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Beiträge zur Tabakforschung International
Contributions to Tobacco Research
Volume 26 · No. 1 · April 2014
DOI: 10.2478/cttr-2014-0003

Relationship Between Cigarette Yields and Smoking Time Under Different Machine Smoking Regimes *

by

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SUMMARY

Many tobacco product regulations worldwide require the reporting of "tar", nicotine and carbon monoxide and set limits on their yields measured following the ISO smoking regime. Within the current regulatory framework, the introduction or recommendation for an additional more intense smoking regime with filter ventilation blocked has been made. The relationship was evaluated between measured yields and the difference between smouldering and smoking times with filter ventilation open or blocked under different smoking regimes. Development and evaluation of a cigarette burning model revealed a straight line relationship passing through the origin, showing that the "tar", nicotine and CO yields from one smoking regime can be used to predict the yields at any smoking time. Consequently, the rationale for conducting laboratory work under an additional specific regime is questionable and the additional data set adds no more value beyond adding a point to a known line. [Beitr. Tabakforsch. Int. 26 (2014) 4–18]

ZUSAMMENFASSUNG

In vielen der weltweiten Rechtsvorschriften für Tabakerzeugnisse wird die Angabe des Gehalts an Kondensat, Nikotin und Kohlenstoffmonoxid verlangt und es werden Grenzwerte für deren Ausbeuten auf der Grundlage der Verfahren zur Messung des Tabakkonsums gemäß ISO festgelegt. Es wurde nun vorgeschlagen, innerhalb des bestehenden Rechtsrahmens ein zusätzliches intensiveres Messverfahren, bei dem die Filterbelüftung blockiert ist, einzuführen bzw. zu empfehlen. Es wurde das Verhältnis zwischen den gemessenen Ausbeuten und die Differenz zwischen Glimm- und Rauchzeiten mit geöffneter bzw. blockierter Filterbelüftung entsprechend unterschiedlicher Messverfahren bestimmt. Die Ermittlung und Analyse eines Zigarettenverbrennungsmodells ergab eine durch den Nullpunkt verlaufende Gerade, mit der gezeigt werden konnte, dass die mit einem Messverfahren ermittelten Ausbeuten an Kondensat, Nikotin und CO verwendet werden können, um die Ausbeuten zu beliebigen Abrauchzeiten zu prognostizieren. Daher ist die Begründung für die Durchführung von Laboruntersuchungen gemäß einem weiteren Messverfahren fragwürdig. Die so gewonnenen zusätzlichen Daten brächten, abgesehen von der Ermittlung eines weiteren Punktes auf einer bereits bekannten Geraden, keinerlei zusätzlichen Nutzen. [Beitr. Tabakforsch. Int. 26 (2014) 4–18]

RESUME

De par le monde, de nombreuses réglementations sur les produits du tabac exigent la déclaration des valeurs de goudrons, de nicotine et de monoxyde de carbone, et imposent des limites sur leurs rendements selon le régime de fumage ISO. Dans le contexte réglementaire actuel, l'introduction ou la recommandation d'un régime de fumage plus intense avec la ventilation du filtre bouchée a été faite. La relation entre les rendements mesurés et la différence entre le temps de combustion libre et de fumage, ventilation filtre ouverte ou bouchée, a été évaluée avec l'application de différents régimes de fumage. Le développement et l'application d'un modèle de combustion

*Received: 11th November 2013 – accepted: 13th February 2014

de la cigarette révèle une relation linéaire passant par l'origine, montrant ainsi que les rendements peuvent être prédits pour n'importe quelle durée de fumage à partir de l'application d'un seul régime de fumage. Par conséquent, la question de l'utilité de conduire des travaux en laboratoire avec un régime additionnel se pose puisque les données supplémentaires n'apportent pas plus de valeur que celle d'ajouter un point sur une ligne déjà connue. [Beitr. Tabakforsch. Int. 26 (2014) 4–18]

KEYWORDS: Smoking regime; Cigarette smoke yields; Cigarette smoking time

INTRODUCTION

Many governmental authorities have introduced regulations on smoke constituents that require manufacturers to print on the pack the yields per cigarette of Nicotine Free Dry Particulate Matter (NFDPM) or "tar" (T), nicotine (N) and carbon monoxide (CO), or set limits on their yields (1). The most widely referenced machine smoking regime and yield measurement methods have been published by the INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (2). Yields are measured on the collected smoke using the prescribed ISO testing methods (3–6) which are intended to provide a means of ranking cigarettes under fixed measuring conditions (7).
Other regulations have asked for yield reporting under different machine smoking regimes (8, 9), and other regimes have been proposed (10, 11). Some recommendations have been made (12, 13) to study smoke yields using both the ISO regime (2) and the Canadian Intense (CI) regime (9) in the former case to characterize cigarette products and to eventually set regulatory limits. However, the question of which regime would provide the better characterisation for regulation is still debated.
Previous work (14) showed that TNCO and water smoke yields determined under 16 smoking regimes formed part of a continuous function linked with puffing intensity (the product of puff volume and puff frequency) and total puff volume (the product of puff volume and puff number). This had been shown to apply to both principal global cigarette styles (i.e., American and Virginia blends) over a broad "tar" range.
In this paper, the relationship was investigated between TNCO yields and either the smoking time or the reduction in the smoking time due to puffing the cigarette (Δt). This parameter Δt was derived from a cigarette burning model and calculated as the difference between the time to smoke the cigarette when puffing under a given regime and the free burn (smouldering) time to the same butt length. Modelling was carried out, based on sequential burning steps to predict smoking time under a series of smoking regimes for a range of cigarettes with the filter ventilation open and blocked, and with both conventional and low ignition propensity[1] cigarette papers. The purpose was to determine whether TNCO yields given by smoking a cigarette type under one smoking regime can be used to predict the yields at any smoking time. So far, our investigations have been limited to TNCO yields and will have to be extended to confirm whether similar relationships exist for other smoke analytes.

EXPERIMENTAL - CIGARETTE SMOKING

Cigarettes tested

In one study, 65 experimental cigarette types were smoked under the ISO 3308 standard smoking conditions to assess the relationship between the puff number and the smoulder rate. These were manufactured with 65 different tobacco grades (Burley, Virginia, Oriental) each having different smoulder rates, but with the same set of filter, tipping and cigarette papers (filter ventilation of 12% and paper ventilation of 15% as determined by methodology given in ISO 9512:2002 (16)). The smoulder rates ranged from 3.1 to 9.7 mm/min, the ISO "tar" ranged from 7.1 mg/cig to 22.3 mg/cig, and ISO puff numbers from 5.0 to 13.8. The smoulder rate was determined from the measurement of the tobacco rod weight loss during combustion, and the conversion of the weight into the corresponding length (17).
In a second study, ten common commercially marketed European products (A to J) were tested under several smoking regimes. They were chosen to cover a wide range of cigarette designs (i.e., cigarette and filter lengths, diameter, filter ventilation, cigarette paper). The range of ISO "tar" was from 1 to 10 mg/cig (3); the range of filter ventilation was from 14 to 87% (16); the paper ventilation from 2 to 14% (16); the diameter from 5.4 to 7.9 mm (18); the cigarette length from 83 to 99 mm; the filter length from 21 to 27 mm and the smoulder rate from 5.0 to 8.8 mm/min (17). Among the products, seven had uniform cigarette paper porosity (products A to G), and three (products H to J) had banded cigarette paper to represent products compliant with the Lower Ignition Propensity (LIP) standard (19). The characteristics relative to each product are described in Table 1.

