Published in final edited form as:

Chem Res Toxicol. 2018 August 20; 31(8): 745–751. doi:10.1021/acs.chemrestox.8b00092.

Effect of Charcoal in Cigarette Filters on Free Radicals in Mainstream Smoke

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Abstract

The addition of charcoal in cigarette filters may be an effective means of reducing many toxicants from tobacco smoke. Free radicals are a highly reactive class of oxidants abundant in cigarette smoke, and here we evaluated the effectiveness of charcoal to reduce free radical delivery by comparing radical yields from commercially available cigarettes with charcoal-infused filters to those without and by examining the effects of incorporating charcoal into conventional cigarette filters on radical production. Commercial cigarettes containing charcoal filters produced 40% fewer gas-phase radicals than did regular cellulose acetate filter cigarettes when smoked using the International Organization of Standardization (ISO, $p = 0.07$) and Canadian Intense (CI, $p < 0.01$) smoking protocols. While mean-particulate-phase radicals were 25–27% lower in charcoal cigarettes, differences from noncharcoal products were not significant ($p = 0.06$ – 0.22). When cellulose acetate cigarette filters were modified to incorporate different types and amounts of activated charcoal, reductions in gas-phase (>70%), but not particulate-phase, radicals were observed. The reductions in gas-phase radicals were similar for the three types of charcoal. Decreases in radical production were dose-responsive with increasing amounts of charcoal (25–300 mg) with as little as 25 mg of activated charcoal reducing gas-phase radicals by 41%. In all studies, charcoal had less of an effect on nicotine delivery, which was decreased 33% at the maximal amount of charcoal tested (300 mg). Overall, these results support the potential consideration of charcoal in cigarette filters as a means to reduce exposure to toxic free radicals from cigarettes and other combustible tobacco products.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.chemrestox.8b00092.

Filtration properties of the three different types of activated charcoal selected in this study to examine the effects on cigarette mainstream free radical and nicotine levels (PDF)

The authors declare the following competing financial interest(s): JF has done paid consulting for pharmaceutical companies involved in producing smoking cessation medications including GSK, Pfizer, Novartis, J&J, and Cypress Bioscience, and has received a research grant and study drug from Pfizer (not relating to cigarette emissions or free radical measurement).

INTRODUCTION

Research on the use of filters to reduce toxicants in cigarette smoke has been ongoing since the 1950s when it became evident that many toxic chemicals are generated in a burning cigarette. Inhaling the combustion compounds from cigarette smoke is irrefutably known to lead to lung cancer,^{1,2} chronic obstructive pulmonary disease (COPD),^{3,4} and many other diseases.^{5,6} Thus, harm-reduction approaches which aim to reduce the delivery of cigarette smoke toxicants to smokers are of great interest from a public health perspective. While clearly the best approach to harm reduction is smoking cessation, nicotine addiction results in many smokers continuing to smoke for decades despite numerous attempts to quit.^{7,8} Renewed interests in harm reduction strategies with the passing of The Family Smoking Prevention and Tobacco Control Act in 2009 have rekindled the interest in charcoal filtration as a potentially feasible option.

Charcoal filtration has been used successfully in many household and industrial applications,^{9–12} but it poses several unique challenges for cigarette smoke, including the presence of thousands of chemicals with different properties and wide-ranging concentrations, rapid flow rate and limited contact time, and high humidity and temperature. Despite these challenges, research has shown that activated charcoal can reduce many volatile and semivolatile toxicants in mainstream cigarette smoke, such as hydrogen cyanide, benzene, aldehydes, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, and 1,3-butadiene.^{13–15} The removal efficiency of a compound from cigarette smoke depends on the activity, amount, and distribution pattern of charcoal in the filter.¹⁶ It can also depend on the vapor pressure, molecular weight, and polarity of the compound, among other factors. In a recent study, incremental increases in charcoal loading led to increases in carbonyl filtration efficiency from cigarettes.¹⁷ Charcoal-filtered (CF) cigarettes are commercially available and consist of two basic designs: one with charcoal dispersed throughout the cellulose acetate filter (carbon-on-tow/Dalmatian style) or another where the charcoal is localized in a cavity (plug style). Cigarettes containing charcoal filters are sold in many countries including South Korea, Venezuela, Hungary, and Russia and dominate the market in Japan.^{18–20} This is

