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Menthol Addition to Cigarettes Using Breakable Capsules in the Filter. Impact on the Mainstream Smoke Yields of the Health Canada List Constituents

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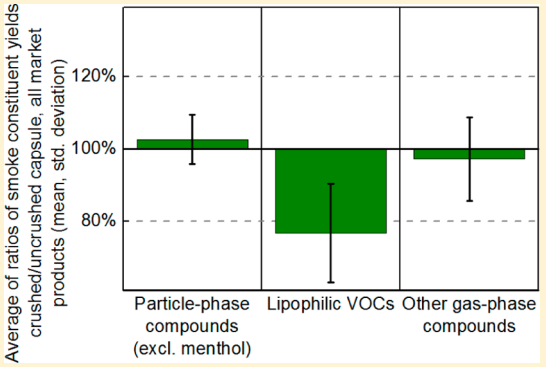
ABSTRACT: Cigarettes with menthol capsules embedded in the filter have been introduced recently in many countries. At the same time, concerns have been expressed that filter performance could be affected by the crushing of the capsule therein, altering mainstream smoke constituent yields, ultimately with the potential to impact the toxicity of these products. The present study investigates the possible mechanisms underlying differences in smoke constituent deliveries following the crushing of a menthol capsule in a cigarette filter. It also includes results from a market survey of a selection of commercial cigarette brands with menthol capsules representing the different designs for this type of product available in different markets worldwide. The yields of 46 Health Canada smoke components were determined according to the International Organization for Standardization (ISO) machine-smoking regime. Data obtained from measurements using cigarettes with the capsule crushed and uncrushed were compared. Except for the intended presence of menthol flavors in smoke, no meaningful differences were identified in the yields of the remaining measured particulate-phase smoke constituents. Regarding the gas-phase smoke constituents, it was found that the delivery of lipophilic volatiles was reduced when the capsule was crushed. Delivery of the other measured gas-phase components remained unaffected. The results from investigations performed in this study did not show any meaningful increase in the yield of smoke constituents listed by Health Canada as a result of crushing the menthol capsule in the cigarette filter.



1. INTRODUCTION

Cigarettes with menthol capsules embedded in the filter have been introduced recently in many countries. This innovative cigarette design enables the consumer to release menthol at any time during smoking by crushing the capsule. The scope of the present work was aimed at investigating whether smoke chemistry could be altered when a menthol-containing capsule is crushed in a filter.

Theoretically, releasing the liquid contents of a capsule by crushing it could have an impact on air flow dynamics or on the functioning of a cigarette filter. For instance, it has been shown that the filter retention of phenolic compounds can be substantially changed by varying the level of triacetin added as a plasticizer to the cellulose acetate.[1] Concerns have indeed been expressed regarding potential increase in toxicity of the cigarette smoke as a result of crushing the menthol capsule present in the filter. Recently, a report concluded that cigarettes with menthol capsules in the filter are more hazardous than regular menthol cigarettes.[2] This conclusion was based on a scientific study reporting a change in smoke composition as a result of crushing the capsule,[3] although the health impact of changes in yields of individual smoke constituents is generally difficult to assess.[4−6]

The present study includes the assessment of a set of prototype cigarettes designed to determine the relative impact of different construction parameters on menthol delivery using generally accepted methods, namely, the methods to be used for the yearly reporting of brands on the Canadian market to Health Canada. In addition, smoke deliveries from a set of capsule-containing brands representative of the different types of such products marketed worldwide were tested both with the capsule crushed and uncrushed to validate our conclusions.

2. MATERIALS AND METHODS

2.1. Cigarette Samples. *2.1.1. Design of Prototype Cigarettes for Mechanistic Investigations.* A number of prototypes were produced, targeting cigarettes with 6-mg and 10-mg ISO tar deliveries,

Table 1. Prototype Designs for Mechanistic Investigations[a]

prototype design	100P	101P	102P	200P	201P
mentholated tobacco	no	no	yes	no	no
tobacco menthol (mg/cig)			4.20		
menthol capsule	yes	no	yes	yes	no
menthol content of capsule (mg)	4.80		4.80	4.80	
tobacco weight (mg)	598	597	604	641	641
target ISO tar (mg/cig)	6	6	6	10	10

[a]Cigarettes were made to king size (KS) specifications (cigarette circumference, 24.65 mm, and length, 84.0 mm).

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Table 2. Construction Design, ISO Tar Yield, and Origin of Sampled Commercial Cigarette Brands[a]

brand name	country	manufacturer[b]	tar level[c]
Menthol in Tobacco Rod Plus Menthol Capsule			
Marlboro Ice Blast KS	Japan	PMI	8 mg
Pianissimo Viv Menthol KS	Japan	JT	6 mg
Bohem Mojito Double KS	Korea	KT&G	6 mg
No Menthol in Tobacco Rod, Menthol Capsule, and Charcoal in the Filter			
Lark Hybrid MNT KS	Japan	PMI	6 mg
Kent Convertibles KS	Lithuania	BAT	4 mg
Kent I Switch 1 100	Japan	BAT	1 mg
No Menthol in Tobacco Rod and Menthol Capsule in the Filter			
Lucky Strike Click And Roll KS	Switzerland	BAT	10 mg
Marlboro Gold B KS	Switzerland	PMI	6 mg
Camel Crush KS	USA	RJR	12 mg

[a]King size (KS) and 100s (100). [b]See text for abbreviations. [c]ISO delivery per cigarette.

Table 3. Methods Used for the Measurement of Mainstream Smoke Deliveries

measured emission[a]	Health Canada method number	number of replicates
nicotine, tar, menthol, carbon monoxide	T-115	8
ammonia	T-101	3
1- and 2-aminonaphthalene, 3- and 4-aminobiphenyl	T-102	3
benzo(*a*)pyrene	T-103	3
formaldehyde, acetaldehyde, acetone, acrolein, propionaldehyde, crotonaldehyde, methyl ethyl ketone, butyraldehyde	T-104	3
filter efficiency (from nicotine retention)	T-106	8
hydrogen cyanide	T-107	3
lead, cadmium, chromium, nickel, arsenic, selenium	T-109	3
nitrogen oxides	T-110	3
pyridine, quinoline, styrene	T-112	3
hydroquinone, resorcinol, catechol, phenol, *o*-cresol, *m*+*p*-cresols	T-114	3
1,3-butadiene, isoprene, acrylonitrile, benzene, toluene	T-116	3
NNN, NNK, NAT, NAB[c]	TMS-135[b]	3

[a]Done by Labstat International ULC, 262 Manitou Drive, Kitchener ON, N2C 1L3, Canada. [b]Method performed by Labstat using LC-MS/MS. [c]NNN, *N*′-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAT, *N*′-nitrosoanatabine; NAB, *N*′-nitrosoanabasine.

in order to investigate the mechanisms underlying possible changes in the smoke constituents deliveries induced by crushing a menthol capsule inside a cigarette filter. Filter rods with menthol capsules positioned at predetermined intervals are prepared by precise adjustment of the feed rate of the filter tow and the timing of capsules injection into the tow web.[7−10] Different prototypes were manufactured with and without a capsule in the filter, using the same filter design (denier per filament 2.7; total denier 35000; Y fiber extrusion shape) for all prototypes, with matching tobacco weight among prototypes with the same ISO tar delivery target.[11]

This protocol offered the possibility to compare mainstream smoke composition of matching cigarettes containing no flavor capsule in the filter, an intact capsule, or a crushed capsule. Construction details for the entire set of prototypes are listed in Table 1.

2.1.2. Selection and Sampling of Commercial Cigarette Brands. A set of commercial cigarette brands containing a menthol capsule was selected to take into account the major possible sources of variability in design and construction. In March, 2012, cigarette products from different international manufacturers were purchased from retail outlets in several countries where capsule-containing products are marketed. The selection included the main design types and is consistent with the market analysis in a recent German Cancer Research Center (DKFZ) report.[2]

Nine brands were selected: three from British American Tobacco plc. (BAT), three from Philip Morris International (PMI), one from Japan Tobacco Inc. (JT), one from the R.J. Reynolds Tobacco Company (RJR), and one from KT&G Corp. (KT&G, formerly Korea Tobacco & Ginseng Corp.). The selected brands spanned a wide range of design features. ISO tar deliveries of the brands ranged from 1 mg (Kent Switch 1) to 12 mg (Camel Crush). Three of the nine brands contained menthol in the cut filler, in addition to a menthol capsule in the cigarette filter. Among the other six brands, three contained a charcoal filter. Brand name, country of origin, manufacturer, and ISO tar level of all selected brands are listed in Table 2.

2.2. Analytical Methods. *2.2.1. Filter Physical Properties.* Cigarette resistance to draw (RTD) and ventilation were measured before and after rupture of the capsule to assess possible alterations of filter performance. These measurements were performed (20 replicates) on all products at the PMI Operations Laboratory in Neuchâtel, Switzerland during April and May of 2012, according to ISO methods 6565[12] and 9512,[13] respectively.

2.2.2. Mainstream Smoke Chemistry. Smoking of the cigarettes and mainstream smoke trapping and analyses were contracted to an external accredited laboratory, Labstat International ULC (Canada). Cigarettes were machine-smoked according to the ISO 3308 standard of one 35-mL puff taken over 2 s every minute.[14] In the present study, smoke deliveries from one commercial cigarette brand smoked under Health Canada Intense (HCI) machine-smoking conditions[15] are also presented for comparison. This standard differs from the ISO 3308 standard in an increased puff volume of 55 mL, a puffing frequency of 2 puffs per minute, and the additional provision that the cigarette ventilation holes are blocked. The capsule-containing cigarettes were smoked with capsules crushed and uncrushed. In order to minimize the variability possibly associated with the release of the contents of the capsule, the capsules were crushed using a mechanical device. A lever, perpendicular to the cigarette axis, was lowered onto the immobilized cigarettes so as to press the filter at the capsule location. The movement was blocked when the lever intrusion into the filter reached a preset value, usually 3 mm. The smoking process on the smoking machine was initiated 5 min (±1 min) after crushing the capsules.

