A Device to Measure a Smoker's Puffing Topography and Real-Time Puff-by-Puff “Tar” Delivery*

by

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SUMMARY

A device for measuring the flow, duration and volume characteristics of human puffing behaviour when smoking cigarettes is described. Cigarettes are smoked through a holder comprising a measured pressure drop across a critical orifice. The holder also contains a Light Emitting Diode (LED) and photodetector that measures light obscuration in order to estimate nicotine-free dry particulate matter (NFDPM, “tar”) delivery. All data are recorded on a puff-by-puff basis and displayed in real time. These NFDPM estimates are known as optical “tar” (OT), and are derived from the calibration of the OT measurement versus gravimetric NFDPM yields of cigarettes under a range of smoking regimes. In a test study, puff volumes from 20–80 mL were recorded to $\pm 6.0\%$ of a pre-set volume, with an absolute error of 4.7 mL for an 80 mL volume drawn on a lit cigarette, and an average error of less than 2.0 mL across the range 20–80 mL. The relationship between NFDPM and OT was linear ($R^2 = 0.99$) and accurate to ± 1.3 mg per cigarette over the range 1–23 mg per cigarette. The device provides an alternative to the widely used part filter methodology for estimating mouth level exposure with an added benefit that no further laboratory smoking replication or analysis is required. When used in conjunction with the part filter methodology, the puffing behaviour recorded can explain anomalies in the data while providing a second independent estimate. [Beitr. Tabakforsch. Int. 26 (2014) 74–84]

ZUSAMMENFASSUNG

Es wird ein Gerät zur Messung von Strom, Dauer und Volumeneigenschaften des menschlichen Rauchverhaltens beim Rauchen von Zigaretten beschrieben. Die Zigaretten

werden über einen Halter mit gemessenem Druckabfall durch eine Messblende für kritische Strömung abgeraucht. Der Halter enthält auch eine Leuchtdiode und einen Photodetektor, der die Lichtschwächung misst, um den Gehalt an nikotinfreiem Trockenkondensat (NFDPM, “Teer”) zu bestimmen. Alle Daten werden für jeden Zug einzeln aufgezeichnet und in Echtzeit angezeigt. Diese NFDPM-Schätzungen werden als optischer “Teer” (OT) bezeichnet. Sie werden von der Kalibrierung der OT-Messung gegen gravimetrische NFDPM-Ausbeuten von Zigaretten nach verschiedenen Verfahren zur Messung des Rauchverhaltens abgeleitet. In einer Studie wurden Zugvolumina zwischen 20–80 mL bis zu $\pm 6,0\%$ eines vordefinierten Volumens aufgezeichnet, mit einem absoluten Fehler von 4,7 mL bei einem Volumen von 80 mL einer angezündeten Zigarette und einem durchschnittlichen Fehler von weniger als 2,0 mL im gesamten Bereich von 20–80 mL. Die Beziehung zwischen NFDPM und OT war linear ($R^2 = 0,99$) und im gesamten Bereich von 1–23 mg pro Zigarette auf $\pm 1,3$ mg pro Zigarette genau. Das Gerät bietet eine Alternative für die verbreitete Teil-Filter-Methode zur Bestimmung der Exposition im Mundraum und hat den zusätzlichen Vorteil, dass keine weiteren Rauchreplikationen oder Analysen im Labor erforderlich sind. Bei Verwendung zusammen mit der Teil-Filter-Methode kann das aufgezeichnete Rauchverhalten Anomalien in den Daten erklären und eine zweite unabhängige Bestimmung darstellen. [Beitr. Tabakforsch. Int. 26 (2014) 74–84]