distinctly different from the U.S. market, where cellulose acetate filters (AF) without charcoal dominate the market. Curiously, Japanese men have a higher smoking prevalence than other developed countries, but their rates of lung cancer are much lower.^{21–24} This phenomenon, known as the “Japanese smoking paradox”, could be due, in part, to the higher prevalence of CYP2A6 alleles associated with reduced or no activity in the Japanese population.^{25,26} However, it has been speculated that the common use of cigarettes with charcoal filters may also be playing a role in the lower lung cancer rates. While there have been relatively few clinical studies of charcoal-filtered cigarettes, in one study, levels of several biomarkers of tobacco exposure were decreased when smokers switched to cigarettes containing activated charcoal.²⁷

Free radicals represent an important class of toxicants found in abundance in both the gas and particulate phases of tobacco smoke. Using electron paramagnetic resonance spectroscopy (EPR), we have shown wide variation in the levels of gas- and particulate-phase radicals in mainstream smoke from U.S.-marketed cigarettes.²⁸ While gas-phase radicals are in nano-mole ranges, particulate-phase radicals are in much lower concentrations (pmol). These radicals are reactive, and their lifetimes range from a few seconds in the gas phase to days in the particulate phase. Free radicals promote protein oxidation, lipid peroxidation, and DNA damage in cells and tissues. Oxidative damage resulting from free radicals in cigarette smoke has been extensively studied as a potential link between cigarette smoking and the development of a number of smoking-related diseases including cancer,²⁹ cardiovascular disease,³⁰ and COPD.^{31–34} To our knowledge, no published reports exist that investigate the impact of charcoal filtration on free radicals in mainstream cigarette smoke. Because of the highly reactive nature of radicals and their presence in both gas and particulate phases, it is difficult to predict the effectiveness of charcoal filtration at reducing free radicals from cigarette smoke.

Our current aim was to examine the effects of charcoal filtration on free radical levels in cigarette smoke. To this end, we first measured the levels of free radicals delivered from commercially available charcoal filter cigarettes and compared them to those from similar noncharcoal filter cigarettes. Experiments were then conducted to examine the effectiveness of different types and amounts of activated charcoal in modified cigarette filters at removing free radicals from mainstream smoke.

MATERIALS AND METHODS

Cigarette Selection.

The 3R4F and 1R6F research cigarettes were obtained from the University of Kentucky (Lexington, Kentucky, U.S.)³⁵ in 2015 and 2016, respectively. Commercially available AF-containing cigarettes, king size (85 mm), were purchased locally (Dauphin and Lebanon Counties, PA, U.S.) in 2016–2017. The four AF cigarette brand varieties were selected to represent U.S. popular brands with varying filter ventilation (Newport Red, 3%; Camel Blue, 32%; Marlboro Silver, 46%; Pall Mall Orange, 58%). Commercially available CF-containing cigarettes Parliament Aqua, Kent, Mevius, Seven Star, and Lark were obtained online in 2015 (<http://www.ciggiesworld.com>). All of the cigarettes were stored over the long term in their original packaging at –20 °C in airtight plastic bags.

Materials.

