, which

also had much higher draw resistance than the Cambridge filter pad, we ensured that the proportion of smoke flowing into each tube was equal. Thus the Cambridge filter retained a constant fraction of smoke for subsequent analysis.

METHOD

Apparatus

The smoke intake measurement apparatus is depicted in Figure 1. The apparatus consisted of an ordinary plastic cigarette holder attached by two flexible tygon tubes (inner diameter 4.8 mm) to the rest of the system. All connections were made airtight with epoxy. Each puff of smoke drawn from the cigarette flowed into two parallel paths, labeled A and B, which branched out from a Y-connector. Within path B, seven glass capillary (hematocrit) tubes were arranged in parallel. Path A contained only one capillary tube, in series with a Cambridge filter pad (contained in an airtight plastic holder). The relative amount of smoke traveling through paths A and B depended on their relative resistance, which was determined mainly by the number of capillary tubes. The di-

Figure 1. Proportional smoke trapping device for measuring mouth intake of nicotine and tar. Path A contains one capillary tube and path B contains seven capillary tubes. The Cambridge filter traps smoke particulate matter flowing through path A for subsequent analysis.

ameter and length of the capillary tubes (1.6 mm diameter, 75 mm length) were chosen so that (1) the resistance of each tube was much greater than that of a Cambridge filter pad (.37 vs. .07 cm H₂O/cc/sec), and (2) the overall draw resistance of the system would be much less than that of a cigarette (.08 vs. .51 cm H₂O/cc/sec for the filter cigarette tested), thus presenting no difficulty for a smoker puffing normally. The resistance remained constant after smoking as many as 25 cigarettes through the apparatus.

Because the relative resistances of the two paths, A and B, were approximately in the ratio 7:1, only one eighth of the smoke was diverted to the Cambridge filter and trapped. Thus the quality of the smoke was not expected to be significantly affected by the apparatus. By determining the amount of tar and/or nicotine trapped in the Cambridge pad after a cigarette was smoked, one could infer how much was taken into the smoker's mouth. Unlike estimates based on analyses of cigarette butts, the use of parallel tubes ensured that the proportion of smoke trapped would be constant and unaffected by flow rate.

Procedure

The proportional smoke trapping system was calibrated first by measuring the airflow through paths A and B when a range of flow rates (20–100 cc/sec) was introduced into the cigarette holder. After verifying that the relative resistances of paths A and B were in the ratio 7:1 (see Results below), we calibrated the system with cigarette smoke. To measure the fraction of smoke trapped by the Cambridge filter in the apparatus, a lit cigarette was inserted into the distal end of the apparatus and puffs of known volume were taken with a syringe. A second Cambridge filter was used to trap the smoke exiting the mouthpiece of the cigarette holder. This permitted a direct assessment of the fraction trapped in the Cambridge pad in path A over a range of puff volumes (30–60 cc), numbers of puffs (10–50), and flow rates (15–60 cc/sec).

We used two methods of determining total smoke particulate matter trapped on the Cambridge filters. In one method, the Cambridge filter was weighed before insertion into the apparatus and again after smoking. To correct for variable water content, the filters were weighed immediately and after 24, 48, and 120 h in a dessicator with anhydrous calcium sulfate. In the second method, the smoke particulate matter was extracted from the filter with methanol, and the fraction of ultraviolet (UV) light absorbed at a wavelength of 400 nm was measured using a spectrophotometer. The absorption of UV light at 400 nm has been reported to correlate with tar delivery (Hinds, First, Huber, & Shea, 1983); neither nicotine nor water absorb significantly at this wavelength.

In addition to measuring tar trapped on the Cambridge filters, one set of five samples was sent in coded vials to the Clinical Psychopharmacology Laboratory at the Veterans Administration Medical Center Sepulveda for nicotine determinations, using high-pressure liquid chromatography.

To investigate whether several cigarettes could be smoked through the device without changing the propor-

tion of smoke trapped, we smoked five cigarettes in succession, drawing 10 puffs (60 cc) from each cigarette. The fraction of smoke trapped by the device after all five cigarettes were smoked was compared with the results from a single cigarette.

It was also important to verify that the calibrations would reflect conditions of actual use. Eight volunteers (males, ages 25–49, who smoked at least one pack of cigarettes per day) were asked to smoke a cigarette through the device, using their own brand. Subjects simulated normal puffing, but the smoke drawn from the mouthpiece of the device was trapped in a Cambridge filter instead of being taken into the mouth. As with the other calibrations, this procedure allowed us to determine the proportion of smoke trapped in the device.