For analytical purposes, cigarette smoke can be separated into the particulate phase, matter which remains on a Cambridge filter pad after passing smoke through it, and the gas-vapor phase, matter which passes through the Cambridge filter pad. In the present study, total particulate matter (TPM) was collected on a Cambridge glass-fiber filter (CF) and determined gravimetrically.[16] Gas chromatography (GC) was used to determine nicotine[17] and water[18] in TPM. Tar yield was calculated as TPM yield minus nicotine and water yields. Carbon monoxide was determined by nondispersive infrared photometry.[19] Filter retention efficiency was determined by measuring nicotine in both the cigarette filter and smoke TPM by GC of the isopropanol extracts. Cigarette mainstream smoke deliveries were assessed for the 46 compounds that were selected by Health Canada,[20] following the Health Canada-recommended methods[21] (see Table 3 for method references and number of replicates). These methods have been extensively tested and validated and are currently a recognized standard mandated by the Canadian regulatory authorities. Briefly, carbonyl compounds were trapped and derivatized by passing unfiltered smoke through two impinger traps containing pyridine-stabilized 2,4-dinitrophenylhydrazine in acetonitrile. Formaldehyde, acetaldehyde, acetone, acrolein, propionaldehyde, crotonaldehyde, methyl ethyl ketone, and butyraldehyde were quantified by high-performance liquid chromatography with ultraviolet detection (HPLC-UV). Volatile organic compounds (VOCs) were sampled by directly passing the smoke through 2 cryogenic traps containing methanol cooled to a temperature below −70 °C. Trapping efficiency was

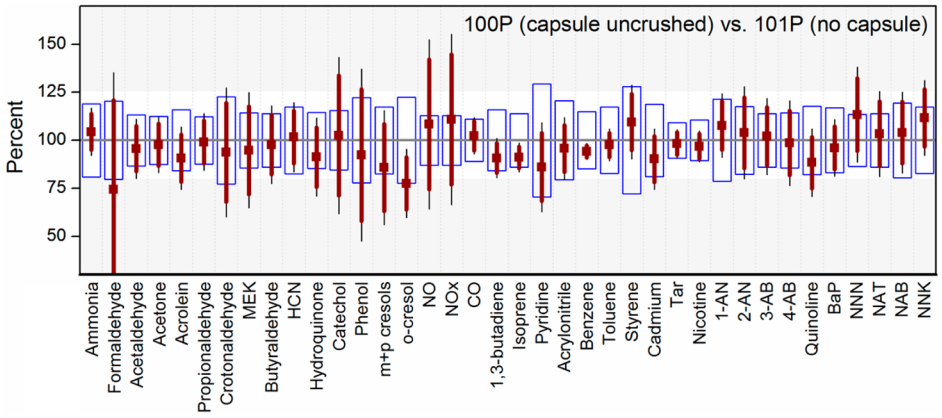

Figure 1. Ratios of yields of smoke constituents of prototype 100P smoked with the capsule uncrushed to respective yields of the noncapsule-containing prototype 101P (solid squares). Solid vertical bars show 90%, and thin vertical lines show 95% confidence intervals of yield differences, scaled accordingly. The equivalence ranges of the present study (open boxes) are in most cases more conservative than the usual 80%−125% bioequivalence ranges[31] (delimited by horizontal light gray bars).

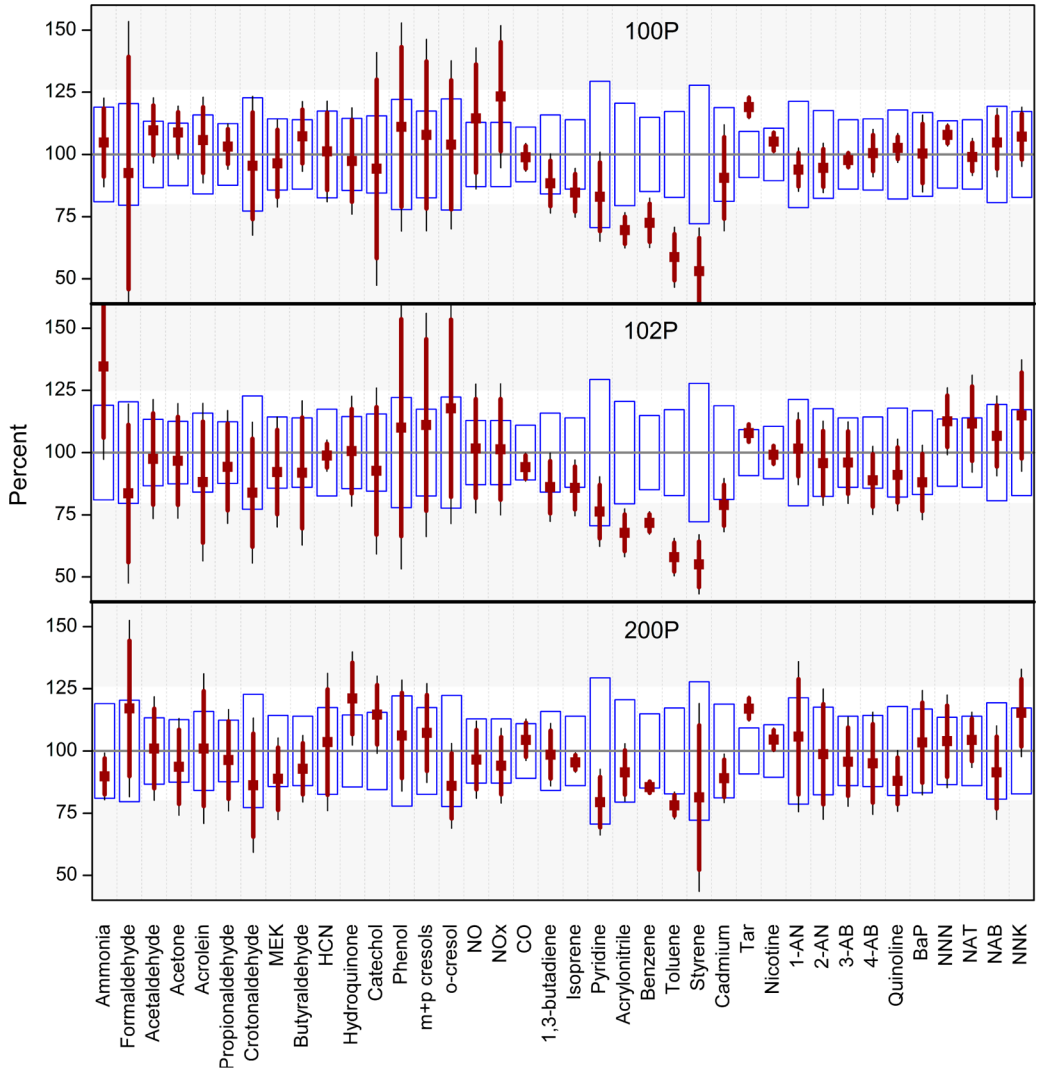

Figure 2. Ratios of yields of smoke constituents of prototypes smoked with the capsule crushed to respective yields of the same prototypes smoked with the capsule uncrushed (solid squares). Solid vertical bars show 90%, and thin vertical lines show 95% confidence intervals of yield differences, scaled accordingly. The equivalence ranges of the present study (open boxes) are in most cases more conservative than the usual 80%−125% bioequivalence ranges[31] (delimited by horizontal light gray bars).

notably found to be very good with this sampling train.[22] The impinger solutions were spiked with D_6-benzene as internal standard (IS), and 1,3-butadiene, isoprene, acrylonitrile, benzene, and toluene were quantified by GC interfaced to a mass spectrometer (GC/MS).

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Table 4. Physical Properties and Menthol Deliveries of Prototype Cigarettes Reported as Mean Values with Their Respective Standard Errors

measured parameter	100P	101P	102P	200P	201P
RTD intact capsule (mmWG)	97 ± 0.6	93 ± 0.5	97 ± 0.8	114 ± 0.9	
RTD broken capsule (mmWG)	98 ± 0.9		97 ± 0.8	113 ± 0.4	
ventilation intact capsule (%)	58 ± 0.5	56 ± 0.3	57 ± 0.4	33 ± 0.6	
ventilation broken capsule (%)	58 ± 0.5		57 ± 0.7	33 ± 0.4	
menthol yield intact capsule (μg/cig)			316 ± 14		
menthol yield broken capsule (μg/cig)	544 ± 34		764 ± 23	951 ± 25	
nicotine retention in filter, intact capsule (%)	50.7 ± 0.4	51.7 ± 0.5	51.1 ± 0.4	48.5 ± 0.5	47.7 ± 0.6
nicotine retention in filter, broken capsule (%)	52.5 ± 0.3		52.2 ± 0.5	47.3 ± 0.5	

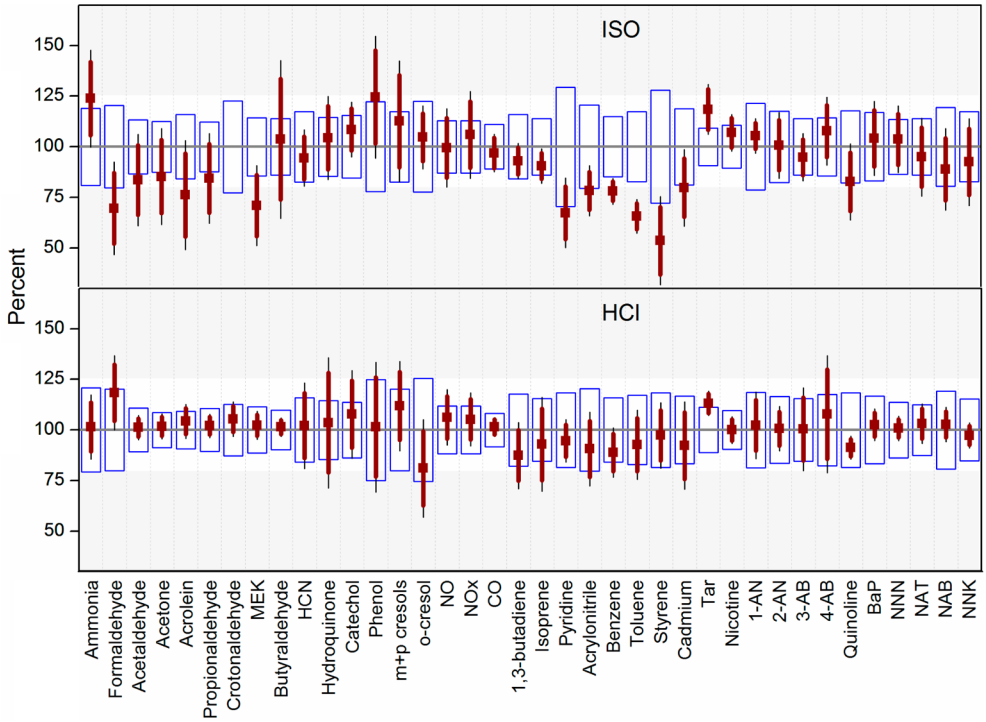

Figure 3. Ratios of yields of smoke constituents of a Marlboro Gold Beyond cigarette brand smoked with the capsule crushed to respective yields of the same cigarette brand smoked with the capsule uncrushed (solid squares). Results are shown for the ISO smoking regime (top) as well as for the HCI smoking regime (bottom). Solid vertical bars show 90%, and thin vertical lines show 95% confidence intervals of yield differences, scaled accordingly. The equivalence ranges of the present study (open boxes) are in most cases more conservative than the usual 80%−125% bioequivalence ranges[31] (delimited by horizontal light gray bars).

