Short Communication

A Digital Image Analysis System for Identifying Filter Vent Blocking on Ultralight Cigarettes

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Abstract

Filter ventilation is the dominant design feature on modern cigarettes, diluting the mainstream smoke with air and reducing tar and nicotine yields in the standard assay. Smokers are generally unaware of vent holes and often cover them with lips or fingers while smoking, reducing or eliminating the air dilution effect and increasing intake of tar and nicotine particularly on ultra–low tar brands. A digital imaging and analysis system for the detection of vent blocking was developed. Two studies were designed to evaluate the effectiveness of three color measures (hue, saturation, and value) at discriminating whether at least 50% blocking had occurred. In study 1, saturation showed perfect discrimination between unblocked Carlton butts and butts with at least 50% of the vents blocked during syringe smoking. In study 2, saturation showed 95% accuracy at identifying Marlboro Ultra Light butts with at least four puffs blocked by smokers’ lips. The results indicate that the pattern of color saturation is related to vent blocking. Implications for tobacco control research and policy are discussed. (Cancer Epidemiol Biomarkers Prev 2005;14(2):533–7)

Introduction

Cigarette smoking causes cancers of the lung, larynx, oral cavity, esophagus, pancreas, bladder, cervix, and stomach (1). Over the past 50 years, changes in cigarette design have led to substantial reductions in machine-measured tar and nicotine yields of cigarettes, yet lung cancer risk has not declined (2). Filter ventilation is a key design feature of the modern cigarette (3) and arguably the most important design influence on standard tar and nicotine yields (4, 5). Vents allow ambient air to dilute the mainstream smoke with air during a puff, reducing the concentration of smoke constituents. However, smokers can and do block filter vents with their lips, fingers, or even tape when smoking (6, 7). This has profound effects on exposure to tar, nicotine, and carbon monoxide, particularly among the lowest-yielding ultralight brands (8).

In 1980, Kozlowski et al. (9) proposed a “stain-pattern” technique for assessing whether vent blocking had occurred. The test is based on the observation that unblocked ventilation tends to produce a central tar stain surrounded by a ring of unstained filter. As vents are occluded, the tar stain spreads to the outside edge of the filter (Fig. 1; ref. 9). The degree of blocking can then be viewed as a function of the stain pattern. As staining on the edge of the filter increases, the more blocking occurred. Several studies have established the reliability and validity of the technique on ultralight and light cigarette brands (6, 10, 11). Most recently, human raters examined butts with a template overlay that divides the butt into eight sections (11). Raters are then asked to estimate the percentage of the outer edge of the filter that is stained. Sweeney (11) showed this system to have good reliability (test-retest and interrater reliabilities >0.90) and accuracy (sensitivity, specificity >0.80) for a variety of light and ultralight brands (e.g., Carlton, Now, Virginia Slims Ultra Lights, Virginia Slims Light, Merit Ultima, Cambridge Ultra Light, Merit, Basic Lights, Doral Ultra Light, GPC Ultra Light, Doral Light, and Camel Light).

Digital Image Analysis to Detect Blocking. Our major goal was to find an objective method for detecting vent blocking that would match or exceed the accuracy and consistency of human raters. We used a computer to analyze digital images of cigarette butts and sort them based on image characteristics, extending our earlier attempts at a computer-based system (12). Image analysis techniques are common in quality control, engineering, and medical diagnostics. Image analysis has been used in dermatology to evaluate pigmented skin lesions and track changes in lesions over time with sensitivities and specificities over 80% (13). These dermatologic systems can grade relatively small lesions by color and appearance.

In assessing the color measures, the major question was whether the system could detect whether a butt has been blocked by covering at least 50% of the holes on all the puffs or blocking with lips on at least 50% of the puffs taken. This would be significant blocking in terms of exposure (14, 15). We conducted two studies, one assessing cigarette butts generated under controlled conditions and another assessing butts generated in the laboratory by smokers. Two brands were examined, Carlton and Marlboro Ultra Light. These were selected because they were the most popular in the 1 mg and 5 mg of tobacco strength butts, respectively, based on smokers’ self-reports in the 2000 National Household Survey on Drug Abuse (16).