RESULTS

Airflow Calibration

In 12 sets of measurements, the airflow tests showed that the proportion of air flowing through the one-capillary side of the apparatus was 11.8% (*SD* = .41). In the range of puff flows from 20–100 cc/sec, there was no effect of flow rate on this proportion (see Table 1), verifying our assumption that the ratio of resistances of paths A and B would be a constant, approximately 7:1.

Measurement of Tar

The weights of Cambridge filters showed a marked decrease over 24 h of dessication, with little change thereafter. Thus, the weight after 24 h of dessication was taken to be most indicative of tar and nicotine delivery. Figure 2 shows the high correlation between weights of particulate matter after 24 h dessication and the UV light (400 nm) absorption. The correlation coefficient, based on 20 measurements, was .99.

Proportion of Smoke Trapped by the Device

The mean proportion of total smoke particulate matter (TPM) trapped by the Cambridge pad in path A of the apparatus, as calculated by weight after 24 h dessication, was 11.3%, (*SD* = 1.11), for 14 measurements. These results agreed fairly well with the proportion calculated from the estimate of tar as determined by UV light absorption measurements: 12.5% (*SD* = 1.56). These proportions were quite consistent across different flow rates and puff volumes (see Table 1) and approximated the intended trapping proportion of 12.5%. In contrast, the trapping fraction calculated from weighing undessicated samples was 9.7% (*SD* = .94). This suggests that differential losses of water and other volatile smoke constituents (including nicotine) from the Cambridge filter in path A of the apparatus, possibly through evaporation, affected the trapping proportion for undessicated samples.

The nicotine determinations for the four sets of (undessicated) Cambridge filters analyzed for nicotine displayed a trapping efficiency not significantly different from that shown by UV light absorption measurement of tar: 11.5% (*SD* = .46) versus 12.2% (*SD* = .63). The correlation

Figure 2. The correlation between the weight of (dissicated) smoke particulate matter trapped in Cambridge filters and the absorbance of ultraviolet light at a wavelength of 400 nm by material extracted from the same filters.

between nicotine and tar delivery was .99 for this set of samples.

The effect of preloading the Cambridge filter by smoking five cigarettes in succession was negligible; in four replications of this procedure, the mean proportion of smoke trapped in the Cambridge filter was 12.5% ($SD = .53$), as determined by UV light absorbance. This result agreed closely with the results of smoking a single cigarette through the apparatus.

The results of the measurements obtained with 8 cigarette smokers also yielded a similar value for the proportion of smoke trapped by the Cambridge filter in the apparatus: 12.4% ($SD = 1.28$), as determined by UV absorbance.

DISCUSSION

We have described a simple system for monitoring smoke particulate delivery that is noninvasive and accurate under a wide range of conditions. In addition to avoiding the problem of varying filtration efficiency in making calculations based on cigarette filters, this apparatus is easily calibrated with any brand of cigarette (including non-filter cigarettes). The method also allows the separate determination of nicotine and tar intake and of intake of individual constituents in tar. Although tar and nicotine delivery are highly correlated when using a standardized smoking procedure, the tar:nicotine ratio cannot be assumed to remain constant as puffing topography changes (Creighton & Lewis, 1978) or as new types of cigarette products may be developed.

One aspect of the apparatus that deserves comment is the volume of dead space in side A of the device (see Figure 1). This dead space was minimized by making tubing connections as short as possible and by placing the

Cambridge filter close to the Y-connector at which the smoke flow is first divided. The total dead space volume between the Y-connector and the Cambridge filter in side A of the apparatus was estimated to be 4.5 cc. This appears to be significant, in that the volume of smoke drawn through side A in each puff was only one eighth of the total, or roughly 5 cc per puff. Hence, on the first puff, a smaller fraction of smoke than expected actually reached the Cambridge pad; the remainder resided in the dead space and was collected on the next puff. After the first puff, essentially all of the dead space air was replaced with smoke. Similarly, the dead space in the remainder of the apparatus (roughly 13 cc) was filled with smoke after the first puff, and was delivered in subsequent puffs. We have found that the quantity of smoke delivered from cigarettes smoked through the apparatus is the same as