Semivolatile hydrocarbons were trapped on a CF followed by 2 cryogenic traps containing methanol. Pyridine, quinoline, and styrene were quantified from the CF extract and both cryogenic trap contents by GC-MS. Ammonia was trapped by two impingers containing an acidic solution and a CF in series, and quantification was done by cation-exchange HPLC. Hydrogen cyanide was trapped on a conditioned CF followed by an impinger containing 0.1 N sodium hydroxide. Both CF extracts and the impinger contents were quantified by continuous flow colorimetric analysis using the König reaction.[23] For the quantification of nitrogen oxides, each unfiltered puff was exhausted into an evacuated smoke mixing chamber for homogenization, and an aliquot of each puff was routed by vacuum through a filter to a dual-channel chemiluminescence nitrogen oxides analyzer. Aromatic amines were extracted from sampled TPM with an acidic solution that was neutralized and counter-extracted with hexane, using D_9-4-aminobiphenyl as IS. 1- and 2-aminonaphthalene and 3- and 4-aminobiphenyl were esterified by pentafluoropropionic acid, and quantified by GC/MS after solid-phase extraction (SFE) cleanup. Benzo[*a*]pyrene was extracted from TPM with cyclohexane, purified by SFE and quantified by HPLC with fluorescence detection. Phenolic compounds were extracted from TPM with a 1% acetic acid solution, and hydroquinone, resorcinol, catechol, phenol, *o*-cresol and *m*- + *p*-cresols were quantified by HPLC with fluorimetric detection. Tobacco-specific nitrosamines (TSNAs) *N*′-nitrosonornicotine (NNN), 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK), *N*′-nitrosoanatabine (NAT), and *N*′-nitrosoanabasine (NAB) were extracted from sampled TPM with an ammonium acetate solution after the addition of deuterated NNN, NAT, NAB, and NNK standards. After filtration, all four nitrosamines were quantified by HPLC with tandem MS detection.[24] Metals were sampled from smoke by electrostatic precipitation. The traps used to precipitate the particulate matter onto a glass tube were followed by an impinger containing a 10% nitric acid solution. The sample was then subjected to microwave digestion using a mixture of hydrochloric and nitric acids and hydrogen peroxide, and lead, cadmium, chromium, nickel, arsenic, and selenium were quantified using graphite furnace atomic absorption.

2.2.3. Other Chemical Analyses. Menthol content of the capsules was measured (4 replicates) at the PMI Operations Laboratory in Neuchâtel, Switzerland in May−June of 2012, according to an in-house GC method.

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Table 5. Yields of Prototype Capsule Cigarettes[a]

		100P				101P		102P				200P				201P	
smoke constituent	unit	uncrushed		crushed		(no capsule)		uncrushed		crushed		uncrushed		crushed		(no capsule)	
ISO Parameters and Menthol																	
tar	[mg/cig]	5.37	(0.24)	6.39	(0.22)	5.47	(0.47)	6.12	(0.23)	6.60	(0.25)	8.20	(0.47)	9.59	(0.27)	8.27	(0.68)
nicotine	[mg/cig]	0.450	(0.022)	0.473	(0.015)	0.465	(0.044)	0.492	(0.017)	0.487	(0.023)	0.691	(0.040)	0.722	(0.017)	0.693	(0.055)
CO	[mg/cig]	4.98	(0.31)	4.92	(0.19)	4.86	(0.52)	5.40	(0.35)	5.09	(0.19)	8.02	(0.68)	8.38	(0.56)	7.95	(0.77)
menthol	[mg/cig]	NQ	NQ	0.544	(0.059)	NQ	NQ	0.316	(0.025)	0.764	(0.039)	NQ	NQ	0.951	(0.044)	NQ	NQ
Carbonyl Compounds																	
formaldehyde	[μg/cig]	14.4	(5.2)	13.3	(1.6)	19.4	(5.2)	15.5	(3.4)	13.0	(0.6)	22.8	(2.9)	26.7	(4.2)	26.3	(3.0)
acetaldehyde	[μg/cig]	194	(12)	212	(10)	203	(15)	218	(29)	212	(16)	396	(23)	400	(46)	387	(18)
acetone	[μg/cig]	107	(6)	117	(4)	110	(8)	118	(14)	114	(10)	215	(9)	201	(25)	201	(11)
acrolein	[μg/cig]	20.9	(0.7)	22.2	(2.2)	23.1	(2.2)	24.5	(4.7)	21.6	(1.3)	45.2	(5.5)	45.7	(6.4)	44.8	(2.0)
propionaldehyde	[μg/cig]	19.8	(0.4)	20.5	(1.0)	20.0	(1.8)	21.6	(2.7)	20.3	(1.4)	36.5	(2.6)	35.2	(3.9)	34.7	(1.6)
crotonaldehyde	[μg/cig]	4.71	(0.62)	4.50	(0.54)	5.02	(0.85)	5.15	(0.88)	4.32	(0.24)	11.67	(1.02)	10.06	(1.68)	10.24	(1.10)
butyraldehyde	[μg/cig]	14.5	(1.2)	15.6	(0.4)	14.9	(1.4)	16.1	(2.5)	14.8	(1.4)	25.8	(0.8)	24.0	(2.0)	23.8	(1.4)
methyl ethyl ketone	[μg/cig]	27.4	(2.5)	26.4	(1.7)	28.9	(4.8)	27.6	(3.2)	25.5	(2.1)	56.6	(3.4)	50.3	(4.7)	49.3	(2.6)
Light Hydrocarbons																	
1,3-butadiene	[μg/cig]	19.4	(0.7)	17.1	(1.3)	21.3	(1.2)	21.4	(1.8)	18.4	(0.3)	34.7	(1.4)	34.2	(2.3)	34.2	(1.9)
isoprene	[μg/cig]	180	(8)	153	(8)	198	(5)	193	(12)	166	(6)	249	(4)	238	(5)	251	(18)
Nitrogen-Containing VOCs																	
acrylonitrile	[μg/cig]	4.74	(0.08)	3.29	(0.19)	4.95	(0.49)	5.18	(0.21)	3.51	(0.23)	7.44	(0.47)	6.80	(0.26)	6.99	(0.70)
pyridine	[μg/cig]	4.26	(0.45)	3.54	(0.16)	4.95	(0.56)	5.22	(0.36)	3.98	(0.28)	9.08	(0.62)	7.21	(0.42)	8.23	(0.95)
Particulate Phase Organics																	
1-aminonaphthalene	[ng/cig]	10.9	(0.2)	10.2	(0.6)	10.1	(1.0)	11.5	(0.8)	11.7	(0.7)	12.5	(1.9)	13.2	(1.4)	12.7	(1.1)
2-aminonaphthalene	[ng/cig]	6.86	(0.39)	6.49	(0.17)	6.60	(0.91)	7.63	(0.51)	7.30	(0.62)	9.02	(1.11)	8.91	(0.98)	9.23	(0.59)
3-aminobiphenyl	[ng/cig]	1.48	(0.02)	1.45	(0.02)	1.45	(0.18)	1.65	(0.15)	1.59	(0.07)	2.14	(0.13)	2.05	(0.20)	2.21	(0.07)
4-aminobiphenyl	[ng/cig]	1.08	(0.03)	1.09	(0.05)	1.10	(0.15)	1.32	(0.07)	1.18	(0.09)	1.67	(0.17)	1.58	(0.12)	1.63	(0.11)
quinoline	[μg/cig]	0.127	(0.002)	0.130	(0.004)	0.143	(0.016)	0.149	(0.011)	0.135	(0.008)	0.272	(0.009)	0.239	(0.019)	0.230	(0.012)
benzo[*a*]pyrene	[ng/cig]	5.10	(0.16)	5.12	(0.47)	5.31	(0.46)	5.63	(0.11)	4.95	(0.51)	7.20	(0.85)	7.45	(0.42)	7.09	(0.38)
TSNAs																	
NNN	[ng/cig]	42.5	(0.8)	45.9	(0.8)	37.5	(5.7)	38.3	(2.8)	43.1	(1.5)	54.9	(3.4)	57.1	(5.4)	55.6	(6.0)
NAT	[ng/cig]	30.5	(0.9)	30.2	(1.1)	29.5	(4.0)	29.8	(3.4)	33.2	(1.3)	53.7	(2.4)	56.1	(2.8)	52.9	(0.9)
NAB	[ng/cig]	5.88	(0.04)	6.16	(0.50)	5.65	(0.74)	5.95	(0.47)	6.35	(0.36)	7.71	(0.61)	7.04	(0.66)	7.72	(0.52)
NNK	[ng/cig]	25.8	(0.5)	27.6	(1.8)	23.1	(2.8)	24.1	(2.8)	27.7	(1.8)	38.4	(3.5)	44.3	(2.3)	38.6	(2.6)
Inorganic Compounds																	
ammonia	[μg/cig]	7.09	(0.36)	7.43	(0.70)	6.80	(0.38)	6.30	(0.78)	8.47	(1.24)	9.43	(0.32)	8.47	(0.45)	8.36	(0.47)
NO	[μg/cig]	72.9	(9.8)	83.4	(8.4)	67.3	(15.7)	81.7	(9.1)	83.1	(9.5)	116.4	(9.5)	112.3	(6.1)	110.7	(3.9)
NOx	[μg/cig]	75.1	(10.2)	92.5	(8.6)	67.7	(15.7)	89.6	(10.3)	90.7	(10.5)	131.4	(10.1)	123.6	(7.0)	124.9	(4.8)
HCN	[μg/cig]	41.2	(4.5)	41.7	(2.6)	40.5	(0.8)	46.5	(1.7)	45.9	(0.7)	88.8	(8.5)	92.0	(12.7)	75.1	(4.8)
Monocyclic Aromatic Hydrocarbons																	
benzene	[μg/cig]	22.8	(0.6)	16.5	(1.3)	24.2	(0.1)	25.0	(0.6)	17.9	(0.4)	33.1	(0.6)	28.3	(0.2)	33.3	(1.6)
toluene	[μg/cig]	42.2	(2.1)	24.8	(2.4)	43.2	(0.8)	47.2	(1.8)	27.4	(1.3)	54.5	(1.3)	42.6	(1.3)	55.1	(3.2)
styrene	[μg/cig]	3.50	(0.38)	1.86	(0.04)	3.20	(0.07)	3.63	(0.20)	2.00	(0.18)	5.41	(0.69)	4.40	(1.07)	5.17	(1.07)