RESUME

Le présent résumé décrit un dispositif permettant de mesurer les caractéristiques de flux, de durée et de volume des bouffées dans le comportement de fumage humain

relatif aux cigarettes. Les cigarettes sont fumées à travers un porte-cigarette comprenant une chute mesurée de pression à travers un orifice critique. Le porte-cigarette contient également une diode électroluminescente et un photo-détecteur qui mesure l'opacité afin d'évaluer la production de matière particulaire anhydre et exempte de nicotine (MPAEN, "goudron"). Toutes les données sont enregistrées "bouffée par bouffée" et affichées en temps réel. Ces évaluations de MPAEN sont connues comme goudron optique (GO) et sont dérivées de l'étalonnage de la mesure de GO comparé aux rendements gravimétriques de MPAEN de cigarettes obtenus dans le cadre d'une série de régimes de fumage. Dans une étude test, des volumes de bouffées de 20–80 mL ont été enregistrés à $\pm 6,0\%$ d'un volume prédéfini, avec une erreur absolue de 4,7 mL pour une bouffée d'un volume de 80 mL sur une cigarette allumée, et une erreur moyenne de moins de 2,0 mL pour la série de 20–80 mL. La relation entre MPAEN et GO était linéaire ($R^2 = 0,99$) et d'une précision de $\pm 1,3$ mg par cigarette pour la série 1–23 mg par cigarette. Le dispositif fournit une alternative à la méthodologie de section de filtre largement utilisée pour estimer l'exposition buccale, avec pour atout supplémentaire qu'aucune autre réplique ou analyse de fumage en laboratoire n'est requise. Lorsque le dispositif est utilisé conjointement à la méthodologie de section de filtre, le comportement de fumage enregistré peut expliquer des anomalies dans les données tout en fournissant une deuxième estimation indépendante. [Beitr. Tabakforsch. Int. 26 (2014) 74–84]

LIST OF ABBREVIATIONS

CSV:	Comma Separated Variable;
DAT:	Data Acquisition and Transmission;
LED:	Light Emitting Diode;
MLE:	Mouth Level Exposure;
MS:	Mouth Spill;
NFDPM:	Nicotine Free Dry Particulate Matter;
OT:	Optical "Tar";
PC:	Personal Computer;
SA7:	Smoking Analyser 7;
TSNA:	Tobacco Specific Nitrosamines.

INTRODUCTION

Tobacco smoking is a recognised risk to health; such risk being dose-related (1–3). Thus, improved estimates of smoke intake and retention in smokers are important in addressing regulatory oversight of tobacco products particularly in the context of modified risk tobacco products (4).

Puffing topography, a detailed description of the initial smoking process, is defined by a series of parameters such as puff volume, duration, frequency, profile and the total number of puffs. These measurements can be used to estimate mouth level exposure (MLE) - that is, the mass of smoke (particulate matter) drawn into the front portion of the mouth, either by modelling or by duplication of the smoking topography on laboratory smoking machines.

One early unobtrusive method of monitoring the smoking

process was to film consumers smoking cigarettes (5). This technique provided information about the total puff number and intervals between puffs but gave no indication of total puff volume or MLE. Typically, MLE is estimated by a part filter methodology, which determines the nicotine or nicotine-free dry particulate matter (NFDPM) ["tar"] retained in a cut segment of the spent cigarette filter as has been previously described (6). In short, a measurement of the deposited smoke constituents, principally NFDPM and nicotine, is made from the spent filter and calibrated versus filters smoked under a range of smoking regimes, covering the range of observed human smoking behaviour. The calibration smoking regimes also allow the emitted smoke to be collected on a Cambridge filter pad, representing the direct gravimetric mass.

Typically, the part-filter method uses the spent filters obtained from individuals smoking in their normal environment; thus, it is an unobtrusive method of estimating the MLE. The part-filter method has been used in a number of studies with various objectives including the comparison of MLE to NFDPM and nicotine by different smoker groups smoking their own product in different markets (7) or within a market (8–11), and groups of smokers switching from higher to lower NFDPM and nicotine yields, or to a reduced toxicant product in a clinical setting (12–15). It has also been used to investigate other chemical constituents such as a series of carbonyl compounds (16), solanesol (17, 18), and tobacco specific nitrosamines (19, 20).