General Materials and Methods

Image Capture. The image capture system consisted of a Sony DFW-V500 color charged–coupled device camera (Sony Electronics USA, Inc., Park Ridge, NJ) connected by IEEE-1394 interface to an IBM-compatible computer. The camera was fitted with a Navitar Zoom 7000 close focus zoom lens (Navitar, Inc., Rochester, NY) and a Hoya 80A daylight blue filter (THK Products, Inc., Long Beach, CA). A Stocker and
Yale Imagelite fiber optic illuminator (Stocker-Yale, Salem, NH) connected to a fiber optic light ring (Edmund Industrial Optics, Barrington, NJ) provided overhead illumination. The illuminator uses an EKE 150 W bulb producing consistent light at 3250 K. The camera is mounted on a 11 × 13 in. platform with an 18 in. vertical post, a swivel arm, and 50 mm focusing thru-hole (Edmund Industrial Optics). The whole apparatus was enclosed in a cardboard box painted black.

To capture an image, butts were placed in a disc-shaped aluminum holder so that they were flush with the surface, mouth end facing up. The holder was then placed under the camera lens and the image captured using Adobe Photoshop 6.0 (Adobe Systems, Inc., San Jose, CA). The disc was rotated and the next image captured. This process repeated for all butts in each study. All butt images were captured as 640 × 480 red-green-blue (RGB) in tagged image file format. We selected the uncompressed tagged image file format because it would not discard information about the image; hence, all colors and image characteristics were preserved. All butts were imaged at least 72 hours after they were smoked. In pilot testing, we found that butt color darkens from the time that it is smoked; change approached an asymptote after 72 hours. Further details about the image capture system are provided elsewhere (17).

Image Processing and Analysis. Captured butt image files were reduced from 640 × 480 to 480 × 480 by eliminating irrelevant portions to the right and left of the butt. Next, the red channel of the image was used to create a binary image, which was in turn used to calculate the image’s centroid (the “center of mass” of the image). Once the centroid was calculated, image size was reduced to 450 × 450 around the centroid. The RGB image was then converted into hue-saturation-value (HSV) space (18), which provides a more intuitive and easier-to-describe space than RGB, using an algorithm provided with MATLAB (The Mathworks, Natick, MA). HSV more closely relate to the perception of color by observers and the selection of colors by artists (19). Hue is a value of 0 to 359 (0 is red by convention) representing the color, on a 0 (fully desaturated or gray) to 1 (fully saturated) scale. Value is a measure of the image’s darkness or lightness, also on a 0 (black) to 1 (white) scale.

We wanted to derive a score that was a ratio of “edge” staining to “central” staining. To do this, binary (0,1) masks were used to cover irrelevant portions of the image. A “ring” mask was used to cover all but a 7-pixel-wide ring around the outer edge of the cigarette butt. Those pixels not equal to zero (i.e., those not covered by the mask) were identified and the mean value taken. A second round “center” mask (80 pixel radius) was applied to the images. All pixels not covered by the mask were identified and the average taken. The color score for each butt was calculated by dividing the edge score by the center score. Three ratio scores were generated: hue, saturation, and value. All programs were written in the MATLAB environment, using the base software and the Image Processing Toolbox.3

Data Analysis. Data analyses were done using SPSS 11.5 (SPSS, Inc., Chicago, IL) and Confidence Interval Analysis 2.0 (20). Mean scores for each color characteristic by blocking condition were obtained and mean differences were tested using Mann-Whitney U tests. Test accuracy was assessed using receiving-operating characteristic curves. In receiving-operating characteristic analysis, the measure of test accuracy is the area under curve (AUC; ref. 21). An AUC of 1.0 indicates a perfect test, whereas an AUC of 0.50 indicates a “useless” test (i.e., one that does no better than chance at discriminating between blocked and unblocked). For each receiving-operating characteristic curve, a set of cutpoints was generated, the lowest cutoff being one minus the lowest observed score and the highest cutoff being one plus the highest observed score. The other cutoffs were determined by the averages of every two consecutive observed values (22). Sensitivities, specificities, predictive values, and their 95% confidence intervals at cutoff scores were calculated in Confidence Interval Analysis 2.0 using Wilson’s method (23).