Analytical grade chemicals nitron spin trap phenyl-*N-tert*-butylnitron (PBN), *tert*-butylbenzene, (2,2,6,6-tetramethyl-piperidin-1-yl)oxyl (TEMPO), and 1- λ 1-oxidanyl-2,2,6,6-tetramethyl-piperidin-4-ol (TEMPOL) were obtained from Sigma-Aldrich (St. Louis, MO, U.S.). Different types of activated charcoal (A = anasorb 747, B = CSC, and C = JXC (SKC Inc., Eighty Four, PA, U.S., material characteristics provided in Supporting Information Table S1)), Suprasil EPR tubes (4 mm o.d.; Wilmad-Labglass, Vineland, NJ, U.S.), Schlenk line (Chemglass Life Sciences, Vineland, NJ, U.S.), 500–750 μ m glass beads (Fisher Scientific, PA, U.S.), and Cambridge filters pads (CFP, Performance Systematix Inc., Grand Rapids, MI, U.S.) were used as supplied. Cigarette holders (Hleeduo ZB-033) were purchased online from Amazon.

Experimental Design and Construction of Modified Cigarettes Containing Charcoal in the Filters.

Our overall experimental approach to the modified cigarette filter construction was similar to that of a previous paper.³⁶ Briefly, premade 25 mm cellulose acetate filters from 1R6F cigarettes were cut perpendicular to their length into two pieces: mouth end (10 mm) and tobacco end (15 mm). The two ends of the filter were inserted into each end of a cigarette holder creating a central cavity and, thus, a plug-space-plug configuration (shown schematically in Figure 1). The cavity was filled with 0–300 mg of preweighed activated charcoal with the remaining space filled with glass beads (500–750 μ m). Charcoal and glass beads were weighed using an analytical balance. This modification resulted in increasing the overall length of the cigarette from 85 to 100 mm. Care was taken to ensure that the cavity was tightly packed and that filter ventilation holes on the filter were completely blocked by the cigarette holder. The plug design ensured that no charcoal could escape into the mainstream smoke and interfere with the EPR signal.

Mainstream Smoke Generation.

The cigarettes were conditioned for testing by removing them from cold storage and placing them in a constant humidity chamber (60% relative humidity, 22 °C) for at least 24 h before smoking. Mainstream smoke was generated by a single-port smoking machine (Human Puff Profile Cigarette Smoking Machine (CSM-HPP), CH Technologies, NJ, U.S.). The cigarettes were smoked to the marked length of the filter overwrap (tipping) plus 3 mm according to the International Organization of Standardization (ISO 3308:2012) standard smoking regimen (35 mL puff volume, 60 s puff interval, 2 s duration, and filter vents not blocked)³⁷ and Canadian Intense (CI) smoking regimen (55 mL puff volume, 2 s duration, 30 s puff interval, and filter vents blocked).³⁸ The modified cigarettes were smoked only with the CI method. Mainstream smoke was separated into particulate phase and gas phase by passing through a Cambridge filters pad (CFP). There were 3–4 cigarettes smoked for each condition.

Nicotine.

The total nicotine from mainstream smoke was trapped onto CFP, extracted as previously described, and analyzed by gas chromatography with flame ionization detection (GC-FID)³⁹.

Analysis of Free Radicals.

All free radicals were analyzed on a Bruker eScan R spectrometer (Bruker-Biospin, Billerica, MA, U.S.) operating in X-band, similar to previous reports.^{28,40} Briefly, concentrations of particulate-phase radicals trapped on a CFP were obtained by direct insertion of the CFP into the cavity of the EPR. The gas-phase radicals were trapped in an impinger containing *tert*-butylbenzene and 0.05 M PBN and were deoxygenated before obtaining EPR spectra. The spin quantification of the gas-phase radical signals to obtain double integral was performed in MatLab. Conversion factors from double integral values to spin concentrations were obtained from the known concentrations of a stable radical standard, TEMPO.

Statistical Analysis.

Statistical analyses comparing charcoal filter to conventional cellulose acetate filter cigarettes were performed using Microsoft Excel. Gas-phase and particulate-phase radicals and nicotine yields with different charcoal amounts were analyzed using a one-way ANOVA coupled with a Tukey's Multiple Comparison test using GraphPad Prism (San Diego, CA). A $p < 0.05$ was used to identify significant differences.

RESULTS

Evaluation of Free Radicals in Commercially Available Charcoal-Filtered Cigarettes.

