Short Communication

Digital Image Analysis of Cigarette Filter Stains as an Indicator of Compensatory Smoking

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Abstract

Objective: Cigarette filters trap a significant portion of carcinogen-containing smoke particulate and may provide an indication of cigarette constituent exposure. A technique for quantifying filter tar staining with digital imaging has shown predictive value between typical total puff volume and filter tar stain intensity. The current study uses smoking topography data acquired during an examination of compensatory smoking of Quest cigarettes and digital analyses of the tar stains of the spent Quest cigarette filters. Due to reduced nicotine levels, we hypothesized compensatory smoking to occur. The purposes of the current study were to describe the physical characteristics of the Quest cigarettes, to further validate the effect of puff volume on filter tar staining, and to examine the effect of compensatory smoking on changes in filter tar staining, hypothesizing that compensatory smoking would result in more intense tar staining.

Methods: Physical characteristics of the Quest cigarettes were measured to characterize the product. Spent cigarette filters were digitally analyzed for color intensity features, matched to smoking topography measures, and examined in regression models. Difference scores for digital imaging and smoking topography were used in a regression model to identify the effect of compensatory smoking on tar stain.

Results: Total puff volume was a significant predictor of $a^*$center (redness) [$\beta = 0.003 (SE, 0.0004), R^2 = 0.42, t = 7.87, P < 0.001$] and $L^*$center (lightness) [$\beta = -0.015 (SE, 0.002), R^2 = 0.45, t = -8.18, P < 0.001$] for Quest cigarettes and a significant predictor of $a^*$center [$\beta = 0.003 (SE, 0.0005), R^2 = 0.37, t = 5.27, P < 0.001$] and $L^*$center [$\beta = -0.009 (SE, 0.002), R^2 = 0.35, t = -5.05, P < 0.001$] for own preferred brand. Regression models indicate total puff volume difference was a significant predictor of $L^*$center difference [$\beta = -0.01 (SE, 0.003), R^2 = 0.171, t = -3.15, P = 0.003$] and approached significance for $a^*$center difference [$\beta = 0.002 (SE, 0.001), R^2 = 0.057, t = 1.99, P = 0.053$].

Conclusion: Results suggest that compensatory smoking may be detectable by darkening and reddening of the tar stain. This type of measure could be useful in quantifying the extent to which human smokers smoke differently than standard testing protocols and in assessing the prevalence of compensatory smoking in population samples. (Cancer Epidemiol Biomarkers Prev 2006;15(12):2565–9)

Introduction

There is substantial variation in how people smoke cigarettes (1), including the type of cigarettes smoked, the number of cigarettes smoked daily, and how each individual cigarette is smoked, including number of puffs, puff volume, duration, and velocity (collectively referred to as smoking topography). Nicotine delivery drives dependent smokers’ smoking topography (2, 3), but topography also affects exposure to the harmful compounds in cigarette smoke (4–7). Evidence of nicotine-driving smoking behavior is seen in brand-switching studies, where smokers are switched to lower nicotine cigarettes (8), and in cigarette reduction studies, where smokers smoke fewer allotted daily cigarettes more intensely to obtain nicotine (4).

The effect of smoking behavior on cigarette smoke toxin exposure has been shown by measuring carbon monoxide boost (9, 10) and carcinogen levels (6, 7, 11). A limitation of some biomarkers, particularly those measured in urine and saliva, is that they are not sensitive to the smoking of individual cigarettes. Knowing the effect of smoking behavior at the per-cigarette level is important because, as Harris (12) showed, smoke constituent compounds do not increase at the same rates during compensatory smoking. Although Bernstein (13) reported that puff volume has no effect on size of particulate matter capable of reaching the lung, others have suggested that puffing can affect which products are generated within the tobacco rod (14, 15). Furthermore, Hecht et al. (6, 7) have shown that when number of cigarettes smoked per day is restricted, carcinogen biomarkers do not decrease in a manner proportionate with the reduced number of cigarettes, showing that compensatory smoking at the per-cigarette level can minimize any perceived harm reduction in smoking fewer cigarettes. It is therefore reasonable to postulate that smoking more intensely may not only expose a smoker to greater quantities of toxin but also to different proportions and types of toxicants.