Cutoff Selection. It was decided a priori that a useful measure should have an overall accuracy of at least 80% as measured by AUC (21). It was further decided that, in terms of selecting cutoffs, minimizing false negatives (i.e., the test showing no blocking when blocking actually took place) was a priority. Hence, specificity was sacrificed for increased sensitivity. The test should have a sensitivity of at least 80% to detect blocking (i.e., accepting a false negative rate of >20%). However, at the same time, the false-positive rate should not be unreasonably high. Cutoff values were therefore selected where the sensitivity was at least 80% and the specificity was at least 70%.

Study 1

Materials and Methods. A sample of 52 Carlton 100 (Brown and Williamson Tobacco Company, Lexington, KY) cigarette butts was assessed. Standard Federal Trade Commission yields were 1 mg tar, 0.1 mg nicotine, and 1 mg carbon monoxide (24). The mean filter ventilation (air dilution) level from a freshly opened pack of 20 cigarettes was 84.4% (SE, 0.221), with vents located 14.7 mm (SE, 0.098) from the mouth end. All cigarettes had been smoked using 60 mL Luer-Lok tipped syringes (Becton, Dickinson and Company, Franklin Lakes, NJ), to draw eight 60 mL puffs (each of 2-second duration) through the cigarette every 30 seconds. The syringe was connected to a CReSS (Plowshare Technologies, Baltimore, MD) mouthpiece, which held the cigarette, to allow for monitoring puff volumes and durations. Cigarettes were not conditioned before smoking. The butts were stored in plastic screw-top 7 mL scintillation vials (VWR International, West Chester, PA) before imaging. Cigarettes were between 2 weeks and 2 months old (i.e., after smoking) when imaged. Of the 52 butts, 24 were unblocked, 12 were partially blocked (~50% coverage), and 16 were fully blocked (~100% coverage). Blocking was accomplished by affixing cellophane tape to cover ~50% or ~100% of the vent area. Half-blocking was done either with two opposing pieces each covering ~25% of the vent area, or with a single piece covering 50% of the area.

Results. Mean scores for each of the thee color measures (hue, saturation, and value) are shown in Table 1. Note that saturation scores increased with blocking whereas hue and value scores decreased with blocking. However, all differences were statistically significant by Mann-Whitney U test.

Figure 1. Prototypical staining patterns on unblocked (A) and fully blocked (B) ultralight cigarettes.

3 MATLAB code for image processing and analysis procedures is available from the first author upon request.
<table>
<thead>
<tr>
<th>Study 1</th>
<th>Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean (SE)</strong></td>
<td><strong>Mean (SE)</strong></td>
</tr>
<tr>
<td>Unblocked</td>
<td>Unblocked</td>
</tr>
<tr>
<td>(n = 24)</td>
<td>(n = 24)</td>
</tr>
<tr>
<td>≥50% Blocking</td>
<td>Four or eight puffs blocked (n = 48)</td>
</tr>
<tr>
<td><strong>U</strong> test</td>
<td><strong>U</strong> test</td>
</tr>
<tr>
<td>Hue 1.263 (0.029)</td>
<td>1.496 (0.053)</td>
</tr>
<tr>
<td>1.119 (0.019)</td>
<td>1.239 (0.041)</td>
</tr>
<tr>
<td>Z -3.21, P = 0.001</td>
<td>Z -3.38, P = 0.001</td>
</tr>
<tr>
<td>Saturation 0.151 (0.010)</td>
<td>0.183 (0.027)</td>
</tr>
<tr>
<td>0.850 (0.063)</td>
<td>0.645 (0.037)</td>
</tr>
<tr>
<td>Z -6.17, P = 0.000</td>
<td>Z -6.14, P = 0.000</td>
</tr>
<tr>
<td>Value 0.987 (0.001)</td>
<td>1.090 (0.027)</td>
</tr>
<tr>
<td>0.965 (0.008)</td>
<td>0.991 (0.007)</td>
</tr>
<tr>
<td>Z -2.57, P = 0.010</td>
<td>Z -3.75, P = 0.000</td>
</tr>
</tbody>
</table>

NOTE: Mean differences were tested by exact Mann-Whitney U test.