Table 1
Calibration of Proportional Smoke Trapping Device

Air Flow Measurements				
Flow Rate	Percentage of Flow 1 Capillary		Ratio of Flows 7:1 Capillary Sides	
20-40 cc/sec	11.9		7.4	
40-60 cc/sec	11.8		7.5	
60-80 cc/sec	11.8		7.5	
80-100 cc/sec	11.8		7.5	
Cigarette Smoke Measurements				
Number of Puffs	Puff Volume (cc)	Puff Duration (sec)	Percentage of Smoke Trapped in 1 Capillary Side Based on	
			TPM Weight	UV Absorbance
10	60	2	10.8	11.8
10	60	4	11.1	11.7
15	30	2	12.5	14.5
50	60	1	12.1	12.5

Note—TPM=total smoke particulate matter; UV=ultraviolet light.

that of cigarettes smoked without the apparatus, demonstrating that there is negligible deposition of particulate matter on the tubing in the device. Therefore, providing several puffs were taken in a smoking period, little error resulted from the dead space. Also, subjects generally felt that smoke obtained through the device was of similar quality (in terms of taste and other sensory characteristics) to that obtained directly from a cigarette.

Thus far we have discussed only the measurement of mouth intake of tar and nicotine in cigarette smoke. However, a portion of these components is exhaled by the smoker, and variations in inhalation depth or duration may significantly affect smokers' nicotine absorption (Herning et al., 1983). Thus, the proportional smoke trapping device described here would not in itself indicate the amount of smoke deposited in a smoker's respiratory tract. However, using a simple extension of our method, it may be possible to determine the actual absorption of tar and nicotine. As shown by Hinds et al. (1983), essentially all of the smoke exhaled after each puff can be collected with a high-efficiency filter attached to a vacuum system. By using this technique to measure the amount of smoke exhaled and measuring the smoke intake with the proportional smoke trapping device, the amount of smoke retained in the subject can be calculated by subtraction.

REFERENCES

- ASHTON, H., & WATSON, D. W. (1970). Puffing frequency and nicotine intake in cigarette smokers. *British Medical Journal*, **3**, 679-681.
- CREIGHTON, D. E., & LEWIS, P. H. (1978). The effect of smoking pattern on smoke deliveries. In R. E. Thornton (Ed.), *Smoking behaviour* (pp. 301-314). Edinburgh: Churchill Livingstone.
- FEDERAL TRADE COMMISSION. (1985). "Tar", nicotine and carbon monoxide of the smoke of 207 varieties of domestic cigarettes. Washington, DC: Author.
- GRIFFITHS, R. R., & HENNINGFIELD, J. E. (1982). Experimental analysis of human cigarette smoking behavior. *Federation Proceedings*, **41**, 234-240.
- GRITZ, E. R. (1980). Smoking behavior and tobacco abuse. In N. K. Mello (Ed.), *Advances in substance abuse* (pp. 91-158). Greenwich, CT: JAI Press.
- GRITZ, E. R., ROSE, J. E., & JARVIK, M. E. (1983). Regulation of tobacco smoke intake with paced cigarette presentation. *Pharmacology Biochemistry & Behavior*, **18**, 457-462.
- GUST, S. W., & PICKENS, R. W. (1982). Does cigarette nicotine yield affect puff volume? *Clinical Pharmacology & Therapeutics*, **4**, 418-422.
- HERNING, R. I., JONES, R. T., BENOWITZ, N. L., & MINES, A. H. (1983). How a cigarette is smoked determines blood nicotine levels. *Clinical Pharmacology & Therapeutics*, **33**, 84-90.
- HINDS, W., FIRST, M. W., HUBER, G. L., & SHEA, J. W. (1983). A method for measuring respiratory deposition of cigarette smoke during smoking. *American Industrial Hygiene Association Journal*, **44**, 113-118.
- JENKINS, R. A., & GAYLE, T. M. (1984). An instrumental cigarette smoke monitor designed for the direct measurement of smoke particulate matter generated in human smoking studies. *Behavior Research Methods, Instruments, & Computers*, **16**, 263-267.
- RAWBONE, R. G., MURPHY, K., TATE, M. E., & KANE, S. J. (1978). The analysis of smoking parameters, inhalation and absorption of tobacco smoke in studies of human smoking behaviour. In R. E. Thornton (Ed.), *Smoking behaviour* (pp. 171-194). Edinburgh: Churchill Livingstone.
- ROSE, J. E., ANANDA, S., & JARVIK, M. E. (1983). Cigarette smoking during anxiety-provoking and monotonous tasks. *Addictive Behaviors*, **8**, 353-359.
- YOUNG, J. C., ROBINSON, J. C., & RICKERT, W. S. (1981). A study of chemical deliveries as a function of cigarette butt length. *Beitrag zur Tabakforschung International*, **11**, 87-95.

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