Smoking regimes

TNCO yields were determined for Product A under 32 different machine smoking regimes, including the ISO 3308:2012 standard methodology (see Table 2), using a linear smoking machine (Cerulean SM450). The study of a broad range of regimes was intended to widely characterize the impact of puff volume, puff frequency and filter ventilation blocking on TNCO yields.
For Products B to J, TNCO yields were determined by the application of 4 different machine smoking regimes, given in Table 3, the ISO 3308 and the Canadian Intense standard methodologies, filter ventilation open and blocked, using a linear smoking machine (Cerulean SM450).

[1] Cigarettes with low ignition propensity papers are designed so that when tested according to an agreed standard (15) they will pass according to the pass rate described in EN 16156, 2010.

Table 1. Design characteristics of the products tested.

Product	ISO "tar" (mg/cig)	LIP (Y/N)	Diameter (mm)	Filter ventilation (%)	Paper ventilation (%)	Cigarette length (mm)	Tipping length (mm)	Filter length (mm)	Smoulder rate (mm/min)
A	3	No	7.8	52	14	83	32	27	6.8
B	10	No	7.8	14	12	83	25	21	6.6
C	6	No	7.8	40	6	83	32	27	6.1
D	4	No	7.8	50	5	83	32	27	6.7
E	1	No	7.8	72	2	83	32	27	7.1
F	7	No	6.1	47	12	97	32	27	8.8
G	1	No	5.4	87	4	99	35	30	8.1
H	10	Yes	7.8	19	13	83	25	21	5.5
I	7	Yes	7.8	32	9	83	32	27	5.6
J	2	Yes	7.9	52	6	83	32	27	5.0

Table 2. Set of smoking regimes applied to product A.

Smoking regime	Puff interval (s)	Puff duration (s)	Puff volume (mL)	Filter ventilation
1	60	2	17.5	Open
2	60	2	35	Open
3	60	2	55	Open
4	60	2	70	Open
5	60	2	17.5	Blocked
6	60	2	35	Blocked
7	60	2	55	Blocked
8	60	2	70	Blocked
9	40	2	17.5	Open
10	40	2	35	Open
11	40	2	55	Open
12	40	2	70	Open
13	40	2	17.5	Blocked
14	40	2	35	Blocked
15	40	2	55	Blocked
16	40	2	70	Blocked
17	30	2	17.5	Open
18	30	2	35	Open
19	30	2	55	Open
20	30	2	70	Open
21	30	2	17.5	Blocked
22	30	2	35	Blocked
23	30	2	55	Blocked
24	30	2	70	Blocked
25	20	2	17.5	Open
26	20	2	35	Open
27	20	2	55	Open
28	20	2	70	Open
29	20	2	17.5	Blocked
30	20	2	35	Blocked
31	20	2	55	Blocked
32	20	2	70	Blocked

Table 3. Set of smoking regimes applied to products B to J.

Smoking regime	Puff interval (s)	Puff duration (s)	Puff volume (mL)	Filter ventilation
1	60	2	35	Open
2	60	2	35	Blocked
3	30	2	55	Open
4	30	2	55	Blocked

CIGARETTE BURNING MODEL

Cigarette smoking consists of successive steps of active burning during each puff then smouldering between each puff. Key assumptions were made to describe and predict the burning phases during cigarette smoking, and from which equations were derived to build a cigarette burning model. It was then fitted and compared to experimental data when smoking the studied cigarettes described in the previous section under different smoking regimes.

Model assumptions and equations

Assumption 1: *During the smouldering phase, the mean burn rate $\overline{SR}$ is constant and independent of the puff number.*

After each puff, a transitory phase occurs between the active and stable passive combustion. This phase corresponds to a continuous decrease of the cigarette burn rate until the steady smouldering stage is reached. Although the instantaneous smoulder rate can change, it is assumed that the mean rate $\overline{SR}$ between two puffs is constant whatever the puff number.

Model equation 1

The length burnt after n puffs $L_{burnt}(n)$ can be expressed as the sum of the lengths burnt during the puffs and the lengths burnt between the puffs:

$$L_{burnt}(n) = \sum_{i=1}^{n} L_{puff}(i) + (n-1) \times \overline{SR} \times \frac{T_{inter}}{60} \qquad [1]$$

where

$\overline{SR}$ is the mean smoulder rate, expressed in mm/min

$L_{puff}(i)$ is the length burnt during Puff i, expressed in mm

T_{inter} is the puff interval, expressed in s.

It is important to note that $\overline{SR}$ is not only related to the burning of the cigarette paper but also to the rod as a whole. In addition to the paper porosity and burn additives, the filling density, the blend composition, tobacco types (for example dark air cured or oriental sun cured) and the proportion of reconstituted or expanded tobacco can also modify the smouldering between puff. It has been observed that after a puff, the paper burn line does not move for 15 to 20 s following a puff (20) but $\overline{SR}$ represents here the mean speed of the combustion front line of the tobacco rod.

Assumption 2: *The length of tobacco burnt during a puff is proportional to the coal airflow Q_{coal}, to the puff duration T_{puff} and to the mean smoulder rate $\overline{SR}$.*

The combustion depends on the amount of oxygen (or air) supplied to the coal; the more air/oxygen is supplied, the more tobacco is burnt. It can be reasonably assumed that the length burnt will be proportional to the volume of air across the coal (21), which is the multiplication of the mean airflow by the puff duration. It can also be reasonably assumed that when a cigarette shows a natural tendency to burn fast under smouldering conditions (for example, due to the combustibility characteristics of the tobacco and cigarette paper), then the length burnt during a puff will also be naturally longer compared to a slow-smouldering product.

Model equation 2

The length of tobacco burnt during a puff $L_{puff}(i)$ can be expressed as follow:

$$L_{puff}(i) = k \times Q_{coal}(i) \times T_{puff} \times \overline{SR} \qquad [2]$$

where

$Q_{coal}(i)$ is the airflow across the coal during the puff i, expressed in mL/s

T_{puff} is the puff duration, expressed in s

k is a factor of proportionality, expressed in s/mL.

Assumption 3: *The airflow at the coal increases linearly as the tobacco rod burns.*

As the tobacco rod burns, the surface of cigarette paper decreases which means that less air enters the cigarette across the paper. Consequently, with standard puffing conditions, the paper ventilation decreases as the cigarette is smoked and the coal airflow increases. The simplest first order approach assumes that the coal airflow increase is proportional to the length burnt.

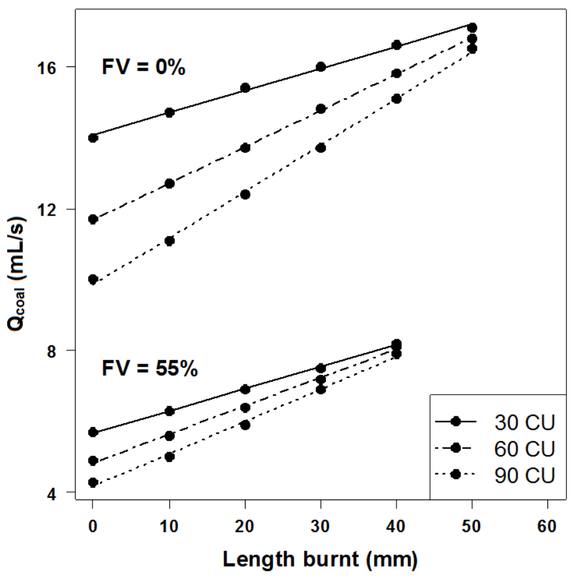

Figure 1. Simulation of the change of the coal airflow as the cigarette burns for a filter-ventilated product (55%) and for a non-ventilated product, at three different paper porosities (30-60-90CU).

