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Puffing and inhalation behaviour in cigarette smoking: Implications for particle diameter and dose

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Abstract. Inhalation of tobacco smoke aerosol is a two-step process involving puffing followed by inhalation. Measured smoke deposition efficiencies in the lung (20-70%) are greater than expected for smoke particles of diameter 150 – 250 nm CMD. Various mechanisms have been put forward to explain this enhanced deposition pattern, including coagulation, hygroscopic growth, condensation and evaporation, changes in composition, or changes in inhalation behaviour. This paper represents one of a series of studies seeking to better quantify smoke chemistry, inhalation behaviour and cumulative particle growth. The studies have been conducted to better understand smoke dosimetry and links to disease as part of a wider programme defining risk and potential harm reduction. In this study, it was noted that particle deposition increased with increasing inhalation depth, and that smoke inhalation volumes were generally greater than normal tidal breathing volumes. A weak association was observed between particle diameter and puff flow, but no strong association between particle diameter and retention efficiency.

1. Introduction

Tobacco smoke is a complex and dynamic matrix consisting of gaseous compounds and particulate material, in which over 4800 constituents have been identified [1]. The subsequent deposition of smoke constituents in the respiratory tract of smokers is an equally complex process both in terms of quantification of dose and location. Indeed an improved understanding of the dose and deposition location of tobacco smoke constituents in the human airways may well elude further information regarding the mechanisms of tobacco related diseases. The paper of Baker and Dixon [2] describes the work which has been carried out in the last century. The overriding message from this paper is that there still remains a great deal of uncertainty as to the principal driving mechanisms governing tobacco smoke deposition in the human airways. A number of studies have also investigated the links between deposition and the physical properties of the aerosol, most notably the particle size of the inhaled aerosol.

Smoking behaviour involves drawing a puff into the mouth cavity with the soft palate closing the throat. Puff volume may be up to 100-120ml. The particle size of the smoke aerosol is principally dependent on its residence time in the cigarette and the time available for coagulation. But it will also be influenced by how long the puff is held in the mouth. Therefore the higher the flow intensity during puffing, the smaller the initial particle size. In contrast, the higher the ventilation level of the cigarette filter, the slower the smoke flows through the rod - resulting in a larger initial particle size. The particle size will continue to grow through coagulation as it is held in the mouth.

The ambiguity which exists between experimental data and predicted data from deposition models [3] has still not been fully addressed in the literature. The published review by Bernstein [4] supports the hypothesis that smokers inhale more deeply than normal tidal breathing.

2. Methods

Informed consent was obtained from seven volunteer smokers (5 males; 2 females) and each given a unique identifier code from a database used for all volunteer or assessment panel studies within the laboratory. The puffing behaviour, inhaled and exhaled particle diameter, and solanesol deposition efficiencies were measured for these seven volunteer smokers at two controlled and one free inhalation depth. These measurements were made using a research cigarette of conventional construction, made only from Virginia tobacco, with an ISO tar yield of 8.8 mg per cigarette as nicotine-free dry particulate matter (NFDPM).

Smoking behaviour was measured using a Smoking Analyser (SA7), developed in-house. Flows leave the cigarette and are measured inside the holder as they move to the smoker's mouth. The SA7 DAT unit uses a pressure transducer to measure pressure differences at 25Hz and converts them to flow and volume values against known flows and pressures. Data on puff number, duration, interval, flow and volume are also analysed. The human profile can be replicated off-line to measure total smoke or individual constituent deliveries, or to measure particle diameter. The screenshot in Figure 1 from the SA7 shows puff flow, puff volume, puff duration, elapsed time, pressure drop and (pre-calibrated) optical tar.

