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The use of charcoal in modified cigarette filters for mainstream smoke carbonyl reduction

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Abstract

Carbonyls are harmful and potentially harmful constituents (HPHCs) in mainstream cigarette smoke (MSS). Carbonyls, including formaldehyde and acrolein, are carcinogenic or mutagenic in a dose-dependent manner. Past studies demonstrate significant reduction of HPHCs by charcoal filtration. However, limits of charcoal filtration and cigarette design have not yet been investigated in a systematic manner. Objective data is needed concerning the feasibility of HPHC reduction in combustible filtered cigarettes. This systematic study evaluates the effect of charcoal filtration on carbonyl reduction in MSS. We modified filters of ten popular cigarette products with predetermined quantities (100–400 mg) of charcoal in a plug-space-plug configuration. MSS carbonyls, as well as total particulate matter, tar, nicotine, carbon monoxide (TNCO), and draw resistance were quantified. Significant carbonyl reductions were observed across all cigarette products as charcoal loading increased. At the highest charcoal loadings, carbonyls were reduced by nearly 99%. Tar and nicotine decreased modestly (<20%) compared to reductions in carbonyls. Increased draw resistance was significant at only the highest charcoal loadings. This work addresses information gaps in the science base that can inform the evaluation of charcoal filtration as an available technological adaptation to cigarette design which reduces levels of carbonyls in MSS.

Keywords

Tobacco; Filtration; Carbonyl; Smoke constituents; Risk-reduction; Charcoal; Technology; Cigarette; HPHC

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Declaration of interests
The authors declare no competing financial interests.

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1. Introduction

Cigarette smoke contains over 7000 chemical constituents, including nearly 70 known carcinogens, present in ingredients or generated during combustion. These and other chemical compounds contribute to heart and respiratory disease, stroke, cancer, and other serious diseases in smokers (Report of the Surgeon General, 2014). As early as the 1950s, cigarette design alterations have been made to reduce death and disease caused by exposure to mainstream cigarette smoke (MSS). Toward this goal, cigarette filters have been modified to selectively filter harmful compounds from MSS (Ikeda et al., 1967; Shepherd, 1994). Factors affecting selective filtration of MSS include the material properties and adsorptive capacity of the filtration media, the volatility and chemical properties of the smoke constituents, and the affinities that the filtration media and smoke constituents have for each other (George, 1968; Tiggelbeck, 1968; Williamson et al., 1965). Selective filtration of MSS has been achieved to differing degrees of effectiveness with a range of filtration media, including activated carbon, or charcoal (Coggins and Gaworski, 2008; Polzin et al., 2008), synthetic polymer carbon (Nother et al., 2016), ion-exchange resins (Branton et al., 2011b), and polymer-based adsorbents (Dittrich et al., 2014; McAdam et al., 2012). Toxicological assays and human biomarker studies demonstrate the efficacy of selective filtration in filtered cigarettes with selective filtration media versus filtered cigarettes alone (Bombick et al., 1997; Gaworski et al., 2009; Hoffmann et al., 1976; Laugesen and Fowles, 2005; Roemer et al., 2004; Thayer and Kensler, 1964).

Charcoal is characterized by high specific surface area and porosity, facilitating the adsorption of volatile and semi-volatile chemicals from MSS, including aldehydes, aliphatic amines, and monocyclic aromatic compounds (Branton et al., 2009; Gaworski et al., 2009; General, 1981; Pauly et al., 1997). Despite limited U.S. market share (Hoffmann et al., 2001), cigarette manufacturers have experimented with charcoal filtration in prototype cigarettes and have included charcoal in marketed cigarette filters from the mid-1950s through today (Barton, 1964; Farr and Revere, 1958; Kensler and Battista, 1963; Mait and Wickham, 1990). The filtration efficacy of volatile MSS constituents by charcoal is influenced by the activity, composition, configuration, and loading of the charcoal. Charcoal with higher activity reduced MSS HPHC yields more than charcoal with lower activity (Mola et al., 2008). Synthetic charcoal-filtration reduced mouth-level exposure of toxicants versus non-charcoal filtered cigarettes (Nother et al., 2016). Decreases in genotoxicity and cytotoxicity have been demonstrated with charcoal filtration (Bombick et al., 1997; Gaworski et al., 2009; Thayer and Kensler, 1964), and decreased levels of human biomarkers of harm were observed when humans switched to charcoal-filtered cigarettes (Sarkar et al., 2008). Additionally, charcoal-filtered MSS resulted in decreased MSS bioactivity compared to non-charcoal filtered cigarettes (Hoffmann et al., 2001), and evidence suggests decreased cancer mortality rates with the use of charcoal filters versus conventional filters (Coggins and Gaworski, 2008; Muscat et al., 2005).

Charcoal has been included in cigarette filters in a range of formats, including charcoal granules dispersed among cellulose acetate (on-tow) (Polzin et al., 2007) or contained within a central cavity (plug-space-plug; PSP) (Branton et al., 2011b; Mola et al., 2008). Charcoal filter design has not yet been systematically optimized, but the PSP filter design may remove

HPHCs more effectively than other filter designs, and the extent of HPHCs reduction is greater with greater amounts of charcoal (McAdam et al., 2012; Mola et al., 2008; Raker et al., 1996; Rees et al., 2007; Shepperd et al., 2013; Xue et al., 2002). Accordingly, lower charcoal loadings have produced only modest MSS HPHC reductions. For example, cigarettes containing 45 mg charcoal on-tow reduced acrolein by between 7% and 22% compared to cigarettes without charcoal. However, cigarettes containing higher loading of 120 mg charcoal on-tow reduced acrolein by 73%, suggesting that constituent reduction follows a dose-response to charcoal filtration (Polzin et al., 2008).

Carbonyls are volatile chemicals in the gas phase of MSS, many of which are known harmful or potentially harmful constituents (HPHCs). Carbonyls are carcinogenic or mutagenic in a dose-dependent manner (Krayzler and Nagler, 2015; Ryu et al., 2013; Stevens and Maier, 2008; Swenberg et al., 2013), contributing to cancer (NCI, (2006) and diseases of the respiratory (Faroon et al., 2008) and cardiovascular systems (Fowles and Dybing, 2003). Despite evidence demonstrating the effectiveness of selective filtration of MSS by charcoal, no study has employed a systematic approach to determine the effects of incrementally increasing charcoal loading on carbonyl filtration efficiency across a diverse sample of currently-marketed cigarettes. Furthermore, none of the available literature has assessed the maximum effectiveness of charcoal filtration on carbonyl reduction in MSS. Even fewer studies have employed the Canadian Intense (CI) smoking regimen in their methods (Branton et al., 2011a, 2011b; Laugesen and Fowles, 2005; McAdam et al., 2012; Polzin et al., 2008; Rees et al., 2007; Shepperd et al., 2013). This proof-of-concept study employs the CI smoking regimen to represent a consumer’s maximum potential level of exposure to MSS constituents. Although the CI smoking regimen does not represent the smoking behavior of all consumers (Purkis et al., 2010), smokers who are not aware of filter ventilation holes may obstruct the holes with their fingers or mouth (Kozlowski and O’Connor, 2002). In addition, although the ventilation and puff ing parameters of the CI smoking regimen may alter gas-particle partitioning of the smoke, which may in turn decrease selective filtration of smoke constituents(Laugesen and Fowles, 2006; Pankow, 2001), the CI smoking regimen has been recommended for tobacco product development and testing by the World Health Organization TobReg, as it provides a balance of the relative strengths and weaknesses of the available standard smoking regimes (WHO, 2004). To address these information gaps regarding charcoal filtration of MSS, we adapted the filters of ten currently marketed cigarettes to include predetermined quantities of charcoal in a PSP configuration. Seven carbonyls (2-butanone, acetaldehyde, acetone, acrolein, crotonaldehyde, formaldehyde, proprionaldehyde) were quantified under a fixed puff count adaptation of the CI smoking regimen to systematically investigate the effectiveness and limits of charcoal filtration on MSS carbonyl yields. Total particulate matter (TPM), tar, nicotine, carbon monoxide (TNCO) and draw resistance were also quantified to assess the effects charcoal filtration on general cigarette attributes.