We were able to obtain five brands of commercial charcoal-filter (CF)-containing cigarettes (Lark, Parliament, Kent, Seven Stars, and Mevius) and compared the levels of radicals to those of cellulose acetate filter (AF) research cigarettes (3R4F and 1R6F) and four popular commercial AF cigarettes (Marlboro Silver, Camel Blue, Pall Mall Orange, and Newport Red) under ISO and CI methods. Despite the fact that there were wide variations in the levels of gas- and particulate-phase radicals in both CF and AF cigarettes, radical levels tended to be lower for CF brands (Figure 2). On average, gas-phase radicals from CF cigarettes were 41% ($p = 0.07$) and 47% ($p < 0.01$) lower than those from AF cigarettes when smoked under ISO and CI methods, respectively. Similarly, particulate-phase radicals from CF cigarettes were 27% ($p = 0.06$) lower than those from AF cigarettes when smoked under the ISO method. When compared using the CI method, CF cigarettes were 25% lower in particulate-phase radicals than were AF cigarettes, but the results were not statistically significant ($p = 0.22$).

To examine the design and charcoal distribution of the commercial charcoal filters, they were cut open and examined visually (Figure 2). All of the CF cigarettes tested were of the carbon-on-tow design where the charcoal was distributed evenly across a small portion of the filter. While lower levels of radicals were observed with the CF cigarettes, we are unable to attribute this difference directly to the CF. Other design features for which we were unable

to control for, such as tobacco type and paper porosity, may also be involved. Thus, for further experiments, we decided to experimentally modify cigarette filters in a controlled manner to examine the specific effects of charcoal addition.

Effect of Different Types of Charcoal on Free Radical and Nicotine Levels in Cigarette Smoke.

Three different types of activated charcoal (Supporting Information Table S1) made from different sources and with different filtration properties were selected to examine the filtration of free radicals and nicotine from cigarette mainstream smoke. We found that all 3 types of charcoal (300 mg each of A, B, and C; plug design) significantly reduced gas-phase radicals by more than 70% compared to the control cigarettes (300 mg glass beads) when the cigarettes were machine smoked under the CI protocol (Figure 3). Of particular note, the puff count and TPM did not change significantly by the addition of charcoal or glass beads. The C-type charcoal, which is a petroleum residue product, was most effective, reducing gas-phase radicals by 88%. Charcoal also reduced nicotine yields by 10–33% based on the charcoal type. However, all charcoal types tested were ineffective at reducing particulate-phase radicals from mainstream smoke even with these high amounts of charcoal.

Dose-Dependent Reduction in Gas-Phase Radical Yields with Increasing Amounts of Charcoal.

On the basis of the effectiveness of the C charcoal to filter gas-phase radicals, we conducted further experiments to examine the dose dependency of the charcoal filtration efficiency. Gas-phase and particulate-phase radicals and nicotine were measured in smoke from cigarettes with different amounts of charcoal ranging from 0 to 300 mg, with the balance of the cavity filled with glass beads to prevent drastic changes in flow and resistance. Results demonstrated that gas-phase radicals were reduced (41–88%) in a dose-dependent manner with the increasing amounts of charcoal (25–300 mg) (Figure 4). Nicotine yields were also reduced, but to a lesser extent, 6–31%, with increasing amounts of charcoal. As expected, on the basis of results with different types of charcoal (Figure 3), particulate-phase radicals were not impacted by the addition of C charcoal.