Instruments for measuring puffing topography have been commercially available for a number of years. Generally, these instruments involve the smoking of cigarettes through a cigarette holder attached to a box of electronics via flexible plastic tubes (21). Flow through the cigarette holder is measured by the differential pressure generated across an orifice contained within the holder. Here we describe and validate a new instrument, the Smoking Analyser 7 (SA7), which also employs the principle of differential pressure for measuring flow and volume characteristics of human puffing behaviour, as well as puff duration and interval, but has an additional functionality, whereby it estimates real-time NFDPM by a light extinction measurement (Patent EP 1 569 530 B1). The SA7 therefore provides an alternative approach to measuring MLE with the advantage that no laboratory analysis of spent filters is required.

EXPERIMENTAL

Smoking analyser 7

The SA7 was developed at British American Tobacco in conjunction with B.E. FROST (Consultant, formerly of Rothmans International). The SA7 consists of three main units: a cigarette holder, a Data Acquisition and Transmission unit (referred to as the DAT) and a PC, shown in Figure 1. The cigarette holder and the handle were constructed from a black acetal homopolymer, known as Delrin, which has excellent machining properties and is relatively inert. The DAT unit was manufactured by C-Matic Ltd. (now Schneider Electric).

Figure 1. Smoking Analyser 7 (SA7).

Calibration of the SA7

A calibration procedure based on known flows and pressures was used to ensure that the SA7 produced accurate flow and pressure measurements. Calibration was performed daily prior to data collection. Optical “tar” (OT) measurements were calibrated by simultaneous determination of OT and NFDPM yields on cigarettes using several different smoking regimes. The NFDPM yields were determined by chemical analysis following ISO 4387:2000 (22). Puff volumes were checked prior to smoking using a soap bubble flow meter (Model 70241000, Borgwaldt KC, Germany).

Puff volume (pressure and flow calibration). A single channel smoking machine (a modified A14 Syringe Driver, Borgwaldt KC, Germany) calibrated for volume and flow was used to produce known flow rates. Flow calibration of the SA7 was achieved by using a series of 35 known flow rates ranging from $2 \text{ mL} \times \text{s}^{-1}$ to $120 \text{ mL} \times \text{s}^{-1}$ drawn through the SA7 cigarette holder via a 100 mmWG pressure drop. This pressure drop is similar to the pressure drop of a cigarette and ensured that the calibration procedure was conducted under conditions similar to those experienced when smoking a cigarette. The DAT unit recorded the pressure transducer readings for each calibration flow and compiled a calibration table.

A 1:10 flow divider system was used to avoid the problem of unsteady flows below $10 \text{ mL} \times \text{s}^{-1}$ generated by the

syringe driver due to low stepper motor frequencies if the syringe was moving very slowly. For example, a flow of $60 \text{ mL} \times \text{s}^{-1}$ generated by the syringe driver would cause a flow of $6 \text{ mL} \times \text{s}^{-1}$ to be drawn through the 100 mmWG pressure drop. The remaining $54 \text{ mL} \times \text{s}^{-1}$ would pass through the easier route of a 10 mmWG by-pass.

Pressure calibration was achieved by drawing flows of $17.5 \text{ mL} \times \text{s}^{-1}$ and $120 \text{ mL} \times \text{s}^{-1}$ through a 100 mmWG pressure drop and the SA7 cigarette holder. The pressure at each flow was measured simultaneously by the DAT unit and a calibrated manometer (Model C9551 manufactured by Comark, UK). For each flow rate, the operator entered the pressure value recorded by the manometer into a text box on the PC screen. The DAT unit then used these manometer readings, and linear interpolation between the corresponding pressure transducer readings, to construct a calibration table of transducer reading versus known pressure.

Optical “tar” calibration. The relationship between the extinction of light during smoking and the smoke concentration is non-linear. To determine this product-specific relationship, discrete cigarette types were smoked using a range of 12 bell-shaped smoking regimes with simultaneous measurements of OT and NFDPM yields. The smoking regimes were chosen to be representative of smoking topography observed for consumers, and consisted of puffs with volumes of 20 and 40 mL with 1.0, 1.5 and 2.0 s puff duration and 60 and 80 mL with 1.5, 2.0 and 2.5 s puff duration; each regime had a 30 s puff frequency. The relationship between light extinction and NFDPM for these regimes (single cigarette, no replicates) for each cigarette type was used to determine OT yields during smoking.

