

The Effect of Tip Dilution on the Filtration Efficiency of Upstream and Downstream Segments of Cigarette Filters*

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SUMMARY

The amount of particulate matter captured by the upstream and downstream segments of ventilated filters was directly determined by a UV method. With 25 mm 3.3 dpf/35,000 total denier filters the dry particulate matter efficiency of the upstream section approximately doubled and the nicotine efficiency increased by about a half in going from 0 to 70 % tip ventilation. The efficiency of the downstream segment showed only minor variations. This resulted in an increase of total filtration efficiency from 48 % to 63 % for dry particulate matter and from 40 % to 49 % for nicotine. The dry particulate matter/nicotine ratio decreased from about 15 for non-ventilated cigarettes to less than 10 at 70 % tip ventilation because the tobacco column produced smoke containing relatively more nicotine and the difference between dry particulate matter and nicotine filtration efficiencies became successively larger as ventilation increased.

ZUSAMMENFASSUNG

Mittels einer UV-Methode wurde direkt gemessen, wieviel Trockenkondensat in den Segmenten ventilerter Zigarettensfilter aufgefangen wird. Bei 25 mm langen Filtern (3,3/35.000 den) verdoppelte sich im tabakseitigen Segment die Kondensatretenion ungefähr, wenn die Ventilation von 0 % bis 70 % anstieg, und die Nicotinretenion nahm etwa um die Hälfte zu. Das Filtrationsverhalten des mundseitigen Segmentes veränderte sich dagegen nur wenig. Auf diese Weise erhöhte sich die Gesamtfiltrationsleistung gegenüber dem Trockenkondensat von 48 % auf 63 % und gegenüber dem Nicotin von 40 % auf 49 %. Bei

70 %iger Ventilation verringerte sich der Wert für das Trockenkondensat/Nicotin-Verhältnis von ungefähr 15 bei nichtventilierten Zigarettensfiltern auf unter 10, da der Tabakstrang mit steigender Ventilation Rauch mit vergleichsweise höherem Nicotiningehalt erzeugt und der Unterschied zwischen Kondensat- und Nicotinretenion sukzessive größer wird.

RÉSUMÉ

C'est directement que l'on a mesuré par une méthode UV, la quantité de condensat anhydre retenue dans les tronçons d'un filtre ventilé. On a constaté que dans les filtres de 25 mm (3,3/35.000 den), la rétention en condensat parvenait, en gros, à doubler dans le tronçon côté tabac, lorsque la ventilation passait de 0 % à 70 % tandis que la rétention en nicotine augmentait à peu près de moitié. Par contre, l'efficacité du tronçon côté lèvres se modifiait à peine. Il en résulta donc une augmentation du pouvoir global filtrant, passant de 48 % à 63 % pour le condensat anhydre et de 40 % à 49 % pour la nicotine. Le rapport condensat-anhydre/nicotine passa d'environ 15 pour les cigarettes non-ventilées à moins de 10 pour les filtres ventilés à 70 %, du fait qu'avec une ventilation croissante, le boudin de tabac produit une fumée à teneur en nicotine relativement plus élevée et que la différence entre la rétention en condensat et en nicotine augmente peu à peu.

INTRODUCTION

Fibrous cigarette filters capture particulate smoke by several different mechanisms (3, 5, 10). Of the principal mechanisms, diffusional capture and inertial impaction are a function of smoke flow velocity, whereas direct interception is not. The balance among the different filtration mechanisms in smoke filtration is such that overall filtration efficiency is rather strongly influ-

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enced by flow velocity. This has been demonstrated by *Keith* and *Derrick* (1) using homogeneous pyrene aerosols, by *Kiefer* (4) smoking cigarettes with various puff volumes and durations, and by *Keith* (3) using cigarettes with different degrees of tip ventilation. The dependence of filtration efficiency on flow rate has assumed much practical significance with the advent of tip-ventilated filter constructions. In such filters, smoke flow velocity through the upstream (from perforations) filter segment can be markedly reduced resulting in a concomitant increase in efficiency. In the downstream segment of the filter, the total flow velocity is up to the standard 17.5 cm³/s but the diluting air generally stays on the periphery of the filter and the smoke aerosol flow path is compressed into a concentric pattern. The purpose of the current work was to directly measure the amount of particulate matter and nicotine deposited on the upstream and downstream filter segments and thereby generate some filtration efficiency (FE) data which would be helpful in the design of future ventilated cigarettes.