DISCUSSION

In this study, we show that charcoal filtration is effective at removing most gas-phase radicals but not particulate-phase radicals from cigarette mainstream smoke. This finding is rather surprising considering that there are many different radical species in cigarette smoke⁴¹ and it might be expected that charcoal would be effective at reducing the more volatile low molecular weight radicals found in the particulate phase but not the more bulky radicals.^{16,42} Conversely, we also might expect there to be some relatively higher molecular weight or more polar radicals in the gas phase that would not be efficiently reduced. While this is the first report on the effectiveness of charcoal for removing radicals, the results are consistent with previous studies showing compound-specific differences in the selective filtration of cigarette smoke. Overall, charcoal is efficient at reducing many gas-phase toxicants from mainstream tobacco smoke but not bulky particulate-phase chemicals or gases such as carbon monoxide.^{42–45} The filtration efficacy of smoke toxicants by charcoal

can be influenced by the activity, composition, configuration, and loading of the charcoal.⁴³ In this study, we examined the characteristics of charcoal that are relevant for overall cigarette filter design. A study showed that polymer-derived charcoal was more effective at removing gas-phase toxicants compared to coconut-shell-derived charcoal, likely due to the larger surface area and pore volume.³⁶ Our results show that different types of activated charcoal did not differ significantly in their ability to adsorb gas-phase radicals.

As little as 25 mg of activated charcoal was effective in reducing gas-phase radicals by 41%. While 300 mg of charcoal was the most effective level, reducing gas-phase radicals by 88%, it also reduced nicotine by 30%. In a previous study, up to 200 mg of charcoal was incorporated into filters without affecting draw resistance.¹⁷ In the current experiments, we did not measure draw resistance, but even with the highest levels of charcoal, no differences in the numbers of puffs taken per cigarette were observed, suggesting that any effects on draw were minimal. We also did not test free radical production at charcoal levels beyond 300 mg due to anticipated increases in draw resistance, greater nicotine reduction, and potential complications concerning the incorporation of such large amounts during cigarette manufacture. While using high levels of charcoal in filters may have limited feasibility, CF cigarettes with 45–180 mg of charcoal are currently commercially available.^{15,17} Others have shown that a cavity of only ~3 mm in the filter is sufficient to accommodate up to 100 mg of charcoal, an amount which substantially reduces gas-phase radicals.¹⁷ Our current experimental approach to the construction of a modified filter was to demonstrate proof of principle rather than provide information on potential design strategies.

For experiments with the experimentally modified filters, free radical delivery was measured using only the Canadian Intense (CI) smoking regimen, which entails larger and more frequent puffs than does ISO and entails the blocking of all filter vents. This was necessitated because the filter modification involved covering the vent holes, prohibiting the use of the ISO protocol. Even under such intense smoking conditions where larger breakthroughs and reduced charcoal trapping efficiencies are reported,^{36,45} we observed significant reductions in gas-phase radicals when charcoal was incorporated into the cigarette filter. Thus, it is likely that, under less intense smoking conditions, the efficacy of gas-phase radical trapping will be similar or even greater.

We also observed that the five brands of commercial CF cigarettes tested produced lower levels of free radicals than those of AF cigarettes, including both commercial brands and research cigarettes. The CF cigarettes included Seven Star and Mevius (previously sold as Mild Seven), which are popular Japanese brands,⁴⁶ and Lark, Kent, and Parliament, which are manufactured by U.S. companies but primarily for international distribution. All CF cigarettes were obtained from online retailers because CF cigarettes have virtually no market share currently in the U.S., perhaps due to higher manufacturing costs and/or reductions in taste satisfaction. All CF cigarettes tested incorporated carbon-on-tow charcoal filtration designs with the charcoal granules mixed into the part of the filter away from the mouth end. We were unable to obtain information on the type and amount of charcoal used in these filters. Visual examination indicated only a light charcoal coating (<50 mg) in one segment of the filter. This is consistent with previous studies that found most commercial CF brands contain charcoal in relatively small amounts.^{15,47} For the commercially available CF

cigarettes, we could not obtain counterpart “control” AF cigarettes; thus, several popular U.S. brands were used for comparison. In a previous comparison study, we showed that these brands are typical of popular U.S. brands for gas-phase radical delivery.²⁸ While the differences in radical delivery between the CF and AF cigarettes tested may be due to the presence of charcoal, it is also possible that differences in other cigarette design factors such as tobacco blend or ventilation may be involved.