Figure 2. The SA7 holder.

Functionality and effect on sensory perception

An analysis was conducted to determine the effect of smoking through the SA7 on consumers' sensory perception and on NFDPM yields. Smokers were recruited by an external agency (SENSUS - Sensory Testing and Consumer Research Limited, Bristol, UK). Participants were over 21 years of age and gave informed consent.

The analysis involved the smoking of three commercial cigarettes with 1 mg, 4 mg or 6 mg ISO NFDPM yields; each product was smoked twice with the SA7 and twice without. Three separate groups of 20 smokers (10 female and 10 male) were assigned to the 1 mg, 4 mg or 6 mg ISO NFDPM cigarettes, which was equivalent to their usual ISO NFDPM product. Each of the 60 smokers visited a central location twice, and smoked two cigarettes of the appropriate type at each visit. There was a rest period of 20 min between the two cigarettes smoked in a session.

After each cigarette, subjects assessed the following sensory properties: draw effort, the perceived amount of effort expended whilst puffing on the cigarette; mouthful of smoke, the sensation of the amount of smoke entering the mouth during the puff; impact, the short-lived sensation experienced at the back of the throat during the inhalation of smoke; irritation, the lingering, tingling, peppery sensation perceived primarily in the throat during and after smoke inhalation; and flavour amplitude, the amount of flavour (gustation and olfaction) perceived irrespective of the character of the flavour.

Each attribute was scored on a scale of 1–5, where 1 represented either low or easy and 5 high or hard depending on the attribute assessed. In addition, subjects were asked to rate the overall acceptability of each cigarette using the same scale (23).

After the cigarettes were smoked, a 7 mm portion of the filter from each cigarette was removed from the mouth end using a custom-built filter cutter and stored. These filter segments were analysed by part-filter analysis for a comparative estimation of MLE (24).

Description of the SA7

When using the SA7, cigarettes are smoked through a specially designed cigarette holder (Figures 1–4). Flows leaving the cigarette towards the smoker's mouth are recorded using a pressure transducer to measure the difference in pressure across a stainless steel orifice (2 mm diameter; Figures 3 and 4) inside the holder. A second pressure transducer measures the difference in pressure within the holder as compared with atmosphere, to determine the suction applied to the cigarette. Higher flows through the holder are associated with greater pressure differences, where flow is proportional to the square root of the pressure.

The SA7 DAT unit measures the pressure differences 25 times a sec (25 Hz) and converts them to flow values according to a prior calibration process. The DAT transmits these readings to the PC via a serial link. The PC measures and displays the flow and pressure values on graphs in real time. Puff volumes and other values are calculated and displayed at the end of each puff.

Simultaneously, a measurement is made of the density of

the smoke aerosol passing through the holder. This measurement is made by an optical method in which light from an LED (wavelength 660 nm) passes through the smoke to a photodetector on the opposite side of the holder; both the LED and photodetector are mounted in a TO5 style can (a standard metal can used in some integrated circuits) with glass lens (Integrated Photometrics Ltd., UK). When no smoke is present, 100% of the light from the LED reaches the opposite side of the holder. When smoke is present, some of the light is scattered and less light is seen by the detector. The reduction (or extinction) of the light signal is measured at 25 Hz by the DAT and converts these instantaneous extinction values and corresponding flow values into OT mass using a product-specific calibration of extinction versus NFDPM, again from machine smoking, across a range of puffing behaviours. Summing these instantaneous values throughout a puff gives the amount of OT generated for that puff.

