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ABSTRACT

Background: There is relatively little information available about the chemical constituents of tobacco and individual toxic emissions from cigarettes and other tobacco products.

Objective: To characterise 21 constituents in whole tobacco and 41 constituents in the smoke emissions of Canadian cigarettes, as well as to compare differences between domestic and imported brands.

Methods: All data were released as part of Canada's Tobacco Reporting Regulations. Data are reported for 247 brands tested in 2004.

Results: The results indicate significant differences in the constituent levels of domestic and imported cigarette tobacco. Levels of ammonia compounds were significantly higher in imported "US blended" tobacco compared to domestically manufactured brands. Toxic emissions for tobacco-specific nitrosamines were significantly higher for imported cigarettes under both the ISO and Canadian Intense testing methods; however domestic cigarettes had higher levels of other toxic constituents, including benzo[a]pyrene. The findings also highlight the extent to which nicotine, heavy metals and tobacco-specific nitrosamines are "transferred" from the whole tobacco to the smoke.

Conclusions: The findings illustrate important differences between domestically manufactured Virginia flue-cured cigarettes and imported US blended cigarettes. Although the findings suggest that domestic cigarettes had lower levels of constituents such as ammonia, which are associated with increased "additives", Canadian cigarettes were by no means "additive-free." Overall, these findings provide important benchmarks for making historical and international comparisons across brands on key constituents.

Tobacco use is responsible for one in 10 global deaths and is the second major cause of mortality in the world.[1] The bulk of this health burden is due to manufactured cigarettes, which account for a majority of global tobacco consumption.[2] Remarkably, cigarettes themselves remain lightly regulated: in the vast majority of countries, there are no effective regulations governing the contents, design or emissions from cigarettes.

A prominent barrier to developing a regulatory framework for tobacco products is a lack of independent data. In most jurisdictions there is a lack of information on basic product attributes, including the chemical constituents of cigarette tobacco. Tobacco constituents provide direct information related to the blend, the amount of nicotine potentially available to smokers, as well as additives and other constituents associated with the sensory, addictive and toxic properties of tobacco smoke.[3] To date, more than 3000 chemicals have been isolated from tobacco.[4 5] Independent research has focused primarily upon the nicotine content of tobacco and, to a lesser extent, upon specific classes of toxicants, such as heavy metals and tobacco-specific nitrosamines (TSNAs).[6–11] Much of the variation in these constituents across cigarette brands reflects differences in tobacco blends and growing conditions. For example, nicotine content is typically higher in Burley air-cured tobacco compared to Virginia flue-cured tobacco, although in each case nicotine is also influenced by the growing conditions.[3] Similarly, heavy metals such as cadmium are influenced by the metal content of the soil, pH, stalk position and the use of pesticides and fertilisers.[12–14]

Tobacco constituents are also modified during the curing process. TSNAs form primarily during the curing process and levels vary according to the curing method. The use of heat-exchange methods for Virginia flue-cured tobacco has been shown to significantly reduce TSNA formation compared to the use of propane gas heaters, for example.[4 15] Rickert *et al* recently examined historical changes in TSNA levels of flue-cured Canadian cigarettes between 1970 and 1999, and noted that all of the TSNAs (NNN, N-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAB, N-nitrosoanabasine; and NAT, N-nitrosoanatabine) more than doubled during this period.[16 17] Increases in the nicotine content of the tobacco lamina and the total nitrate content of Canadian cigarettes, which were also found to increase between 1969 and 1995, may have contributed to this rise, but the most important factor may have been the introduction of propane gas heaters in the mid 1960s for curing.[16] The switch to heat-exchangers around the year 2000 appears to have resulted in a significant reduction of TSNAs in the subsequent years.

Chemicals are also added to the tobacco during the manufacturing process, including those that serve to enhance the sensory properties of the cigarette and the bioavailability of nicotine.[18–20] Common "additives" include ammonia compounds, which alter the pH level of smoke and increase the proportion of "free nicotine", as well as sugars and other flavours used to mask the harshness of smoke.[21] Industry documents and government disclosure suggest that additives such as sugars, humectants, ammonia compounds, cocoa and liquorice are commonly used; however, the levels of these additives in specific brands are largely unknown.[22 23]

More than 1000 of the chemical constituents present in unburnt "whole" tobacco are also present as emissions in tobacco smoke.[4] Emissions are measured by machine-smoking cigarettes according to a particular smoking protocol, typically using the ISO/FTC smoking method.[24 25] A vast literature has demonstrated that tar, nicotine and carbon monoxide emissions generated under machine-smoking methods have little or no association with individual measures of exposure.[26–28] More recent studies have increasingly focused upon the individual toxic constituents in "tar", including heavy metals, polycyclic aromatic hydrocarbons (PAHs) and TSNAs.[3 8 29–34] However, relatively few studies have examined the association between the level of constituents present in the unburned tobacco and the same constituents in tobacco smoke emissions. This information has the potential to highlight the transfer of chemicals to smoke during pyrolysis, as well as to shed further light on the role of filtration and other design features under machine-testing conditions.