As shown in Figure 1, the application of the experimentally validated model published by DWYER (22) confirms this hypothesis for both non ventilated and ventilated products.

Model equation 3

A linear relationship linking the coal airflow to the tobacco rod length burnt can be derived from assumption 3.

$$Q_{coal}(L) = \frac{Puff_{vol} \times (1-FV) \times PV}{T_{puff} \times (L_{cig} - L_{tip})} \times L + \frac{Puff_{vol}}{T_{puff}} \times (1-FV) \times (1-PV) \qquad [3]$$

where

L is the length burnt at the start of the puff, expressed in mm

PV is the paper ventilation cigarette, unlit

FV is the filter ventilation cigarette, unlit

$Puff_{vol}$ is the volume of the puff, expressed in mL

L_{cig} is the cigarette length, expressed in mm

L_{tip} is the tipping length, expressed in mm.

If $L = 0$ then $Q_{coal}(L) = \frac{Puff_{vol}}{T_{puff}} \times (1-FV) \times (1-PV)$

If $L = (L_{cig} - L_{tip})$ then $Q_{coal}(L) = \frac{Puff_{vol}}{T_{puff}} \times (1-FV)$.

Assumption 4: *An underestimation of the filter and paper ventilations, and then an overestimation of the coal airflow, can be compensated by a modification of the level of factor k.*

This assumption is closely related to assumption 2 and the corresponding equation [2] linking together the coal airflow and the factor of proportionality k.

The filter and paper ventilations are measured when the cigarette is unlit (16). When the cigarette is lit, the coal generates an additional pressure drop, due to the air temperature increase, which leads to an increase in both the filter and paper ventilations during puffing (22) and a subsequent decrease in the airflow across the coal and a decrease in the length burnt during the puff (see assumption 2). The increases in ventilation are not easily measurable experimentally and can vary from one product to another as a function of the cigarette design. For example, the tobacco filling density, the diameter of the cigarette, the position of the ventilation holes along the filter are all parameters likely to influence the pressure drop during smoking and hence the paper and filter ventilations. So it is simpler to use the ventilation values measured on the unlit cigarette. Considering equation [2], an underestimation of the filter and paper ventilations which would lead to an overestimation of the length burnt during a puff, can be easily compensated by modifying factor k. Consequently, the unlit cigarette paper and filter ventilations are used in equation [3].

Model outputs

A number of parameters available from the smoking regime or from basic cigarette design information are needed to be input into the model: the smoulder rate, the filter and paper ventilations, the puff duration, the puff interval, the puff volume, the tipping length, the cigarette length and the butt length. The following parameters can then be readily deduced from the model: the puff number; the length of rod actively burnt during all *puffs* $L_{T\_activeburnt}$ (equation [4]); the weight of tobacco actively burnt $M_{T\_activeburnt}$ (equation [5]); the mean mass per puff and the smoking time $T_{T\_Smoking}$ (equations [6a] and [6b]).
The puff number is obtained from equations [1] and [2] by counting the puffs until the combustion front reaches the butt length. Because the number of puffs is easily measured during smoking, the predicted values were only used in the model validation process to compare with actual data.

$$L_{T\_activeburnt} = \sum_{i=1}^{n} L_{puff}(i) \qquad [4]$$

where

$L_{T\_activeburnt}$ is the total length burnt during the puffs, expressed in mm.

$$M_{T\_activeburnt} = \frac{L_{T\_activeburnt}}{L_{cig} - L_{filt}} \times M_{T\_Tob} \qquad [5]$$

where

M_{T_Tob} is the total mass of tobacco burnt during the puffs

$L_{T\_activeburnt}$ is the total mass of tobacco in the rod

L_{filt} is the filter length, expressed in mm.

If the puff number for a single cigarette is an integer then the smoking time, up to a given butt length, is the time for all puffs plus the puff intervals and the remaining smoulder time after the last puff.

$$T_{T\_Smoking} = (Puff_n - 1) \times \frac{T_{inter} + T_{puff}}{60} + \frac{T_{puff}}{60} + \frac{L_{T\_burnt} - L_{burnt}(Puff_n)}{\overline{SR}} \qquad [6a]$$

where

$T_{T\_Smoking}$ is the smoking time (or duration of smoking), expressed in min

$Puff_n$ is the number of puffs

L_{T_burnt} is the total length burnt, expressed in mm.

If the puff number for a single cigarette is not an integer then the smoking time is the time for all puffs and puff intervals.

$$T_{T\_Smoking} = Int(Puff_n) \times \frac{T_{inter} + T_{puff}}{60} + (Puff_n - Int(Puff_n)) \times \frac{T_{puff}}{60} \qquad [6b]$$

where

$Int(Puff_n)$ is the integer part of the number of puffs.

RESULTS

Measured puff numbers for the 65 experimental cigarettes, obtained under ISO smoking during the first study, are represented in Figure 2. A clear relationship linking puff number and smoulder rate can be observed. As the speed of burning increases, the number of puffs decreases under standard puff frequency conditions. Simulated values from the model using the filter and paper ventilation values measured on the unlit cigarette (FV = 12%; PV = 15%) are also drawn. The model prediction reproduces the curvature relating puff numbers and a wide range of smoulder rates derived from measured data with a coefficient of determination of 90.4%. This tends to validate the four assumptions made previously.

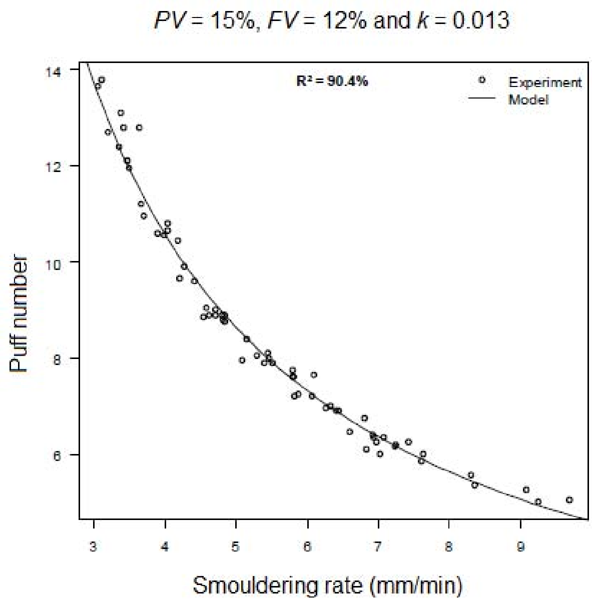

Figure 2. Calculated and measured values of puff numbers of prototypes as a function of smoulder rate.
PV = 15%, FV = 12% and k = 0.013
A coefficient of determination of R^2 = 90.4% between the measured and calculated puff numbers is an indication of a good fit when the factor k is set to 0.013.