Flow, pressure, and light extinction signals are monitored by the SA7 from the moment the record is started by the operator. Minimum flow ($2.0 \text{ mL} \times \text{s}^{-1}$) and pressure (1.0 mmWG) threshold values are used to decide when a puff starts and ends. The default threshold values set for this purpose have proved suitable over multiple studies. If puff volume and duration thresholds of 2.0 mL and 200 ms, respectively, are not exceeded (as might be expected from simple movement of the cigarette holder in the hand), then the puff is recorded as a phantom puff and its contribution to the topography is ignored. Throughout a puff, flow, pressure and OT measurements are plotted on the computer screen (Figure 5). As a smoking session proceeds, puff parameters are collected on a puff-by-puff basis and total values calculated for that smoking session. The DAT unit continues to send information to the PC until the operator stops the session.

The record of each smoking session is stored as a CSV text file. This file consists of a header, a puff-by-puff summary and a record of all the raw data (25 Hz). The header records a subject identifier and details relating to the current smoking session. Hardware performance, puff thresholds and various calculation factors are also stored here. The header is followed by a puff-by-puff summary of puff volume, puff duration, puff OT.

Lastly, the raw data recorded during the smoke session are also stored in the file. These raw data allow subsequent duplication of the complete smoke session on a specialised smoking machine (Prototype Model LM4X, Borgwaldt KC, Germany) if required. The SA7 also has the ability to record and display analog input values from external equipment, and the status of external switches if required.

RESULTS

Validation and calibration of the SA7

Puff volumes and durations recorded by the SA7 were compared with known puff volumes drawn by a smoking machine. Puff volumes taken by the smoking machine were checked by the soap bubble flow meter. The SA7 accurately recorded the puff volumes taken by a smoking machine for the normal range of puff volumes taken by

Figure 3. Schematic diagram of the SA7 holder with dimensions.

Figure 4. Internal dimensions of the SA7 holder.

Table 1. Average SA7 parameters recorded from products of nominal 1 mg, 4 mg and 8 mg ISO NFDPM yields.^a

Pre-set volume/duration/interval (mL) / (s) / (s)	Soap bubble volume (mL)	SA7 volume (mL)	Volume error (%)	Duration (s)
20 / 1.0 / 30	20.3 ± 0.00	20.0 ± 0.11	-1.5	0.7 ± 0.04
20 / 1.5 / 30	20.3 ± 0.00	19.7 ± 0.10	-3.0	1.2 ± 0.05
20 / 2.0 / 30	20.3 ± 0.00	19.5 ± 0.18	-3.9	1.6 ± 0.07
40 / 1.0 / 30	39.8 ± 0.10	41.4 ± 0.22	4.0	0.8 ± 0.02
40 / 1.5 / 30	39.7 ± 0.05	40.7 ± 0.36	2.5	1.3 ± 0.02
40 / 2.0 / 30	39.7 ± 0.05	40.3 ± 0.24	1.5	1.8 ± 0.03
60 / 1.5 / 30	60.2 ± 0.17	62.6 ± 0.84	4.0	1.4 ± 0.03
60 / 2.0 / 30	59.9 ± 0.09	61.9 ± 1.09	3.3	1.9 ± 0.02
60 / 2.5 / 30	59.9 ± 0.09	61.7 ± 1.03	3.0	2.1 ± 0.01
80 / 1.5 / 30	79.5 ± 0.10	84.2 ± 0.97	5.9	1.4 ± 0.02
80 / 2.0 / 30	79.4 ± 0.00	82.5 ± 1.34	3.9	1.9 ± 0.02
80 / 2.5 / 30	79.5 ± 0.10	82.5 ± 1.27	3.8	2.2 ± 0.04

^a Values are given as mean ± sd

human smokers (Table 1). The puff volume measurements showed that volumes were measured correctly for lit cigarettes even though the flow calibration was carried out using air.

Various checks were made to confirm that the DAT unit's pressure transducer readings for each flow and pressure value measured during calibration were in line with predicted values. For example, it was checked that the DAT unit's flow and pressure readings at a given flow were higher than those for the previous lower flow reading.