In 2000, the Canadian government introduced regulations that require disclosure of 26 chemical constituents in tobacco and 41 smoke emissions for every brand sold in Canada.[35] The Canadian cigarette market is somewhat unusual in that it consists almost exclusively of Virginia flue-cured tobacco. Imported brands represent only a small market share and are almost exclusively "US blended" cigarettes, which typically contain approximately 35% Virginia flue-cured tobacco, 30% Burley air-cured, 20–30% reconstituted tobacco, as well as smaller amounts of Maryland air-cured and oriental tobaccos.[3] In addition to differences in tobacco blend, anecdotal evidence suggests that Canadian cigarettes also include relatively few additives. However, to our knowledge, the constituents of whole tobacco in contemporary Canadian cigarettes have yet to be characterised in any systematic way in the published literature.

The current study sought to characterise constituent levels in unburned cigarette tobacco, as well as the smoke emissions from Canadian cigarette brands. The study also sought to examine the extent to which nicotine, heavy metals and TSNAs were "transferred" from the whole tobacco to the smoke emissions. Finally, the study examined differences between domestic Canadian brands and imported brands to explore possible blend-dependent differences in constituents and emissions.

METHODS

Canada's federal Tobacco Reporting Regulations require that manufacturers report the level of 26 chemical constituents in the whole tobacco, as well as tobacco weight and pH on an annual basis.[35] For products with less than 1% of the Canadian market share, manufacturers are only required to report nicotine, nitrosamines, nickel, lead, cadmium, chromium, arsenic, selenium and mercury content. Products must be analysed according to ISO 8243[36] or Official Method T-40237, developed by the Canadian Department of Health.[37] The mean, standard deviation and 95% confidence limit of the amount of each constituent are based on three replicates and must be reported in milligrams, micrograms or nanograms per gram of tobacco and per cigarette.

The Tobacco Reporting Regulations also require disclosure of 41 smoke emissions tested under two machine smoking conditions: (1) ISO 3308[25] (35 ml puff, drawn for 2 seconds at 60-second intervals) and (2) the "intense" Health Canada method[38] (55-ml puff, drawn for 2 seconds at 30-second intervals, with all filter ventilation holes completely blocked by tape). Tar, nicotine and carbon monoxide (TNCO) emissions must be reported twice per year, and all other emissions must be reported once per year. Cigarettes with total sales less than 1% of the Canadian market share are only required to report TNCO, benzene, hydrogen cyanide and formaldehyde every two years. For smoke emissions, the mean, standard deviation, and 95% confidence limits are based on 20 replicates in the case of TNCO emissions, and seven replicates for other emissions.

We present data publicly released by Health Canada in 2007 for 247 brands tested in 2004.[39] The dataset includes 22 tobacco constituents, 41 smoke emissions, as well as pH levels and tobacco weight. For both smoke emissions and whole tobacco, the "detectable limit" (DL) and "non-quantifiable limit" (NQL) of constituents were based upon the lowest identifiable level from a minimum of 10 separate analyses. The DL was calculated as three times the standard deviation of these determinations, while the NQL was calculated as 10 times the standard deviation of these determinations. Values below these levels are not reported.

Cigarettes were categorised as either domestic or imported brands based on information obtained from Health Canada. A total of 15 imported brands from six brand families were identified. All but two brand families (Gauloise Blonde and Gitanes) were imported from the United States (Camel, Winston, Salem and More). Fourteen of the 15 brands are believed to be US tobacco blends; the one exception, Gitanes, contains primarily dark air-cured tobacco.[40] The remaining 232 brands were from Canadian manufacturers.

Analysis

All values are reported on a per cigarette basis, which was calculated by multiplying the levels per gram of tobacco by the total tobacco weight for each brand. Means and standard deviations are reported. t Tests were conducted to examine differences in the mean levels between domestic and important brands. Pearson correlation coefficients were used to examine bivariate associations between constituents in tobacco and smoke emissions. All analyses were conducted using SPSS (Version 15.0) statistical software.