In an unventilated filter cigarette:

$$DPM_F = DPM_T (1 - FE_{DPM}) ,$$

in a tip-ventilated cigarette:

$$DPM_F = DPM_T \frac{P_F}{P_T} (1 - TDIL) (1 - FE_{DPM}) ,$$

and since:

$$(1 - FE_{DPM}) = (1 - FE_{DPM_U}) (1 - FE_{DPM_D}) ,$$

it follows that:

$$DPM_F = DPM_T \frac{P_F}{P_T} (1 - TDIL) (1 - FE_{DPM_U}) (1 - FE_{DPM_D}) ,$$

where:

DPM is dry particulate matter,

TDIL is fractional tip dilution,

FE_{DPM} is fractional filtration efficiency for dry particulate matter,

P_F/P_T is the ratio of puff number of the ventilated cigarette to that of the same cigarette with the filter removed (tobacco column only),

Subscripts T and F denote tobacco column only and filter cigarette, respectively,

Subscripts U and D denote upstream and downstream filter segments with respect to the location of perforations.

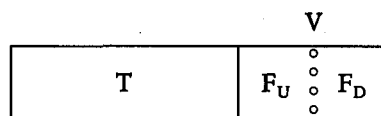
Since tip ventilation affects puff number, the P_F/P_T term has been explicitly incorporated in the equation in order for FE to represent a real filtration efficiency.

EXPERIMENTAL MATERIALS AND METHODS

The study was carried out with 84 mm blended cigarettes having 25 mm 3.3 dpf/35,000 total denier filters of 80 mm w.g. encapsulated pressure drop and 32 mm tipping. Combinations of various perforated tippings and porous plug wraps were used to manufacture nine cigarette samples varying in dilution from about 15 to 70 % (see Table 2 for perforation position of each sample and for the perforation technique used).

An unventilated control filter cigarette sample was generated from a composite of the nine ventilated samples by taping the perforations shut. A tobacco column only control sample was assembled similarly by removing the filters from some of each of the nine samples.

The test samples were selected within dilution ranges of ± 1.0 % using an Instrument Technical Representatives ventilation meter. The pressure drops of the cigarettes were measured in various ways to permit the calculation of tip dilution by the two following methods:



$$\text{method I (2, 12): } TDIL = \frac{CPD_E - CPD}{CPD_E - FPD_D}$$

$$\text{method II (11): } TDIL = \frac{1}{1 + \frac{PD_V}{PD_T + FPD_U}}$$

where

CPD is cigarette pressure drop,

CPD_E is cigarette pressure drop with filter encapsulated,

FPD is filter pressure drop,

subscripts U and D denote the upstream and downstream filter segments,

PD_V is pressure drop of the vents,

PD_T is pressure drop of the tobacco column.

Table 1 compares the experimental values with the two methods for calculating air dilution from pressure drop measurements. Both methods use Ohm's Law analogy to calculate tip dilution and the expressions are mathematically equivalent. There are some random differences between the calculated values which apparently arise from the experimental variability of pressure drop measurements, i. e. the two methods use a different set of pressure drop measurements to arrive at the value for tip dilution. The correlations between the calculated

Figure 1.
Dry particulate matter (DPM) yield.