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Table 5. continued

smoke constituent	unit	100P				101P		102P				200P				201P	
		uncrushed		crushed		(no capsule)		uncrushed		crushed		uncrushed		crushed		(no capsule)	
Phenols																	
phenol	[μg/cig]	5.92	(1.27)	6.58	(0.89)	6.41	(1.27)	6.29	(2.22)	6.92	(0.24)	11.11	(1.38)	11.80	(0.70)	10.30	(0.66)
catechol	[μg/cig]	34.2	(7.6)	32.2	(6.5)	33.4	(3.8)	33.2	(5.2)	30.8	(4.6)	40.3	(3.2)	46.1	(2.2)	41.7	(2.1)
hydroquinone	[μg/cig]	32.5	(2.1)	31.7	(3.8)	35.6	(4.0)	35.8	(4.1)	36.0	(2.7)	40.5	(4.2)	49.1	(2.2)	43.4	(1.8)
m+*p* -cresols	[μg/cig]	4.89	(0.64)	5.27	(0.98)	5.70	(0.83)	4.92	(1.37)	5.47	(0.14)	7.83	(0.82)	8.40	(0.53)	7.35	(0.53)
o-cresol	[μg/cig]	1.56	(0.11)	1.62	(0.31)	2.01	(0.20)	1.48	(0.36)	1.74	(0.23)	3.29	(0.29)	2.83	(0.19)	2.57	(0.20)
resorcinol	[μg/cig]	NQ; quantification limit for mainstream smoke under ISO machine-smoking regimen 1.74 μg/cig															
Elements																	
cadmium	[ng/cig]	11.8	(0.9)	10.7	(1.3)	13.1	(0.9)	13.1	(0.8)	10.3	(0.3)	27.5	(1.3)	24.5	(1.0)	28.3	(0.9)
Lead	[ng/cig]	NQ; quantification limit for mainstream smoke under ISO machine-smoking regimen 12.8 ng/cig															
chromium	[ng/cig]	NQ; quantification limit for mainstream smoke under ISO machine-smoking regimen 19.8 ng/cig															
nickel	[ng/cig]	NQ; quantification limit for mainstream smoke under ISO machine-smoking regimen 21.6 ng/cig															
arsenic	[ng/cig]	NQ; quantification limit for mainstream smoke under ISO machine-smoking regimen 3.75 ng/cig															
selenium	[ng/cig]	NQ; quantification limit for mainstream smoke under ISO machine-smoking regimen 7.37 ng/cig															

[a]Reported are the means (standard deviation). 100-series prototypes were smoked with the capsule intact or crushed in different smoking blocks; the corresponding 3R4F monitor cigarette yields are provided in Table 6 and 7, respectively. 200-series prototypes were smoked within the same smoking block with the capsule intact and crushed. NQ, not quantifiable.

2.3. Data Processing and Analysis. Data analysis in the present study follows a descriptive approach, with the goal of comparing the yields of cigarettes smoked with the capsule crushed to the corresponding yields of cigarettes smoked with the capsule intact.

Prototype cigarette smoke constituent yields are reported as pairs (cigarettes smoked with the capsule crushed and with the capsule uncrushed) expressed on a per cigarette basis, i.e., yield per cigarette. The yields of one cigarette brand in the market sample are also presented on a per cigarette basis both under ISO and HCI machine-smoking conditions. Because of the large number of market brands, sample-averaged results are further presented. Moreover, because the yields of the different brands differ by as much as an order of magnitude, normalization was required. Comparisons are done based on yields per unit weight TPM (TPM basis) as well as per unit weight nicotine (nicotine basis).

2.3.1. Prototype Cigarettes. Results of a *t*-test for differences of the yields are presented. However, several limitations of the *t*-test applied to smoke constituent yield data have been discussed.[25−29] In particular, small numbers of replicates may lead to an overestimation of variability; thus, no difference might be observed in the presence of one; conversely, variability of both production and analytical methods has been shown to result in apparent differences between two smoke constituent yield determinations for the same cigarette sample.

To facilitate the presentation and interpretation of results, it is therefore necessary to set a scale to judge the magnitude of any difference. One widely used complement to the *t*-test to achieve this objective is the statistical equivalence test.[30,31] This procedure is a U.S. Food and Drug Administration-recommended standard for the pharmaceutical industry,[30,31] and has gained wider adoption in medical, chemical, and other industrial applications.[30] Essentially, it allows the determination of whether the yields of a given constituent are equal within some predefined precision by means of checking whether the 90% confidence interval on the difference of the yields is fully contained within a chosen equivalence range. In the present study, the approach was used in a descriptive manner. The scale was chosen to take into account the possible sources of variability,[32] similar to what has been done in previous studies:[26,27] the equivalence range was based on the 95% tolerance interval of historical values scaled by the delivery of the respective prototype.[27] The historical values used in the present study were obtained by Labstat International ULC (Canada) for the University of Kentucky 3R4F reference cigarette, which they use as a monitor of analytical performance.

2.3.2. Commercial Cigarette Brands. Comparisons for one brand (Marlboro Gold Beyond) on a cigarette basis smoked under ISO and HCI machine-smoking regimes were performed in the same way as that for the prototypes, described above.

In order to describe the effects of crushing the menthol capsule on mainstream smoke deliveries within the market cigarette sample as a whole, it is necessary to account for the wide range of design features observed in the different brands. Therefore, a blocked ANOVA approach[33] was adopted, whereby the variability in smoke constituent deliveries between the different cigarette brands was captured in block means, and the effect of crushing the capsule was tested as a within-block effect.

3. RESULTS

3.1. Prototypes. Before investigating the possible effects of crushing the capsule in the cigarette filter on mainstream smoke deliveries, the influence of introducing the capsule into the cigarette filter was investigated. This was achieved by comparing mainstream smoke deliveries of a capsule-containing prototype (100P) smoked with the capsule uncrushed to the respective deliveries of a noncapsule-containing similarly constructed prototype (101P). The results (Figure 1) show that the introduction of the capsule had no measurable effect on mainstream smoke deliveries.

The measured physical properties, menthol deliveries, and filtration efficiencies (as measured by nicotine filter retention)

Table 6. Yields of Commercial Cigarette Brands Smoked with the Capsule Intact and the 3R4F Monitor Cigarette[a]