2. Methods

2.1. Materials

Activated coconut shell charcoal (20–40 mesh, 1100–1200 m^2/g surface area) was purchased from Fisher Scientific. Combustible, cellulose acetate-filtered cigarettes were purchased in June 2015 from greater metropolitan Atlanta area retail outlets (Table 1). All cigarettes were stored in freezers at −12 °C (short-term) or −30 °C (long-term).

2.2. Cigarette selection

Products constituted popular cigarette products representative of the marketplace diversity with regard to tar yield, length, and mentholation. Five products were king-size and five were 100s. Two products were menthol cigarettes. Each product was assigned a product code (a–j) used for identification throughout the text (Table 1). The products used in the present study were selected from a group of 50 popular cigarette products with 'tar' levels that were quantified previously under the CI smoking regimen (Vu et al., 2015). Tar yields reported previously are not identical to those reported in the present study due to slight differences to the smoking regimen employed (Section 2.4.). Product characteristics and tar yields are available in Supplementary Table 1 and Fig. 1, respectively.

2.3. Experimental cigarette design and construction

Filter segments of the experimental cigarettes were modified to contain a central cavity containing charcoal granules between two plugs of cellulose acetate filter in a PSP configuration (Fig. 2). For each modified cigarette, the two cellulose acetate (CA) plug portions of the filter were equal in length. First, the cigarette filter was cut in half perpendicular to the cigarette length. The portion of CA adjacent to the tobacco rod was separated from the portion of CA at the mouth end of the cigarette (CA2) by a charcoal-containing cavity. Pre-weighed charcoal loadings were placed between CA1 and CA2, and held in place with non-porous tipping paper and adhesive tape positioned to block ventilation holes on the un-modified cigarette tipping paper. The charcoal-containing cavity was the minimum length required to contain the charcoal granules. The modified king-size cigarettes included 100 mg, 200 mg, 300 mg, or 400 mg charcoal, while the modified 100s cigarettes included 100 mg, 200 mg, or 300 mg charcoal. Due to the extent of carbonyl reduction observed for king-size cigarettes, it was deemed unnecessary to include the 400 mg charcoal condition in 100s cigarette testing. Unmodified cigarettes of each of the 10 products served as control conditions (0 mg). Control cigarette filters were not modified, but all filter ventilation holes were covered by nonporous tape. Experiments were conducted in two sequential phases wherein king-size cigarettes were constructed and analyzed first, followed by construction and analysis of 100s cigarettes. Although there have been reports of release of charcoal granules during smoking (Pauly et al., 1997), observation of the mouth end of experimental cigarettes after machine smoking did not suggest charcoal release in the present study. All experimental and control cigarettes were conditioned for at least 48 h at 22 °C and 60% relative humidity prior to machine smoking.

2.4. Smoking conditions

All cigarettes were smoked on a linear smoking machine under a fixed puff count CI smoking regimen to represent and make comparisons within scenarios with the highest potential constituent yields. For carbonyl quantification, three cigarettes were machine smoked per charcoal loading. For TNCO analysis, three cigarettes were machine smoked for each of three replicates, for a total of nine cigarettes per condition. Cigarettes were smoked to a prescribed number of puffs, which was one puff less than the standard 3 mm plus overwrap procedure indicated by the CI smoking regimen (HC, 1999). This adaptation was made to ensure that all cigarettes for a particular product have identical smoke volumes, despite modifications to the filter segment. Puff counts used for each product are included in Tables 2 and 3.

2.5. Carbonyl determination

Carbonyl analysis was based on a recently published method on the derivatization and quantification of 7 carbonyls in cigarette MSS (Ding et al., 2016). Prior to smoking, Cambridge filter pads (CFP) were pre-treated with derivatization reagent. Cigarettes were smoked through the treated pads according to the fixed puff count CI smoking regimen on a linear smoking machine. MSS carbonyls were derivatized and collected on the pre-treated CFPs. Derivatized carbonyls were extracted in the solvent and an aliquot of the sample was diluted and injected into an ultra-high pressure liquid chromatography coupled with a triple quadruple mass spectrometer (UPLC-MS/MS).

2.6. Physical parameter determination

Cigarette rod length and filter plug were measured manually using a Vernier caliper. Charcoal amount for each cigarette was manually weighed using an analytical balance before it was assembled into the filter segment. Cigarette draw resistance was measured on the C^2 instrumentation (Cerulean; Milton Keyes, UK).

2.7. TNCO instrumentation and analysis

The standard procedures previously described for TNCO determinations were used with few modifications. Briefly, the gas and particulate phases of MSS from 3 cigarettes per sample were collected in vapor phase collection bags and on CFPs, respectively. The percentage by volume of CO (%CO) was determined from vapor phase collection bags using a built-in COA205 non-dispersive IR analyzer. The total particulate matter (TPM) was determined gravimetrically by calculating the weight difference of the CFP before and after smoking divided by the number of cigarettes smoked per pad. The TPM was then extracted with 20 mL of extraction solution (isopropanol containing approximately 0.1 mg/mL anethole and 1 mg/mL methanol ISTDs) by gently shaking at 160 rpm for 30 min. A blank, conditioned CFP was extracted concurrently with smoke samples for background water subtraction. The extract was then analyzed for nicotine and water by gas chromatography-flame ionization detection (GC-FID) and GC-thermal conductivity detection (GC-TCD), respectively. Calibration curves were constructed with 10 different analyte concentrations (ranging from 0.004 to 1.0 mg/mL for nicotine and 0–5.0 mg/mL for water) plotted against the area ratios of analyte-to-internal standard. A linear regression analysis (1/X weighed) of the calibration curve provided the slopes and intercepts from which the nicotine and water concentrations of unknown sample extracts could be calculated. A multiplier (i.e., number of cigarettes smoked per CFP divided by the extraction solution volume used) was then applied to calculate nicotine and water amounts in mg/cigarette. The determined water content of the blank CFP was then subtracted from all samples. Finally, tar content was derived by subtraction of the determined water and nicotine contents from TPM.

2.8. Statistical analysis

Two-tailed student's t-tests were used to determine statistical significance of carbonyl reduction at each charcoal loading. The average yield of each carbonyl across all cigarettes of each length class (king-size or 100s) were compared for each charcoal loading versus the carbonyl yield of king-size or 100s cigarettes without charcoal (Table 4). Tests used the nominal level of significance of $\alpha = 0.05$, and results were considered significant when $p \leq 0.05$.

3. Results

3.1. Charcoal filtration reduced carbonyl yields in a dose-dependent manner

MSS carbonyl yields were quantified for all cigarettes (Fig. 3). For every product, significant reductions of all carbonyls were observed with increasing charcoal mass. For control products, acetaldehyde levels were highest, followed by acetone, and levels of the remaining five carbonyls were less. Although significant reductions in formaldehyde yields were observed (median 32% reduction at 100 mg charcoal), the effect of charcoal filtration on formaldehyde yields was least substantial among yields of other carbonyls (median 80.5% reduction at 100 mg charcoal). The percent reductions of carbonyl yields compared to the control products are tabulated for king-size (Table 2) and 100s products (Table 3).

The most substantial decreases in carbonyl yields occurred between controls and the 100 mg charcoal condition, with $p \leq 0.01$ for all carbonyls except formaldehyde, where $p = 0.13$ for king-size products and $p = 0.03$ for 100s products. Notably, among king-size and 100s products, crotonaldehyde decreased by an average of 91% and 87%, respectively, between the control and the 100 mg charcoal condition. For king-size products, the absolute yield of crotonaldehyde between the control and the 100 mg charcoal condition decreased by greater than seven-fold from 42.9 μg/cig to 5.6 μg/cig. Similarly, for 100s products, the absolute crotonaldehyde yield between the control and the 100 mg charcoal condition decreased nine-fold from 47.6 μg/cig to 5.2 μg/cig.

Acrolein yields for the 100 mg charcoal-filtered cigarettes decreased between 81% and 79% on average among king-size and 100s products, respectively. For king-size products with 100 mg charcoal, the absolute acrolein yield decreased by greater than fourfold, from 130.8 μg/cig to 28.8 μg/cig. Similarly, for 100s products with 100 mg charcoal, the absolute acrolein yield decreased by five-fold, from 124.2 μg/cig to 24.5 μg/cig, on average.