Cigarette filters trap a significant portion of the smoke particulate matter during smoking and, therefore, may provide an indication of particulate exposure to the smoker (16, 17). Kozlowski (16) first reported a strong positive correlation between number of puffs and intensity of tar stain using a visual scoring mechanism. Others have reported on more subtle smoking behaviors and tar stains (18, 19) as well as on the effect of blocking filter vents on tar staining (20).
O’Connor et al. have refined a technique for quantifying filter tar staining with digital imaging (21, 22) that has shown predictive value discriminating between blocked and unblocked filter vents. Recently, O’Connor et al. showed a relationship between smokers’ typical total puff volume and filter tar stain intensity (23) using the CIELAB color system (24). A limitation noted by the authors was the inability to link smoking topography measures to specific cigarette filters. Mean smoking topography measures were compared with mean tar stain measures. In addition, variability in cigarette type and ventilation levels required analyses of both the edge and core of the filter stain.

A new type of potential reduced exposure product, Quest, uses genetically modified tobacco to provide three “steps” of gradually reduced nicotine. Unlike Light cigarettes, because the nicotine content of the rod itself is reduced, smoking Quest cigarettes more intensely should not allow the smoker to extract additional nicotine. Yet, smokers are often unaware of the complexities of cigarette design and may continue to attempt to extract nicotine by increased puffing behavior. A recent publication has reported that smokers initially increase their total puff volume when smoking the lowest-nicotine (0.05 mg) Quest cigarette compared with the highest-nicotine (0.6 mg) Quest cigarette and, subsequently, have a significant increase in carbon monoxide boost (25). The current study uses the smoking topography data from the Quest cigarettes and digital analyses of the tar stains of the spent Quest cigarette filters. The purposes of the current study were to (a) describe the physical characteristics of the Quest cigarettes; (b) to further validate the effect of puff volume on filter tar staining, by linking smoking topography data to specific cigarette filters; and (c) to examine the effect of compensatory smoking on changes in filter tar staining, hypothesizing that compensatory smoking would result in more intense tar staining.

Materials and Methods

Participants and Procedures. Participants were recruited via community-based flyers, and eligibility was determined by telephone. Eligibility requirements included being over age 18, report smoking at least 10 daily cigarettes, smoking for a minimum 5 years, not currently trying to quit smoking, report inhaling when smoking, not currently using nicotine replacement therapies, and not consuming >25 alcohol-containing drinks per week. Procedures are provided in detail elsewhere (25), but briefly, participants smoked four cigarettes using the Clinical Research Support System (CReSS) desktop smoking topography machine (Flowshare, Baltimore, MD). The first cigarette was always their own preferred brand cigarette followed by Quest 1 (0.6 mg nicotine), Quest 2 (0.3 mg nicotine), and Quest 3 (0.05 mg nicotine) cigarettes. Quest cigarette nicotine level was blinded to researcher and participant, and order of presentation was randomized and counterbalanced across participants to minimize order effects. All cigarettes were smoked 30 minutes apart. Used cigarette filters were stored at −80°C in labeled plastic re-sealable bags until analysis. Fifty participants was determined as an appropriate sample size based on effect sizes (ES = 0.4) from previous smoking topography studies (5, 9), with α set to 0.05 for a two-tailed test, and power >80% to detect between-cigarette nicotine level differences in total puff volume. The study was approved by the University Institutional Review Board.

Measures

Smoking Topography. Cigarettes were smoked using the CReSS smoking topography machine (Flowshare). The smoking topography device employs a pressure transducer that measures pressure changes during puffing. Pressure changes are amplified, digitized, and sampled at 1,000 Hz, and software converts signal to airflow (mL/s) in real time (s), which is subsequently converted to data. Cigarettes are placed in a sterilized mouthpiece during smoking. This device has been previously used in our laboratory to assess smoking behavior (5, 9), has been shown to be a valid and reliable means to measure smoking behavior (26), and was calibrated before each session.

