RESEARCH PAPER

Dependence of tar, nicotine and carbon monoxide yields on physical parameters: implications for exposure, emissions control and monitoring

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Objective: To estimate the extent to which tar, nicotine and carbon monoxide (TNCO) yields are dependent on cigarette design features such as burn rate, filter ventilation and paper porosity, and to consider the implications for human exposure and the regulation of TNCO emissions. A related aim is to determine whether accurate prediction of TNCO yields is possible using only simple physical parameters.

Design and methods: Datasets that include quantitative design parameters as well as measurements of TNCO yields collected under standard conditions with vents unblocked (International Organization for Standardization) and under intense conditions with vents fully blocked (Health Canada) were compiled from the literature (primarily US and UK brands). Forward stepwise multiple regression analysis is used to assess the relative importance of each design feature in explaining variability in the observed emissions. Using randomly split data subsets, multiple linear regression is used to model the dependence of TNCO yields on design features in the training subset and validated against the test subset. Tar and carbon monoxide correlate with many of the particulate- and volatile-phase toxins in smoke, and brand values normalised to nicotine yield are used as surrogate measures of exposure within the bounds defined by non-intense and intense smoking protocols.

Results and conclusions: Filter ventilation is the dominant control on measured TNCO emissions, but other factors including burn rate, amount of tobacco and paper porosity also contribute. Yields are predictable with reasonable accuracy and precision using only measured physical parameters. Surrogate exposure indicators suggest that filter ventilation does not lead to any reduction in exposure and that highly ventilated (low-yield) brands may actually increase exposure to the more volatile toxins.

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Major reductions in tar, nicotine and carbon monoxide (TNCO) emissions as measured by smoking machines have been achieved by modifying cigarette design, thus enabling manufacturers to comply with regulations,¹ although the strategy of setting limits on emissions and publishing TNCO yields obtained under the International Organization for Standardization (ISO) smoking conditions is seriously questioned among public health practitioners.² All aspects of cigarette design, including filter, paper wrap, tobacco filler and additives, can be modified to influence machine-measured yields to varying degrees,³ but little information is available on how each feature contributes to overall yield reduction, at least outside the tobacco industry.

One design feature, namely filter ventilation (V^f), has been singled out for particular criticism on health grounds, because it reduces apparent emissions, yet can be overcome wittingly or unwittingly by blocking the vents with the fingers or lips,¹ and the smoker typically engages in other forms of compensatory behaviour to replace the deficiency in nicotine delivery. The literature largely assumes that filter ventilation is the only (or at least dominant) design feature that has been used by the tobacco industry to reduce yields.⁴ It is important to test this assumption in order to justify future research on the nature and extent of counteractive and compensatory behaviour. If other, less-easily defeated design features make significant contributions to reducing yields, then by the same token their potential for reducing exposure to smoke emissions should not be overlooked. There is presently a dearth of useful quantitative information to inform policy on the relevance of these factors to emissions control and disclosure. The purposes of this paper are to (1) assess the relative contributions of filter ventilation and

other design features to overall reductions in machine-measured TNCO yields, (2) consider whether reduction in yields translates to reduction in exposure to toxins and (3) test whether the relationship between physical parameters and TNCO emissions can be used to generate adequate models for predicting the latter from the former. This may have relevance for the monitoring and surveillance of products in the absence of a laboratory with the capacity for chemical testing of emissions.