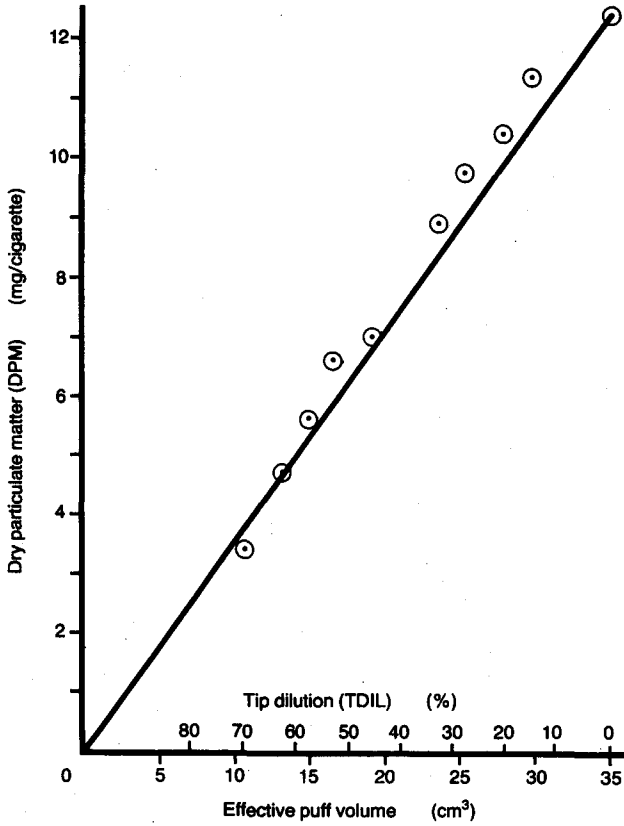


Figure 2.
Nicotine yield.

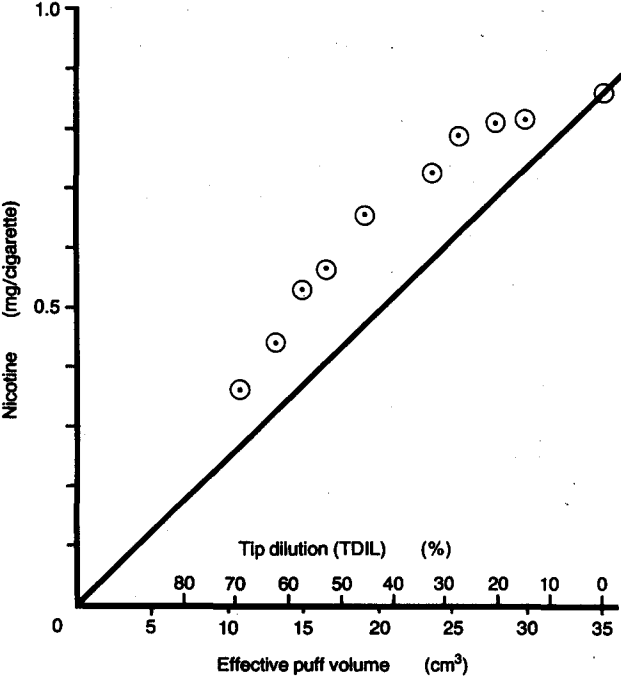


Figure 3.
Yield reduction of dry particulate matter (DPM), nicotine and CO.

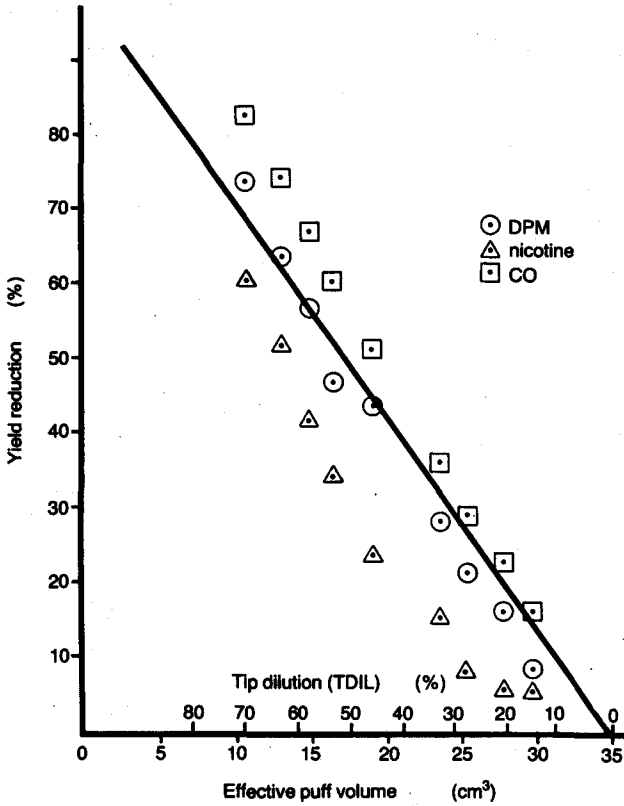


Figure 4.
Total dry particulate matter (DPM) output and the amounts retained by the filter and the upstream and downstream segments.