On completion of the calibration process, a quality control procedure was carried out (Figure 6). The SA7 instructed the syringe driver to generate bell, triangle, square, and typical human profiles, each at volumes of 25, 50, 75 and 100 mL and durations of 1.0, 2.0 and 3.0 s (Figure 5). The calibration was only accepted by the operator if the puff volumes were as expected (i.e., within ± 1.0 mL of the pre-determined puff volume drawn by the syringe driver). The NFDPM and OT estimates determined during the smoke calibration were also compared. Table 2 and Figure 7 show the comparison of OT and simultaneous NFDPM yields for the three test products and smoking regimes, the R^2 for this relationship was 0.99. In addition, Figure 7 shows the 95% confidence and prediction lines for this relationship, calculated using a fitted line plot in Minitab 16. The largest absolute error in the OT yields was +1.3 mg of the measured NFDPM yield (19.9 mg) over the range 1–23 mg/cig, which were derived from the products of nominal ISO values of 1, 4 and 8 mg (Table 1).

Functionality and effect on smoker's sensory perception

Table 3 reports the sensory perception scores, as judged by three groups of 20 smokers, for the three commercial cigarettes smoked with and without the SA7. There were no statistically significant differences in the sensory perception when smoking test cigarettes with and without the cigarette holder, with the exception of irritation for the 6 mg product. Table 4 reports the MLE to NFDPM and nicotine for these three groups of smokers, smoking the same three commercial cigarettes with and without the SA7. Using a

2-sample t-test, the only statistically significant difference in MLE for the three cigarettes was seen for the 6 mg product.

DISCUSSION

SA7 accuracy and precision

For the SA7, the pressure and flow calibrations are performed using air at room temperature and atmospheric pressure. However, cigarette smoke has a small effect on measured puff volumes. To compensate for this, the SA7 adjusts the flow measurement by taking into account the corresponding smoke concentration.

A more significant effect can be caused by the temperature of the smoke. As a cigarette burns, the temperature of the smoke exiting the filter increases as the burning coal approaches the filter. The effect of this rise in temperature is most significant for the later puffs of high yield (+10 mg/cig) cigarettes when smoked with puffs of large volume taken at short intervals. The increase in temperature results in an over-estimation of puff volume. As an example, when an 8 mg ISO NFDPM cigarette was smoked with 80 mL puffs, puff volumes of 84.4 and 85.2 mL were recorded by the SA7 on the final two puffs. However, the effect of temperature on total puff volume and OT for the whole cigarette is small, equating to less than 5% of the recorded total puff volume.

This effect will be even less in ventilated cigarettes. Ventilation of cigarettes results in a smaller fraction of a puff being drawn through the hot coal. This results in a lower temperature of the smoke exiting the filter and only a small effect on the puff volumes measured by the SA7. Another potential confounder that a holder may introduce is the potential for vent blocking (25). A small lip designed into the SA7 mouthpiece where the cigarette is inserted prevents any potential vent blocking of the cigarette in the holder, allowing the cigarette to be inserted no further than 9 mm. Ventilation blocking by smokers fingers is unlikely to occur as subjects generally hold the SA7 holder rather

Figure 5. SA7 data collection screen.

Figure 6. Quality control (QC) checks.

Table 2. Optical “tar” and corresponding NFDPM yields smoked under calibration regimes.

Pre-set	8 mg		4 mg		1 mg	
Volume/duration/interval (mL) / (s) / (s)	OT (mg/cig)	NFDPM (mg/cig)	OT (mg/cig)	NFDPM (mg/cig)	OT (mg/cig)	NFDPM (mg/cig)
20 / 1.0 / 30	7.1	7.9	4.2	4.1	1.6	1.5
20 / 1.5 / 30	8.4	9.3	4.1	3.7	1.3	1.3
20 / 2.0 / 30	8.2	8.0	2.8	2.4	0.7	1.2
40 / 1.0 / 30	14.2	14.1	9.6	10.3	5.6	5.5
40 / 1.5 / 30	15.4	15.1	9.7	9.7	8.1	8.5
40 / 2.0 / 30	16.8	16.7	9.3	8.8	10.4	9.2
60 / 1.5 / 30	21.1	20.2	13.6	13.5	8.7	9.3
60 / 2.0 / 30	22.6	22.2	14.7	13.7	5.4	4.8
60 / 2.5 / 30	21.2	19.9	18.1	18.7	4.6	5.1
80 / 1.5 / 30	22.6	23.0	13.1	14.3	7.3	7.4
80 / 2.0 / 30	21.4	22.7	14.1	14.1	6.8	6.2
80 / 2.5 / 30	22.4	22.7	14.7	14.9	8.5	9.0