RESULTS

Tobacco constituents

Tobacco weight was significantly greater among domestic cigarettes (mean 761.5 g, SD 100) compared to imported brands (mean 721.0 g, SD 53.7; $p<0.001$). The pH level of tobacco was significant higher for imported brands (mean 5.4, SD 0.3) than domestic brands (mean 5.2, SD 0.1, $p<0.001$).

Table 1 shows the mean constituent levels in whole tobacco for all domestic and international brands, as well as the number of brands with levels below the detectable limit. Nicotine levels per cigarette were significantly higher among domestic brands ($p = 0.002$) and accounted for approximately 1.7% of the total tobacco weight, compared to 1.5% of the total weight for imported brands (NS). Nornicotine levels were higher among imported brands ($p<0.001$), as were most heavy metals. For example, the amounts of nickel in tobacco were 2.5 times higher than domestic brands ($p<0.001$). The one exception was cadmium, which was significantly higher among domestic brands ($p<0.001$).

Nitrosamine levels were substantially higher among imported brands. Levels of NNN were more than six times higher ($p<0.001$), while total TSNA levels were more than 2.5 times higher in imported than in domestic brands (3445.5 vs 1219.1 ng/cigarette, $p<0.001$). Nitrate, ammonia, glycerol and propylene glycol were also significantly higher among imported brands (all $p<0.001$).

Table 1 Constituents in whole tobacco (per cigarette)

Constituent	Domestic Mean (SD)	Domestic Brands below detection limit	Imported Mean (SD)	Imported Brands below detection limit
Alkaloids				
Nicotine (mg/cig)	12.6 (1.6)	0	11.1 (2.2)**	0
Nornicotine (μg/cig)	289.3 (67.1)	0	422.5 (98.4)***	0
Anabasine (μg/cig)	67.1 (9.4)	0	63.3 (6.5)	1
Anatabine (μg/cig)	477.1 (64.1)	0	398.0 (93.4)***	0
Metals				
Arsenic (ng/cig)	151.4 (64.4)	5	169.2 (26.2)	0
Nickel (ng/cig)	250.4 (100.2)	0	823.3 (121.9)***	0
Lead (ng/cig)	257.7 (77.7)	0	257.0 (66.5)	0
Cadmium (ng/cig)	929.7 (201.8)	0	765.8 (69.8)**	0
Chromium (ng/cig)	353.3 (115.3)	0	581.4 (103.0)***	0
Selenium (ng/cig)	–	236	110.5 (–)	11
Mercury (ng/cig)	26.8 (4.6)	169	–	12
Nitrosamines				
NNN (ng/cig)	286.9 (118.3)	14	1776.2 (817.2)***	0
NNK (ng/cig)	448.5 (237.4)	39	437.2 (376.1)	8
NAT (ng/cig)	378.8 (169.3)	0	992.1 (332.4)***	0
NAB (ng/cig)	82.0 (5.3)	232	240.0 (–)***	11
Other				
Benzo[a]pyrene (ng/cig)	6.1 (8.6)	0	5.7 (7.8)	0
Triacetine (ug/cig)	23.1 (15.6)	11	36.3 (9.3)**	1
Nitrate (mg/cig)	1.2 (0.6)	0	5.9 (2.0)***	0
Ammonia (ug/cig)	261.1 (90.3)	0	1136.9 (613.8)***	0
Glycerol (mg/cig)	13.2 (1.3)	223	13.5 (0.0)	9
Propylene glycol (mg/cig)	1.7 (0.2)	207	4.7 (0.0)***	9

Significance level: *$p<0.05$, **$p<0.01$, ***$p<0.001$.
NNN, N-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAT, N-nitrosoanatabine; NAB, N-nitrosoanabasine.
Note that myosmine, sodium propionate, sorbic acid, eugenol and tri-ethylene glycol were below detectable limits for all brands.