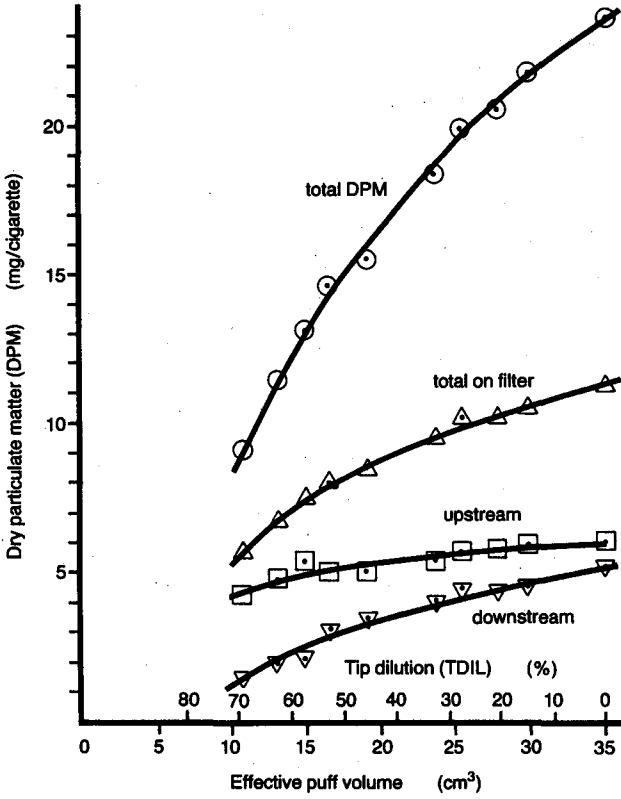


Table 1. Measured and calculated tip dilutions.

Tip-ventilated sample	Tip dilution (TDIL)		
	measured	calculated	
		method I *	method II **
B	0.149	0.180	0.167
C	0.203	0.231	0.178
D	0.259	0.271	0.257
E	0.325	0.332	0.353
F	0.455	0.434	0.463
G	0.505	0.510	0.502
H	0.575	0.589	0.576
I	0.625	0.631	0.627
J	0.695	0.674	0.694

$$* \text{ I: TDIL} = \frac{\text{CPD}_E - \text{CPD}}{\text{CPD}_E - \text{FPD}_D}$$

$$** \text{ II: TDIL} = \frac{1}{1 + \frac{\text{PD}_V}{\text{PD}_T + \text{FPD}_U}}$$

Correlation between calculated and measured values:

measured TDIL = 1.064 multiplied by TDIL_{method I} - 0.0341 ($r = 0.997$)

measured TDIL = 0.9992 multiplied by TDIL_{method II} - 0.0026 ($r = 0.997$)

and measured values given in Table 1 show that electrical analogy represents the actual flow conditions in the cigarette very closely.

25 cigarettes of each sample were smoked under standard conditions with five to each Cambridge pad. The smoked filters were saved, sectioned along the lines of perforations (or in the center of the lines of perforations in case of more than one line) and the dry particulate matter was determined by an UV spectrophotometric method previously described by Sloan and Curran (13) using five filters per analysis. The UV method was calibrated with Cambridge pad extracts versus the gravimetric dry particulate matter yield and it was found to have a good linear correlation in the range of 1–10 mg dry particulate matter/cigarette, i. e. over the range of dry particulate matter found on the filters. Nicotine on the filter sections was determined by the routine GC method used in smoke analysis.

RESULTS AND DISCUSSION

Table 2 summarizes the smoking and analytical data for the tobacco column only, for the unventilated control and for the nine tip-ventilated samples. Figures 1 and 2 depict the dry particulate matter and nicotine yields of the cigarettes as a function of effective puff volume (EPV) and tip dilution (TDIL) [note: 35 cm³ EPV coincides with 0 % TDIL while 17.5 cm³ EPV simulates 50 % TDIL, etc.]. The solid line in Figures 1 and 2 represents the unventilated yield reduced proportionately with tip dilution. The dry particulate matter values fol-

low the line fairly closely, whereas nicotine yield levels diverge considerably.

Figure 3 shows the same data as well as the CO results in terms of yield reductions. Thus, tip-diluted smoke is depleted in CO and enriched in nicotine relative to dry particulate matter as has been shown in several prior studies (7, 8).