With 200 mg charcoal, the cumulative percent reduction of all carbonyls increased across all king-size products ($p < 0.01$ for all carbonyls except formaldehyde, where $p = 0.02$) and 100s products ($p \leq 0.0015$). For example, crotonaldehyde yields of king-size and 100s products with 200 mg charcoal decreased by 96% and 94%, respectively, from control 100s cigarettes. At the 200 mg charcoal level, several data points were below the limit of quantification (Fig. 3).

With 300 mg charcoal, carbonyl levels either decreased further or remained relatively consistent to those observed at the 200 mg level, since reductions of several carbonyls began to approach 100% with higher charcoal loadings. For example, with 300 mg charcoal, the cumulative percent reduction of crotonaldehyde was 98%, on average, across all king-sized products and 94%, on average, across all 100s products, elevated only slightly from or similar to the 96% and 94% cumulative percent reductions observed for the 200 mg charcoal condition. For king-size products with 300 mg charcoal, all carbonyls had significantly lower yields than controls ($p \leq 0.001$ for all carbonyls except formaldehyde, where $p = 0.005$). For 100s products with 300 mg charcoal, all carbonyls had significantly lower yields than controls ($p < 0.001$).

With 400 mg charcoal, carbonyl levels of king-size cigarettes approached limits of quantification ($p < 0.001$ for all carbonyls except acetaldehyde, where $p = 0.0075$). However, many of the carbonyl levels observed for the 400 mg charcoal condition were below the LOD for the detection assay, indicating that the additional charcoal reduced the carbonyl levels further, despite those levels being as much as 98% less than those of the controls.

3.2. TNCO yields of charcoal-filtered cigarettes did not decrease substantially

TPM and TNCO yields were quantified for king-size (Fig. 4A) and 100s (Fig. 4B) cigarettes. There were no statistically significant reductions in mean TPM or TNCO yields between the control and charcoal-filtered king-size cigarettes at any of the prescribed charcoal amounts. For 100s cigarettes, there were no significant reductions in TPM and TNCO for cigarettes containing 100 mg charcoal versus control cigarettes. However, with 200 mg and 300 mg charcoal, there was a statistically significant reduction in TPM compared to controls for 100s cigarettes ($p = 0.03$ and $p = 0.004$, respectively). Additionally, at the highest charcoal level for 100s cigarettes (300 mg), there was a statistically significant decrease in tar ($p = 0.007$) and nicotine ($p = 0.009$), relative to controls. Fig. 5 illustrates the relative percent reductions in TNCO (dark shaded bars) and carbonyl (light shaded bars) levels in charcoal-filtered cigarettes versus control cigarettes in king-size (Fig. 5A) and 100s (Fig. 5B) products. Across all products filtered with 100 mg charcoal, the median reductions of tar and nicotine were 16% and 8%, respectively. Comparatively, with 200 mg charcoal, the median reductions of tar and nicotine were 20% and 19%, respectively.

3.3. Cigarette draw resistance increases were significant at higher charcoal loadings in king-size cigarettes

Cigarette draw resistance is a measure of pressure differential across the length of a cigarette, is correlated with smoking behavior, and influences puffing topography and consumer acceptance of cigarettes. In this study, cigarette draw resistance was quantified for king-size (Fig. 6A) and 100s (Fig. 6B) control and charcoal-filtered cigarettes. Draw resistance is tabulated in Tables 2 and 3 for king-size and 100s cigarettes, respectively. Among king-size cigarettes, there were no significant increases in draw resistance with 100 mg or 200 mg charcoal loadings. Draw resistance increased significantly compared to controls at higher charcoal loadings of 300 mg and 400 mg ($p = 0.02$ and $p = 0.006$, respectively). There were no significant increases to draw resistance for 100s cigarettes at any charcoal loading. P-values for all draw resistance comparisons versus control cigarettes for king-size and 100s cigarettes are included in Table 4.

4. Discussion

Carbonyls were substantially reduced when filters of popular cigarette products were modified to contain prescribed amounts of charcoal and smoked under intense smoking conditions. Additionally, changes to TNCO yields and to pressure drop were relatively limited in comparison to changes in carbonyl yields of the products evaluated.

4.1. Carbonyl reduction by charcoal filtration

The effect of charcoal filtration on carbonyl yields was similar across all products analyzed, and carbonyl yields decreased with increasing charcoal mass (Fig. 3). For all products, there were substantial reductions in all carbonyls, even at the lowest charcoal loading (100 mg). The space portion of the modified cigarettes required approximately 3 mm to accommodate 100 mg charcoal, suggesting that substantial carbonyl reduction may be achieved with minor changes to cigarette design and appearance.

Reductions in carbonyls increased with increasing charcoal load, and plateaued at approximately 99% reduction at the higher charcoal loadings for all products and for all carbonyls except for formaldehyde. As demonstrated previously (Branton et al., 2011b; Dittrich et al., 2014), formaldehyde was reduced to a lesser extent than other carbonyls. Branton et al. propose that its relatively high vapor pressure at room temperature may reduce formaldehyde absorption by charcoal (Branton et al., 2011a, 2011b). In addition, the difficulty of MSS formaldehyde quantification has been noted by several, which merits further investigation as it relates to charcoal filtration of mainstream smoke (Parrish and Harward, 2000; Thomas and Koller, 2001). We are also aware of the possibility of alternate reactions of formaldehyde and acetaldehyde which may lead to the formation of reaction products (methanediol and lactonitrile, respectively) with decreased volatility (Dube and Green, 1982; Johnson et al., 1966; Rickert et al., 2007; Socrates, 1969). Accordingly, the measurements of formaldehyde and acetaldehyde may slightly underrepresent the absolute quantities of these constituents in the smoke. Nevertheless, the differences in formaldehyde and acetaldehyde yields in charcoal-filtered versus control conditions indicates substantial reduction of all constituents that were examined. Although the present study demonstrates substantial reductions in acetaldehyde in charcoal-filtered cigarettes, alternate filtration materials may be required to obtain similar reductions of formaldehyde, and altering the configuration and composition of charcoal granules may improve removal of a wider range of volatile aldehydes from MSS (Branton et al., 2009, 2011a). Additionally, future research may necessitate the use of alternate quantification methods to optimize formaldehyde detection in MSS of charcoal filtered cigarettes. Accordingly, the observed trend of limited formaldehyde removal efficiency by charcoal may be due to both the chemical and physical nature of formaldehyde and its interaction with charcoal, meriting further investigation.

A loading of 180 mg charcoal was the highest charcoal loading found in published studies that analyzed smoke composition of charcoal-filtered cigarettes under the CI smoking regimen (Polzin et al., 2008; Rees et al., 2007). Polzin et al. quantified yields of several volatile smoke constituents and TNCO from four commercially available test market charcoal-filtered cigarette prototypes, one of which used 180 mg charcoal in a PSP filter format. With 180 mg charcoal loading, the MSS contained 574.4 μg/cig acetaldehyde and 64.3 μg/cig acrolein. By comparison, the MSS of the non-charcoal containing control cigarettes contained 1221 μg/cig acetaldehyde and 235.3 μg/cig acrolein. As such, 180 mg charcoal removed 53% of the acetaldehyde and 73% of the acrolein from the cigarette MSS.

Despite experimental differences between Polzin's work and this study, reductions in acetaldehyde and acrolein of the previous work align with the results observed here. To illustrate this point, the reductions of acetaldehyde and acrolein in the MSS of cigarettes modified to contain 100 mg and 200 mg charcoal in the present study were compared to the reductions in acetaldehyde and acrolein observed by Polzin et al., with 180 mg charcoal. Here, 100 mg charcoal removed 50% of acetaldehyde (1542.1 μg–764.0 μg) and 80% of acrolein (127.5 μg–26.7 μg) from the across all products. With a higher loading of 200 mg charcoal, 78% of the acetaldehyde (1542.1 μg–339.3 μg) and 92% of acrolein (127.5 μg–10.2 μg) was removed from the MSS of all products. These results are consistent with previously reported studies and indicate that a substantial portion (>50%) of carbonyl yields can be removed with between 100 mg and 200 mg charcoal (Polzin et al., 2008; Rees et al., 2007).