Constituents in smoke emissions

Smoke pH level was significantly higher among imported than domestic brands under both the ISO (mean 6.1, SD 0.1 vs mean 5.9, SD 0.2; $p<0.001$) and the Canadian Intense testing method (mean 6.0, SD 0.2 vs mean 5.7, SD 0.1; $p<0.001$). Table 2 shows the mean constituent levels in smoke emissions using the ISO method and Canadian Intense method. No significant differences between domestic and imported brands were observed for tar, nicotine or CO. However, some significant differences were observed for individual toxic emissions. Imported cigarettes were higher in non-nicotine alkaloids, TSNAs, gas-phase constituents such as hydrogen cyanide, nitric oxide and nitrogen oxide, and isoprene under both testing methods; levels of acetaldehyde and propionaldehyde were significantly higher among imported cigarettes only under the Canadian Intense method. In contrast, domestic cigarettes had significantly higher levels of benzo[a]pyrene, formaldehyde, acrolein, resorcinol under both methods; hydroquinone and catechol were higher among domestic cigarettes only under the Canadian Intense method, and crotonaldehyde was only higher under the ISO method. Few differences were observed among the heavy metals, with the exception of higher mercury levels in imported cigarettes under the Canadian Intense method.

In general, differences between domestic and imported brands were consistent across the ISO and Canadian Intense methods. The primary effect of the Canadian Intense testing method was to increase the absolute value of emissions considerably. For example, tar levels under the ISO method almost tripled, while nicotine levels under the ISO method more than doubled under the Canadian Intense method. Although the absolute values increased, changes in relative amounts of certain constituents were less uniform. Table 3 shows the level of smoke emissions per mg of nicotine. For example, the level of tar per mg of nicotine increased 14% under the Canadian Intense method, while the level of quinoline decreased by 33%.

Association between constituents in tobacco and smoke emissions

Table 4 shows the correlation between constituents in whole tobacco and constituents in smoke emissions under both ISO and Canadian Intense testing methods. Table 4 also shows the amounts in smoke as a percentage of the amounts present in the whole tobacco ("percentage transfer"). The results indicate that the strength of association varies significantly depending upon the constituent. The correlation between the amount of nicotine present in the tobacco and the smoke emissions was modest, whereas the correlation for other constituents, such as NNN and benzo[a]pyrene was high regardless of the emission testing method used. Although there was relatively little difference between emission testing methods, correlations tended to be somewhat higher under the Canadian Intense method, particularly for mercury and ammonia.

DISCUSSION

The product information released by Health Canada is among the richest public source of information on tobacco products. Although the primary purpose of this paper is to provide an overview of this information, several findings merit particular attention.

Table 2 Constituents in smoke emissions: ISO and Canadian Intense machine-smoking methods