As shown in Table 4, similar values of coefficient of determination have been obtained for a wide range of PV, FV and k combinations. This confirms the validity of assumption 4.
The aim of the first study was to assess the impact of the smoulder rate on the puff numbers; the aim of the second study was to assess the impact of the applied smoking regime. The impact of different smoking regimes on the burning process was well characterised first for Product A (Table 2), having the common "King Size" format. This product was purposely selected with a high level of filter ventilation (52%) to assess the impact of the filter ventilation blocking on the cigarette burning. A more limited number but broad range of smoking regimes (Table 3) was subsequently applied to Products B to J to determine whether findings on Product A apply to a wider range of product design.

Table 4. Quality of the statistical fit of the calculated and experimental puff numbers vs. the smoulder rate. Combination 2 corresponds to the case described in assumption 3. The other combinations correspond to theoretical sets of filter/paper ventilation values to evaluate if the adjustment of the factor *k* could compensate the effect of the coal on the ventilations. For each combination, *k* was determined by successive iteration of 0.001 until the highest coefficient of determination between the measured and calculated puff number was obtained.

Combination	Filter ventilation (%)	Paper ventilation (%)	Factor *k* adjusted	R^2 (%)
1	8	15	0.012	90.5
2	12	15	0.013	90.4
3	16	15	0.013	90.7
4	20	15	0.014	90.4
5	24	15	0.015	90.5
6	8	20	0.012	91.1
7	12	20	0.013	90.6
8	16	20	0.014	90.6
9	20	20	0.014	90.9
10	24	20	0.015	90.6
11	8	25	0.013	90.5
12	12	25	0.014	90.5
13	16	25	0.014	90.7
14	20	25	0.015	90.5
15	24	25	0.016	90.6
16	8	30	0.013	91.1
17	12	30	0.014	90.7
18	16	30	0.015	90.6
19	20	30	0.015	91.0
20	24	30	0.016	90.9
21	8	35	0.014	90.7
22	12	35	0.014	91.3
23	16	35	0.015	91.0
24	20	35	0.016	90.8
25	24	35	0.017	90.7

It has been shown previously (14) that TNCO yields were linearly related to the total puff volume when different smoking regimes were applied to a same cigarette. In other words, when the total puff volume was doubled, the TNCO yields were also doubled. This observation is confirmed and represented for Product A in Figure 3 when the filter ventilation is open and blocked. The difference between the slopes with filter ventilation open and blocked is linked by the level of the ventilation as given by equation [7].

$$Slope_{Open} \approx (1 - FV) \times Slope_{Blocked} \qquad [7]$$

Application of the burning model

For Products A to J described in Table 1, the smoking times have been estimated with the model developed in burning model section, and the smouldering time has been derived from the measured smoulder rate, the cigarette and the butt lengths. The burning model was used in conjunction with the publicly available software system R (23) to represent graphically for a given smoking regime, where the puffs occur, and to calculate the model outputs such as the puff number, the smoking time, and the weight of tobacco burnt according to physical parameters, such as lengths, *PV, FV,* M_{T_Tob}, and $\overline{SR}$. Figure 4 shows the position of the puffs when four different smoking regimes are applied to Product A: the ISO and CI regimes and the intermediate regimes with the filter ventilation open and blocked respectively; the corresponding number of puffs, smoking time and weight of tobacco burnt are given. The puff number increases when the puff frequency increases, the length burnt during each puff increases when the puff volume increases and when the filter ventilation is blocked, leading to higher yields.

Validation of the burning model

As seen in Figure 2, the good estimation of the puff number versus the smoulder rate supports the validity of the cigarette burning model. In this case, the data was generated from a single smoking regime although the model can also predict puff numbers for a wide range of smoking regimes. Figure 5 represents the calculated and measured puff numbers for the 32 smoking regimes applied to Product A (Table 2); on the left side when the filter ventilation is open, and on the right when the ventilation is blocked. The points represent the measured values and the continuous lines are the predictions.
ST.CHARLES proposed a simple and effective way (equation [8]) to estimate the smoking time as a function of the puff number, and the puff and inter-puff durations (24).

$$T_{T\_Smoking} \approx (Puff_n - 0.5) \times \left(\frac{T_{puff} + T_{inter}}{60} \right) \qquad [8]$$

This way of estimating the smoking time offers the possibility for comparison with the values derived from the developed model. Figure 6 represents both estimations and the 1:1 curve. Over a typical range of smoking time from 3 to 7 min, both estimations are consistent.

Relationship between smoke yields and smoking time

The relationship between the TNCO yields and the calculated smoking time is represented in Figure 7 for Product A when 32 smoking regimes were applied. Four observations can be made:

i) a unique relationship links yield and smoking time
ii) the relationship is linear
iii) the line crosses the x-axis at a time corresponding to the smoulder time
iv) vent blocking does not change the relationship between yields and time. For given puff conditions, the vent blocking leads to an acceleration of the burning, but the data points (time, yields) belong on the same straight line.

Observation (iii) is important as it means that a unique line passing through zero, and which can be then characterized by a single point, can be drawn by simply considering the difference Δt between the smouldering and the smoking times. Δt is directly related to the smoking intensity: when the intensity of smoking increases, the smoking time decreases and Δt increases. The corresponding relationships are represented in Figure 8 for Product A.