4.2. TNCO removal

We assessed TNCO yields of control and charcoal-filtered cigarettes, as they are important properties of cigarette smoke (1988; Gunby, 1988). As expected, CO was not significantly influenced by charcoal filtration at any loading, since charcoal has not been associated with removal of CO in the gaseous state. While tar and nicotine yields decreased to some extent with increasing charcoal in all products, the removal of tar and nicotine by charcoal was modest. Due to the well-documented non-selective nature of charcoal filtration, modest removal of tar and nicotine was not surprising (Rahman et al., 2006). Substantial reductions in carbonyls without proportional TNCO reductions suggest that, especially for lower charcoal loading conditions, substantial decreases in carbonyls may be possible without impacting nicotine deliveries.

4.3. Cigarette draw resistance

Although the modified cigarettes were intended to provide a proof-of-concept for charcoal filtration of carbonyls in MSS, we analyzed draw resistance to determine whether charcoal inclusion would cause technical design limitations for modified cigarettes. We observed statistically significant increases to draw resistance at higher charcoal loadings (300 mg and 400 mg) only. A recognized limitation of charcoal filtration is the potential for draw resistance increase to render the cigarette unpleasing to the consumer (Raker et al., 1996). The draw resistance of 50 popular currently marketed cigarettes (Vu et al., 2015) was between 83 mmH_2O and 194 mmH_2O (unpublished data). In this case, several charcoal-containing cigarettes had draw resistance values within the range of draw resistance that is found in currently marketed cigarettes that do not have filter modifications. For example, products a, d, and j modified with 100 mg charcoal had draw resistance values of 139 mmH_2O, 130 mmH_2O, and 133 mmH_2O, each of which is within the range of draw resistance that is observed in currently marketed cigarettes. As such, several cigarettes modified to contain 100 mg and, in some cases, 200 mg and 300 mg charcoal, exhibited substantial carbonyl reduction while incurring only moderate increases to draw resistance compared to currently marketed cigarettes.

Reduced-exposure cigarettes likely require integration of complementary design modification technologies to achieve reduced harm to health. Several cigarette design adaptations, including increased smoke dilution, novel tobacco substitutes, alternate filter adsorbents, and alternate filter tow plasticizers, have been investigated for their combined effect on constituent reduction (Dittrich et al., 2014; Liu et al., 2011; McAdam et al., 2011, 2012). In addition, filter configuration and design can be optimized to achieve target levels of constituent reduction. Generally, to achieve optimal reduction of volatile smoke constituents, the interaction between the smoke and the surface of the charcoal particles or alternate adsorbent should be maximized (Branton et al., 2009). Approaches toward this goal include optimization of the filter design format to ensure that the smoke passes through a sufficiently dense bed of charcoal, avoiding empty pockets of space within the cavity region (Pauly et al., 1997). Including alternate, high surface area nano-materials, such as carbon nanotubes, may yield similar carbonyl reductions without adversely influencing draw resistance or other critical design parameters. Additionally, more detailed information regarding the influence of charcoal filtration on smoke flavor would aid the design of reduced-exposure cigarettes. To this point, prototype charcoal-filtered cigarettes with alternate flavor systems, such as a flavored cotton thread woven into the filter and crushable menthol beads, have been used to enhance acceptability or overcome flavor changes caused by charcoal filtration (Gordon et al., 2011; Rees et al., 2007; Strasser et al., 2013).

Although machine yields provide insight to constituent exposure to human smokers, without toxicological and human biomarker studies, potential exposure reduction cannot be used alone to determine health outcomes of reduced exposure cigarettes of this study. Therefore, although outside of the scope of the present work, additional research on product shelf life and stability, as well as consumer perception and behavioral studies, toxicity studies, and human biomarker levels, will help to predict health outcomes that may be expected when consumers use reduced-exposure products. Ultimately, a combination of technologies or adaptations could be formulated to construct a reduced-exposure cigarette without sacrificing consumer acceptability. The proof-of-concept presented here may inform the design of reduced exposure cigarettes intended for consumer use.

This work suggests the potential for substantial reduction of select harmful smoke constituents without concurrent broad sacrifices to other cigarette design parameters. Combined, these data indicate the potential for an achievable cigarette design modification that may reduce exposure to some carbonyls. At higher charcoal loadings, carbonyl yields of modified cigarettes have improved our understanding of the utility of charcoal filtration in combustible cigarettes and the limits associated with such modifications, as several carbonyls were nearly completely removed from MSS at high loadings. The knowledge gained here may also be used to inform technologies that may further reduce yields of other HPHCs in cigarette smoke.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.yrtph.2017.02.019.

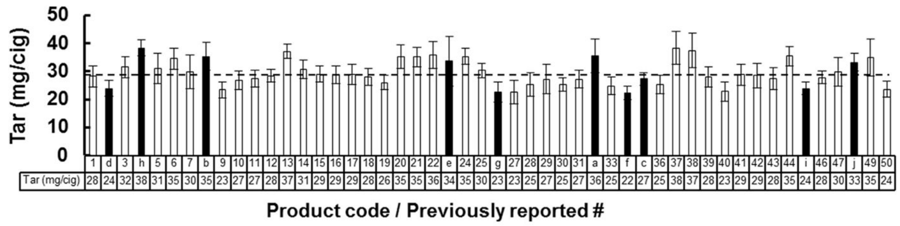

Fig. 1.

CI tar yields for 50 cigarettes representative of the current marketplace. Tar yields of the cigarette products selected and used in the present study (black bars). Horizontal dashed line indicates overall average tar yield. The product code (a–j) used for reference in this study for each of the selected cigarettes is indicated below the x-axis. (n = 20).

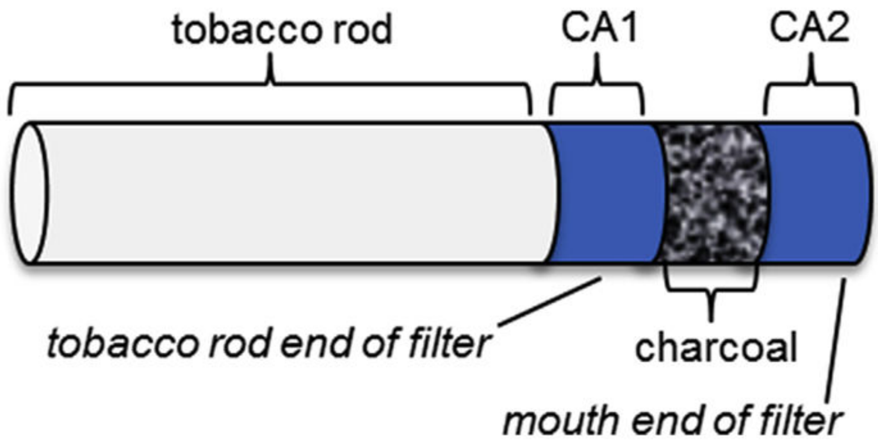

Fig. 2.
Schematic overview of modified cigarette design. Cellulose acetate plugs (CA1 and CA2) are of equal lengths. Nonporous tape (not pictured) is wrapped around entire filter construct to contain charcoal and block any ventilation holes.

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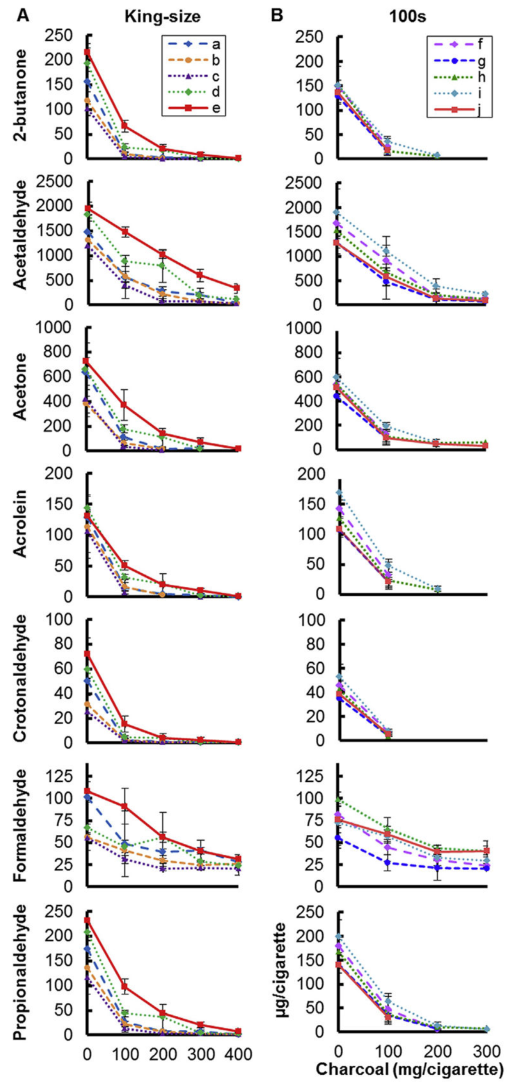

Fig. 3.