Filter ventilation involves inserting small holes in the filter tip of a cigarette that act as vents allowing the introduction of external air during puffing so that a lower proportion of the puff volume is drawn at the burning coal.³ The effect is to reduce all emissions due to burning tobacco, although the effect is greatest on carbon monoxide (CO).^{3–6} While filter ventilation is effective in reducing machine-measured yields, the publication of such data can be misleading, as, no allowance is made for vent blocking or other modified behaviour by smokers in their quest for a desired level of nicotine delivery.^{7–8} Because smokers of “low-yield” cigarettes might gain a false sense of reduced harm,^{2,9} there has been a vigorous debate with tobacco industry scientists on the evidence for vent blocking and the degree to which it applies in real-world smoking.^{10–11} Perhaps more relevant is strong evidence for the use of a range of strategies by smokers to compensate for the lower nicotine yield.² What is not clear is how ventilation and compensation

Abbreviations: CO, carbon monoxide; HC, Health Canada; ISO, International Organization for Standardization; LGC, Laboratory of the Government Chemist; NFDPM, nicotine-free dry particulate matter; PM, Philip Morris; TNCO, tar, nicotine and carbon monoxide

act to modify exposure. Raw-yield data are uninformative, but if these inter-relationships were better understood, ventilation and all other design features could be assessed objectively in the context of reducing the smoker's exposure to toxins.

Cigarette design is constrained by the need to maximise the commercial potential of a brand while complying with legal limits on yields where these exist. Smoke is an aerosol of more than 4000 distinct components distributed among particulates and the gas phase. "Tar" is the collective term used for compounds in particulate form, CO is dominantly gaseous, whereas nicotine is partitioned between particulates and the gas phase.¹² These components are generated through the processes of distillation and pyrolysis (thermal decomposition) of tobacco and the oxidation of char during the heating of tobacco. Controlling the process to generate only those components sought by the smoker (such as nicotine, flavour, texture) is unrealistic; hence design strategies are used to maximise the delivery of these components at the mouth end of the cigarette while keeping the delivery of toxic components within specified limits.

The undesirable components of smoke are widely understood by the public to be TNCO,⁹ yet there is consensus among the scientific community that most of the harmful effects are primarily attributable to specific components, typically volatile organic compounds, polycyclic aromatic hydrocarbons (PAHs), tobacco-specific nitrosamines and the heavy metals.^{13–14} Tar is a complex entity that contains several major carcinogens (including the PAHs), and the term is used in this study as the weight of particles trapped on a filter after a machine smoking test, less its nicotine and water content (nicotine-free dry particulate matter, NFDPM). The concentrations of the toxins in tar may vary because of several factors; some are derived from the leaf but most are generated by the combustion process, which in turn is strongly influenced by cigarette design and smoking behaviour. Nicotine is not regarded as highly toxic, whereas CO is implicated in cardiovascular disease.

The usefulness of these measured parameters is not in their toxicities but rather in the ways in which they can efficiently reflect other aspects of emission. Nicotine concentration will largely determine the way in which a cigarette is smoked in order to satisfy the smoker's addiction. Measured tar correlates linearly with many important toxins that tend to partition into the particulate phase, including the important PAHs. This has been observed in many studies and is also the case in the datasets used in this study. CO correlates usefully with those toxins that partition into the vapour phase, again borne out by linear correlations in these datasets. Many of those toxins that partition between particulate and vapour phases can also be modelled by multiple regression. Overall, most of the major tobacco smoke toxins in the "Hoffmann list",¹⁵ with the exception of the nitrosamines and some other nitrogenous compounds, correlate significantly with measured tar, CO or both.

Over the latter half of the 20th century, the sales-weighted average tar yield of US cigarettes reduced to about half that of the 1950s.¹⁶ The more important design features responsible for this reduction include new tobacco blends (although blending is more about generating flavours than the control of emissions³), the cut of tobacco in terms of strands per inch, the weight of tobacco used and dimensions of the cigarette, and use of reconstituted tobaccos (particularly expanded tobaccos, some of which contain additives to control combustion). High porosity and permeability of wrap paper facilitate ventilation with external air. This reduces the proportion of a puff derived from the burning coal, thus reducing all yields. In addition, vapour-phase components such as CO may diffuse outwards, further reducing their yields. Additives are used in paper

manufacturing to increase burn rates, thus reducing measured yields.¹⁷ Filters, typically of cellulose acetate, extract particulate phases from the aerosol and reduce tar and nicotine with various degrees of efficiency, although they have little effect on volatile emissions such as CO. Filter ventilation reduces the draw on the burning coal, thus reducing the emissions and diluting the smoke with external air. This is probably the most effective single design feature for reducing machine-measured TNCO emissions, although the effects on the vapour and particulate phases differ and hence reductions in TNCO yields are not necessarily uniform.