Figure 4 depicts the amounts of smoke collected on the upstream and downstream segments of the filter, the total filter and the total amount of smoke produced. The latter quantity represents the sum of the amount collected on the filter and the yield.

The location of the perforations in all the samples was 14.0 mm from the mouth end except for sample H where it was 12.5 mm (see Table 2). For the purposes of the comparative filtration efficiency plots, all efficiencies were corrected for a 12.5 mm segment length.

The correction was carried out as follows:

1. It was assumed that FE_D per unit length was constant.
2. The efficiency of the first 1.5 mm segment of F_D and the amount of DPM (or nicotine) collected by this segment were calculated and added to the amount collected on F_U and subtracted from that on F_D. The corrected efficiency for F_U was calculated from the amount of DPM impinging on F_U and the corrected amount collected on F_U; the corrected efficiency for F_D was calculated from the corrected amounts of DPM impinging on and collected by F_D.

Example calculation (control cigarette, DPM, data from Table 2):

$$\text{a) } (1 - \text{FE}_{D, 1.5}) =$$

$$^{0.333}\sqrt{(1 - 0.298)} \times \text{FE}_{D, 1.5} = 0.0372$$

$$\text{b) } \text{DPM}_{\text{imp., F}_D} \times \text{FE}_{D, 1.5} = 17.67 \times 0.037 = 0.65$$

$$\text{DPM}_{\text{coll., F}_U} + 0.65 = 6.03 + 0.65 = 6.68$$

$$\text{c) } 6.68 / \text{DPM}_{\text{imp., F}_U} =$$

$$6.68 / 27.30 = 0.282 = \text{corrected FE}_U$$

$$\text{d) } \text{DPM}_{\text{coll., F}_D} - 0.65 = 5.27 - 0.65 = 4.62$$

$$\text{e) } \text{DPM}_{\text{imp., F}_U} - 6.68 = 23.70 - 6.68 = 17.02$$

$$\text{f) } 4.62 / 17.02 = 0.271 = \text{corrected FE}_D$$

Table 2. Summary of analytical data.*

Sample	Puff number	Tip dilution (TDIL)	Effective puff volume (cm ³ / 2 s)	Impinging on F _U		Collected on F _U		Impinging on F _D		Collected on F _D		Cigarette yield		FE _U		FE _D		FE _{total}	
				DPM	N	DPM	N	DPM	N	DPM	N	DPM	N	DPM	N	DPM	N	DPM	N
Tobacco column	6.3	—	35.0	23.58	1.446	—	—	—	—	—	—	23.58	1.446	—	—	—	—	—	—
Control	6.3	—	35.0	23.70	1.448	6.03	0.316	17.67	1.132	5.27	0.272	12.40	0.860	0.254	0.218	0.298	0.240	0.477	0.406
B	6.3	0.150	29.8	21.82	1.273	5.93	0.272	15.89	1.001	4.54	0.186	11.35	0.815	0.272	0.214	0.286	0.186	0.480	0.360
C	6.8	0.205	27.8	20.55	1.243	5.82	0.264	14.73	0.979	4.33	0.169	10.40	0.810	0.283	0.212	0.294	0.173	0.494	0.348
D	6.9	0.275	25.4	19.94	1.242	5.70	0.257	14.24	0.985	4.49	0.195	9.75	0.790	0.286	0.207	0.315	0.198	0.511	0.364
E	6.7	0.325	23.6	18.36	1.165	5.40	0.262	12.96	0.903	4.06	0.178	8.90	0.725	0.294	0.225	0.313	0.197	0.515	0.378
F	7.1	0.455	19.1	15.45	1.062	5.01	0.240	10.44	0.822	3.44	0.167	7.00	0.655	0.324	0.226	0.330	0.203	0.547	0.383
G	7.2	0.530	16.5	14.60	0.952	4.92	0.244	9.68	0.708	3.08	0.143	6.60	0.565	0.337	0.256	0.318	0.202	0.548	0.406
H	7.5	0.575	14.9	13.03	0.947	5.34	0.275	7.69	0.672	2.09	0.142	5.60	0.530	0.410	0.290	0.272	0.211	0.570	0.440
I	7.3	0.625	13.1	11.40	0.812	4.80	0.245	6.60	0.567	1.90	0.127	4.70	0.440	0.421	0.302	0.288	0.224	0.588	0.458
J	7.7	0.695	10.7	9.09	0.712	4.26	0.230	4.83	0.482	1.43	0.122	3.40	0.360	0.469	0.323	0.296	0.253	0.626	0.494

* N: nicotine DPM: dry particulate matter F: filter segment FE: fractional filtration efficiency

Subscripts U and D denote upstream and downstream filter segments with respect to the location of perforation.