CI carbonyl yields in MSS of (A) king-size and (B) 100s product controls and charcoal-containing cigarettes. Missing data points indicate value below limit of detection for the assay. (n = 3).

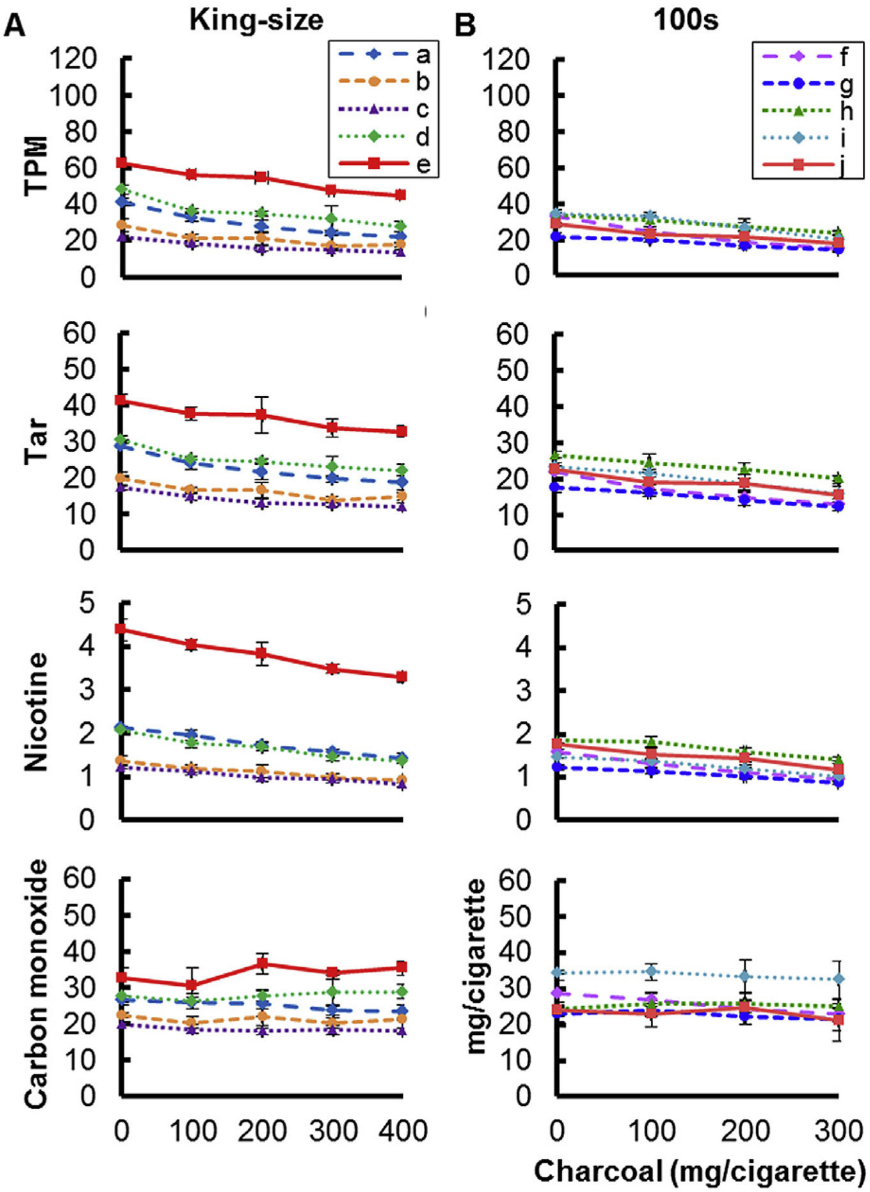

Fig. 4.

CI TPM and TNCO yields in MSS of (A) king-size and (B) 100s product controls and charcoal-containing cigarettes. (Error bars are S.D.; n = 3).

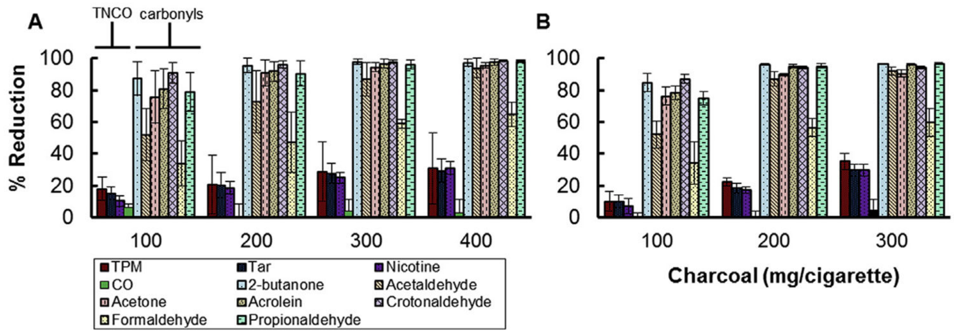

Fig. 5.

Percent reduction compared to unmodified controls of TPM, TNCO (dark shading) and carbonyls (light shading) in MSS of king-size (A) and 100s (B) charcoal-filtered cigarettes. (Error bars are S.D.; n = 3).

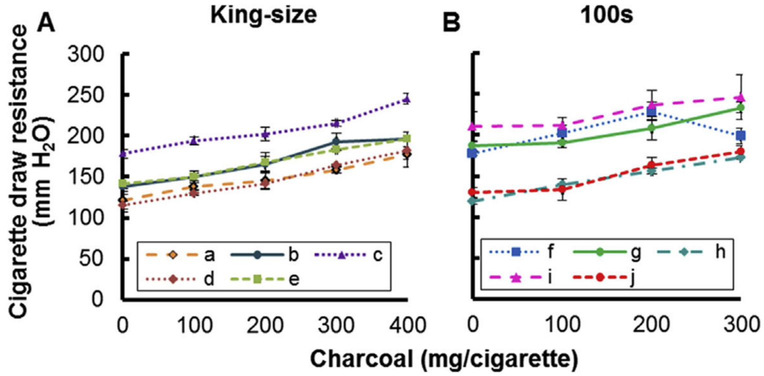

Fig. 6.

Cigarette draw resistance of king-size (A) and 100s (B) control and modified charcoal-filtered cigarettes. (Error bars are S.D.; n = 3).

Table 1

Construction characteristics for charcoal-containing cigarettes used in the study.

Code	Cigarette Length class	Charcoal	Overall length/filter length (Unmodified)	CA1	Cavity (space)	CA2	Modified filter	Modified cigarette
	Unit (per cigarette)	**mg**	**mm/mm**	**mm**	**mm**	**mm**	**mm**	**mm**
a	Camel Filters King Size	100	82/21	10.5	3.0	10.5	24.0	87.0
		200			8.0		29.0	91.0
		300			12.3		33.3	94.3
		400			16.3		37.3	98.3
	Doral Gold King Size	100	83/22	11.0	9.3	11.0	31.3	92.3
		200			14.3		36.3	97.3
		300			18.7		40.7	101.7
		400			22.7		44.7	105.7
b	Kent Golden King Size	100	83/24.6	12.3	5.3	12.3	29.9	88.3
		200			10.0		34.6	93.0
		300			15.7		40.3	98.7
		400			19.0		43.6	102.0
d	Marlboro Red King Size	100	79/18	9.0	5.3	9.0	23.3	84.3
		200			10.0		28.0	89.0
		300			14.7		32.7	93.7
		400			19.3		37.3	98.3
e	Natural American Spirit Turquoise King Size	100	84/23	11.5	4.7	11.5	27.7	88.7
		200			9.0		32.0	93.0
		300			13.0		36.0	97.0
		400			17.3		40.3	101.3
f	Carlton White 100s	100	98/30	15.0	3.7	15.0	33.7	101.7
		200			8.3		38.3	106.3
		300			13.0		43.0	111.0
g	Marlboro Silver 100s	100	99/32	16.0	4.3	16.0	36.3	103.3
		200			7.7		39.7	106.7
		300			12.0		44.0	111.0
h	Newport Green Menthol 100s	100	97/27	13.5	4.0	13.5	31.0	101.0