The approach taken in this study is to isolate the effect of filter ventilation from other design features by statistically comparing emissions data for cigarettes smoked with filter vents unblocked with data for the same cigarettes smoked with vents fully blocked. A similar approach was used in assessing the contributions of tobacco nicotine and filter ventilation to machine-measured yields in the US, Canada and the UK,¹⁸ although the present study differs in focusing only on the physical controls. Studies of modern cigarettes from different geographical regions have highlighted the very strong negative correlation between yields of tar and other emissions with degree of filter ventilation.^{4–19} Vent blocking would be expected to destroy this correlation unless other design features act in concert with filter ventilation to reduce yields.

The relationship between machine-measured yield and human exposure to smoke toxins is not simple and yield data can be a highly misleading guide to exposure.²⁰ Machines cannot replicate human smoking and there is very good evidence that smokers of highly ventilated cigarettes engage in other behaviours in order to satisfy their need for a given delivery of nicotine, such as puffing more frequently, taking deeper puffs (facilitated by ventilation), smoking more cigarettes, etc.^{8, 21} thus exposing themselves to the higher levels of emissions associated with unventilated brands. Furthermore, the lighter taste of ventilated brands encourages a false sense of security and reduces the motivation to quit.² These are important factors to consider when interpreting machine-measured yields in terms of exposure to tobacco smoke toxins.

METHODS

Intense smoking protocols use puff volumes and other parameters that differ from the long-standing ISO (or FTC) protocol,²² and a crucial difference is that ventilation is reduced by either 50% or 100% by blocking the vents with tape. The Health Canada (HC) protocol²³ is becoming the de facto standard for intense smoking with 100% blocked vents and is based on a larger puff volume (55 ml compared with 35 ml) with a shorter interval between puffs (30 s compared with 60 s). Recent compilations of machine-measured emissions from the same samples under ISO and HC conditions provide an opportunity to evaluate the effect of filter ventilation on yields.

$C_{i,tar}^{ISO}$, $C_{i,nic}^{ISO}$ and $C_{i,co}^{ISO}$ represent concentrations of tar (as NFDPM), nicotine and CO, respectively, in cigarette brand *i* measured using the ISO protocol, and $C_{i,tar}^{HC}$, $C_{i,nic}^{HC}$ and $C_{i,co}^{HC}$ represent the same variables measured under conditions of the HC protocol. Puff count is an important parameter²⁴ and the more intense HC protocol results in fewer puffs for the same brand ($N_i^{ISO} > N_i^{HC}$). Values of *C* are expressed in units of mg/cigarette and the average weights of tobacco in each brand are expressed as *W_i* in grams. Other variables are filter ventilation (V_i^F) and paper porosity (*S_i*). No data for butt length were available, although this parameter is also important.²⁵

A parameter $\hat{C}_{ij}^{ISO}$ was used to model the emission of variable *j* (tar, nicotine or CO) under ISO conditions but with all vents blocked ($V_i^F = 0$). The parameter was derived from HC emission

data using a formula that allows for differences in puff volumes and the observed numbers of puffs:

$$\hat{C}_{i,j}^{ISO} = C_{i,j}^{HC} \frac{35N_i^{ISO}}{55N_i^{HC}}$$

Note that this volumetric correction makes no allowance for any other variations in yield due to differences in smoking intensity. If these other factors are much less important, then values for modelled ISO emissions with vents blocked and actual ISO emissions from brands with no filter ventilation (ie, $\hat{C}_{i,j}^{ISO}$ and $C_{i,j}^{ISO}$ at $V_i^f = 0$) should be nearly identical. As described in the Results section, there was indeed close agreement for the datasets used in this study, providing support for the validity of the $\hat{C}_{i,j}^{ISO}$ parameter.