Imaging Techniques. The specifics of the imaging system and technique are described in greater detail elsewhere (22, 23). In brief, the system involves using a color CCD digital camera (DFW-x710, Sony USA, New York, NY) to capture a 1024 × 768 pixel resolution image of a cigarette butt (mouth end) and then processing that image to extract color information from the center of the spent filter, as well as a 7-pixel-wide ring around the outside of the filter. All image processing and analysis is done using MATLAB (The Mathworks, Natick, MA). Red, Green, Blue (RGB) values captured by the camera are converted to the CIELAB color space (L* or lightness, a* or red-green, and b* or yellow-blue) using standard formulas (see ref. 24). Each filter imaged then receives six imaging values: L*, a*, and b* at each of the center and the edge of the filter.

Physical Characteristics of Cigarettes. New Quest cigarettes were assessed for physical characteristics, including total cigarette length, diameter, tobacco rod length, filter length, tipping paper length, tobacco mass, filter mass, filter components length and mass, pressure drop, and ventilation. Lengths were measured using digital calipers (VWR, Philadelphia, PA); mass was assessed using a digital analytic balance (AB-104s, Mettler-Toledo, Columbus, OH); and pressure drop and ventilation was measured using a KC-3 apparatus (Borgwaldt-KC, Richmond, VA). Results are in Table 1.

Analytic Plan. Participants, Quest cigarettes, smoking topography measures, and CIELAB data were characterized using descriptive statistics. We hypothesized that L*center score, a measure of lightness, and a*center, a measure of redness to greenness, would be most responsive to total puff volume, as observed previously (17, 23). We addressed these questions using (linear) regression methods, using the robust variance estimate to account for the repeated measures. Model 1 examined the effect of total puff volume on L*center and a*center which first examined for the Quest cigarettes only, controlling for cigarette nicotine level. Model 2 examined the effect of total puff volume on L*center and a*center using the participant own brand cigarettes, which varied substantially in standard tar and nicotine yield, as well as design

Table 1. Descriptive characteristics of Quest cigarettes

<table>
<thead>
<tr>
<th>Quest 1</th>
<th>Quest 2</th>
<th>Quest 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported nicotine level (mg)</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Reported tar level (mg)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Cigarette length (mm)</td>
<td>24.9</td>
<td>24.9</td>
</tr>
<tr>
<td>Cigarette diameter (mm)</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Tobacco mass (g)</td>
<td>0.60</td>
<td>0.57</td>
</tr>
<tr>
<td>Tipping paper length (mm)</td>
<td>30.0</td>
<td>30.1</td>
</tr>
<tr>
<td>Filter length (mm)</td>
<td>24.9</td>
<td>24.8</td>
</tr>
<tr>
<td>Filler length, mouth end (mm)</td>
<td>12.1</td>
<td>12.0</td>
</tr>
<tr>
<td>Total filter mass (g)</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Filter mass, mouth end (g)</td>
<td>0.071</td>
<td>0.073</td>
</tr>
<tr>
<td>Filter mass, rod end (g)</td>
<td>0.068</td>
<td>0.068</td>
</tr>
<tr>
<td>Filter carbon mass (g)</td>
<td>0.100</td>
<td>0.102</td>
</tr>
<tr>
<td>Pressure drop (mm H2O)</td>
<td>111.1 (1.1)</td>
<td>101.5 (1.4)</td>
</tr>
<tr>
<td>Ventilation (%)</td>
<td>1.1 (0.1)</td>
<td>1.4 (0.1)</td>
</tr>
</tbody>
</table>

NOTE: Pressure drop and ventilation are measured on 20 sticks of a freshly opened pack. Physicals are measured on five rods from freshly opened pack. Weights derived from combined mass of five rods per filter divided by five.

*The readability of the ventilation tester is ± 1%; thus, these are essentially 0.
characteristics, such as ventilation. Analyses were repeated (models 3 and 4) using mean puff velocity as the predictor for tar staining. Puff velocity has predicted tar staining during machine-based smoking simulation (17) and with other biomarkers (9). Finally, difference scores were calculated between the highest and lowest nicotine Quest cigarettes for total puff volume, L*center (lightness) and a*center (redness/greenness), to be used as measures of compensatory smoking. Models 5 and 6 used puff volume changes to predict tar stain changes.