than the cigarette itself, whilst it is not possible to block the ventilation on the cigarette by the lips, since, the subject lips only touch the plastic mouthpiece. However, it has been shown that there is potentially a slight sensory impact of smoking cigarettes through the SA7 (Table 3) whereby subjects tended to score irritation slightly higher when smoking through the SA7 compared to smoking the same product without the SA7, although this was statistically different only for the 6 mg product. Although, not statistically different subjects scored the mouthful of smoke slightly lower for each product when smoking through the SA7. When smoking a cigarette through the SA7 the cigarette is further from the subject, thus the smoke takes slightly longer to reach the mouth, hence, the mouthful of

smoke score is lower. This may result in a slightly higher puff volume drawn by some subjects in the first one or two puffs.

A market survey across eight countries and 106 products (7) reported the MLE for 5710 smokers, representative of each market. The mean “tar” MLE for all smokers was 14.0 mg/cig, which falls well within the calibrated OT range of 1–23 mg/cig, which covered 93% of the population of these smokers.

The present study has described and validated a new instrument to measure a smoker's puffing topography and real-time NFDPM estimates puff by puff. The SA7 was shown to be a reliable, accurate and precise instrument capable of recording consumers' puffing parameters. Puff

Figure 7. NFDPM against optical “tar” from products of nominal 1 mg, 4 mg and 8 mg ISO NFDPM yields.

Table 3. Consumer sensory scores with and without the SA7 holder. ^a

Sensory property	1 mg + SA7	1 mg	4 mg + SA7	4 mg	6 mg + SA7	6 mg
Draw effort	3.0 ± 1.2	3.0 ± 1.1	2.8 ± 1.0	2.7 ± 0.9	2.9 ± 0.8	3.0 ± 0.8
Mouthful	3.5 ± 1.1	3.6 ± 0.9	2.7 ± 0.7	3.0 ± 0.9	3.0 ± 0.6	3.2 ± 0.6
Impact	3.9 ± 0.9	3.9 ± 0.8	2.8 ± 0.9	3.0 ± 1.2	3.0 ± 0.7	3.0 ± 0.7
Irritation	3.9 ± 0.9	3.8 ± 1.1	2.6 ± 0.9	3.0 ± 1.0	2.9 ± 0.9 *	2.7 ± 0.9 *
Flavour amplitude	3.9 ± 0.9	3.9 ± 0.8	3.0 ± 0.9	3.5 ± 1.0	3.2 ± 0.6	3.1 ± 0.7
Acceptability	2.3 ± 0.9	2.6 ± 1.1	3.0 ± 1.0	2.8 ± 1.0	3.8 ± 0.9	3.7 ± 0.9

^a Values are given as mean ± sd

* Indicates significant difference ($p \leq 0.05$)

volumes were recorded across the range 20–80 mL with a precision of ± 1.34 mL (at 80 mL). The largest absolute error of 4.7 mL was recorded for an 80 mL volume drawn on a lit cigarette. The SA7 recorded puff volumes where the flow rate within the puff was between 1 and 120 mL $\times$ s⁻¹. The puff frequency measurements reflect both the accuracy of the smoking machine and the ability of the SA7 to record the puffs correctly. It was seen that the SA7 accurately measured the interval between puffs taken by the smoking machine. Each and every puff interval recorded by the SA7 corresponded to a puff frequency of 30 s, with no variation. Similar to the SPA/m (Sodim, France), the SA7 stores both the puff profile and summary for all puffs, which allows replication of the records on a smoking machine in the laboratory if required at a later date.