Datasets of mainstream smoke emissions generated using both blocked and unblocked filter ventilation protocols are still scarce. A recent study presented comprehensive yield data for 48 Philip Morris (PM) US and EU brands along with products from several other countries worldwide.¹⁹ An earlier study of 12 UK brands from various manufacturers by the Laboratory of the Government Chemist²⁶ (LGC) used the original British Columbia protocol, a precursor to the HC protocol that also covered all filter vents²⁶ but using 56 ml puffs (volume correction applied in this study). Each dataset was generated at a well-established testing laboratory independent of the tobacco industry. Combining these data into a single dataset for this study (60 brands plus the 1R4F reference cigarette) spans the range of V_i^f typically found in commercial products (0–80%) as well as covering a range of geographical sources, mainly in the developed world. All the sample cigarettes had filters, mostly of cellulose acetate, but nine of the PM brands had charcoal filters. These were not excluded from the analysis even though there is some evidence that these filters reduce certain emissions.

Linear correlation and regression analysis were used to compare C^{ISO} and $\hat{C}^{ISO}$ in the combined dataset. Forward stepwise regression was used to assess the relative contributions of filter ventilation of other design variables to TNCO yields. The method first selects the variable that contributes most to each linear regression model using Student's *t* statistic. A second variable is added only if its inclusion improves the model with a probability threshold of $p < 0.05$, and the model then takes on the multiple linear regression form. The process continues until the addition of a new variable exceeds this threshold. The relative influence of the design variables is gauged by the increase in R^2 , which reflects the proportion of the variability of the dependent variable explained by the model. This was applied to the PM dataset only, as the LGC dataset did not include information for some variables such as paper porosity.

A different regression approach was used to develop predictive measures of TNCO yields under ISO conditions. The dataset was randomly divided into a training subset and a validation subset. Multiple linear regression was applied separately to each of the tar, nicotine and CO dependent variables in the training dataset. Regression equations so derived were then used to predict values for the same variables in the validation subset. Comparison of the predicted values with the measured values in the test subset provides a means of gauging the accuracy and precision of these models.

RESULTS

Variation of TNCO yields with ventilation

Model values of ISO yields at zero ventilation ($\hat{C}^{ISO}$ at $V_i^f = 0$) range approximately from 10 to 20 mg/cigarette for tar, from

0.7 to 1.3 mg/cigarette for nicotine and from 10 to 27 mg/cigarette for CO (fig 1). The lowest values of $\hat{C}^{ISO}$ are actually lower than measured values for brands with no filter ventilation by approximately 6 mg/cigarette for tar and 0.4 mg/cigarette for nicotine. The equivalent difference for CO is relatively smaller (~2 mg/cigarette).

As observed in many studies, ISO tar, nicotine and CO yields (C_{tar}^{ISO} , C_{nic}^{ISO} and C_{co}^{ISO}) show strong negative correlations with filter ventilation (filled symbols in fig 1). Model ISO yields with blocked vents ($\hat{C}_{tar}^{ISO}$, $\hat{C}_{nic}^{ISO}$ and $\hat{C}_{co}^{ISO}$) are less well correlated (open symbols in fig 1). All linear correlations are significant at $p < 0.01$. The 95% confidence bands around the regression lines

Figure 1 Variation of tar (nicotine-free dry particulate matter (NFDPM)), nicotine and carbon monoxide (CO) with filter ventilation. Filled symbols represent measured yields under ISO conditions (cd); open symbols represent measured yields under Health Canada conditions (ventilation holes covered) recalculated to equivalent ISO puff volumes. Dashed lines are linear regressions with associated 95% confidence limits (shaded). See text for model calculations and data sources. C, concentration; cig, cigarette; ISO, International Organization for Standardization; LGC, Laboratory of the Government Chemist; PM, Philip Morris.

overlap at 0% ventilation, indicating that the $\hat{C}_f^{ISO}$ parameter is a good estimate of ISO yields with fully blocked vents.