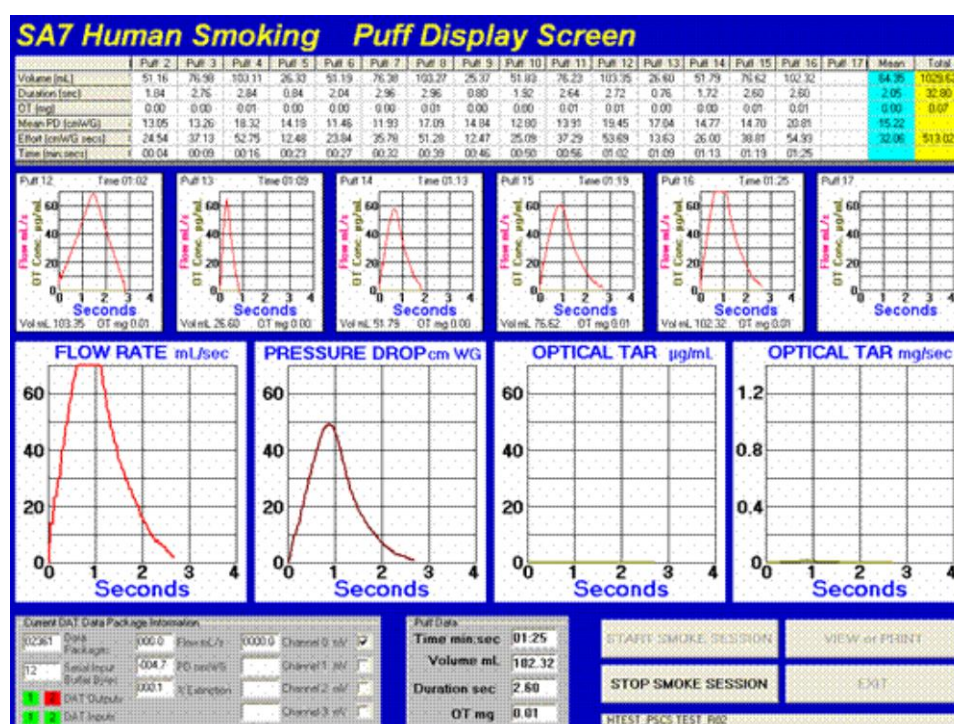


Figure 1 : Smoking profile analyser

Inhalation behaviour was controlled by pre-screening and measuring the lung vital capacity (VC) of each subject. Pre-prepared inhalation volumes of 15% and 25% of their vital capacity (VC_{15} and VC_{25}) were used as well as a free inhalation regime, under the free will of the subject. Three measurements were conducted per inhalation profile, with a further three free inhalation replicates used in a parallel experiment to measure exhaled particle diameter.

Particle deposition efficiency in the lung was estimated by Liquid Chromatography-Mass Spectrometry measurement of solanesol, a tobacco-specific high boiling point alcohol ($C_{45}H_{94}O$: MW = 630) which remains associated with the particulate phase of smoke [5] and represents approximately 3% of the particulate matter mass. For any cigarette type, the solanesol as a proportion of the particulate matter (by mass or UV measurement) remains constant at smoking flow rates from 1.05 to 4.5 l.min⁻¹, covering measured human smoking flows. Inhaled particulate phase solanesol was calculated from solanesol measurement in the residual cigarette filter tip using filtration efficiency measurements from prior calibrations. Exhaled solanesol was measured from an exhalate capture filter pad. These two values were used to calculate particle deposition efficiency in the respiratory system for each test. Solanesol losses in the exhale capture system were assessed by wiping the internal surfaces of the pad holder, with no measureable losses detected.

Particle size and concentration measurements for smoke used a fast, electrical, differential mobility spectrometer (DMS-500, Cambustion, UK) at 10 Hz resolution [6,7] with the inhaled particle size distribution subsequently measured by re-smoking cigarettes on a smoking simulator (Smoking Cycle Simulator (SCS), Cambustion, UK) using human puffing profiles which had previously been recorded by the SA7 portable smoking analyser. The SCS has been described previously [7]. Sample losses in transport to the spectrometer were calculated to be <0.1% for 150 nm CMD particles in an 8 mm diameter tube at 8.5 l.min⁻¹ (8).

3. Results

3.1. Particle size and puffing behaviour

Table 1 shows average puffing behavior for each volunteer, showing significant differences in the total puff volume and average puff durations between volunteers, but less variation in the average puff flow.

The data were analysed to look for correlation between the puffing behavior and the particle size of the inhaled smoke. Puffing behavior was recorded in terms of total puff volume, total puff duration and average puff flow. Statistical analysis showed inhaled particle size was not correlated to total puff volume or total puff duration. However, there was a weak correlation between inhaled particle size and average puff flow, with particle size decreasing with increasing puff flow (Figure 2). Linear regression between inhaled particle size and average puff flow gave a coefficient of determination of 17.1%.