Smoking machine puff durations measured by the SA7 were consistently a little shorter than the intended duration set for the smoking machine. One possible reason for this is the use of the flow thresholds to detect the start and end of puffs. A second reason is that smoking machine puff durations tend to be slightly shorter than the intended value. Puff durations are expected to be measured more accurately for larger puffs where the rise and fall of flow rates at the start and end of a puff are steeper.

Instruments for measuring puffing topography have been commercially available for several years, and developments in electronics and computing have enabled the size and portability of these instruments to be improved. There are currently two portable units commercially available: namely, the SPA/m and the CReSSmicroTM (Borgwaldt KC, Germany, previously Plowshare Technologies, USA). In particular, the CReSSmicroTM has been used in a number of studies, recording the puffing parameters of consumers smoking test products in a controlled laboratory

environment (26–28) and to monitor behaviour over an extended 24 h period in the consumers' natural environment (29, 30). Nevertheless, the SPA/m and the CReSSmicroTM do not allow real time measurement of “tar” delivery; instead, MLE has to be analysed subsequently by the part-filter approach.

The SA7 estimates NFDPM delivery in real time by the OT technique. The estimated OT was on average within ± 0.5 mg of the measured NFDPM, with a largest absolute error of 1.3 mg (at 20 mg) across the range 1–23 mg per cigarette. This is well within the error set by ISO 4387:2000 (22); that is, accuracy to $\pm 15\%$ or ± 1 mg, whichever is the greater.

Smoking through the SA7 was found to have only a slight impact on the subjects' sensory assessment of a cigarette. The SA7 proved useful in understanding the subjects' interaction with the product and in assessing the amount of smoke generated during smoking. There is always the possibility that smokers might behave a little differently from normal when involved in studies. The MLE yields shown in Table 4 suggest that, in some cases, consumers may smoke more intensely when smoking through the SA7 holder, particularly for the 6 mg product.

In summary, the SA7 provides an alternative to the widely used part filter methodology with the added benefit that no further laboratory analysis is required to determine the subjects' MLE. Although the part-filter approach is less intrusive for the consumer, the puffing data simultaneously recorded by the SA7 can explain anomalies in the data. Furthermore, if the SA7 is used in conjunction with the part-filter methodology, two independent estimates of the consumers' MLE can be determined with little effect on the overall cost and time of the study.

Table 4. Comparison of MLE yields with and without the SA7 holder. ^a

ISO “tar” level	NFDPM (mg/cig)			Nicotine (mg/cig)		
	With holder	Without holder	Pr > t	With holder	Without holder	Pr > t
1 mg	6.4 ± 3.3	6.1 ± 2.9	0.672	0.67 ± 0.32	0.70 ± 0.30	0.689
4 mg	12.6 ± 3.7	12.4 ± 3.2	0.801	1.29 ± 0.32	1.30 ± 0.32	0.965
6 mg	14.5 ± 4.4	12.8 ± 3.1	0.049	1.41 ± 0.44	1.21 ± 0.27 *	0.016

^a Values are given as mean ± sd

* Indicates significant difference ($p \leq 0.05$)

COMPETING INTERESTS

Sandra J. Slayford is employed by British American Tobacco; Barrie E. Frost was paid as a consultant by British American Tobacco during the development of the SA7. All work was funded by British American Tobacco.

AUTHOR'S CONTRIBUTIONS

Barrie E. Frost was responsible for the design, software and development of the SA7. Sandra J. Slayford contributed to the development and testing of the SA7 and software. The manuscript was jointly written by Sandra J. Slayford and Barrie E. Frost. Both authors have read and approved the final manuscript.

ACKNOWLEDGEMENTS

BAT wish to acknowledge the contribution by Mr. N. Oakes (formerly of C-Matic Systems Ltd.) for his support with the design and construction of the DAT unit.

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