Results

Descriptive Statistics. Fifty participants (54% male) completed the laboratory session, thus providing 200 cigarette filters. Three filters of participant own brand could not be digitally analyzed due to filter damage. Participant characteristics are presented elsewhere in extensive detail (25), but briefly, participants reported smoking about a pack per day (21.3; SD, 8.1; range, 10-40) and had moderate nicotine dependence scores 5.5 (SD, 1.9; range, 2-10; FTND; ref. 27). Fifty percent of participants usually smoked a Regular brand cigarette, 48% smoked Light brand cigarettes, and 2% Ultra-Light brand cigarettes.

In general, the three versions of Quest were nearly identical in terms of cigarette construction. Unlike virtually all other Light cigarettes, none of the Quest cigarettes had measurable filter ventilation (indeed, no holes are visible under a ×5 magnification lens). This meant that uniform smoke flow through the filter could be expected, and center scores would be sufficient to examine. The ratios of edge scores to center scores tended to be around 1.

Mean total puff volume was 615.43 mL (SE, 17.5), and mean puff velocity was 34.92 mL/s (SE, 0.63). Mean total puff volume and mean puff velocity for each Quest cigarette level and participant own brand are reported in Table 2. Mean L*center (lightness) score was 72.65 (SE, 0.32), and mean a*center (redness/greenness) score was 0.98 (SE, 0.08). L*center and a*center values for each Quest cigarette level and participant own brand are reported in Table 2.

Regression Models: Smoking Topography and Filter Stains

Model 1: Total Puff Volume and Tar Stain (Quest Cigarettes). When controlling for Quest cigarette nicotine level, total puff volume was a significant predictor of a*center (redness/greenness) [β = 0.003 (SE, 0.0004), R² = 0.42, t = 7.87, P < 0.001] and L*center (lightness) [β = −0.015 (SE, 0.002), R² = 0.45, t = −8.18, P < 0.001].

Model 2: Total Puff Volume and Tar Stain (Own Brand Cigarettes). In a model using own brand cigarette data, total puff volume was a significant predictor of a*center (redness/greenness) [β = 0.003 (SE, 0.0005), R² = 0.37, t = 5.27, P < 0.001] and L*center (lightness) [β = −0.009 (SE, 0.002), R² = 0.35, t = −5.05, P < 0.001].

Model 3: Mean Puff Velocity and Tar Stain (Quest Cigarettes). When controlling for Quest cigarette nicotine level, mean puff velocity was not a significant predictor of a*center (redness/greenness) [β = −0.012 (SE, 0.012), R² = 0.10, t = −1.04, P = 0.303] or L*center (lightness) [β = 0.074 (SE, 0.054), R² = 0.11, t = 1.39, P = 0.171].

Model 4: Mean Puff Velocity and Tar Stain (Own Brand Cigarettes). In a model using own brand cigarette data, mean puff velocity was not a significant predictor of a*center (redness/greenness) [β = 0.006 (SE, 0.027), R² = 0.02, t = 0.22, P = 0.831] or L*center (lightness) [β = 0.020 (SE, 0.090), R² = 0.02, t = 0.22, P = 0.828].

Models 5 and 6: Compensatory Smoking. We assessed compensatory smoking by first creating difference scores between the greatest-nicotine level Quest cigarette and the lowest-nicotine level Quest cigarette. Total puff volume difference was defined as the total puff volume obtained during smoking of the 0.6 mg nicotine cigarette minus total puff volume obtained during smoking of the 0.05 mg nicotine cigarette, whereby negative values would indicate compensatory smoking for the lower nicotine level cigarette. L*center difference was defined as L*center score for 0.6 mg nicotine cigarette minus L*center score for 0.05 mg nicotine cigarette, whereby a positive value would indicate a darkening of the tar stain. a*center difference was defined as a*center score for 0.6 mg nicotine cigarette minus a*center score for 0.05 mg nicotine cigarette, whereby a positive value would indicate a reddening of the tar stain.4 Regression models indicate total puff volume difference was a significant predictor of L*center (lightness) difference [β = −0.01 (SE, 0.003), R² = 0.171, t = −3.15, P = 0.003] and approached significance for a*center (redness/greenness) difference [β = 0.02 (SE, 0.001), R² = 0.057, t = 1.99, P = 0.05]. These results suggest that compensatory smoking may be detectable by darkening (L*center) and reddening (a*center) of the tar stain (Fig. 1).