Code	Cigarette Length class	Charcoal	Overall length/filter length (Unmodified)	CA1	Cavity (space)	CA2	Modified filter	Modified cigarette
	Unit (per cigarette)	mg	mm/mm	mm	mm	mm	mm	mm
		200			8.7		35.7	105.7
		300			13.0		40.0	110.0
i	Salem Silver Menthol 100s	100	98/30	15.0	4.7	15.0	34.7	102.7
		200			9.7		39.7	107.7
		300			13.7		43.7	111.7
j	Winston Red 100s	100	97/32	16.0	4.0	16.0	36.0	101.0
		200			7.7		39.7	104.7
		300			12.3		44.3	109.3

Values shown for unmodified and modified cigarette and filter segment lengths are mean measured values (n = 3). CA1: tobacco column end cellulose acetate segment; CA2 mouth-end cellulose acetate segment.

Table 2

CI yields of TNCO and carbonyls ±S.D for king-size products.

Code	Charcoal	Puff count	CDR	TPM	Tar	Nicotine	CO	MEK	ACETALD	ACET	ACRL	CROT	FORM	PROP
Unit	mg/cig	puffs/cig	mm H_2O	mg/cig	mg/cig	mg/cig	mg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig
a	0	9.3	121.6 ± 14.3	41.3 ± 1.8	29 ± 0.8	2.1 ± 0	26.6 ± 1.2	156.3 ± 20.8	1480 ± 40.4	635.3 ± 45.9	128.3 ± 13.6	50.2 ± 2.5	101.8 ± 6.3	173.3 ± 16.9
	100	9.3	138.6 ± 4.4 (14)	33.1 ± 2.6 (−20)	24.3 ± 1.7 (−16)	2 ± 0.1 (−8)	25.9 ± 1.7 (−3)	10.9 ± 9 (−93)	564.1 ± 431.3 (−62)	109.5 ± 4.9 (−83)	15.4 ± 13.7 (−88)	2.4§ ± 1.7 (−95)	48.7 ± 37.4 (−52)	26.5 ± 20.6 (−85)
	200	9.3	145.6 ± 11.2 (20)	27.8 ± 3.7 (−33)	21.8 ± 2.3 (−25)	1.7 ± 0.1 (−19)	25.6 ± 3.4 (−4)	2.4§ ± 0.7 (−98)	275.7 ± 94.2 (−81)	19.7§ ± 1.9 (−97)	4.1§ ± 0.5 (−97)	0.9§ ± 0.2 (−98)	39.2 ± 3.5 (−62)	8 ± 1.4 (−95)
	300	9.3	158.5 ± 4 (30)	24.3 ± 1.4 (−41)	19.8 ± 1 (−32)	1.6 ± 0.1 (−27)	23.9 ± 1.4 (−10)	2.9§ ± 0.8 (−98)	207.7 ± 126.1 (−86)	22.5§ ± 18.8 (−96)	3§ ± 2.3 (−98)	0.8§ ± 0.3 (−98)	41 ± 3.5 (−60)	7.1 ± 3.8 (−96)
	400	9.3	177.7 ± 16.4 (46)	22.3 ± 2.9 (−46)	18.8 ± 2.1 (−35)	1.4 ± 0.1 (−33)	23.4 ± 2 (−12)	LOD (*−97*)	36.1§ ± 3.4 (−98)	LOD (*−96*)	0.4§ ± 0.04 (−100)	0.4§ ± 0.2 (−99)	27.7 ± 5.2 (−73)	1.9§ ± 0.4 (−99)
b	0	7	138.5 ± 10.3	28.3 ± 3.6	20.1 ± 1.8	1.4 ± 0.1	22.5 ± 0.6	118 ± 29.9	1310.3 ± 380	385 ± 107.3	112.8 ± 50.3	31 ± 7.3	56.1 ± 14.6	135.7 ± 32.3
	100	7	150.2 ± 7.3 (8)	21.7 ± 1.5 (−23)	16.7 ± 0.6 (−17)	1.2 ± 0.1 (−14)	20.4 ± 1.6 (−9)	9.8 ± 2.9 (−92)	580 ± 103.8 (−56)	65.5 ± 20.6 (−83)	16.5 ± 6.5 (−85)	2.1§ ± 1.1 (−93)	41.3 ± 5.9 (−26)	21.7 ± 5.5 (−84)
	200	7	165.1 ± 10.1 (19)	21.5 ± 3.7 (−24)	16.6 ± 2.2 (−17)	1.1 ± 0.1 (−24)	22.1 ± 2.3 (−2)	2.1§ ± 1.5 (−98)	214.3 ± 88.1 (−84)	16.7§ ± 10.2 (−96)	3.1§ ± 2.4 (−97)	0.8§ ± 0.8 (−98)	29.4 ± 2.8 (−48)	7 ± 3.5 (−95)
	300	7	193 ± 9.9 (39)	16.9 ± 1.3 (−40)	14 ± 1 (−30)	1 ± 0.1 (−26)	20.3 ± 1.4 (−10)	LOD (*−96*)	65.9 ± 13.7 (−95)	LOD (*−94*)	LOD (*−96*)	0.7§ ± 0.5 (−98)	24.5 ± 5.1 (−56)	2.4§ ± 0.4 (−98)
	400	7	196.3 ± 8.9 (42)	17.5 ± 1 (−38)	14.8 ± 1 (−26)	0.9 ± 0 (−29)	21.4 ± 0.5 (−5)	LOD(*−96*)	24.7§ ± 11.9 (−98)	LOD(*−94*)	LOD(*−96*)	0.7§ ± 0.5 (−98)	26.3 ± 5.1 (−53)	1.9§ ± 1.2 (−99)
c	0	6	177.9 ± 5.6	22.4 ± 0.4	17.3 ± 0.7	1.2 ± 0.1	19.9 ± 0.3	101.6 ± 14.3	1200 ± 270	418.3 ± 109.6	105.7 ± 33.5	25.4 ± 4.7	54.9 ± 6	115.8 ± 33.3
	100	6	194.2 ± 4.7 (9)	18.5 ± 1.1 (−17)	14.8 ± 0.8 (−17)	1.1 ± 0.1 (−8)	18.7 ± 1.3 (−6)	5 ± 1.8 (−95)	396 ± 60.2 (−67)	34.6 ± 7.8 (−92)	7.4 ± 2.7 (−93)	1.5§ ± 0.9 (−94)	31 ± 4.8 (−44)	13.6 ± 4.2 (−88)
	200	6	202 ± 8.5 (14)	15.5 ± 1.4 (−30)	13.1 ± 1 (−30)	1 ± 0.1 (−20)	18 ± 0.8 (−9)	0.5§ ± 0.1 (−99)	66.7 ± 15.9 (−94)	8.4§ ± 0.9 (−98)	LOD(*−95*)	0.7§ ± 0.4 (−97)	20.5 ± 2.6 (−63)	2.5§ ± 0.7 (−98)
	300	6	215.8 ± 3.7 (21)	14.9 ± 0.5 (−34)	12.8 ± 0.6 (−34)	0.9 ± 0 (−23)	18.4 ± 1.3 (−8)	0.6§ ± 0.3 (−99)	71.2 ± 49.5 (−94)	LOD(*−94*)	0.3§ ± 0.1 (−100)	0.6§ ± 0.5 (−97)	21.6 ± 2.4 (−61)	3.0§ ± 1.5 (−97)
	400	6	245.4 ± 6.9 (38)	13.9 ± 0.9 (−38)	12.2 ± 1 (−38)	0.8 ± 0 (−33)	18.2 ± 0.8 (−8)	LOD(*−95*)	28.6§ ± 24.4 (−98)	LOD(*−94*)	LOD(*−95*)	0.6§ ± 0.5 (−98)	20.5 ± 7.2 (−63)	1.9§ ± 1.1 (−98)
d	0	9.3	115.5 ± 4.2	48 ± 2.7	30.7 ± 1	2.1 ± 0.1	27.9 ± 1.8	192.5 ± 40.3	1820 ± 10	657 ± 213.5	144 ± 21.2	59.5 ± 7.6	66.7 ± 7.2	208 ± 17