Table 1 - Puffing behaviour and inhaled particle size per cigarette for each volunteer averaged over triplicate measurements and quoted with \pm standard deviation

Subject	Total Puff Volume (ml)	Mean Puff Volume (ml)	Average Puff Duration (s)	Average Puff Flow (ml.s ⁻¹)	CMD (nm)
1	572	95 \pm 2	3.3 \pm 0.2	29.5 \pm 2.4	154 \pm 5
3	576	72 \pm 1	1.7 \pm 0.3	40.7 \pm 1.7	156 \pm 4
9	376	63 \pm 13	1.9 \pm 0.3	35.0 \pm 2.9	159 \pm 9
12	400	57 \pm 1	1.7 \pm 0.1	34.5 \pm 1.1	159 \pm 1
102	717	119 \pm 7	2.6 \pm 0.5	27.5 \pm 3.0	160 \pm 8
105	440	73 \pm 4	1.5 \pm 0.2	35.0 \pm 0.9	172 \pm 7
112	441	55 \pm 5	3.3 \pm 0.2	29.5 \pm 2.4	156 \pm 1

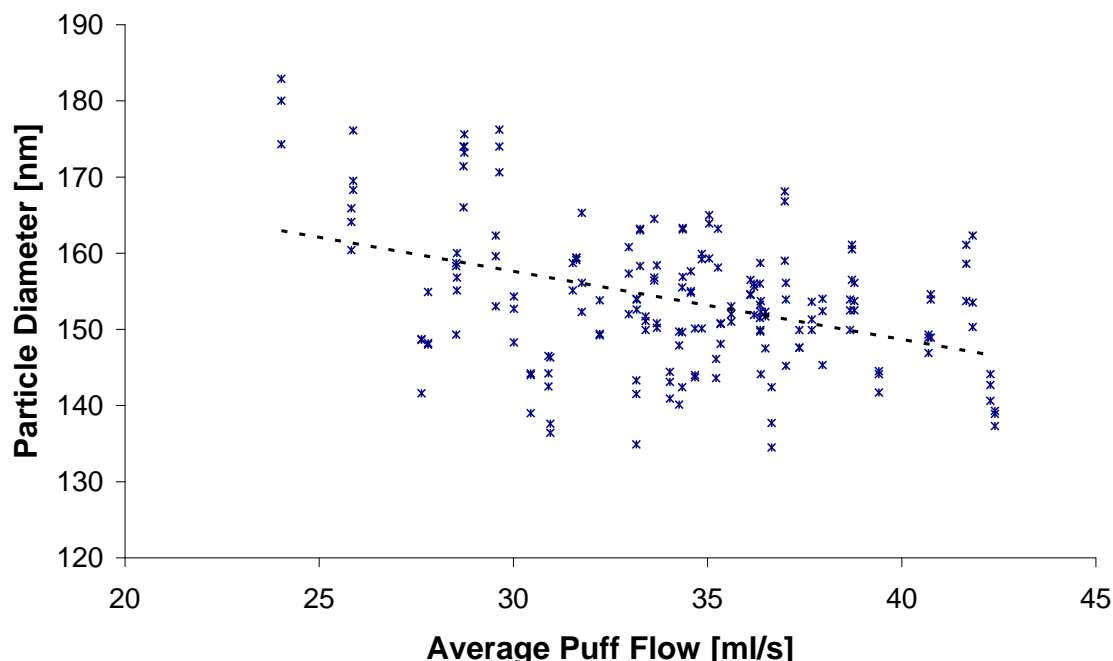


Figure 2 - Particle diameter (CMD) versus average puff flow

3.2. Particle size and retention

Analysis by ANOVA showed that there were statistically significant differences between only a few of the volunteers in terms of the particle size of inhaled cigarette smoke, but in general there were not significant differences between all subjects. In addition, the particle size measurements and the solanesol retention measurements were performed during separate experiments, so it is not possible to draw any direct conclusions in regards to the effect of particle size on retention from these data.

3.3. Retention and inhalation regime

Analysis by ANOVA showed that retention was statistically different for the VC₁₅ regime compared to VC₂₅ and Free, but not statistically different between VC₂₅ and VC_{Free}. The average retention values for VC₁₅, VC₂₅ and Free were 40.2%, 51.2% and 47.8% respectively. This implies that when allowed to inhale freely, the volunteers inhaled closer to VC₂₅ than VC₁₅.