Discussion

This study is the first to match participant smoking topography to tar stain patterns that have been digitally analyzed. Furthermore, this study used filters that seem to be nearly identical on several physical characteristics that have been shown to affect smoking topography and the pattern of tar stains (5, 22). Total puff volume was a significant predictor of a*center (redness/greenness) and L*center (lightness), such that increases in total puff volume lead to increased reddening.

Table 2. Smoking topography and tar stain image values by cigarette type and overall

<table>
<thead>
<tr>
<th></th>
<th>Quest 1</th>
<th>Quest 2</th>
<th>Quest 3</th>
<th>Own brand</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total puff volume (mL)</td>
<td>540.6 (20.5)</td>
<td>518.1 (20.6)</td>
<td>570.5 (22.2)</td>
<td>827.1 (50.9)</td>
<td>615.4 (17.5)</td>
</tr>
<tr>
<td>Mean puff velocity (mL/s)</td>
<td>34.5 (1.3)</td>
<td>34.4 (1.3)</td>
<td>35.1 (1.4)</td>
<td>35.6 (1.2)</td>
<td>34.9 (0.63)</td>
</tr>
<tr>
<td>a*center</td>
<td>0.51 (0.1)</td>
<td>0.56 (0.1)</td>
<td>0.99 (0.1)</td>
<td>1.92 (0.2)</td>
<td>0.98 (0.08)</td>
</tr>
<tr>
<td>a*edge</td>
<td>−0.03 (0.1)</td>
<td>0.17 (0.1)</td>
<td>0.27 (0.1)</td>
<td>0.13 (0.1)</td>
<td>0.134 (0.04)</td>
</tr>
<tr>
<td>b*center</td>
<td>20.7 (0.3)</td>
<td>20.0 (0.3)</td>
<td>21.0 (0.3)</td>
<td>21.6 (0.2)</td>
<td>20.8 (0.14)</td>
</tr>
<tr>
<td>b*edge</td>
<td>18.3 (0.5)</td>
<td>18.3 (0.3)</td>
<td>18.7 (0.3)</td>
<td>16.3 (0.6)</td>
<td>17.9 (0.20)</td>
</tr>
<tr>
<td>L*center</td>
<td>74.4 (0.4)</td>
<td>74.4 (0.5)</td>
<td>72.3 (0.5)</td>
<td>69.2 (0.7)</td>
<td>72.6 (0.3)</td>
</tr>
<tr>
<td>L*edge</td>
<td>76.1 (0.4)</td>
<td>75.7 (0.5)</td>
<td>74.6 (0.5)</td>
<td>75.8 (0.7)</td>
<td>75.6 (0.3)</td>
</tr>
</tbody>
</table>

NOTE: Data are presented as mean (SE). Total puff volume refers to the sum of all puffs taken; mean puff velocity is defined as the mean of all velocities obtained for each puff. a* refers to redness/greenness color space measure; b* refers to the yellowness/blueness color space measure; L* refers to lightness color space measure. Center refers to the central core of the cigarette filter and edge refers to the outer edge of the cigarette filter.
and darkening of the tar stain. However, mean puff velocity was not a significant predictor of any of the digital imaging values. Because previous research of varying puffing variables, including puff velocity, had been shown to affect tar stain intensity, we had hypothesized to observe similar results. The lack of association may be attributable to the use of mean puff velocity values as opposed to identical, repeating puff velocity values, as used in prior research using machine-driven syringes to mimic puff behavior (17, 28).