	ISO method		Canadian Intense method	
	Domestic	Imported	Domestic	Imported
Constituent	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Tar (mg/cig)	10.7 (4.1)	11.6 (4.0)	30.4 (3.9)	31.3 (5.6)
Alkaloids				
Nicotine (mg/cig)	0.9 (0.3)	0.9 (0.2)	2.4 (0.3)	2.2 (0.3)
Pyridine (μg/cig)	12.6 (4.0)	15.5 (6.2)*	34.9 (3.1)	46.1 (6.1)***
Quinoline (μg/cig)	0.2 (0.3)	0.5 (0.5)*	1.0 (0.3)	1.1 (0.3)
Metals				
Lead (ng/cig)	16.7 (6.2)	11.3 (9.0)	37.2 (13.9)	34.2 (7.7)
Cadmium (ng/cig)	57.6 (21.6)	52.3 (20.4)	160.8 (32.1)	157.1 (28.7)
Mercury (ng/cig)	3.2 (0.6)	3.5 (1.1)	6.5 (0.8)	7.2 (0.9)*
Nitrosamines				
NNN (ng/cig)	25.2 (7.8)	168.1 (52.6)***	53.1 (12.6)	353.3 (91.3)***
NNK (ng/cig)	54.0 (18.6)	101.0 (45.8)***	110.3 (33.2)	212.1 (90.8)***
NAT (ng/cig)	40.6 (11.4)	49.5 (64.7)	81.9 (17.2)	106.0 (134.6)
NAB (ng/cig)	3.8 (1.3)	35.6 (12.1)***	6.7 (1.8)	79.7 (26.0)***
Polyaromatic hydrocarbons				
Benzo[a]pyrene (ng/cig)	11.8 (5.0)	7.1 (1.6)**	24.1 (8.4)	15.9 (2.0)***
Volatile organic compounds				
Benzene (μg/cig)	45.6 (12.1)	42.0 (9.6)	89.3 (8.7)	90.9 (6.7)
1,3-Butadiene (μg/cig)	42.9 (11.0)	42.8 (11.6)	92.9 (7.6)	98.2 (11.8)*
Toluene (μg/cig)	69.8 (22.5)	68.6 (17.1)	155.1 (29.2)	163.1 (11.9)
Styrene (μg/cig)	11.5 (10.4)	9.8 (3.6)	28.1 (23.4)	26.5 (2.6)
Formaldehyde (μg/cig)	72.7 (31.3)	40.1 (17.2)***	181.5 (32.0)	100.2 (20.7)***
Acetaldehyde (μg/cig)	590.6 (173.1)	576.9 (160.7)	1230.3 (103.0)	1352.8 (174.1)***
Propionaldehyde (μg/cig)	49.3 (14.4)	48.9 (13.3)	105.0 (8.5)	115.0 (15.9)*
Crotonaldehyde (μg/cig)	28.1 (7.8)	22.9 (8.8)*	67.8 (7.8)	64.0 (8.4)
Butyraldehyde (μg/cig)	32.2 (9.3)	33.1 (9.5)	69.9 (6.5)	77.5 (11.3)*
Acrolein (μg/cig)	71.7 (21.1)	56.7 (17.5)*	160.2 (19.4)	142.9 (17.3)*
Isoprene (μg/cig)	288.6 (89.3)	318.7 (80.5)	608.8 (97.2)	740.0 (81.3)***
Hydroquinone (μg/cig)	62.6 (15.4)	57.2 (18.8)	150.1 (20.1)	127.0 (30.8)***
Other gas-phase				
Carbon monoxide (mg/cig)	10.5 (4.2)	12.2 (3.8)	27.2 (2.8)	29.3 (4.9)
Hydrogen cyanide (μg/cig)	119.0 (40.6)	145.1 (58.6)*	293.5 (41.2)	423.1 (84.6)***
Nitric oxide (μg/cig)	63.7 (19.6)	199.1 (41.9)***	138.7 (24.0)	421.8 (114.8)***
Nitrogen oxide (μg/cig)	70.2 (20.9)	205.1 (44.4)***	150.5 (28.1)	460.1 (123.8)***
Acetone (μg/cig)	307.0 (82.2)	308.0 (86.5)	630.3 (51.9)	686.6 (82.3)*
Aromatic amines				
1-Aminonaphthalene (ng/cig)	13.7 (2.9)	19.1 (4.3)***	22.7 (5.9)	34.5 (6.8)***
2-Aminonaphthalene (ng/cig)	8.5 (1.7)	12.1 (2.4)***	21.0 (6.2)	21.9 (3.6)
3-Aminobiphenyl (ng/cig)	1.9 (0.4)	2.7 (0.5)***	3.7 (0.7)	5.8 (0.9)***
4-Aminobiphenyl (ng/cig)	1.7 (0.5)	2.2 (0.4)***	3.7 (0.8)	4.7 (0.6)***
Other				
Ammonia (μg/cig)	12.4 (3.3)	13.7 (4.3)	26.5 (4.4)	40.5 (18.0)***
Acrylonitrile (μg/cig)	9.2 (2.4)	9.7 (2.9)	21.8 (2.4)	24.3 (1.6)***
Resorcinol (μg/cig)	1.1 (0.2)	0.8 (0.6)*	2.9 (0.6)	2.5 (0.8)*
Catechol (μg/cig)	74.2 (18.7)	69.9 (23.3)	170.0 (28.2)	145.7 (40.0)*
Phenol (μg/cig)	22.2 (13.7)	23.3 (13.1)	42.2 (26.7)	41.4 (27.4)
m,p-Cresol (μg/cig)	12.4 (4.9)	14.4 (5.9)	24.1 (10.7)	26.1 (13.2)
o-Cresol (μg/cig)	4.7 (2.2)	5.7 (2.4)	9.9 (4.9)	10.2 (5.0)

NNN, N-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAT, N-nitrosoanatabine; NAB, N-nitrosoanabasine.
Significance level: *$p<0.05$, **$p<0.01$, ***$p<0.001$.

The nicotine content of whole tobacco showed little variation, with only modest differences between domestic and imported brands. Canadian cigarette tobacco had an average of 12.6 mg of total nicotine, only slightly lower than 13.5 mg reported from a sample of 23 Canadian brands tested in 1998.[6] More recent findings released by the state of Massachusetts reported a mean nicotine content of 13.9 mg/cigarette for US cigarettes, which is somewhat higher than the 11.1 mg/cigarette found among the 15 imported brands sold in Canada.[7] These differences are most probably due to differences in the number and type of cigarettes included in each analysis, although others have reported recent increases in the nicotine level of whole tobacco for US cigarettes.[41] It also appears that the main reason for the higher levels in domestic cigarettes was the greater amount of tobacco per cigarette; indeed, nicotine levels per gram of tobacco were not significantly different between imported and domestic tobacco.