Both tar and nicotine show falling levels of $\hat{C}_f^{ISO}$ with increasing filter ventilation, although the gradient is relatively gentle with a high degree of scatter. On the other hand CO shows a slight increase with filter ventilation. This trend is largely controlled by two points (samples E35 and E39 in Table 1 of Counts *et al.*¹⁹ both Virginia Slims from Japan). Removing these points leads to a correlation coefficient that is not significant at $p < 0.01$ —that is, there is no covariance of CO with degree of ventilation when vents are blocked. There is no a priori reason to expect any decline in model tar and nicotine emissions with ventilation when vents are fully blocked unless other design features are being used in combination with ventilation to reduce emissions in the lower-yield brands.

Relative importance of design features in determining TNCO yields

The most important design features in reducing yields are tobacco blend, tobacco weight, cigarette dimensions, paper porosity, burn rate and filter ventilation. Data for weight (W), paper porosity (S) in CORESTA (Cooperation Centre for Scientific Research Relative to Tobacco) permeability units (cm/min), burn rate and cigarette dimensions (related in number of puffs, N^{ISO}), and filter ventilation (V^f) are available in the PM dataset. No useful quantitative parameter for blend is available. Yields in the form of the dependent variables C_{tar}^{ISO} , C_{nic}^{ISO} and C_{co}^{ISO} were separately regressed against these four independent variables using the stepwise method. The results are presented in table 1.

R^2 estimates the variance in the dependent variable explained collectively by all of the independent variables, and the relative importance of an independent variable is gauged by the increase in R^2 at each step. Thus, ventilation is clearly the dominant design feature in determining all yields. The number of puffs taken (N^{ISO}) also influences both tar and nicotine yield, but to a much lesser extent. CO yield is influenced by the weight of tobacco (W), while paper porosity (S) makes a small but significant contribution. The independent variables not represented in table 1 are unimportant in explaining the observed yield trends.

Table 1 R^2 values for the introduction of independent variables at each step in stepwise multiple regression models for tar, nicotine and carbon monoxide under ISO conditions

	Tar (C_{tar}^{ISO})	Nicotine (C_{nic}^{ISO})	CO (C_{co}^{ISO})
Step 1 variable	V^f	V^f	V^f
R^2	0.903	0.853	0.892
Step 2 variable	N^{ISO}	N^{ISO}	W
R^2	0.933	0.940	0.942
Step 3 variable			S
R^2			0.951
Model intercept	8.560	0.346	7.142
β_1	$-0.174V^f$	$-0.012V^f$	$-0.133V^f$
β_2	$0.799N^{ISO}$	$0.095N^{ISO}$	$10.128W$
β_3			$-0.022S$
F (df)	321.8 (2, 46)	358.8 (2, 46)	292.9 (3, 45)

C , concentration; ISO, International Organization for Standardization; N^{ISO} , number of puffs; S , paper porosity; V^f filter ventilation; W , weight of tobacco filter.

Note that filter ventilation (V^f) is introduced in step 1 as the first (most important) explanatory variable, with very high R^2 values for all three emissions. Values of F and associated degrees of freedom (df) as well as the regression coefficients are given for each model.

Prediction of TNCO yields

The fact that filter ventilation, puff count, tobacco filler weight and paper porosity can be used to model TNCO emissions with R^2 values of 0.93–0.95 indicates that reasonably good predictive models of emissions are possible using physical parameters only. A training subset of 28 brands was randomly selected from the main dataset and subject to multiple regression analysis. Prediction equations for TNCO yields for brand i (P_{ij}^{ISO}) are as follows:

$$P_{i,tar}^{ISO} = 8.41 - 0.167V_i^f + 0.792N_i^{ISO} \quad (R^2 = 0.91)$$

$$P_{i,nic}^{ISO} = 0.23 - 0.0106V_i^f + 0.105N_i^{ISO} \quad (R^2 = 0.93)$$

$$P_{i,co}^{ISO} = 4.71 - 0.122V_i^f + 13.6W_i - 0.0281S_i \quad (R^2 = 0.94)$$

The validation subset consisted of 33 brands for tar and nicotine and 21 brands for CO. The difference in number is due to the lack of information on tobacco weight and paper porosity in the LGC dataset, and therefore these brands were used for validating tar and nicotine only. Predicted values for TNCO yields ($P_{i,tar}^{ISO}$, $P_{i,nic}^{ISO}$ and $P_{i,co}^{ISO}$) are plotted against measured values ($C_{i,tar}^{ISO}$, $C_{i,nic}^{ISO}$ and $C_{i,co}^{ISO}$) in fig 2. Accuracy can be gauged by the degree of correspondence between perfect agreement (dashed line) and the 95% confidence bands for a linear regression between measured and predicted values for each variable. Whether the method generates an acceptable prediction is estimated using the cross-validity coefficient—that is, the correlation coefficient between predicted and observed values ($r_{pred,obs}$). The difference between R^2 for the training set and $(r_{pred,obs})^2$ for the test set is known as shrinkage, smaller values representing increasing confidence in the predictive reliability of the model, although no confidence limit tests are available for this parameter.

The prediction model for tar (fig 2) is generally accurate, predicted values being slightly divergent (higher) only in the ultra-light range. Prediction of nicotine is similarly slightly high at low nicotine levels, and the shrinkage factor is +1.2%. The model for CO is particularly good, with close agreement throughout the range and a shrinkage value of only 0.1%. For all three variables, the large majority of points fall within the $\pm 15\%$ tolerance at the EU limits of 10–1–10 mg (tar, nicotine, CO), and no points are very seriously adrift. For all three variables, the shrinkage factor is $< 1.5\%$.

DISCUSSION

Simple and stepwise regression techniques clearly demonstrate that filter ventilation is by far the most important variable in determining the machine-measured yields of TNCO in cigarettes, at least in those brands represented by the available datasets. However, the methodology demonstrates that other factors significantly influence the generation of emissions. Reduced tar and nicotine yields also correlate with smaller puff counts—that is, the number of smoke puffs of fixed volume taken before machine smoking is stopped at a defined distance from the filter or its overwrap, which in turn reflects the combined effects of burn rate and cigarette dimensions. This is consistent with earlier findings.^{24–25} CO emission is also influenced by tobacco weight and paper porosity. The lack of data on filter length, butt length, blend and other physical parameters²⁷ makes the analysis less complete. However, compared with filter ventilation these would all appear to have second- or lower-order influences on TNCO yields. An analogous study of UK brands tested by the ISO method similarly found that filter ventilation was dominant among all the design features.²⁸

In terms of public health benefits, it is important to distinguish between the machine-derived yields discussed above and a smoker's exposure to tobacco smoke toxins. There is no universally agreed measure of exposure, and four new parameters are defined to facilitate discussion:

Figure 2 Comparison of measured tar, nicotine and carbon monoxide yields with predicted yields for a subset of samples not used in the multiple regression analysis. Dashed line represents 1:1 agreement, and shaded areas represent 95% confidence limits around linear regressions. Error bars of $\pm 15\%$ are shown at the 10–1–10 EU Directive limits. cig, cigarette; LGC, Laboratory of the Government Chemist; NFDPM, nicotine-free dry particulate matter; PM, Philip Morris.