The physical characteristics of the Quest cigarettes were similar across the three nicotine levels. Quest cigarette size was most similar to king size (85 mm) cigarettes: none of the filters seem to be ventilated, and all are similarly constructed for each of the three nicotine levels; pressure drop, a measure of draw resistance, was comparable across the three nicotine levels. Thus, the most plausible explanation for observed differences in tar staining would be differential puffing on the cigarettes.

Changes in a*score and L*score were related to changes in total puff volume between the highest-nicotine level Quest cigarette and the lowest-nicotine level Quest cigarette. Results suggest that a darker red tar stain results from compensatory smoking. Hence, relative changes in the intensity of tar staining (particularly darkening and reddening) may be useful as an indicator of per-cigarette compensatory smoking. A measure such as this could be useful for a number of applications, including quantifying the extent to which human smokers smoke differently than smoking machines. For example, butts from a cigarette smoker could be compared with the same brand smoked under FTC/ISO conditions, and the relative difference in color would serve as a compensation index. This measure is sensitive to relatively small changes in color, by virtue of using the CIELAB system (cf. 24), meaning that the imaging analysis could reveal compensation where the human eye might not discern a color difference.

The value of digital imaging as a technique for assessing compensatory smoking can be illustrated by a few examples, based on the generated regression equations. An a*score difference of $-0.441$ would be indicative of zero compensation, and any value greater would indicate compensation. An a*score difference of $-0.511$ would mean compensation of $35$ mL occurred, the volume of a puff during standardized cigarette testing. An L*score difference of $1.814$ would suggest no compensation, and any value greater would be indicative of compensation. An L*score difference score of $2.164$ would suggest $35$ mL greater volume taken when smoking the $0.05$ mg nicotine cigarette.

Another application of our results could pertain to reduced-cigarette smoking studies. Some smokers may attempt to reduce harm exposure by smoking fewer daily cigarettes. However, research suggests that the decrease in number of daily cigarettes does not produce equivalent decreases in carcinogen biomarkers (6, 7). The discrepancy between cigarette reduction and reduced harm exposure is most likely due to compensatory smoking, which can allow a smoker to extract more nicotine and, consequently, more tar from low-yield cigarettes. Comparison of tar stain intensity and pattern may provide support for evidence of compensatory smoking. Disease implications from compensatory smoking during reduced smoking are evident in epidemiologic results of lung cancer diagnoses in those who reduce number of daily cigarettes versus those who do not reduce and those who successfully quit smoking (29).

Tar contains many chemicals and has been used as an indicator of general particulate exposure. Some of the components in tar are known carcinogens (30), and the relationship between variations in smoking topography and resultant carcinogen exposure has been well shown (11, 17). However, tar is not homogeneous, and its correlation with carcinogens varies (31). Harris (12) showed that if smokers compensate to obtain equivalent levels of nicotine from a lower-nicotine cigarette, there is increased exposure to several carcinogens relative to the higher-nicotine cigarette. In addition, these carcinogens do not increase uniformly. Therefore, linking smoking topography and tar staining to multiple biomarkers of carcinogens would be preferred, but many biomarkers are not sensitive to single smoking sessions due to long half-lives (32).

Other potential methods for assessing compensatory smoking exist, including flow meter devices such as CReSS (or its portable version CReSS Micro), or filter analysis of solanesol (33). Measurement of puffing variables requires using a device that is not typically used during normal behavior, and their cost precludes use on a large scale for epidemiologic studies. Filter solanesol is a promising method but is technically complicated, expensive, and requires wet laboratory facilities and trained chemists. The imaging technique could be done in most office or laboratory facilities with minimal training and cost. The literature would benefit from comparative studies of topographic, chemical, and image-based measures of compensation to elucidate relative strengths and weaknesses.

A limitation of this study is the inability to link per-cigarette estimates of compensatory smoking to multiple biomarkers of exposure. Further studies are planned to examine the link between average daily smoke intake and average cotinine levels in smokers. In addition, because Quest is a unique cigarette, these results may not replicate across more traditionally designed brands (including those with filter vents). In addition, results are limited by participants smoking only one cigarette at each nicotine level. Ongoing work is examining the measurement of compensatory smoking in popular U.S. cigarette brands using the technique described here.
References


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