		Noncrushed																	
smoke constituent	unit	3R4F		Camel Crush		Kent Convertibles		Bohem Mojito Double		Marlboro Gold B		Marlboro Ice Blast		Pianissimo Viv MNT		Lark Hybrid MNT		Kent I Switch		Lucky Strike Click and Roll	
ISO Parameters and Menthol																					
tar	[mg/cig]	7.72	(0.29,9)	10.2	(0.52)	2.98	(0.32)	4.71	(0.20)	4.54	(0.55)	7.13	(0.18)	5.01	(0.29)	4.67	(0.41)	0.70	(0.31)	8.90	(0.49)
ncotine	[mg/cig]	0.63	(0.02,9)	0.82	(0.04)	0.25	(0.04)	0.45	(0.02)	0.39	(0.04)	0.50	(0.02)	0.37	(0.02)	0.43	(0.02)	0.10	(0.01)	0.66	(0.04)
CO	[mg/cig]	9.82	(0.34,9)	10.08	(0.53)	2.52	(0.37)	4.02	(0.23)	4.08	(0.36)	6.99	(0.21)	4.90	(0.40)	4.38	(0.40)	0.95	(0.12)	8.72	(0.51)
menthol	[mg/cig]	no data		NQ	(NQ)	BDL	(BDL)	0.49	(0.05)	NQ	(NQ)	0.67	(0.05)	0.65	(0.01)	NQ	(NQ)	0.01	(0.02)	NQ	(NQ)
Carbonyl Compounds																					
formaldehyde	[ng/cig]	24.15	(2.77,4)	27.32	(2.08)	6.86	(0.68)	12.60	(2.44)	15.70	(1.82)	18.85	(2.13)	13.46	(3.46)	17.16	(1.54)	2.62	(0.21)	27.46	(4.82)
acetaldehyde	[ng/cig]	417.95	(30.98,4)	412.38	(19.12)	111.50	(21.32)	144.73	(7.55)	190.72	(4.12)	257.53	(3.55)	224.99	(45.50)	129.97	(22.96)	18.38	(1.37)	383.03	(10.71)
acetone	[mg/cig]	217.85	(15.92,4)	211.99	(9.29)	59.00	(12.65)	72.98	(3.37)	102.89	(2.44)	126.00	(4.62)	115.56	(19.29)	48.74	(7.84)	8.15	(0.91)	190.81	(4.02)
acrolein	[mg/cig]	47.17	(4.62,4)	53.63	(2.87)	8.61	(1.85)	17.53	(0.95)	21.30	(1.04)	27.36	(1.37)	23.40	(5.84)	11.26	(2.39)	NQ	(NQ)	44.96	(0.29)
propionaldehyde	[mg/cig]	38.19	(2.95,4)	40.35	(1.26)	10.81	(2.67)	14.81	(0.79)	18.24	(0.47)	22.91	(0.25)	20.64	(3.63)	10.18	(1.34)	NQ	(NQ)	36.57	(0.47)
crotonaldehyde	[mg/cig]	10.41	(1.74,4)	9.69	(0.22)	NQ	(NQ)	NQ	(NQ)	6.19	(1.22)	5.31	(0.25)	6.36	(1.76)	NQ	(NQ)	BDL	(BDL)	10.38	(0.82)
butyradehyde	[mg/cig]	24.55	(1.21,4)	26.61	(3.80)	8.72	(0.71)	11.71	(2.03)	12.78	(1.11)	15.26	(0.66)	15.15	(3.07)	8.29	(0.37)	BDL	(BDL)	26.87	(1.37)
methyl ethyl ketone	[mg/cig]	55.48	(6.49,4)	48.92	(0.63)	15.19	(0.80)	20.07	(3.51)	28.47	(0.87)	28.68	(1.73)	30.34	(5.56)	11.06	(1.19)	BDL	(BDL)	49.65	(3.91)
Light Hydrocarbons																					
1,3-butadiene	[mg/cig]	32.12	(3.50,5)	39.86	(2.60)	9.79	(0.51)	16.89	(1.36)	16.77	(0.56)	23.00	(3.38)	15.58	(0.98)	13.91	(0.93)	2.37	(0.06)	32.93	(2.01)
i soprene	[mg/cig]	285.36	(26.39,5)	386.75	(20.49)	83.96	(4.21)	159.69	(14.47)	155.54	(7.23)	188.52	(23.68)	124.02	(9.40)	100.48	(7.05)	20.37	(0.29)	277.85	(17.22)
Nitrogen-Containing VOCs																					
acrylonitrile	[mg/cig]	7.95	(0.74,5)	9.64	(0.35)	1.68	(0.16)	2.88	(0.21)	4.12	(0.26)	6.25	(0.90)	4.06	(0.69)	2.02	(0.20)	NQ	(NQ)	8.10	(0.43)
pyridine	[mg/cig]	7.58	(0.80,5)	8.83	(0.51)	1.13	(0.27)	2.64	(0.40)	4.32	(0.35)	6.72	(0.34)	4.68	(0.89)	1.48	(0.15)	NQ	(NQ)	10.18	(1.75)
Particulate Phase Organics																					
1-aminonaphthalene	[ng/cig]	14.97	(1.62,5)	16.95	(1.86)	6.98	(0.49)	9.75	(0.52)	8.98	(0.37)	14.25	(2.08)	7.89	(1.03)	10.69	(0.41)	2.59	(0.06)	16.08	(1.29)
2-aminonaphthalene	[ng/cig]	9.54	(0.83,5)	11.01	(1.39)	4.30	(0.22)	6.42	(0.51)	5.92	(0.54)	8.19	(1.01)	5.02	(0.63)	6.47	(0.23)	1.78	(0.01)	10.50	(0.84)
3-aminobiphenyl	[ng/cig]	2.11	(0.15,5)	2.33	(0.34)	0.91	(0.01)	1.29	(0.04)	1.37	(0.09)	1.87	(0.18)	1.27	(0.05)	1.34	(0.07)	0.40	(0.03)	2.14	(0.08)
4-aminobiphenyl	[ng/cig]	1.41	(0.02,5)	1.82	(0.20)	0.78	(0.03)	0.96	(0.06)	0.98	(0.03)	1.42	(0.12)	0.98	(0.08)	1.04	(0.05)	0.33	(0.01)	1.66	(0.05)
quinoline	[mg/cig]	0.19	(0.02,5)	0.20	(0.02)	0.06	(0.01)	0.11	(0.02)	0.13	(0.00)	0.18	(0.01)	0.15	(0.01)	0.15	(0.01)	BDL	(BDL)	0.22	(0.03)
benzo[*a*]pyrene	[ng/cig]	6.75	(0.47,5)	9.06	(0.55)	3.55	(0.20)	4.98	(0.68)	4.38	(0.24)	6.63	(0.25)	5.51	(0.47)	7.23	(0.70)	1.01	(0.11)	8.08	(0.21)
TSNAs																					
NNN	[ng/cig]	124.24	(6.68,5)	79.07	(7.43)	44.53	(2.05)	19.68	(1.51)	40.05	(3.06)	59.07	(2.20)	66.27	(7.27)	18.15	(0.82)	18.84	(1.96)	95.07	(6.06)
NAT	[ng/cig]	96.32	(6.78,5)	75.73	(2.57)	24.01	(2.52)	15.93	(2.21)	32.31	(1.98)	41.33	(2.31)	49.20	(2.08)	15.08	(0.84)	18.84	(1.79)	52.00	(2.50)
NAB	[ng/cig]	13.98	(0.87,5)	13.71	(0.28)	4.61	(0.26)	3.86	(0.22)	6.11	(0.61)	7.51	(0.23)	8.36	(0.58)	3.12	(0.21)	3.69	(0.22)	9.64	(0.45)
NNK	[ng/cig]	88.88	(6.02,5)	39.43	(3.95)	14.40	(1.32)	11.44	(1.78)	26.48	(3.28)	35.29	(1.51)	35.24	(0.84)	16.24	(1.18)	9.00	(0.69)	34.68	(3.11)
Inorganic Compounds																					
ammonia	[mg/cig]	9.97	(0.78,5)	15.46	(1.84)	3.12	(0.42)	5.83	(0.47)	5.31	(0.73)	9.15	(0.96)	5.56	(0.61)	4.70	(0.66)	NQ	(NQ)	11.88	(0.96)
NO	[mg/cig]	198.14	(11.77,6)	176.36	(15.99)	40.67	(10.21)	45.23	(2.89)	66.18	(6.33)	75.98	(14.44)	79.04	(3.52)	44.85	(8.74)	15.29	(1.73)	112.72	(19.14)
NOx	[mg/cig]	211.51	(13.58,6)	187.96	(16.59)	44.05	(10.69)	49.89	(2.91)	69.15	(7.68)	83.26	(16.23)	83.17	(1.51)	48.55	(9.56)	17.00	(1.81)	118.98	(17.95)
HCN	[mg/cig]	91.62	(3.90,5)	122.85	(21.69)	17.09	(2.67)	27.04	(2.09)	33.85	(0.74)	60.41	(1.31)	43.80	(5.22)	23.49	(0.50)	NQ	(NQ)	106.40	(3.11)
Monocyclic Aromatic Hydrocarbons																					
benzene	[mg/cig]	34.91	(2.77,5)	38.75	(1.80)	7.89	(0.85)	18.74	(1.37)	20.84	(0.38)	24.58	(4.68)	17.13	(2.33)	10.20	(1.33)	NQ	(NQ)	32.63	(2.03)
toluene	[mg/cig]	64.59	(8.06,5)	69.18	(1.03)	14.13	(1.64)	31.51	(1.38)	38.87	(1.92)	46.00		32.91	(5.47)	17.83	(1.11)	NQ	(NQ)	59.14	(5.73)
styrene	[mg/cig]	5.38	(0.40,5)	6.89	(0.28)	0.83	(0.45)	1.97	(0.35)	3.00	(0.27)	4.73	(0.13)	2.92	(0.40)	1.19	(0.24)	NQ	(NQ)	6.60	(0.90)

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Table 6. continued

smoke constituent	unit	3R4F	Camel Crush	Kent Convertibles	Bohem Mojito Double	Marlboro Gold B	Marlboro Ice Blast	Pianissimo Viv MNT	Lark Hybrid MNT	Kent I Switch	Lucky Strike Click and Roll
Noncrushed											
Phenols											
phenol	[mg/cig]	6.71 (1.71,5)	12.20 (1.57)	3.95 (0.85)	4.62 (1.14)	5.13 (0.72)	9.50 (2.51)	5.62 (0.98)	6.89 (0.32)	BDL (BDL)	9.75 (1.91)
catechol	[mg/cig]	38.10 (2.83,5)	56.22 (4.78)	22.06 (2.82)	30.60 (4.19)	30.11 (1.91)	40.51 (6.33)	24.88 (4.21)	42.08 (3.58)	NQ (NQ)	51.55 (4.48)
hydroquinone	[mg/cig]	33.01 (3.68,5)	51.22 (4.85)	22.51 (0.60)	26.92 (5.09)	28.02 (2.84)	50.24 (3.74)	32.46 (1.27)	42.30 (2.32)	6.14 (0.05)	47.19 (4.00)
m+*p*-cresols	[mg/cig]	6.18 (1.15,5)	9.45 (1.14)	3.36 (0.53)	3.95 (0.73)	4.32 (0.76)	6.43 (1.05)	4.30 (0.82)	5.54 (0.12)	NQ (NQ)	7.76 (1.17)
o-cresol	[mg/cig]	2.09 (0.45,5)	2.86 (0.57)	NQ (NQ)	NQ (NQ)	1.45 (0.05)	2.49 (0.59)	1.72 (0.09)	1.69 (0.22)	BDL (BDL)	2.33 (0.29)
resorcinol	[mg/cig]	0.44 (0.03,5)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)
cadmium	[ng/cig]	27.59 (2.48,3)	29.55 (0.63)	1.63 (0.52)	7.90 (0.23)	10.59 (1.03)	12.63 (0.81)	9.34 (1.17)	3.29 (0.44)	NQ (NQ)	23.09 (1.29)
mercury	[ng/cig]	2.10 (0.08,6)	2.05 (0.08)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	BDL (BDL)	1.76 (0.14)
lead	[ng/cig]	10.66 (1.58,3)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)
chromium	[ng/cig]	3.31 (0.94,3)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)
nickel	[ng/cig]	4.23 (0.30,3)	BDL (BDL)	BDL (BDL)	NQ (NQ)	BDL (BDL)	BDL (BDL)	NQ (NQ)	BDL (BDL)	NQ (NQ)	BDL (BDL)
arsenic	[ng/cig]	2.69 (0.11,3)	NQ NQ	BDL (BDL)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	BDL (BDL)	BDL (BDL)	NQ (NQ)
selenium	[ng/cig]	0.86 (0.09,3)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)

[a]All yields were determined according to the ISO smoking regimen within the same smoking block. Reported are the means (standard deviation). For the 3R4F monitor cigarette, the means (standard deviation, sample size) are reported. NQ, not quantifiable; BDL, below detection limit; NQ, below quantitation limit.

are presented in Table 4 (refer to Table 1 for the design properties of the prototype cigarettes). For each prototype, the mainstream smoke yields of all constituents in the Health Canada list were measured under the ISO machine-smoking regimen,[14] with the capsule both crushed and uncrushed, where applicable. The ISO smoking regime was selected, rather than other smoking regimes such as Health Canada intense smoking regime,[15] because the present study was aimed at detecting phenomena taking place inside the filter. It has been demonstrated[34,35] that when smoking under HCI machine-smoking conditions the selective adsorption of constituents is substantially inhibited in comparison with that in the ISO smoking regime, and therefore, the choice to smoke cigarettes with the ISO smoking regime seemed more appropriate. In addition, a prior study[3] investigating changes in smoke composition induced by crushing a menthol capsule was performed with the ISO smoking regime as well. Results of the assessment are shown in Figure 2. All data are expressed on a per-cigarette basis, as yields of prototypes are closely matched to be directly comparable. Equivalence was demonstrated in the case of several TSNAs, nicotine, CO, HCN, several aromatic amines, and ammonia. The only consistent increase in a smoke constituent, observed as a consequence of crushing the capsule, was the yield of tar. This is the expected result of menthol addition into smoke, as menthol is entirely found in the particle phase.[36] Other smoke particle-phase constituent yields did not increase in a consistent way among the prototype cigarettes.