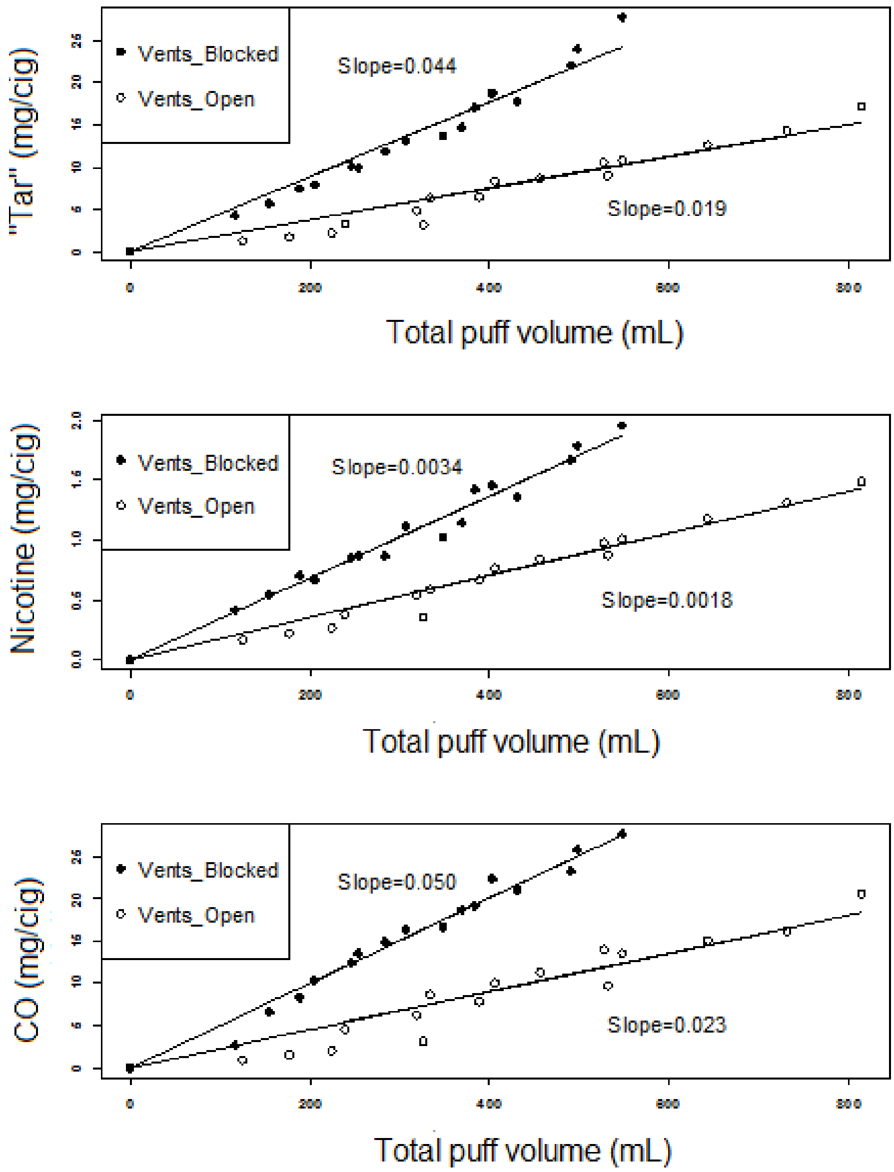

Figure 3. Relationship between TNCO yields and puff volume for Product A with filter ventilation open and blocked.

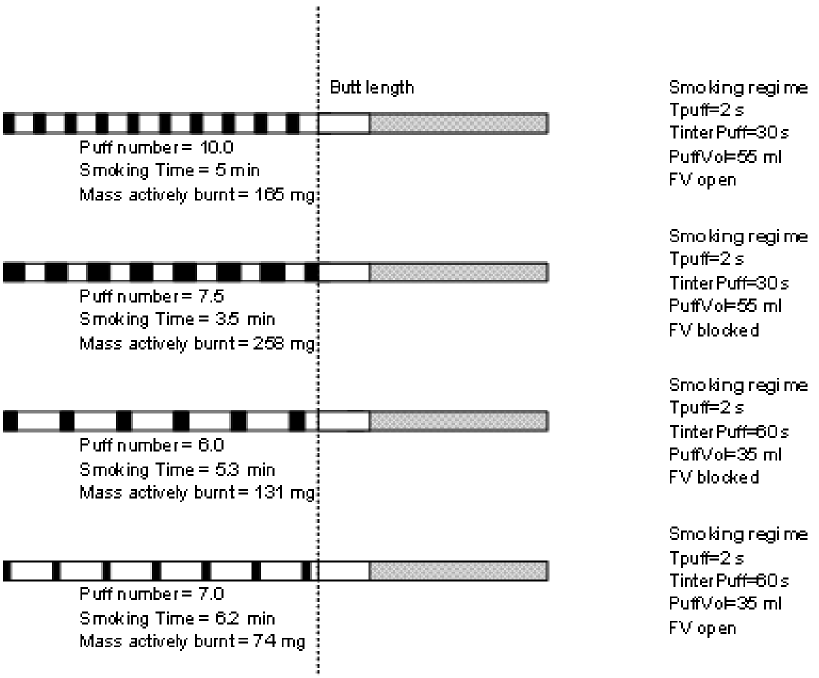

Figure 4. Product A - Puff location, puff number, smoking time and weight of tobacco burnt when four different smoking regimes are applied.

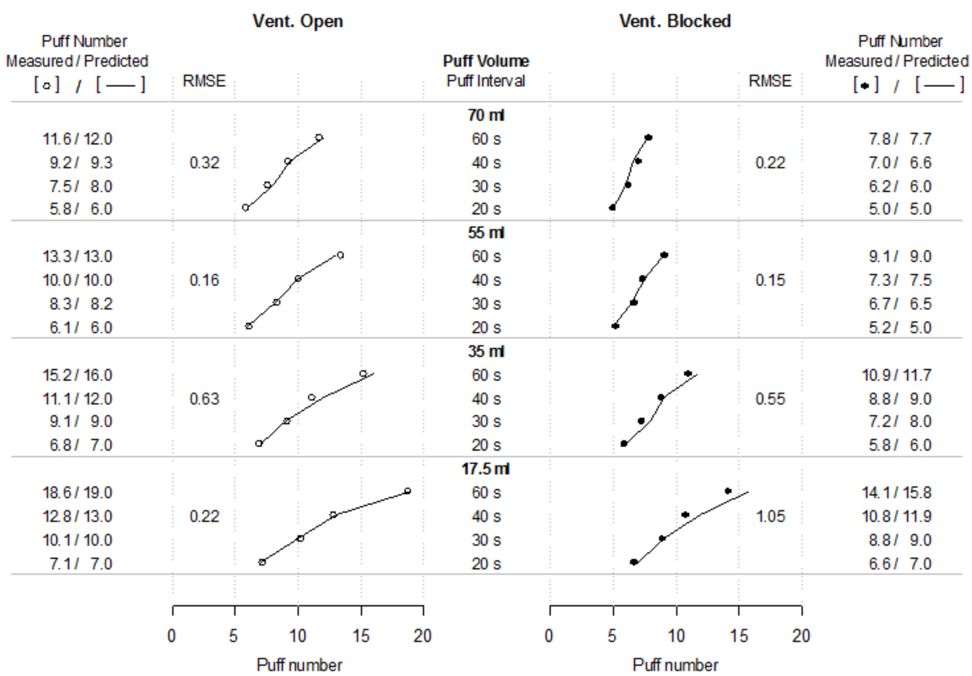

Figure 5. Product A - Comparison of the puff number measured and predicted by the model for thirty-two applied smoking regimes. Factor *k* was adjusted to a value of 0.010 with which prediction fitted well with the measured puff numbers for all 32 regimes (Table 2). On the left the filter ventilation is open, on the right the filter ventilation is blocked. The root mean square errors (RMSE) are given as indicators of the quality of fit.

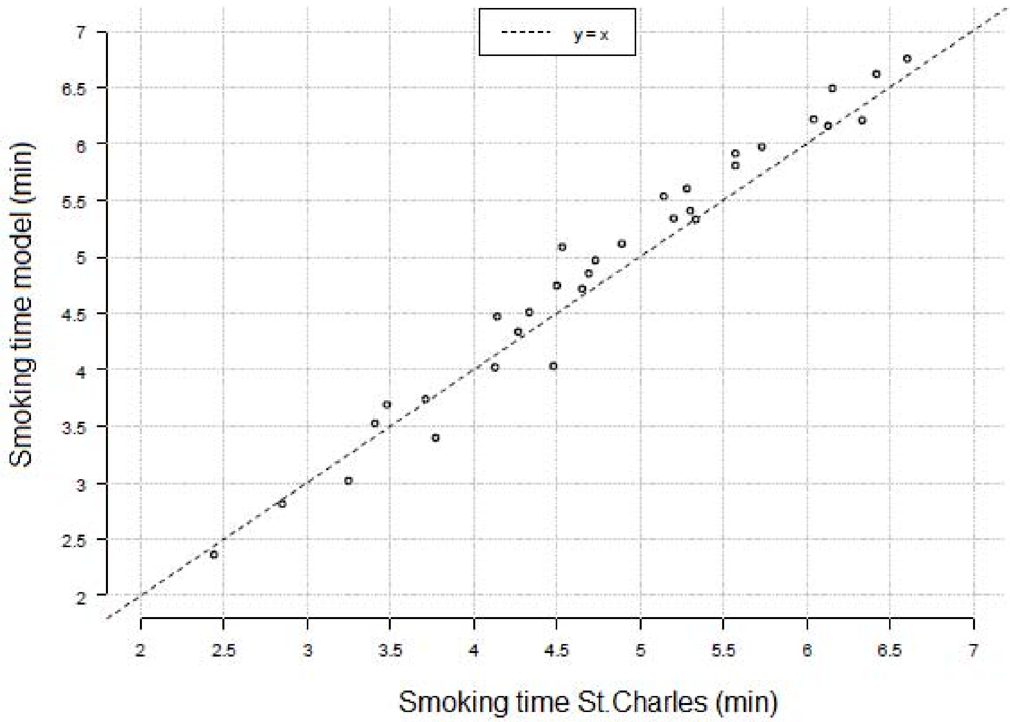

Figure 6. Product A - Comparison of the smoking time estimated by ST. CHARLES (24) and by the model developed in this paper. The dotted line corresponds to the 1:1 relationship.