Table 3 Difference between ISO and Canadian machine-testing methods in smoke emission levels per mg of nicotine†

	ISO	Canadian Intense
Constituent (per mg nicotine)	Mean (SD)	Mean (SD)
Tar (mg)	11.5 (2.5)	13.1 (1.0)***
Alkaloids		
Carbon monoxide (mg)	11.3 (2.8)	11.8 (1.6)**
Pyridine (μg)	13.8 (3.5)	16.5 (2.7)***
Quinoline (μg)	0.3 (0.3)	0.4 (0.1)***
Metals		
Lead (ng)	17.6 (7.7)	18.6 (6.8)
Cadmium (ng)	58.6 (14.3)	71.4 (10.3)***
Mercury (ng)	3.4 (0.6)	3.0 (0.4)***
Nitrosamines		
NNN (ng)	50.5 (53.0)	44.0 (46.6)***
NNK (ng)	64.2 (25.1)	56.7 (22.3)***
NAT (ng)	45.7 (30.5)	38.0 (24.5)***
NAB (ng)	10.1 (13.7)	9.0 (13.4)***
Other		
Hydroquinone (μg)	66.7 (8.3)	66.0 (9.2)
Resorcinol (μg)	1.0 (0.4)	1.1 (0.2)*
Catechol (μg)	79.4 (9.0)	75.4 (10.8)***
Phenol (μg)	23.1 (10.2)	18.3 (8.8)***
m,p-Cresol (μg)	13.3 (3.2)	10.8 (3.8)***
o-Cresol (μg)	5.1 (1.6)	4.3 (1.6)***
1,3-Butadiene (μg)	46.3 (8.6)	42.6 (7.2)***
Isoprene (μg)	319.7 (86.0)	288.9 (72.4)***
Acrylonitrile (μg)	9.8 (2.4)	10.1 (1.9)
Benzene (μg)	49.2 (11.3)	40.7 (7.3)***
Toluene (μg)	76.4 (21.6)	71.6 (17.8)***
Styrene (μg)	12.0 (7.6)	12.3 (7.4)
Ammonia (μg)	13.2 (3.3)	12.8 (3.0)*
1-Aminonaphthalene (ng)	16.0 (3.2)	10.8 (2.7)***
2-Aminonaphthalene (ng)	10.0 (2.1)	9.8 (3.5)
3-Aminobiphenyl (ng)	2.2 (0.6)	1.8 (0.4)***
4-Aminobiphenyl (ng)	1.9 (0.7)	1.8 (0.5)*
Benzo[a]pyrene (ng)	12.0 (5.4)	10.5 (4.7)***
Formaldehyde (μg)	70.8 (33.6)	77.2 (25.0)**
Acetaldehyde (μg)	628.8 (144.6)	566.1 (93.2)***
Acetone (μg)	331.2 (66.0)	288.8 (42.7)***
Acrolein (μg)	73.4 (17.3)	71.3 (11.8)
Propionaldehyde (μg)	52.5 (12.2)	48.2 (7.4)***
Crotonaldehyde (μg)	28.3 (8.0)	30.3 (4.8)**
Butyraldehyde (μg)	34.8 (7.9)	32.3 (5.4)***
Hydrogen cyanide (μg)	129.5 (44.3)	143.7 (36.0)***
Nitric oxide (μg)	90.9 (56.6)	82.0 (48.7)***
NO_x (μg)	97.8 (57.7)	89.6 (53.8)***

NNN, N-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAT, N-nitrosoanatabine; NAB, N-nitrosoanabasine.
*$p<0.05$ **$p<0.01$ ***$p<0.001$.
†Among brands with detectable limits.

The variation in ISO nicotine emissions measured in cigarette smoke emissions was substantially greater than the variation in nicotine content. Whereas nicotine content of unburned tobacco showed less than a twofold difference, ISO nicotine emissions showed a 25-fold difference from lowest to highest. The variation in nicotine emissions was considerably less when cigarettes were tested under the Canadian Intense emission testing method and only slightly greater than the variation measured in whole tobacco. This suggests that cigarette design parameters—most notably filter ventilation—can produce much larger differences under machine-smoking conditions than are found in the tobacco itself. Indeed, many brand variants within the same brand family (for example, *Export A Full Flavour*, *Export A Light*, etc) contained identical tobacco, but yielded very different levels under machine testing.