Figure 3 plots average retention for each subject by inhalation regime, with the subjects arranged by increasing retention for the Free regime. As shown by the ANOVA analysis, in general the retention when using the VC₂₅ regime is higher than for VC₁₅, with the Free regime giving retention figures much closer to VC₂₅ than VC₁₅. The two volunteers with the lowest average VC₁₅ retentions (volunteer 12 and 112) were also the only volunteers where retention during the Free regime was closer to VC₁₅ than VC₂₅. Thus in any study comparing different cigarette types, it may be important to identify or control for the two different behaviour types.

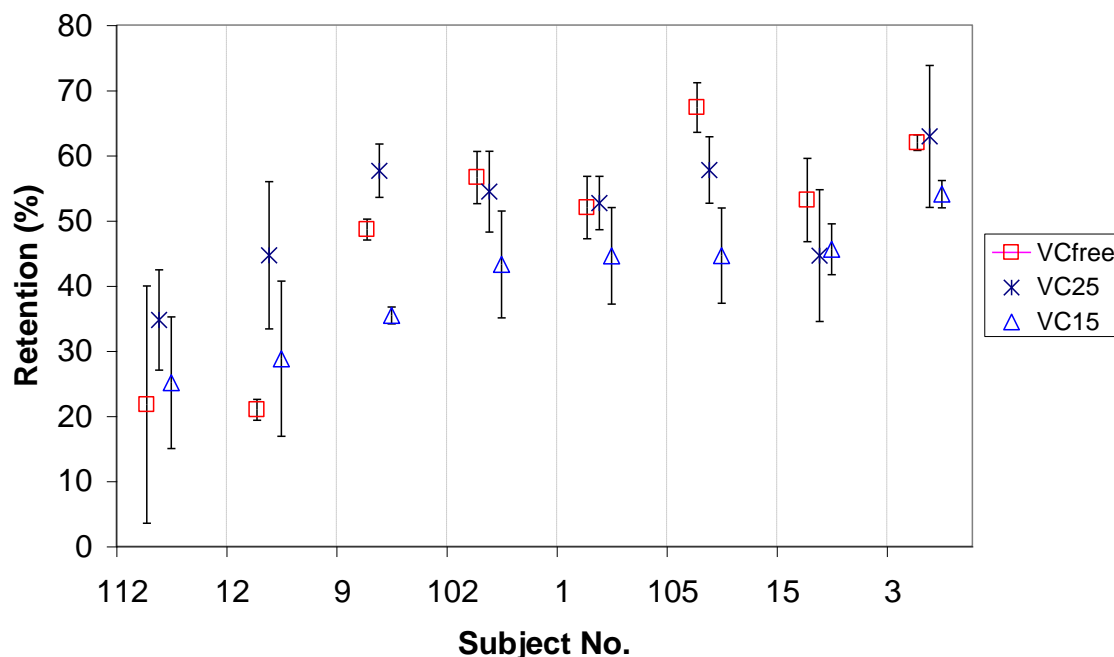


Figure 3 – Average deposition (Mean \pm SD for triplicate measures) for each volunteer by inhalation regime, with the volunteers arranged by increasing deposition at VC15.

4. Discussion

These measurements show the importance of inhalation regime on the retention of the particulate phase of cigarette smoke. There is a clear trend of increasing retention when moving from inhalation at VC₁₅ to VC₂₅. Additionally, when volunteers were allowed to inhale freely, they tended to achieve retention closer to those measured for VC₂₅ than VC₁₅. In retention studies it is common to control smoke inhalation, by forcing the volunteer to inhale to either VC₁₅ or VC₂₅. The results from this study imply that in general using VC₂₅ will give a retention measurement closer to a volunteer's retention when no inhalation regime is imposed. However, for some volunteers this will give misleading results.

The study also showed that smoking profile had a small effect on the particle size of the inhaled cigarette smoke, with a decrease in particle size with increasing average puff flow. However, the correlation was not strong. The data were not sufficient to show any effect of particle size on retention.

Future work will provide better data to examine the effect of particle size on retention, by providing quantitative measurement of the particle size distribution and number concentration for both inhaled and exhaled smoke.

Ethical Considerations

This study was conducted in line with the principles of the Declaration of Helsinki. Volunteers were all current smokers recruited from the workforce at BAT GR&D Centre. Each volunteer was interviewed and provided with study information prior to enrolment. Informed consent was obtained from each participant and each was made aware they were free to leave the study at any time.

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