Considering the smoke constituents present in the gas phase, the deliveries of most constituents were also unaffected. No clear trends were observed. For several compounds, however, the smoke delivery was decreased when the capsule was crushed. In particular, a decrease in the yields of benzene, toluene, pyridine, isoprene, styrene, acrylonitrile, and cadmium was observed for all prototypes.

Table 5 lists the yields of all the measured smoke constituents obtained for all the prototype cigarettes smoked with both the capsule crushed and uncrushed whenever applicable.

3.2. Market Products. Smoke constituent yields were also measured for the commercial cigarette brands, with the capsule both crushed and uncrushed under ISO machine-smoking regimen as for the prototypes. The results are provided in Table 6 (smoking block of market products smoked with the capsule uncrushed and the corresponding 3R4F monitor cigarette yields) and Table 7 (smoking block of market products smoked with the capsule crushed and the corresponding 3R4F monitor cigarette yields).

One commercial product was nevertheless also smoked under the Health Canada intense machine-smoking regimen to explore the changes in smoke composition under these intense conditions. Results on a per cigarette basis are shown in Figure 3, where the yields of Marlboro Gold Beyond cigarettes smoked with the capsule crushed are compared to respective yields of cigarettes of the same brand smoked with the capsule uncrushed. Results obtained under both the ISO and the HCI machine-smoking regimens are shown.

To present sample-averaged results over all commercial cigarette brands, it is necessary to account for the large differences in design among the brands when investigating the effect of crushing the capsule. Therefore, normalization factors are further applied (Figure 4). TPM-normalization was used, but as menthol addition increases the tar and thus reduces TPM-normalized yields, nicotine-based data are also reported.

Table 7. Yields of Commercial Cigarette Brands Smoked with the Capsule Crushed and the 3R4F Monitor Cigarette[a]

			Crushed																	
smoke constituent	unit	3R4F	Camel Crush		Kent Convertibles		Bohem Mojito Double		Marlboro Gold B		Marlboro Ice Blast		Pianissimo Viv MNT		Lark Hybrid MNT		Kent I Switch		Lucky Strike Click and Roll	
ISO Parameters and Menthol																				
tar	[mg/cig]	8.21 (0.34,8)	11.84	(0.39)	3.57	(0.44)	6.37	(0.35)	5.38	(0.49)	8.11	(0.63)	6.00	(0.33)	6.06	(0.37)	1.32	(0.17)	10.21	(0.63)
nicotine	[mg/cig]	0.68 (0.04,8)	0.90	(0.02)	0.26	(0.02)	0.51	(0.04)	0.42	(0.03)	0.54	(0.04)	0.42	(0.03)	0.47	(0.03)	0.12	(0.01)	0.71	(0.04)
CO	[mg/cig]	9.96 (0.45,8)	9.88	(0.64)	2.51	(0.29)	4.14	(0.22)	3.95	(0.34)	6.75	(0.50)	5.14	(0.46)	4.20	(0.26)	0.79	(0.07)	8.37	(0.57)
menthol	[mg/cig]	no data	1.0	(0.06)	0.44	(0.08)	0.99	(0.11)	0.41	(0.02)	1.23	(0.14)	0.64	(0.07)	0.61	(0.04)	0.21	(0.06)	0.93	(0.14)
Carbonyl Compounds																				
formaldehyde	[μg/cig]	23.14 (0.47,2)	21.82	(4.76)	5.99	(0.36)	11.38	(1.98)	10.93	(1.32)	19.94	(1.30)	12.32	(2.89)	11.44	(1.61)	2.18	(0.28)	18.79	(0.52)
acetaldehyde	[μg/cig]	437.32 (16.77,2)	400.25	(40.29)	117.72	(13.94)	146.41	(15.31)	159.35	(26.60)	292.93	(13.32)	213.06	(35.16)	116.04	(14.19)	17.77	(2.86)	367.23	(7.29)
acetone	[μg/cig]	229.92 (2.65,2)	202.97	(14.53)	58.81	(8.90)	62.60	(10.93)	87.72	(15.01)	138.74	(5.77)	105.46	(19.09)	45.19	(5.19)	7.60	(0.53)	181.49	(7.49)
acrolein	[μg/cig]	51.90 (0.60,2)	48.03	(5.09)	8.17	(0.89)	14.16	(3.20)	16.22	(3.43)	29.27	(1.82)	21.57	(4.25)	9.36	(1.74)	NQ	(NQ)	40.23	(2.03)
propionaldehyde	[μg/cig]	41.06 (0.54,2)	38.90	(2.73)	10.84	(1.62)	12.71	(2.11)	15.39	(2.48)	25.11	(1.40)	20.00	(2.89)	8.76	(1.18)	NQ	(NQ)	35.22	(1.43)
crotonaldehyde	[μg/cig]	9.80 (0.78,2)	8.25	(1.51)	NQ	(NQ)	NQ	(NQ)	NQ	(NQ)	5.95	(0.59)	4.53	(2.17)	NQ	(NQ)	BDL	(BDL)	7.71	(0.47)
butyraldehyde	[μg/cig]	28.07 (2.84,2)	26.42	(1.68)	8.89	(0.91)	9.37	(1.41)	13.25	(2.90)	17.23	(0.66)	13.32	(1.96)	6.37	(1.23)	NQ	(NQ)	24.68	(0.47)
methyl ethyl ketone	[μg/cig]	58.59 (4.27,2)	44.83	(2.94)	11.91	(2.32)	13.04	(3.10)	20.20	(3.41)	30.60	(1.36)	25.13	(6.06)	8.25	(1.07)	NQ	(NQ)	40.84	(1.46)
Light Hydrocarbons																				
1,3-butadiene	[μg/cig]	30.97 (2.54,4)	36.08	(0.82)	11.04	(0.55)	15.43	(1.56)	15.60	(0.73)	23.08	(0.82)	15.51	(1.21)	13.01	(0.70)	2.16	(0.17)	29.99	(1.63)
isoprene	[μg/cig]	277.16 (21.32,4)	336.86	(15.77)	93.98	(4.16)	132.36	(13.66)	140.75	(3.94)	180.56	(7.59)	125.13	(5.56)	93.52	(4.48)	16.90	(1.63)	252.64	(6.39)
Nitrogen-Containing VOCs																				
acrylonitrile	[μg/cig]	7.03 (0.59,4)	7.72	(0.49)	1.69	(0.25)	2.05	(0.29)	3.23	(0.19)	5.37	(0.35)	3.35	(0.18)	1.68	(0.28)	BDL	(BDL)	6.81	(0.27)
pyridine	[μg/cig]	8.06 (0.48,4)	7.04	(0.73)	0.84	(0.29)	1.77	(0.24)	2.91	(0.30)	4.86	(0.44)	4.22	(0.25)	1.27	(0.27)	NQ	(NQ)	6.94	(0.63)
Particulate Phase Organics																				
1-aminonaphthalene	[ng/cig]	14.16 (1.08,4)	16.68	(1.66)	6.58	(0.46)	8.86	(0.74)	9.46	(0.30)	14.58	(0.67)	8.87	(0.89)	10.79	(0.65)	3.17	(0.14)	17.35	(1.35)
2-aminonaphthalene	[ng/cig]	9.13 (0.99,4)	10.77	(0.32)	4.23	(0.41)	5.83	(0.79)	5.96	(0.27)	8.33	(0.11)	5.25	(0.28)	6.69	(0.47)	1.99	(0.06)	10.91	(0.64)
3-aminobiphenyl	[ng/cig]	1.99 (0.12,4)	2.20	(0.10)	0.94	(0.10)	1.19	(0.09)	1.30	(0.04)	1.92	(0.13)	1.34	(0.05)	1.28	(0.07)	0.48	(0.02)	2.43	(0.17)
4-aminobiphenyl	[ng/cig]	1.40 (0.08,4)	1.71	(0.07)	0.76	(0.02)	0.95	(0.11)	1.06	(0.10)	1.53	(0.10)	1.03	(0.06)	0.99	(0.02)	0.39	(0.03)	1.83	(0.13)
quinoline	[μg/cig]	0.19 (0.01,4)	0.18	(0.02)	0.07	(0.01)	0.11	(0.00)	0.11	(0.02)	0.18	(0.01)	0.15	(0.01)	0.14	(0.01)	NQ	(NQ)	0.20	(0.02)
benzo[*a*]pyrene	[ng/cig]	6.55 (0.66,4)	9.57	(0.47)	3.42	(0.28)	6.19	(0.66)	4.56	(0.44)	7.09	(0.89)	5.19	(0.60)	8.22	(0.74)	1.27	(0.17)	8.29	(0.65)
TSNAs																				
NNN	[ng/cig]	116.30 (7.80,4)	71.07	(1.80)	54.93	(5.06)	20.25	(2.22)	41.51	(2.75)	65.60	(3.82)	69.20	(2.62)	18.75	(2.58)	20.32	(0.21)	94.13	(2.01)
NAT	[ng/cig]	88.10 (8.48,4)	72.67	(1.51)	29.41	(2.10)	16.85	(1.24)	30.65	(3.34)	47.47	(1.62)	48.13	(3.00)	16.01	(1.29)	20.41	(1.44)	52.40	(4.45)
NAB	[ng/cig]	12.62 (1.01,4)	13.28	(1.03)	5.47	(0.32)	4.10	(0.35)	5.43	(0.46)	8.64	(0.82)	7.93	(0.48)	3.24	(0.31)	3.95	(0.09)	9.77	(0.86)
NNK	[ng/cig]	81.80 (7.25,4)	37.60	(3.26)	17.29	(0.60)	12.49	(2.07)	24.49	(1.34)	39.09	(1.23)	35.99	(3.31)	17.69	(2.69)	10.81	(0.92)	35.59	(3.92)
Inorganic Compounds																				
ammonia	[μg/cig]	10.72 (0.66,4)	15.20	(0.45)	3.93	(0.73)	6.60	(0.80)	6.58	(0.31)	11.12	(1.53)	6.30	(0.81)	5.68	(0.50)	NQ	(NQ)	12.37	(0.38)
NO	[μg/cig]	195.45 (7.65,3)	169.12	(28.18)	67.73	(17.94)	52.67	(11.61)	65.80	(4.90)	97.69	(12.50)	78.55	(4.12)	45.90	(4.50)	14.96	(2.33)	141.22	(15.45)
NOx	[μg/cig]	217.25 (8.01,3)	187.26	(32.28)	72.64	(19.16)	56.58	(12.90)	73.26	(5.17)	106.54	(14.05)	85.75	(4.68)	48.68	(4.37)	16.28	(2.84)	155.15	(16.53)
HCN	[μg/cig]	80.60 (4.31,4)	126.27	(4.97)	17.43	(3.48)	25.37	(2.37)	31.98	(2.86)	61.40	(1.69)	46.90	(0.48)	23.01	(4.32)	NQ	(NQ)	100.24	(4.62)
Monocyclic Aromatic Hydrocarbons																				
benzene	[μg/cig]	33.10 (2.58,4)	31.75	(0.93)	7.89	(1.10)	10.32	(1.43)	16.26	(0.74)	20.59	(0.77)	15.67	(0.66)	7.31	(0.86)	BDL	(BDL)	28.01	(0.71)
toluene	[μg/cig]	60.88 (3.68,4)	49.69	(3.62)	10.26	(1.85)	14.28	(2.43)	25.51	(0.68)	33.04	(2.27)	25.90	(0.85)	NQ	(NQ)	NQ	(NQ)	45.33	(3.84)
styrene	[μg/cig]	4.94 (0.41,4)	3.63	(0.25)	NQ	(NQ)	0.99	(0.09)	1.61	(0.31)	2.50	(0.14)	2.08	(0.23)	0.66	(0.28)	NQ	(NQ)	3.50	(0.17)