Code	Charcoal	Puff count	CDR	TPM	Tar	Nicotine	CO	MEK	ACETALD	ACET	ACRL	CROT	FORM	PROP
Unit	mg/cig	puffs/cig	mm H_2O	mg/cig	mg/cig	mg/cig	mg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig
	100	9.3	130.1 ± 2.6 (13)	36.5 ± 1.5 (−24)	25.4 ± 0.1 (−17)	1.8 ± 0.1 (−14)	26.2 ± 2.1 (−6)	23.1 ± 7.9 (−88)	887.3 ± 114.2 (−51)	178 ± 32.7 (−73)	31.9 ± 4.1 (−78)	4.7 ± 1 (−92)	45.7 ± 7.1 (−31)	43.4 ± 6.2 (−79)
	200	9.3	141.2 ± 5.5 (22)	34.8 ± 1.6 (−27)	24.6 ± 0.8 (−20)	1.7 ± 0.1 (−18)	28 ± 1.6 (0)	17.1 ± 13 (−91)	787.7 ± 325 (−57)	111.1 ± 73.9 (−83)	21.2 ± 16.6 (−85)	4 ± 3.4 (−93)	55.9 ± 28.4 (−16)	36 ± 26 (−83)
	300	9.3	163.7 ± 2 (42)	31.7 ± 7.5 (−34)	23.1 ± 2.9 (−25)	1.5 ± 0.1 (−29)	28.7 ± 3.8 (3)	1.8§ ± 1.3 (−99)	188.3 ± 61.2 (−90)	14.8§ ± 7.7 (−98)	2.1§ ± 1.6 (−99)	0.6§ ± 0.1 (−99)	29.2 ± 9.5 (−56)	5 ± 2.9 (−98)
	400	9.3	182 ± 10.5 (58)	27.8 ± 2.7 (−42)	22.2 ± 1.7 (−28)	1.4 ± 0 (−35)	29 ± 2 (4)	0.5§ ± 0.2 (−100)	110.6 ± 71.8 (−94)	LOD(*−96*)	1.1§ ± 0.7 (−99)	0.5§ ± 0.2 (−99)	23.8 ± 1.5 (−64)	3.5§ ± 1.5 (−98)
e	0	17	141.3 ± 9.2	62.8 ± 4.7	41.3 ± 1.7	4.4 ± 0.2	32.8 ± 3	215.3 ± 8.1	1950 ± 130	724 ± 33.1	130.3 ± 6.4	72.1 ± 12.7	108.1 ± 10.4	231.7 ± 21.9
	100	17	149.4 ± 4.8 (6)	56.4 ± 4.6 (−10)	37.8 ± 1.9 (−8)	4 ± 0.1 (−8)	30.7 ± 4.7 (−6)	66.6 ± 11.8 (−69)	1470 ± 100 (−25)	373 ± 123.4 (−48)	51.1 ± 7.3 (−61)	15.1 ± 6.4 (−79)	90.8 ± 20.2 (−16)	97.3 ± 15.5 (−58)
	200	17	168 ± 11.6 (19)	54.7 ± 8.6 (−13)	37.5 ± 5 (−9)	3.8 ± 0.3 (−13)	36.6 ± 3 (12)	20.8 ± 4.3 (−90)	1020 ± 80 (−48)	139 ± 14.8 (−81)	19.4 ± 0.6 (−85)	4.4 ± 1.1 (−94)	56.2 ± 5.5 (−48)	43.5 ± 1.1 (−81)
	300	17	182.7 ± 1.3 (29)	47.3 ± 3.9 (−25)	33.9 ± 2.4 (−18)	3.5 ± 0.1 (−20)	34.1 ± 0.7 (4)	8.2 ± 5.6 (−96)	597.3 ± 124.6 (−69)	69.9 ± 35.6 (−90)	10.3 ± 4.3 (−92)	2.6 ± 1.9 (−96)	40.5 ± 12.1 (−63)	20.2 ± 6.1 (−91)
	400	17	196.9 ± 4.2 (39)	45 ± 2.9 (−28)	32.9 ± 1.5 (−20)	3.3 ± 0.1 (−25)	35.5 ± 2 (8)	1.0§ ± 0.7 (−100)	332 ± 101.7 (−83)	18.0§ ± 10 (−98)	1.7§ ± 1.3 (−99)	0.7§ ± 0.7 (−99)	31.5 ± 4.9 (−71)	7.1 ± 0.7 (−97)

Percent change vs. controls in parentheses rounded to nearest integer. Italicized percent change based on limit of quantitation

(LOQ). Numbers without S.D. indicate quantitation limits.

§Value below LOQ. LOD: value < limit of detection of the assay.

(CDR:cigarette draw resistance; n = 3; MEK:2-butanone, ACETALD:acetaldehyde; ACET:acetone; ACRL = acrolein; CROT = crotonaldehyde; FORM = formaldehyde; PROP = propionaldehyde).

Table 3

CI yields of TNCO and carbonyls ± S.D for 100s products.