Perhaps most important, all 247 brands contained ample nicotine to promote and sustain addiction.[42] This fundamental, though unremarkable, finding should not be obscured by the apparent differences in nicotine emissions generated under machine-testing methods, none of which are related to human exposure or uptake, which is relatively constant across conventional cigarette brands.[26 43]

Nitrate levels were significantly higher in both the whole tobacco and the smoke emissions of imported cigarettes. Higher nitrate levels in the Burley tobacco used in US blended cigarettes result in much higher levels of nitrogen oxides, which influence

Table 4 Association between constituents in tobacco and smoke emissions.

Tobacco constituents	ISO emissions		Canadian Intense emissions	
	Correlation	Mean transfer %† (SD)	Correlation	Mean transfer % (SD)
Alkaloids				
Nicotine (μg/g)	0.28***	3.6 (1.6)	0.44***	7.9 (2.9)
Metals				
Lead (ng/g)	0.63***	4.9 (2.1)	0.73***	11.8 (3.9)
Cadmium (ng/g)	0.36**	6.8 (2.7)	0.59***	19.5 (5.4)
Mercury (ng/g)	0.02	11.7 (2.7)	0.56***	25.8 (4.3)
Nitrosamines				
NNN (ng/g)	0.94***	7.4 (2.7)	0.96***	15.6 (4.7)
NNK (ng/g)	0.62***	9.8 (3.7)	0.54***	20.9 (7.9)
NAT (ng/g)	0.52***	8.0 (3.8)	0.49***	16.8 (7.6)
Other				
Ammonia (μg/g)	0.30**	3.6 (1.6)	0.87***	7.9 (2.9)
Benzo[a]pyrene (ng/g)	0.84***	–	0.89***	–
Nitrate (mg/g) vs nitric oxide (μg)	0.87***	–	0.93***	–
Nitrate (mg/g) vs NO_x (μg)	0.88***	–	0.94***	–

NNN, N-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAT, N-nitrosoanatabine.
*p<0.05, **p<0.01, ***p<0.001.
†Transfer % = constituent levels/smoke emission level.
NAB excluded owing to insufficient data (n = 5).
Brands with levels below detectable limits were excluded from each analysis.

TSNA formation.[3] Not surprisingly, the TSNA levels of imported brands were significantly higher than domestic Virginia-flue cured cigarettes. The TSNA levels of domestic Canadian cigarettes were at the lower end of values reported in Canadian cigarettes tested in 1990 and substantially lower than values measured in 2000.[9 17] The current data were collected in 2004, following a $20 million government subsidy in 2001 to replace propane gas heaters with heat-exchange curing methods for domestically grown Virginia-flue cured tobacco. The lower levels of TSNAs reported in the current paper appear to reflect the impact of these new curing practices.

Although domestic Virginia flue-cured cigarettes had significantly lower levels of TSNAs than imported brands with US tobacco blends, other toxic constituents were notably higher, including volatile organic compounds such as formaldehyde, acrolein and crotonaldehyde, as well as benzo[a]pyrene.[3] An "inverse" relation between TSNAs and PAHs such as benzo[a]pyrene has previously been noted with respect to Canadian cigarettes.[44 45] One potential explanation is that nitrate, which is present in higher levels in Burley air-cured tobacco and contributes to TSNA formation, may serve as a free-radical scavenger during combustion/pyrolysis and reduce PAH formation.[3] The nature of this relation, however, remains unclear. Whatever the differences in emissions between blends may be, the current findings underscore the extraordinary range of toxicants present in all cigarette smoke.

The smoke emissions data provide an opportunity to examine the impact of different smoking conditions on the chemical profile of tobacco smoke. The comparison between ISO and the Canadian Intense method indicates that different smoking conditions can change both the absolute level, as well as the relative levels of chemicals in many cases. The levels of various toxicants per mg of nicotine changed by as much as 33%, depending upon which smoking method was used. Using the Canadian Intense method increased the levels per mg of nicotine for eight constituents and lowered the levels per mg for 24 constituents. Overall, the use of two testing methods underscores the basic finding that all cigarettes are capable of delivering a wide range of constituents depending upon how they are smoked, and there is no single "tar" or nicotine level associated with each product. More comprehensive discussions of the different smoking methods are provided elsewhere.[24 45 46]