All yields are in mg/cigarette.

Notes on perforation:

1. Samples E and I were laser perforated, all others were mechanically perforated.
2. Number of lines of perforations for sample E: 2, H: 5, I: 2, J: 7; all others had 1 line of perforations.
3. Distance of center of perforations from mouth end: sample H = 12.5 mm, all others 14.0 mm.

Error estimates:

The relative standard deviations for both dry particulate matter (DPM) and nicotine determinations ranged from 2.8 to 9.1 % with the majority of the determinations being in the neighborhood of 5 %.

Figure 5.
Dry particulate matter (DPM) filtration efficiency of the filter and the upstream and downstream segments.

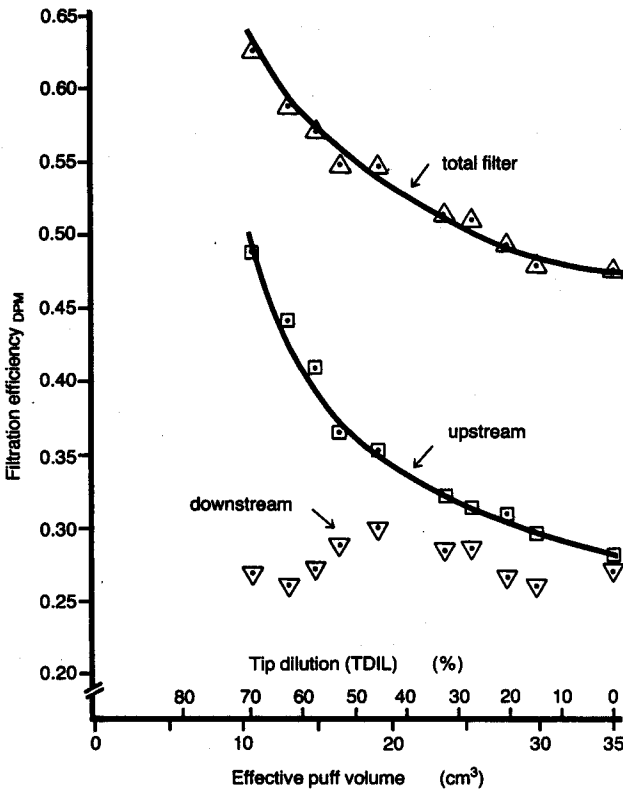
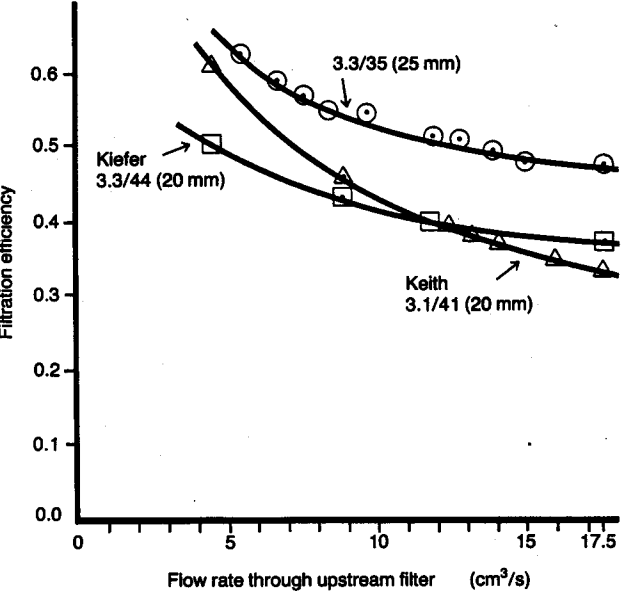


Figure 5 depicts the dry particulate matter filtration efficiency of the filter and its segments at different effective puff volumes. As the smoke flow rate through the upstream segment was gradually reduced, the filter efficiency rose markedly at higher levels of dilution. The efficiency of the downstream segment increased slowly with increasing dilution followed by a decrease at high levels of dilution. The observed slight variations are most probably simply due to experimental variability. It is interesting that at 0 % TDIL, the upstream section has a slightly higher efficiency than the downstream

Figure 6.
Filtration efficiency as a function of flow velocity.