The slopes of the TNCO yields versus Δt relationships can be derived from the measured smoulder rate and the application of one smoking regime. These slopes characterise the dynamic response of a cigarette to different smoking intensity, and are then more informative than a set of specific yields generated by a set of specific smoking regimes. This also means that more than one smoking regime does not give added experimental value; it is just adding points to a known line.

k is an important factor of the model as the level influences the estimation of the number of puffs, which in turn, influences the estimation of the smoking time. If *k* is underestimated, the length burnt per puff is also underestimated. This leads to an overestimation of the number of puffs and smoking times. An error on *k* can then potentially affect the quality of the linear regression. Our investigations showed that an error of ± 25% mainly affects the slope (± 12%) and much less the linearity (R^2 remains higher than 90%). In each case, it is important to determine the level of *k* on the basis of the best fit between predicted and measured number of puffs in order to reduce errors.

In order to check if the model and observations were still valid for a wide range of cigarette formats and LIP products, a similar exercise was conducted with Products B to J, applying the four smoking regimes as described in Table 3. With LIP cigarette paper, assumption 1 from the model is questionable due to the presence of bands with low air permeability along the rod; such bands increase the likelihood of self-extinguishment. At the single cigarette scale, the smoulder rate is probably not constant between the puffs with banded papers. However, the assumption is likely to be valid at a product batch level as a factor of random position of the bands. It has been shown previously that this random position corresponds to an optimal state when independent smoker behaviour is considered (25).

Yields and puff numbers were recorded when the four smoking regimes were applied to Products B to J (Table 3). Smoke yields were plotted against the difference of smouldering and smoking times derived from the burning model. As shown on Figure 9, a linear relationship passing through zero is observed in a similar manner to data from Product A. This confirms that the total duration of smoking is the key parameter and that a single smoking regime (a single point on the line) is sufficient to characterize products for TNCO yields regarding the relationship between yields and smoking intensity (or time of smoking), whatever their design.

As the relationship is linear, it is possible to estimate the TNCO yields at any smoking time from the information obtained with a single smoking regime. As an example, the relationship between the measured and predicted CO yields is represented on Figure 10 for Products B to J. Predictions were made for the regimes No. 1 to 3 as described on Table 3 from the corresponding smoking times and the CO yields measured with the regime No. 4.

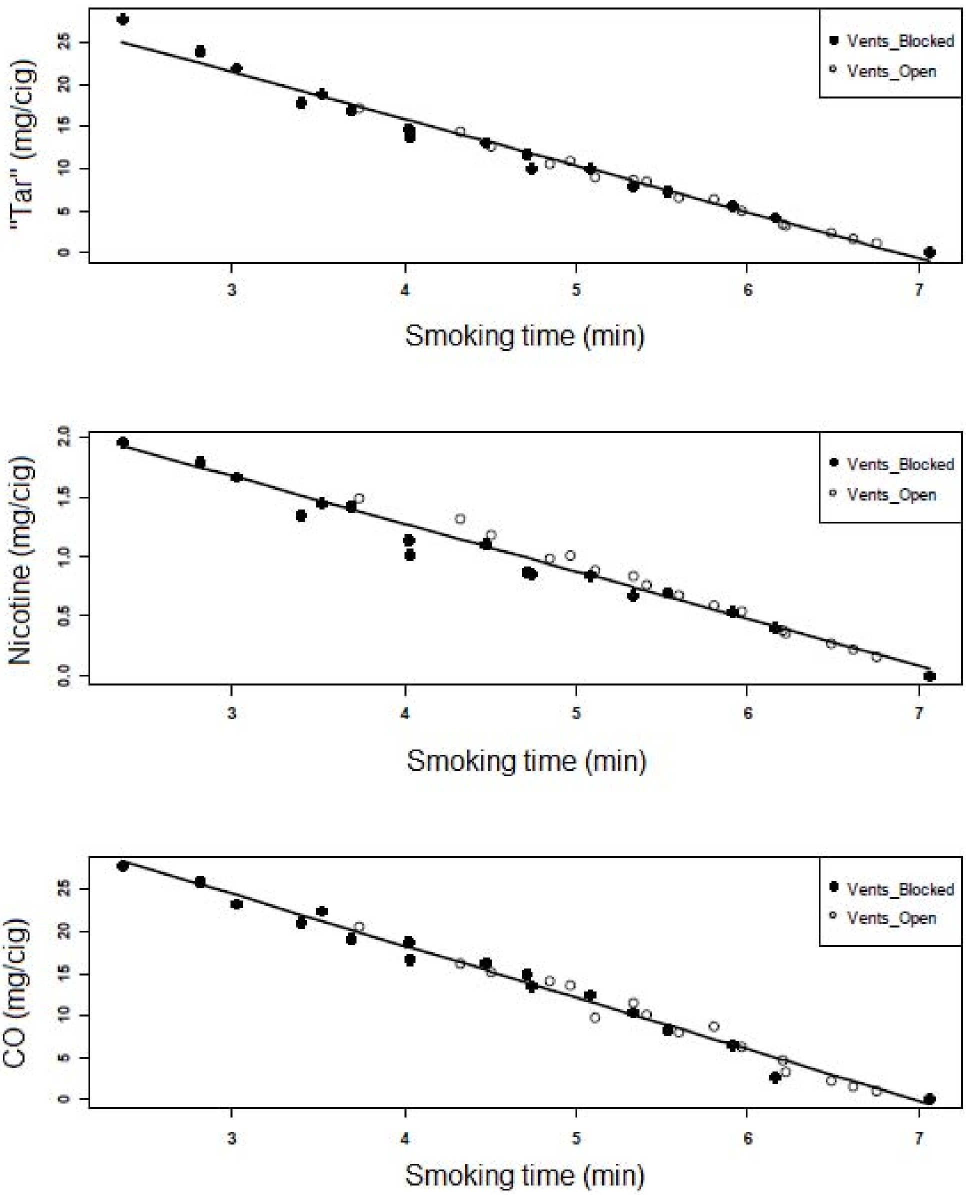

Figure 7. Relationship between TNCO yields and smoking time for Product A.