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Table 7. continued

smoke constituent	unit	3R4F	Camel Crush	Kent Convertibles	Bohem Mojito Double	Crushed Marlboro Gold B	Marlboro Ice Blast	Pianissimo Viv MNT	Lark Hybrid MNT	Kent I Switch	Lucky Strike Click and Roll
						Phenols					
phenol	[μg/cig]	7.41 (0.44,4)	9.05 (1.58)	3.77 (0.42)	4.11 (0.41)	6.39 (0.64)	8.62 (0.43)	7.61 (0.66)	9.29 (0.47)	NQ (NQ)	9.00 (1.89)
catechol	[μg/cig]	36.50 (5.53,4)	49.88 (3.53)	22.88 (1.68)	34.11 (2.29)	32.67 (1.70)	38.63 (7.11)	29.63 (5.29)	45.37 (10.70)	NQ (NQ)	42.97 (4.88)
hydroquinone	[μg/cig]	32.73 (1.55,4)	44.65 (1.87)	21.49 (0.69)	27.73 (0.82)	29.25 (2.22)	49.96 (0.89)	35.42 (0.41)	47.25 (6.98)	6.57 (0.53)	45.31 (3.26)
m+p-cresols	[μg/cig]	6.44 (0.68,4)	7.32 (0.90)	3.19 (0.19)	3.65 (0.35)	4.86 (0.25)	6.78 (0.08)	5.98 (0.15)	6.72 (1.36)	NQ (NQ)	6.96 (0.76)
o-cresol	[μg/cig]	2.26 (0.22,4)	2.32 (0.36)	NQ (NQ)	NQ (NQ)	1.52 (0.13)	2.10 (0.20)	2.04 (0.20)	1.61 (0.44)	BDL (BDL)	2.16 (0.31)
resorcinol	[μg/cig]	0.52 (0.01,4)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)
cadmium	[ng/cig]	24.21 (2.03,4)	24.36 (1.72)	NQ (NQ)	5.10 (0.38)	8.45 (0.70)	9.97 (0.55)	8.74 (0.13)	3.01 (0.41)	NQ (NQ)	19.57 (1.82)
mercury	[ng/cig]	2.34 (0.32,4)	2.45 (0.04)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	1.99 (0.12)
lead	[ng/cig]	8.28 (0.81,4)	NQ (NQ)	BDL (BDL)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	NQ (NQ)	BDL (BDL)	NQ (NQ)
chromium	[ng/cig]	4.32 (0.34,4)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)
nickel	[ng/cig]	3.63 (0.39,4)	NQ (NQ)	BDL (BDL)	BDL (BDL)	BDL (BDL)	NQ (NQ)	NQ (NQ)	BDL (BDL)	NQ (NQ)	BDL (BDL)
arsenic	[ng/cig]	2.52 (0.18,4)	NQ (NQ)	BDL (BDL)	NQ (NQ)	NQ (NQ)	BDL (BDL)	NQ (NQ)	BDL (BDL)	BDL (BDL)	NQ (NQ)
selenium	[ng/cig]	1.08 (0.43,4)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)	BDL (BDL)

[a]All yields were determined according to the ISO smoking regimen within the same smoking block. Reported are the means (standard deviation). For the 3R4F monitor cigarette, the means (standard deviation, sample size) are reported. NQ, not quantifiable; BDL, below detection limit; NQ, below quantitation limit.

Results of the market cigarette products are fully consistent with the results reported for the prototype cigarettes. The only yield observed to increase was the tar delivery, both on a TPM and on a nicotine basis, due to the addition of menthol. On a TPM basis, most constituent yields appear to decrease, in part due to the increased levels of tar. On a nicotine basis, the decrease in volatile compounds observed for the prototypes was also confirmed, whereas the particle-phase constituents remain essentially unchanged.

4. DISCUSSION

4.1. Prototypes. Considering the impact of using a menthol capsule on cigarette smoke deliveries, there were two questions that needed to be answered. First, it needed to be determined whether the formation of smoke constituents at the high-temperature coal end of the cigarette was substantially impacted. Since the tobacco rod remains intact, this can only occur if the volume of air actually drawn into the hot coal region during a puff would change as a result of crushing a capsule (and the surrounding filter) and releasing its contents into the filter, altering the pattern of airflow. In the present study, neither cigarette RTD nor ventilation measured before and after the capsule rupture (Table 4) reveals any differences. Therefore, the volume of air entering the high temperature region of the cigarette upon puffing was not altered by crushing the capsule. Consequently, smoke generation processes were unchanged, and changes in smoke deliveries could only be related to removal, upload, or exchange processes affecting the aerosol in the filter.

Thus, the second question that needed to be addressed was whether there were changes in smoke deliveries arising from alteration of the filter performance. It has been hypothesized that the presence of the capsule in the filter and its crushing before smoking might hinder the filtration process, which was interpreted as making the products even more dangerous.[2] Results for filter efficiency from the present study (Table 4) readily demonstrate that crushing the capsule did not significantly alter particulate matter retention by the filter. This was confirmed by the comparison of smoke constituent yields from prototypes in which the capsule had been crushed to the same prototypes in which the capsule remained intact (Figure 2). The only consistent increase in a smoke constituent, observed as a consequence of crushing the capsule, was the yield of tar. This was expected since menthol is present in smoke in the particle phase. No other measured smoke particle-phase constituents increased in yield in a consistent way among the prototypes.

To understand the reasons underlying the observed changes, it is necessary to consider the construction of the menthol capsules. The common features of menthol capsules are described in several patents,[37−39] in manufacturer-posted information and in the recent DKFZ report.[2] Menthol is mixed with high-boiling point compounds as a carrier, which are food-grade and lipophilic. The encapsulation process that involves coextrusion to generate the spherical capsules by coacervation requires the encapsulated liquid mix to be lipophilic.[39] The choice of triglycerides as a high-boiling point lipophilic substance is commonly mentioned.[37,39] The capsule shell is usually made of hydrocolloids such as gelatin or alginates.[2] When crushed, the capsule contents flow and cover the neighboring filter fibers. Except for short-range capillary migration, these compounds remain localized given the short time between capsule crushing and cigarette lighting: menthol is the compound that is most likely to migrate, yet only about