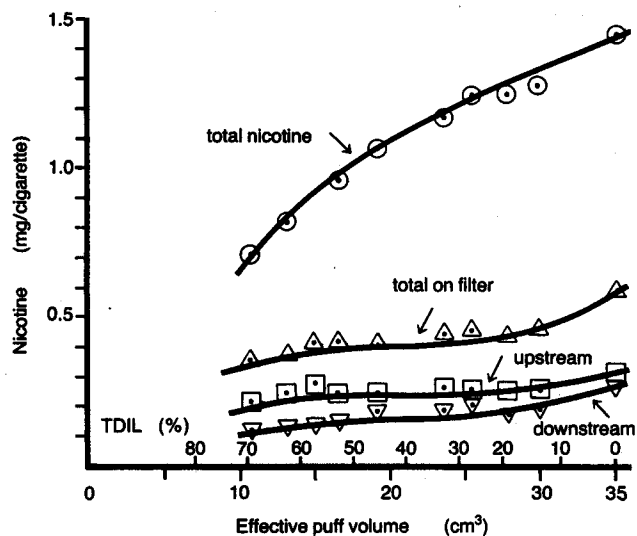


section. This observation has previously been made by *Kiefer* (6) who postulated that since the efficiency of fibrous filters is a function of smoke particle size, the upstream section depletes the smoke of particle sizes that are more easily filtered out leaving more of the difficultly filterable particles for the downstream section. The condensation of particulate smoke on the front end of the filter during late puffs may also contribute to the higher observed efficiency of the upstream filter. Figure 6 compares our findings to previously published data by *Kiefer* (4) and by *Keith* (3). *Kiefer's* data are for whole 20 mm filters smoked with different puff volumes and velocities, whereas *Keith's* and ours are for ventilated filters smoked with 35 cm³/2 s puffs (i.e. only the upstream velocity changes). Thus, the data are not strictly comparable since filter length affects efficiencies.

Table 3. Dry particulate matter (DPM) and nicotine filtration efficiencies corrected for 12.5 mm upstream and downstream filter segment lengths.

Sample	Filtration efficiency _{upstream}		Filtration efficiency _{downstream}		Filtration efficiency _{total}	
	DPM	nicotine	DPM	nicotine	DPM	nicotine
Control	0.282	0.241	0.271	0.217	0.477	0.406
B	0.297	0.231	0.260	0.168	0.480	0.360
C	0.310	0.229	0.267	0.155	0.494	0.348
D	0.314	0.225	0.287	0.179	0.511	0.364
E	0.322	0.241	0.285	0.180	0.515	0.378
F	0.353	0.245	0.300	0.183	0.547	0.383
G	0.365	0.274	0.288	0.182	0.548	0.406
H	0.410	0.290	0.272	0.211	0.571	0.440
I	0.442	0.320	0.261	0.203	0.588	0.458
J	0.488	0.344	0.269	0.229	0.626	0.494

Figure 7.
Total nicotine output and the amounts retained by the filter and the upstream and downstream segments.



Comparable data for nicotine yields are shown in Figure 7. The picture was similar to the dry particulate matter data except that the transition from non-ventilated to ventilated filters caused a significant drop in the amount of nicotine retained on the filter. In the case of dry particulate matter, there was very little difference between the non-ventilated filter retention and the first low levels of tip ventilation.

Figure 8.
Nicotine filtration efficiency of the filter and the upstream and downstream segments.