Code	Charcoal	Puff count	CDR	TPM	Tar	Nicotine	CO	MEK	ACETALD	ACET	ACRL	CROT	FORM	PROP
Unit	mg/cig	puffs/cig	mm H_2O	mg/cig	mg/cig	mg/cig	mg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig
f	0	8	177.5 ± 2.6	33.2 ± 3.4	21.8 ± 1.8	1.6 ± 0.1	28.7 ± 3.6	149 ± 12	1680 ± 181	538 ± 83.3	143 ± 14	45.8 ± 3.8	81.6 ± 12.3	179 ± 14
	100	8	202.5 ± 9.4 (14)	24.2 ± 1.8 (−27)	17.2 ± 1 (−21)	1.3 ± 0.1 (−17)	27 ± 1.8 (−6)	25.6 ± 16.1 (−83)	907 ± 499 (−46)	130 ± 75 (−76)	32.3 ± 21.1 (−77)	7.3 ± 0.9 (−84)	44.8 ± 16.1 (−45)	47.2 ± 27.1 (−74)
	200	8	228.8 ± 11.3 (29)	18.7 ± 2.6 (−44)	14.6 ± 2 (−33)	1.1 ± 0.1 (−31)	24.4 ± 2.2 (−15)	LOD (*−97*)	172 ± 78.9 (−90)	LOD (*−91*)	LOD (*−97*)	LOD (*−95*)	30.3 ± 6.5 (−63)	6.3 ± 1.3 (−96)
	300	8	198.3 ± 9.5 (12)	15.1 ± 1.8 (−54)	12.8 ± 1.5 (−41)	0.9 ± 0.1 (−41)	22.9 ± 2 (−17)	LOD (*−97*)	136 ± 31.1 (−92)	LOD (*−91*)	LOD (*−97*)	LOD (*−95*)	24.2 ± 2.5 (−70)	LOD (*−97*)
g	0	8	186.6 ± 5.1	21.8 ± 2	17.7 ± 1.6	1.2 ± 0.1	22.9 ± 2	128 ± 13.4	1290 ± 117	439 ± 25	107 ± 11.6	34.9 ± 2.3	55.4 ± 11.6	141 ± 18.2
	100	8	190.8 ± 6.4 (2)	20 ± 1.1 (−8)	16.1 ± 0.9 (−9)	1.1 ± 0.1 (−7)	24 ± 1.9 (5)	15 ± 6.8 (−88)	478 ± 353 (−63)	96.5 ± 54.5 (−78)	20.6 ± 7.4 (−81)	3.9 ± 0 (−89)	27.4 ± 9.1 (−51)	34 ± 12.2 (−76)
	200	8	208 ± 14.2 (11)	16.7 ± 1.6 (−24)	13.8 ± 1.2 (−22)	1 ± 0.1 (−17)	22.1 ± 1.9 (−3)	LOD (*−96*)	112 ± 35.2 (−91)	LOD (*−89*)	LOD (*−95*)	LOD (*−93*)	21.5 ± 14.4 (−61)	6.9 ± 0 (−95)
	300	8	233.7 ± 6.9 (25)	14.3 ± 1.5 (−34)	12.3 ± 1.2 (−30)	0.9 ± 0 (−29)	21.6 ± 3.3 (−6)	LOD (*−96*)	71.1 ± 1.6 (−94)	LOD (*−89*)	LOD (*−95*)	LOD (*−93*)	20.9 ± 1.2 (−62)	LOD (*−96*)
h	0	8	118.9 ± 3.4	33.7 ± 1.8	26.7 ± 0.9	1.9 ± 0.1	24.5 ± 1.7	153 ± 8.1	1520 ± 159	544 ± 45.2	127 ± 8.1	42.2 ± 3	99.2 ± 8.2	167 ± 6.5
	100	8	139.5 ± 0.8 (17)	31.1 ± 4 (−8)	24.5 ± 2.6 (−8)	1.8 ± 0.1 (−3)	25.9 ± 3.3 (6)	15.8 ± 4 (−90)	671 ± 28.6 (−56)	109 ± 39.5 (−80)	22.7 ± 2.3 (−82)	3.8 ± 0.2 (−91)	66.3 ± 12.4 (−33)	35.5 ± 4 (−79)
	200	8	155.8 ± 3.8 (31)	27.5 ± 2.2 (−18)	22.7 ± 1.5 (−15)	1.6 ± 0.1 (−14)	26 ± 2.6 (6)	5.6 ± 0 (−96)	213 ± 109 (−86)	56.3 ± 28.1 (−90)	7.6 ± 0 (−94)	LOD (*−94*)	43.9 ± 2.8 (−56)	9.8 ± 4.9 (−94)
	300	8	172.2 ± 1.9 (45)	24 ± 0.9 (−29)	20.1 ± 0.9 (−25)	1.4 ± 0.1 (−25)	25.3 ± 0.7 (3)	LOD (*−97*)	115 ± 71.3 (−92)	64.3 ± 0 (−88)	LOD (*−96*)	LOD (*−94*)	40 ± 6.1 (−60)	6.8 ± 0 (−96)
i	0	11	211 ± 17.6	34.5 ± 2.4	23.3 ± 0.9	1.5 ± 0	34.5 ± 0.5	151 ± 38.7	1900 ± 474	596 ± 158	169 ± 42.7	53 ± 10.4	72.3 ± 25.7	200 ± 34.1
	100	11	211.4 ± 10.4 (0)	32.8 ± 0.6 (−5)	21.5 ± 1.1 (−8)	1.4 ± 0 (−5)	34.8 ± 2.3 (1)	35.9 ± 10.4 (−76)	1110 ± 115 (−42)	196 ± 27.9 (−67)	47.7 ± 11.1 (−72)	7.6 ± 2.2 (−86)	57 ± 7.6 (−21)	63.8 ± 17.3 (−68)
	200	11	236.6 ± 17.9 (12)	26.3 ± 5.3 (−24)	18.6 ± 2.5 (−20)	1.2 ± 0.1 (−18)	33.5 ± 4.5 (−3)	6.9 ± 0 (−95)	391 ± 153 (−79)	60.3 ± 0 (−90)	9.2 ± 4 (−95)	LOD(*−95*)	33 ± 3.7 (−54)	13.1 ± 7.8 (−93)
	300	11	246.7 ± 27.2 (17)	20.2 ± 4 (−41)	15.6 ± 2.3 (−33)	1 ± 0.1 (−31)	32.5 ± 5.1 (−6)	LOD(*−97*)	229 ± 34.7 (−88)	LOD(*−92*)	LOD(*−97*)	LOD(*−95*)	29.3 ± 7.1 (−59)	6.2 ± 0.6 (−97)

Code	Charcoal	Puff count	CDR	TPM	Tar	Nicotine	CO	MEK	ACETALD	ACET	ACRL	CROT	FORM	PROP
Unit	mg/cig	puffs/cig	mm H_2O	mg/cig	mg/cig	mg/cig	mg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig	μg/cig
j	0	9	130 ± 6.4	28.3 ± 1.3	22.5 ± 0.8	1.8 ± 0	24 ± 1.6	136 ± 9.3	1270 ± 229	511 ± 51.2	108 ± 10.5	38.5 ± 2.9	76.2 ± 15.2	140 ± 8
	100	9	133.4 ± 12.7 (3)	22.9 ± 4.4 (−19)	18.9 ± 3.1 (−16)	1.5 ± 0.1 (−14)	22.9 ± 3.7 (−5)	17.1 ± 9.6 (−87)	576 ± 193 (−55)	99.4 ± 62.9 (−81)	20.7 ± 11.8 (−81)	5.3 ± 1.5 (−86)	59.6 ± 8.6 (−22)	30.8 ± 13.9 (−78)
	200	9	162.6 ± 9.8 (25)	21.9 ± 2.6 (−23)	18.5 ± 1.7 (−18)	1.4 ± 0.1 (−19)	24.6 ± 2.5 (2)	LOD(*−96*)	140 ± 16.8 (−89)	48.8 ± 0 (−90)	LOD(*−95*)	LOD(*−94*)	39.3 ± 4.7 (−48)	LOD(*−96*)
	300	9	179.5 ± 6.8 (38)	18.1 ± 3.9 (−36)	15.6 ± 3.1 (−31)	1.2 ± 0.2 (−33)	21.2 ± 5.7 (−12)	LOD(*−96*)	93.1 ± 24.1 (−93)	31.5 ± 0 (−94)	LOD(*−95*)	LOD(*−94*)	40.8 ± 11.2 (−46)	LOD (*−96*)

Percent change vs. controls in parentheses rounded to nearest integer. Italicized percent change based on limit of quantitation

(LOQ). Numbers without S.D. indicate quantitation limits.

§Value below LOQ. LOD: value < limit of detection of the assay.

(CDR:cigarette draw resistance; n = 3; MEK:2-butanone, ACETALD:acetaldehyde; ACET:acetone; ACRL = acrolein; CROT = crotonaldehyde; FORM = formaldehyde; PROP = propionaldehyde).

Table 4

p-values of cigarette draw resistance, TNCO, and carbonyl yields compared to unmodified cigarettes. Two-tailed Student's t-test between mean constituent yields of control cigarettes and modified cigarettes at specified charcoal level across all products within length class.

Length class	Charcoal (mg)	CDR	TPM	Tar	Nicotine	CO	MEK	ACETALD	ACET	ACRL	CROT	FORM	PROP
King-size	100	0.409	0.480	0.527	0.788	0.634	**5.73E-04**	**0.01**	**0.0019**	**1.07E-05**	**0.0016**	0.13	**0.0010**
	200	0.136	0.356	0.430	0.646	0.973	**1.44E-04**	**0.0017**	**1.27E-04**	**4.12E-06**	**8.21E-04**	**0.02**	**1.66E-04**
	300	**0.02**	0.183	0.256	0.475	0.819	**4.14E-04**	**6.24E-05**	**0.0012**	**1.28E-06**	**6.91E-04**	**0.0052**	**6.48E-05**
	400	**0.006**	0.130	0.216	0.379	0.912	**0.0075**	**1.49E-05**	**<0.001** *	**9.64E-06**	**6.46E-04**	**2.13E-03**	**5.02E-05**
100s	100	0.665	0.265	0.229	0.388	1.000	**5.33E-08**	**0.0015**	**1.43E-06**	**4.35E-05**	**2.80E-06**	**0.03**	**1.24E-05**
	200	0.202	**0.034**	0.058	0.081	0.790	**1.35E-05**	**6.93E-06**	**9.32E-06**	**0.0015**	**<0.001** *	**6.64E-04**	**6.46E-06**
	300	0.108	**0.004**	**0.007**	**0.009**	0.473	**<0.001** *	**3.03E-06**	**1.13E-04**	**<0.001** *	**<0.001** *	**4.95E-04**	**4.17E-04**

p-values based on means above LOD. <0.001

* based on LOQ. Bolded values indicate statistical significance at or below α = 0.05 level.

(CDR:cigarette draw resistance; n = 3; MEK:2-butanone, ACETALD:acetaldehyde; ACET:acetone; ACRL = acrolein; CROT = crotonaldehyde; FORM = formaldehyde; PROP = propionaldehyde).