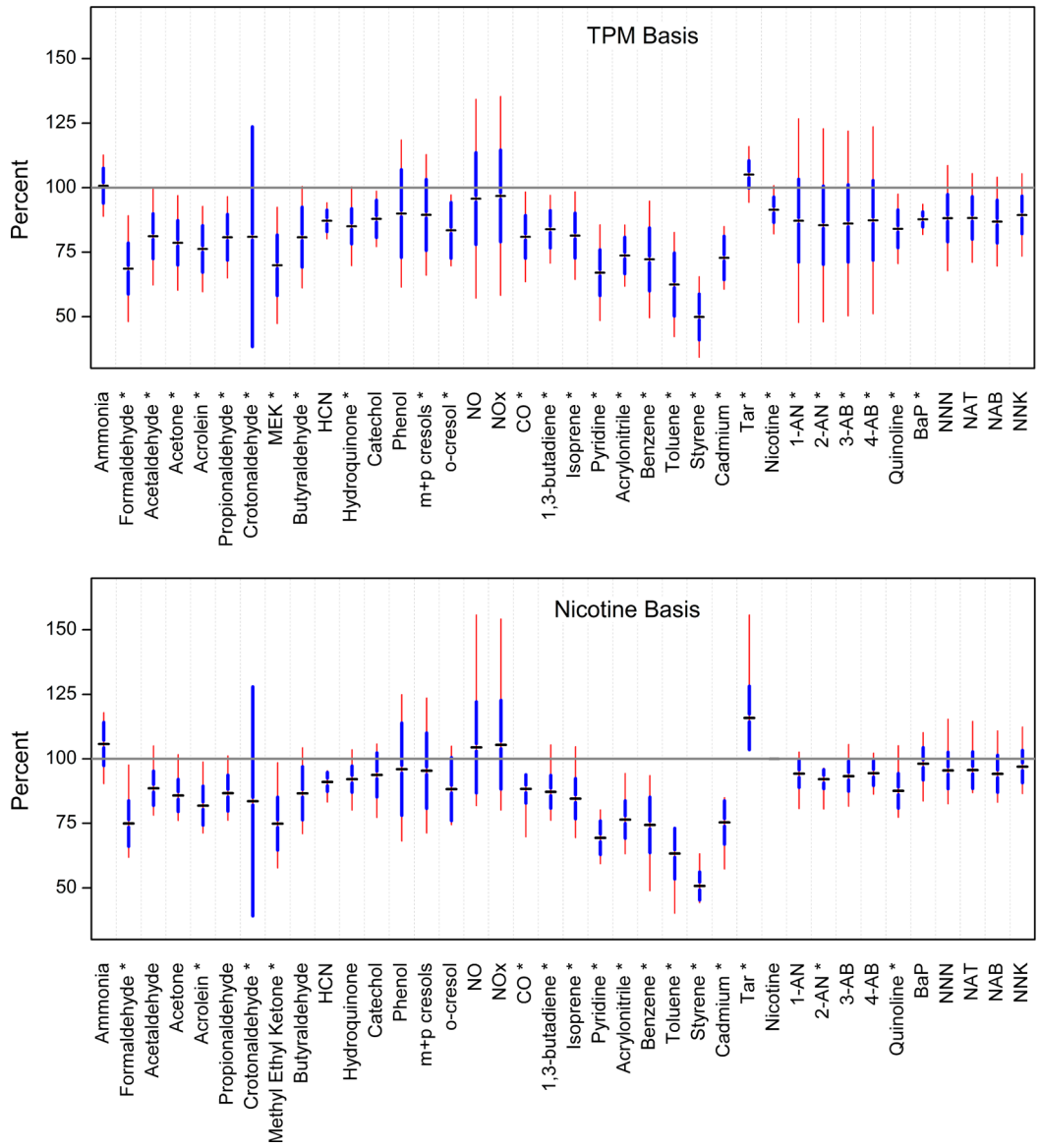

Figure 4. Ratios of yields of smoke constituents from all market brands, smoked crushed as a percentage of uncrushed. Yields are TPM-normalized on the top and nicotine-normalized on the bottom. Horizontal bars show the average yields across brands, and vertical solid bars represent the corresponding 95% confidence intervals; red bars represent minimum and maximum values among the different brands. A star in the label reflects a statistically significant difference as observed by blocked ANOVA at the 5% type-I error rate (see Data Processing and Analysis).

10% of the menthol deposited on a filter was shown to have migrated out of the filter after 24 h.[40,41]

Consequently, it was not unexpected that the compounds which were observed to decrease in yield after crushing the capsule were lipophilic compounds (hydrocarbons or nitrogen-containing compounds in which the nitrogen was not linked to hydrogen). As discussed previously, smoke generation and transfer in the tobacco rod were essentially unchanged, and therefore, these gas-phase constituents were likely to have been retained because of increased lipophilic absorption properties of the filter. The presence of triglycerides from the capsule contents on the filter fibers is a likely explanation for this observation.

4.2. Market Products. Considering the changes in smoke composition when crushing the capsule, the results shown in Figures 3 and 4 are consistent with the trends observed from the prototype cigarettes. Tar was found to increase when the capsule was crushed, even when normalized to TPM. No other analyzed compound was found to increase (Figures 3 and 4). Indeed, the only statistically significant (at a Type-I error rate of 5%) increase was the yield of tar.

Under the ISO smoking regime (Figure 3, top, and Figure 4), the deliveries of particle-bound compounds remained unchanged, except for cadmium, which was reduced in yield. The deliveries of lipophilic compounds were lowered, as was observed for the prototypes. The oxygen-containing volatile compounds were consistently lowered as well, but only a few of them achieved statistical significance (formaldehyde, acetone, acrolein, and crotonaldehyde). In the special case of the HCI smoking regime (Figure 3, bottom), the yields of all constituents except tar are essentially unchanged, and neither decreases nor increases in VOC yields can be observed. This is consistent with the general observation that VOC filtering efficiency is strongly reduced under HCI machine-smoking conditions.[42,34] This finding further strengthens the conclusion that changes in smoke constituent yields detailed for the prototype cigarettes are due to changes inside the filter. Further studies would be warranted to systematically

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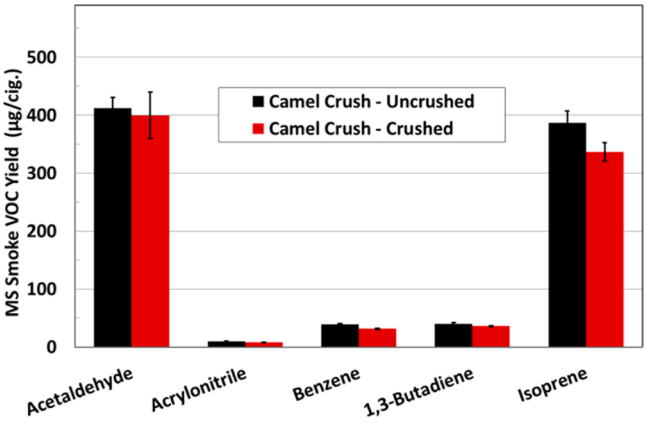

Figure 5. Results obtained using Health Canada-recommended determination methods for Camel Crush in the present study. Error bars show the standard deviation.

investigate the influence of the intensity of the smoking regime on the observed phenomena.

4.3. Overall Trends. In the present study, the analyses were performed using generally accepted off-line validated standard methods required by Health Canada. The results consistently show that the yields of particle-phase constituents remain unchanged. Similarly, most of the gas-phase constituents remain unchanged following crushing of the capsule with the exception of some VOCs, which are found to be decreased to varying levels. This effect is likely due to selective filtration of the smoke resulting in the release of the lipophilic compounds from the crushed capsule.

An earlier study by Gordon et al.[3] included an online puff-by-puff quantification of VOCs in the smoke using the Camel Crush cigarette brand, a cigarette with a menthol-containing capsule in the filter. Upon crushing the capsule, the authors observed no change in the yields of particle-phase constituents, in agreement with the results of the present study. However, they observed up to 2-fold increases in the yields of several gas-phase constituents, notably in 5 VOCs (acetaldehyde, acrylonitrile, benzene, 1,3-butadiene, and isoprene), which were also quantified in the present study. This discrepancy is possibly due to the different methods used in the two studies.

Gordon et al. relied on a real time detector, a proton transfer reaction mass spectrometer (PTR-MS) for the VOC quantification. Even though PTR-MS is a very sensitive detector frequently used to monitor trace contaminants in air,[43] it has been reported that it may be prone to difficulties[44] when dealing with complex concentrated mixtures. Furthermore, reliable quantification of smoke constituent yields in whole smoke with an online detector requires special attention.[45] For these reasons, in the present study the choice was made to rely on off-line analyses using generally accepted methods as proposed by Health Canada. Quantification of these VOCs in the Health Canada set of methods corresponds to the following procedures; acetaldehyde is sampled by passing whole smoke through an impinger,[46] whereas the others are sampled from the gas phase of the smoke (i.e., after passing smoke through a Cambridge filter), by direct trapping in a methanol solution cooled to a temperature at or below minus 70 °C.[47]

Since Camel Crush was used in both studies, we also include the relevant VOC smoke data obtained in the present study in Figure 5. The Camel Crush smoke yields per cigarette are shown with the standard deviation as the error bar. The results differ from the results reported by Gordon et al.[3] even when the cigarette yields with the capsule uncrushed are compared. In this case, no menthol is present, and no capsule has been crushed. The results of the present study for isoprene and acrylonitrile are consistent with the published smoke yields of the University of Kentucky 2R4F reference cigarette,[48] differing no more than 25% and 9%, respectively. These yields are representative of 10-mg American-blend brands. The agreement is good whether determined using real-time[45] or off-line[48] methods. On the contrary, the results reported by Gordon et al. differ by as much as a factor of 3 and 2 for isoprene and acrylonitrile, respectively. Furthermore, it is known that the yield of 1,3-butadiene in the first puff of a cigarette is much higher than in subsequent puffs,[49−52] but this characteristic pattern is not seen in the puff profile reported (Figure 4, p. 1748, in ref 3) by Gordon et al.

■ CONCLUSIONS

This study demonstrates that the yields of smoke constituents from the Health Canada list do not increase as a result of crushing the menthol capsule in the filter of a cigarette (with the exception of the tar increase due to menthol flavor addition). In fact, the yields of a number of aromatic volatile constituents are actually decreased, most probably due to increased filter retention by the lipophilic compounds liberated from the crushed capsule. These conclusions are valid for prototype cigarettes as well as for the wide range of sampled capsule-containing commercial brands, regardless of whether the smoke constituent yields are assessed on a cigarette, TPM, or nicotine basis.

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Notes

The authors declare the following competing financial interest(s): All authors are employees of Philip Morris International.

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■ ABBREVIATIONS

CF, Cambridge filter; HCI, Health Canada Intense; IS, internal standard; ISO, International Organization for Standardization; MEK, methyl ethyl ketone; NO_x, nitrogen oxides; NNN, *N*′-nitrosonornicotine; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NAT, *N*′-nitrosoanatabine; NAB, *N*′-nitrosoanabasine; KS, King Size; PTR-MS, proton transfer reaction-mass spectrometer; RTD, resistance to draw, reported in mm of water (mmWG); TPM, total particulate matter; TSNA, tobacco-specific nitrosamine; VOC, volatile organic compound

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