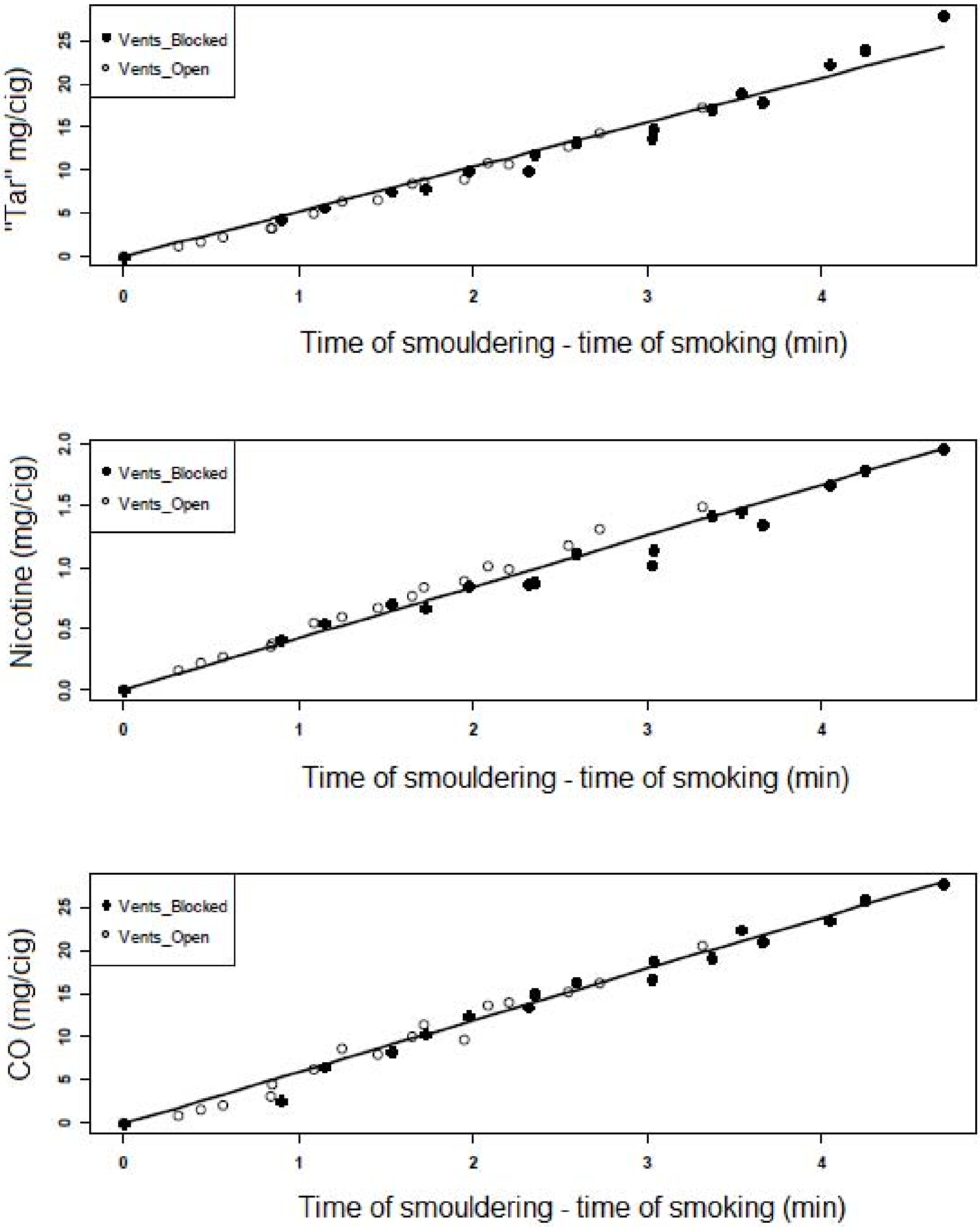

Figure 8. Product A - Relationship between TNCO yields and Δ*t* (time of smouldering – time of smoking).

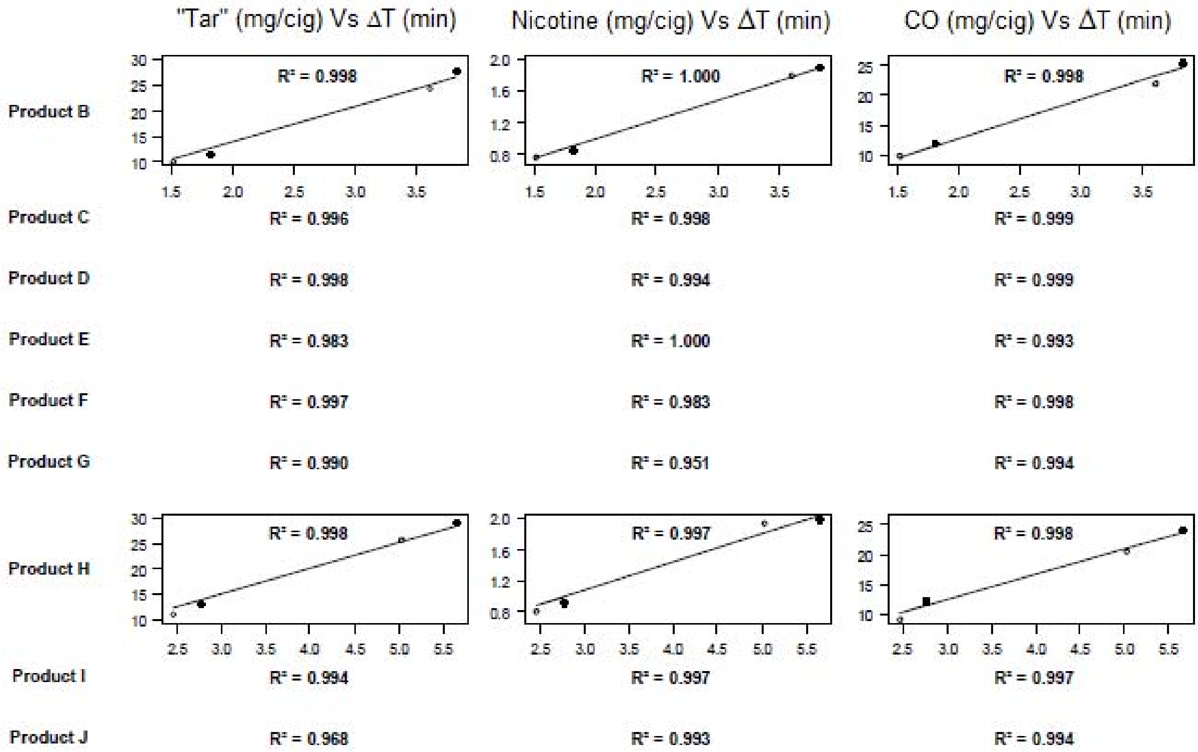

Figure 9. Products B to J - Relationship between TNCO yields and Δ*t* (time of smouldering – time of smoking). Factor *k* has been adjusted in order to fit the calculated puff number to the measurements (typical range: 0.009-0.016). One non-LIP and one LIP paper product are graphically shown (○ = ventilation open; ● = ventilation blocked).