The data appear to provide partial support to anecdotal evidence and industry assertions that Canadian cigarettes contain fewer chemical "additives." In particular, ammonia compound levels of imported cigarettes were more than four times greater than domestic cigarettes, as were other "additives" such as triethylene glycol. Ammonia levels can be manipulated in various ways during manufacturing, including the addition of ammonia-related compounds, including ammonium hydroxide; ammonium bicarbonate, diammonium phosphate (DAP) and urea—none of which were included in the Canadian reporting guidelines.[21] The level of ammonia in tobacco smoke is closely related to nitrate and has a strong effect on the pH level of smoke, which was also significantly higher among imported cigarettes. Higher smoke pH levels can increase the proportion of unprotonated or "free" nicotine, which increases the efficiency and rate at which nicotine is absorbed into the bloodstream; however, it is unclear whether the magnitude of difference in pH levels observed between imported and domestic Canadian cigarettes is sufficient to significantly alter free nicotine levels.[18]

At the same time, the current data clearly indicate that the tobacco in Canadian cigarettes is by no means "additive-free." Domestic brands had similar levels of glycerol and detectable levels of propylene glycol—both of which serve as humectants to retain moisture and alter flavour. In addition, many additives applied to cigarette paper and the filter are exempt from reporting guidelines, including adhesive and binders, plasticisers, colours for papers and salts, all of which can leach into the tobacco after it is packaged. Other common tobacco additives, including theobromine, menthol and cocoa, were also exempt from reporting. As a result, it is not possible to fully evaluate the level of additives in domestic Canadian cigarettes.

Limitations

The data released by Health Canada represent information reported directly by tobacco manufacturers. Although there is

What this paper adds

Relatively few studies have examined the association between the level of constituents present in the unburned tobacco and the same constituents in tobacco smoke, particularly using market-wide data. The current paper presents comprehensive constituent and emission data on Canadian cigarettes that helps to characterise variations across brands and tobacco blends.

no feasible way to verify all of this information, subsequent analyses of smoke emissions commissioned by Health Canada did not reveal any systematic biases or errors in the data reported by manufacturers. The low number of imported brands included in this dataset should also be noted. The imported brands included several leading international varieties; however, it would be inappropriate to generalise data from the current study to all US blended cigarettes. In addition, the constituent levels reported in the current paper for unburnt tobacco only included brands that tested above the minimum detectable and quantifiable limits. As a result, the mean levels presented in this paper will be somewhat higher than the actual means for all brands sold in Canada.

Although the Canadian reporting requirements are among the most comprehensive in the world, they do not include a number of constituents that may be of interest to public health authorities, including chemicals such as glucose, sucrose, menthol and urea. These constituents are particularly important given their potential to enhance the addictive properties of smoking. In addition, the Canadian requirements fail to include basic design features, such as filter ventilation, that are critical to understanding how cigarettes perform under emission testing and how consumers use the product. Differences between cigarette brands in the level of ISO smoke emission have been shown to be almost perfectly correlated with filter ventilation.[6] Filter design also has an important influence upon smoking behaviour and the intensity with which each cigarette is smoked. As a result, this information is critical to interpreting the data reported in the Health Canada dataset. Filter efficiency for nicotine (that is, the amount of nicotine trapped in the filter of the smoking machine) is included in the Canadian reporting requirements, although no data have been publicly released to date.

Finally, there are no reporting regulations that require in vivo measures of product use. Thus, reporting requirements give no indication of how products are used by consumers or the level of consumer exposure. It remains possible, but unclear, whether future reporting regulations could evolve to include biomarker profiles or patterns of use collected through "clinical trials" of tobacco products. Irrespective of whether mandatory reporting regulations should include in vivo measures, information on human patterns of use and exposure is essential in order to interpret the product measures reported by tobacco companies. Product measures alone—ingredients, design and emissions—are not reliable indicators of a product's risk or likely exposure level. Indeed, on their own, these measures can be seriously misleading to the public and regulators when interpreted out of context.

Conclusions

The framework for collecting information on tobacco product design and constituents is rapidly evolving. Although this information has the potential to inform product regulation, to date very little of the information collected by regulators has been publicly released and subject to scientific scrutiny. In the future, regulators should strive for common reporting guidelines across jurisdictions, as well as measures to ensure public access to this information. These measures will be especially important to help develop product testing and reporting guidelines under Articles 9 and 10 of the Framework Convention on Tobacco Control, the world's first public health treaty.

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