The health risks associated with smoking are dose-related to toxicants and are affected by the number of cigarettes smoked per day and years smoked. Some tobacco harm reduction strategies aim to decrease mortality and morbidity without eliminating tobacco and nicotine use by replacing traditional cigarette smoking by potentially reduced-exposure products (PREPs).⁴⁸ This is an approach that is particularly appealing to those individuals that are unable to quit due to their addiction. While CF cigarettes may represent one such reduced-exposure product, there is limited data on the long-term health consequences related to smoking CF cigarettes.⁴⁴ In short-term studies, glutathione (GSH) levels were higher in CF smokers⁴⁹ suggesting lower oxidative stress. However, GSH induction can also be a sign of increased oxidant exposure. The selective elimination of gas-phase radicals, but not particulate-phase radicals, from mainstream smoke also has unknown health implications. To date, there is little data on the relative toxicity of different types of radicals and their impact on cigarette-associated harm to help inform this issue. In the U.S. market, cellulose acetate filtered cigarettes saw a dramatic rise in sales from 0.5% in 1950 to more than 97% by 1997 as machine-smoked tar delivery dropped from 38 to 12 mg and as consumers became aware of the toxicity of cigarettes.⁵⁰ This shows that consumers are seeking a “safer” cigarette with fewer toxic agents. There are no studies to conclude that charcoal filter cigarettes are indeed safer. Charcoal filter cigarettes have had poor acceptance in U.S. perhaps due to the altered sensory characteristics of smoke, it should also be cautioned that the use of charcoal filters would likely have no impact on radical exposure to passively exposed individuals. Concern has also been raised regarding the health effects of inhaling charcoal granules released from the filters.⁵¹ Finally, there are concerns regarding the “safer cigarette” strategy as it might lead to a lessening of the public’s concern about the negative health effects of smoking, resulting in increases in smoking initiation and reductions in quitting.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Funding

This work was supported in part by the National Institute on Drug Abuse of the National Institutes of Health and the Center for Tobacco Products of the U.S. Food and Drug Administration (under award number P50-DA-036107). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the Food and Drug Administration.

ABBREVIATIONS

CFP	Cambridge filter pad
EPR	electron paramagnetic resonance spectroscopy
ISO	International Organization of Standardization
CI	Canada Intense

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Figure 1.

Pictorial representation showing the construction of a modified 1R6F charcoal filter cigarette. Both ends of the filter were inserted into a cigarette holder to create a plug–space–plug configuration that was tightly packed with charcoal and glass beads. Ventilation holes on the filter were completely blocked in the modified cigarette.

Figure 2.

(a) Gas- and particulate-phase free radical yields from a commercial charcoal filter (CF) and cellulose acetate filter (AF) per cigarette under ISO and CI standardized smoking regimens. (b) Photographs showing the design and distribution of charcoal in the commercial cigarettes filters used in this study. All of the cigarettes tested were of the carbon-on-tow design where the charcoal was distributed evenly across a portion of the filter. ISO = machine smoked with 35 mL puff volume, 60 s puff interval, 2 s puff duration, and filter vents open; CI = machine smoked with 55 mL puff volume, 30 s puff interval, 2 s puff duration, and filter vents 100% blocked. Values are mean $\pm$ standard deviation ($n = 3-4$).

Figure 3.

Free radical and nicotine yields per cigarette with 300 mg of charcoal of different types (A–C) compared to 300 mg glass beads incorporated in the 1R6F cigarette filter as the plug design. Cigarettes were smoked with the CI standardized smoking regimen. Values are mean $\pm$ standard deviation ($n = 3-5$). Different letters indicate significantly different ($p < 0.05$) values, and ns indicates not significant.

Figure 4.

Free radical and nicotine yields per cigarette with 0–300 mg type C charcoal incorporated in the 1R6F cigarette filter as the plug design. Cigarettes were smoked with the CI standardized smoking regimen. Values are mean $\pm$ standard deviation ($n = 5-6$). Different letters indicate significantly different ($p < 0.05$) values.