$$E_{i,tar}^{ISO} = \frac{C_{i,tar}^{ISO}}{C_{i,nic}^{ISO}}, \quad E_{i,tar}^{HC} = \frac{C_{i,tar}^{HC}}{C_{i,nic}^{HC}}, \quad E_{i,co}^{ISO} = \frac{C_{i,co}^{ISO}}{C_{i,nic}^{ISO}}, \quad E_{i,co}^{HC} = \frac{C_{i,co}^{HC}}{C_{i,nic}^{HC}}$$

where E represents the yield of tar or CO under either the ISO or the HC protocol normalised to the nicotine yield in the same sample under the same machine-smoking conditions for a given brand i . It is suggested that these nicotine-normalised parameters are better surrogates for exposure than are raw yields, given the strong evidence from biomarker studies for complete compensation for reduced nicotine delivery by smokers of highly ventilated brands.^{8–21} Indeed, such nicotine normalisation has long been advocated.^{24–29–31} Positive linear correlations between many of the particulate- and vapour-phase toxins with tar and CO, respectively,²⁸ support the use of

E_{tar} and E_{co} as toxin exposure surrogates, although the nitrosamines are rather poorly correlated with NFDPM in this dataset.¹⁹

Nicotine normalisation controls numerically for compensation but does not take into account how the smoker achieves that compensation. Topography studies on smoking indicate that compensation is a complex process,²⁰ and this must be taken into account in any consideration of exposure. While the ISO and HC machine smoking protocols do not reflect human smoking behaviour, it is reasonable to assume that few people smoke less intensively than the ISO method. Conversely, intensive methods such as HC, in which vents are totally blocked, should “approximate the maximum exposure level to which an ordinary smoker could reasonably be expected to be subject”.³² Rather than attempting to define an “average” smoker’s exposure, it is more convenient to define exposure as a region within the limits defined by E_{tar}^{ISO} and E_{tar}^{HC} . Although it is recognised that these limits may vary with improved understanding of the relationships between human exposure and machine yields, relatively small changes will have little effect on the broad outcomes of this study.

In fig 3, the 95% confidence bands for both smoking protocols are regressed against filter ventilation and are seen to converge near zero ventilation for both tar and CO. As filter ventilation increases, these regression bands diverge. This effect has been noted previously for tar in a small UK dataset.³³ The triangular areas between the regressions can be considered to model the variation in typical exposure with ventilation. Indeed, the graphs indicate that ventilation largely controls exposure, because without ventilation nicotine-normalised yields are practically indistinguishable, whether smoked under ISO or under HC conditions. The important differences occur at high ventilation. E_{tar}^{HC} is invariant with ventilation but E_{tar}^{ISO} decreases significantly, implying that ventilation reduces exposure. The extent of this reduction is small compared with the considerable reduction in raw yield (fig 1), but even the E_{tar}^{ISO} trend could be claimed as evidence that filter ventilation effects a significant reduction in exposure. However, this would occur only if the smoker closely replicated ISO smoking behaviour and compensated solely by smoking more cigarettes under the same ISO-like conditions. This is considered highly unlikely, and recent evidence from in vivo studies of compensation suggests that smokers of low-yield brands smoke more intensively than those using regular brands.²⁰

The evidence in fig 3 for CO is more disturbing. CO is itself a cardiovascular risk factor and many important tobacco smoke toxins are volatile and correlate strongly with CO yields in these datasets, including 1,3-butadiene, acrylonitrile, acetaldehyde and benzene, which have among the highest cancer risk index values for smokers.¹³ E_{co}^{ISO} is invariant with filter ventilation and a low-intensity ISO-like smoker (if such exists) of a very low-yield brand would experience no less exposure than an intense HC-like smoker of a high-yielding brand. However, E_{co}^{HC} actually correlates positively with filter ventilation ($r = 0.73$). If a smoker of a highly ventilated brand compensates for low nicotine delivery by vent blocking (estimates of extent vary^{6–20–34}), he or she will typically be represented somewhere along a vertical join above $E_{i,co}^{HC}$ between the regression lines for the different protocols. Such a smoker will therefore, on average, be exposed to a greater flux of toxins in the volatile phase than the smoker of an unventilated brand.