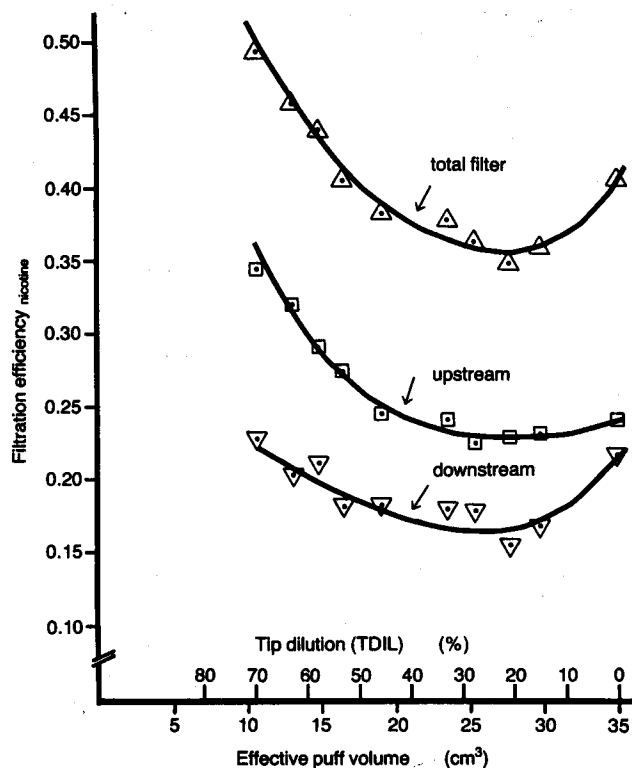


Figure 9.
Dry particulate matter (DPM) to nicotine ratio from the tobacco column, from the upstream filter segment and from the mouth end of the cigarette.

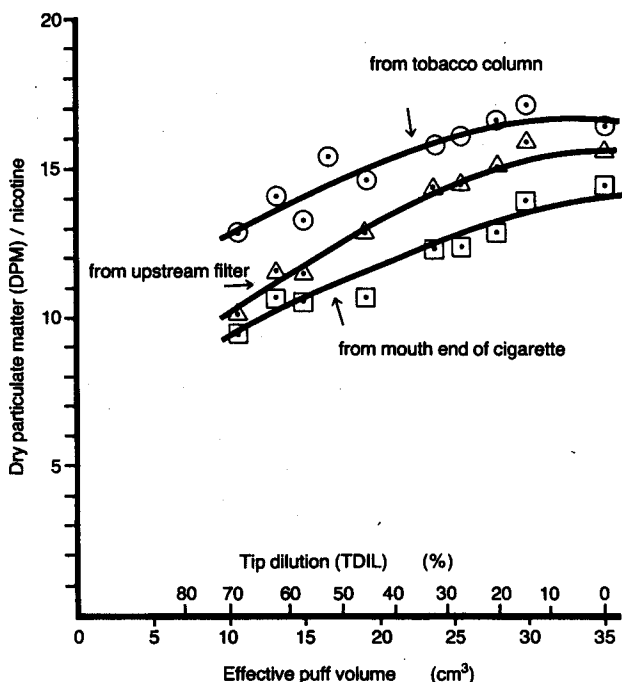


Figure 8 shows the nicotine filtration efficiencies (again corrected for filter segment length). Here an initial decrease in filtration efficiency was observed going from unventilated to ventilated filters. With highly ventilated filters, the efficiency of the upstream segment increased, but much less rapidly than that for dry particulate matter. The efficiency of the downstream segment appeared to show a modest increase at very high degrees of ventilation, but the variations are not statistically significant.

As shown in the data in Table 2, smoke from ventilated cigarettes is relatively enriched in nicotine, i. e. the dry particulate matter / nicotine ratio decreases as a function of tip dilution. Figure 9 depicts graphically where the reduction of this ratio originates. First of all, smaller puff volumes taken on the tobacco column (i. e. higher degree of tip ventilation) produce relatively less particulate matter and relatively more nicotine. The reduced air flow past the fire cone results in a more compressed thermal profile, i. e. a shallower cone which should enhance nicotine transfer and suppress its pyrolysis (9). The upstream filter segment, particularly at very low flow rates, shows an increasingly larger difference between dry particulate matter and nicotine filtration efficiencies. The downstream filter segment shifts the ratio still further, but its contribution diminishes with more highly ventilated cigarettes. Finally, particle size distribution may also play a role in the nicotine content enhancement of ventilated cigarettes. *Morie and Baggett* (7) have reported that the intermediate size smoke particles which are more difficult to filter con-

tain more nicotine than the small or large particles. Hence, if the upstream efficiency increases predominantly at the expense of large and small particles, such smoke would contain relatively more of the nicotine-rich intermediate size particles.

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