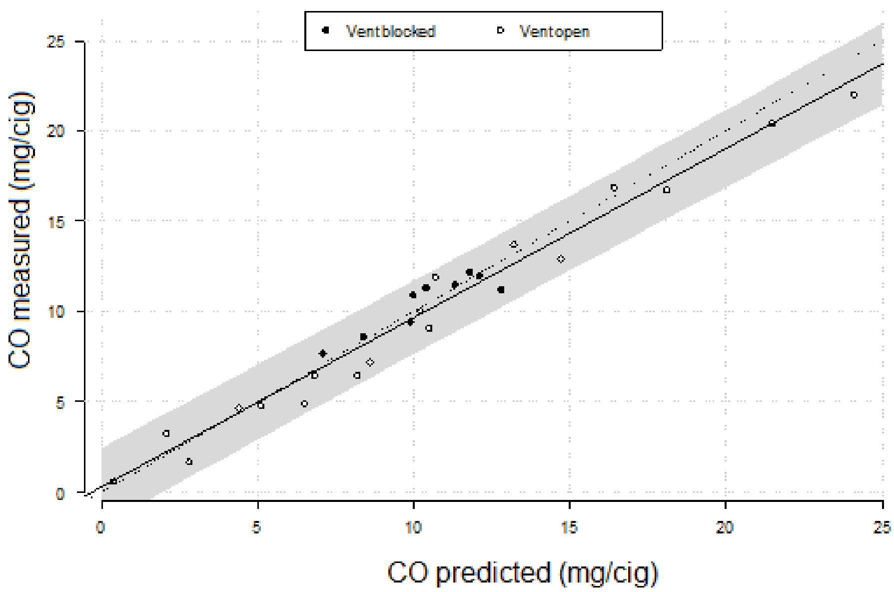

Figure 10. Prediction and confidence interval of CO yields from smoking time. Yields predicted for regimes No.1 to 3 (Table 3) from the corresponding smoking times and yields generated by regime No. 4. The dotted line corresponds to the 1:1 relationship.

DISCUSSION

Neither yield from ISO nor from other machine smoking regimes provide valid estimates of human exposure (26). Exposure relating to human behaviour is dependent on complex factors such as the product characteristics, the individual consumer environment or their judgement on their available time for smoking.

The actual cigarette smoking time taken is a tool to compare machine smoking with human smoking exposure (27) when the cigarette burnt length is fixed. This paper indicates that this could be most easily applied by using Δt values to predict human smoke intake or yields from different machine regimes for a known butt length.

This work has shown that TNCO yields obtained under more than one smoking regime are superfluous. If TNCO obtained under the ISO machine smoking regime are considered as misleading (28) then yields obtained under another machine regime are no less misleading. No machine smoking regime represents human smoking patterns, exposure or risk. Regulators now recommend removing yields from the packs (12, 29). The question is whether another smoking regime would confer any advantage, as a replacement for or in addition to the ISO standard protocols. Difficulties have always been encountered when it comes to answering this question (28). Smoking regimes have been more often described by what they should not be (misleading, confusing) rather than by what they should be (reliable, characteristic, capacity of discrimination). For a single cigarette, the exposure depends essentially on the speed at which the cigarette is smoked. Smoking behaviour and the number of cigarettes smoked are the drivers that should be considered in human exposure more than machine smoking yields.

The work presented in this paper shows that the application of a single smoking regime reported alongside the filter ventilation and cigarette dimensions, provides sufficient information to address product characterisation and monitoring requirements. In addition, the association of the smoulder rate to the TNCO yields obtained from a single regime give access to the dynamic response of a cigarette to smoking intensity, i.e., the link between yields and smoking time. One benefit is that the application of a single regime would conserve laboratory resources which could be employed for more complex chemistry and other assessments. The question then turns to which regime should be used. The ISO 3308 regime is a robust tried and tested method with known measurement tolerances (30) and enables a better discrimination and comparison of products than the CI regime (31). The more intense conditions, used in the CI smoking regime, provide higher yields but also present higher yield variability between laboratories as demonstrated in collaborative studies (32, 33, 34) and raise other issues discussed previously (35, 36). In addition there are unresolved differences observed in smoke trapping between linear and rotary smoking machines, currently being addressed at the ISO/TC126 Working Group 10 (37, 38) suggesting that, of the two, the ISO regime is a more appropriate regime for regulatory testing.

The association of ISO yields with a corresponding smoking time, easily derived from the number of puffs (equation [8]), would provide information that links yields with smoking behaviour (time); which is valid with filter ventilation either open or blocked. Such information, e.g., "*10 mg of tar are produced when the product is smoked in 5 minutes*", could be useful to regulators seeking to provide information that is understandable and not misleading to lay persons (39).

It has yet to be determined whether or not other smoke components identified by regulators as of public health concern will behave like TNCO, and this should be the subject of further investigations. In assessing such relationship, only robust, recognised and validated methodologies of trapping and analysis should be used.

It can be noted that a weakness of the model developed is the absence of a parameter related to the filtration efficiency. A filtration which would be significantly modified by the smoking intensity would influence the relationship between yields and smoking time. This has not been observed in this study with the brands tested and not further explored. Such investigations should be conducted, for example, with filters potentially influenced by high smoke temperature under intense smoking conditions such as active carbon filters.

CONCLUSIONS

The burning of a cigarette smoked under various regimes has been described by a general sequential model of successive steps of puffing and smouldering. Our investigations led to original observations regarding the link between yields and smoking time.

- Cigarette smoke TNCO yields each give a linear correlation with the difference between the time of smouldering and the time of smoking.
  - The correlation line passes through the origin and describes these yields with the ventilation either open or blocked. Ventilation blocking accelerates the burning of a finite rod length but does not change the product characteristics.
  - The slope of the corresponding relationship is characteristic of the dynamic response of a cigarette to different smoking intensity.
  - Estimates of TNCO yields at any smoking times can be obtained from this relationship.
- Data on the smouldering time, ISO smoking regime yields and puff numbers are required to establish the link yields to smoking intensity for a given product.
- ISO TNCO yields can be associated with smoking time and this could add a missing dimension useful to Regulators seeking to provide information that is understandable and not misleading.
  - Smoking time can be derived from puff numbers.

Further work will have to be carried out on other smoke analytes to confirm or not whether they are similar to TNCO relationships.

ACKNOWLEDGEMENTS

The authors wish to acknowledge for the helpful comments made on the manuscript by their co-worker John Pritchard.

Glossary of terms and units

FV	is the filter ventilation cigarette unlit
Int($Puff_n$)	is the integer part of the number of puffs
k	is a factor of proportionality related to the combustibility characteristics during puff, expressed in s/mL
$L_{puff}(i)$	is the length burnt during the puff *i*, expressed in mm
L	is the length burnt at the start of the puff, expressed in mm
L_{cig}	is the cigarette length, expressed in mm
L_{filt}	is the filter length, expressed in mm
L_{tip}	is the tipping length, expressed in mm
L_{T_burnt}	is the total length burnt, expressed in mm
$L_{T\_activeburnt}$	is the total length burnt during the puffs, expressed in mm
$M_{T\_activeburnt}$	is the total mass of tobacco burnt during the puffs
M_{T_Tob}	is the total mass of tobacco in the rod
$Puff_n$	is the number of puffs
$Puff_{vol}$	is the volume of the puff, expressed in mL
PV	is the paper ventilation cigarette unlit
$Q_{coal}(i)$	is the airflow across the coal during the puff *i*, expressed in mL/s
$\overline{SR}$	is the mean smoulder rate, expressed in mm/min
T_{inter}	is the puff interval, expressed in s
T_{puff}	is the puff duration, expressed in s
$T_{T\_Smoking}$	is the smoking time (or duration of smoking), expressed in min
Δt	is the difference between smouldering and smoking times, expressed in min

TNCO yields refer to “tar” (T), nicotine (N) and carbon monoxide (CO) mainstream smoke yields.

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