Modelling the effect of filter ventilation on yields suggests that the 10–1–10 mg (tar–nicotine–CO) limits set recently set by the EU Directive¹ are probably achievable with little or no recourse to filter ventilation (fig 1). Furthermore, nicotine-normalised yields of around 10 mg for tar are among the lowest measured in the UK since the mid-1970s,³⁰ and if the surrogate

Figure 3 Variation of nicotine-normalised tar (nicotine-free dry particulate matter) and carbon monoxide yields with filter ventilation under ISO (squares) and Health Canada (HC) (circles) conditions. Linear regressions and associated 95% confidence limits are indicated by solid lines and shading. Linear correlations are indicated only when significant at $p < 0.01$. HC, Health Canada; ISO, International Organization for Standardization.

measures accurately reflect real exposure, then values near 10 mg for both tar and CO identify the brands leading to least exposure. It is evident in the datasets used to construct fig 3 that values of around 10 mg can be achieved in brands with $<10\%$ filter ventilation.

Others have made a case for banning the use of filter ventilation,^{2 4 35} and the results of this study suggest that at best this design feature does not significantly reduce human exposure to most measured smoke toxins and at worst it significantly increases exposure to several major volatile toxins for smokers of the lowest-yield brands. Nicotine yield is the main control on these surrogate exposure values and low values imply high relative levels of nicotine. A better normalising parameter would take into account the differing forms of nicotine (protonated or unprotonated, often known as freebase nicotine), their partitioning between volatile and particulate

phases,³⁶ and their relative availability and addictiveness, but this is not presently possible with current data. Notwithstanding, the analysis suggests that the interests of public health might be served better by cigarettes designed without or with little filter ventilation, and with the lowest achievable tar/nicotine and CO/nicotine values irrespective of raw yields.

The recognition that multiple regression of physical parameters can predict chemical emissions of TNCO under ISO conditions with reasonable accuracy was not expected. Indeed, the equations for $P_{i,j}^{ISO}$ presented above would probably work well for popular brands in the USA and UK. This is significant because regular testing of smoke emissions is an integral feature of Article 11 of the Framework Convention on Tobacco Control,³⁷ as it is considered to be an important tool in the surveillance of products for the protection of public health. The physical proxies described above require no chemical testing and can be generated using a relatively simple laboratory configuration.

The developing world will bear the heaviest burden of tobacco-related disease in the coming years, with an estimated seven million of the predicted global 10 million tobacco-related deaths projected for 2020, yet few of these countries have the capacity to perform routine testing of tobacco products. The Framework Convention recognises the need to “strengthen national and regional capacity for the testing and research of the contents and emissions of tobacco products, pursuant to Article 9”. It can take several years and a large investment in laboratory and human resources to develop comprehensive testing facilities; hence, the possibility that relatively simple physical measurements could provide reasonably accurate and precise proxies for TNCO emissions suggests a means of introducing surveillance in advance of emissions testing. Physical proxy estimates should not be considered adequate long-term substitutes for properly conducted laboratory determinations of emissions, but for countries/regions without dedicated smoke analysis laboratories, the proxy approach might provide an acceptable short-term alternative. It is essential to recognise, however, that care must be taken to allow for regional differences that can significantly influence yields,³⁸ and that local calibrations must be appropriately established and checked on a regular basis by validated laboratories. With these caveats, physical proxies would certainly be sensitive to major changes in product emissions, and could provide an affordable low-technology approach to product monitoring and surveillance.

What this paper adds

- Filter ventilation has the largest influence on reducing tar, nicotine and carbon monoxide yields in the brands studied, but it is not the only design feature involved. Tar and nicotine yields are also lower in light and ultra-light brands that last for fewer numbers of puffs, whereas CO yield is reduced by higher paper porosity and lower tobacco mass. Physical parameters alone can predict TNCO yields with reasonable accuracy and precision in well-defined market sectors.
- Using surrogate measures of exposure to tobacco smoke toxins, it is shown that filter ventilation probably does not reduce the typical smoker's exposure to any significant degree, and for smokers of the lowest-yield brands it may actually increase their exposure to the more volatile toxins.

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The Lighter Side

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