Receiving-operating characteristic curve analysis showed that some measures were clearly better than others at distinguishing no blocking from any blocking. Saturation showed an AUC of 1.0, whereas neither of the remaining measures achieved our a priori criterion of 0.80. Cutoff scores and corresponding sensitivity, specificity, and predictive values are shown in Table 2. Overall, there is good evidence that saturation scores are reliable discriminators of blocking in this sample.

Discussion. HSV saturation was effective at discriminating at least 50% blocking from no blocking in this sample. The analysis of butts from Carlton cigarettes, smoked under ideal conditions, showed how good the system could be under ideal conditions. That is, the results from study 1 support the viability of these measures as able to detect the presence of a significant level of blocking.

Study 2

Materials and Methods. Twelve undergraduate smokers were recruited for a 2-day smoking study through advertisements on the Pennsylvania State University campus. Details on the participants are available elsewhere (17). Marlboro Ultra Light 100 cigarettes (Philip Morris USA, Richmond, VA) were used throughout the study. Standard Federal Trade Commission yields were 5 mg tar, 0.5 mg nicotine, and 8 mg carbon monoxide (24). The position of the vents was marked by drawing a red line ~1 mm before the farthest vents and 1 mm after the closest vents. Vent distance and ventilation measurements were taken on a freshly opened pack of 20 cigarettes. The closest vents were 12.3 mm (SE, 0.077) from the mouth end. The mean ventilation level was 49.4% (SE, 0.328).

Subjects participated in two 2-hour smoking sessions, each featuring four cigarettes. Subjects were instructed to block zero, two, four, or eight of the eight puffs to be taken on each cigarette with their lips. In the two-puff and four-puff conditions, subjects were instructed to block the first two or four puffs taken. This was done to make the manipulation easier for subjects. In the blocking conditions, the smoker was asked to place their lips on or beyond the second line (furthest from the mouth end), whereas in the unblocked condition subjects were told to keep their lips behind the first red line (nearest the mouth end). The experimenter, who was seated in the room with the participant during smoking, confirmed successful blocking. Order of presentation was randomized on both days and counterbalanced using orthogonal Latin squares. The Penn State Institutional Review Board approved this protocol. The two puffs blocked condition was not assessed in the current analysis to maintain consistency with study 1.

Results. Mean scores by color rating are shown in Table 1. Saturation scores showed the greatest separation between unblocked and blocked scores, suggesting this measure might perform well as a discriminator. Hue and value scores showed small numerical differences between unblocked and blocked, suggesting these scores might not discriminate well between the two blocking conditions.

Receiving-operating characteristic analysis showed that saturation score (AUC, 0.946) was the best discriminator between unblocked and blocked butts. The remaining measures had AUCs <0.80, not meeting the a priori standard. Table 2 shows AUC and maximizing cutoff values for the aforementioned measures.

Discussion. Study 2 represented a more realistic test of the discrimination ability of the various measures, as human smokers produced these butts. Saturation did well in classifying butts into unblocked and blocked bins, with high sensitivity (96%) and negative predictive value (91%). This is important from the standpoint of being confident that true absence of blocking will lead to a negative test and that a negative test indicates true absence of blocking.

General Discussion

Overall, the results supported the hypothesis that color digital image analysis would be capable of distinguishing butts blocked to a significant extent from those not blocked at all. Finding support for the hypothesis was not surprising given the wealth of literature suggesting that stain patterns can be

Table 2. Color computer rating score cutoff values and corresponding sensitivities, specificities, and predictive values for detecting at least 50% blocking (versus no blocking)

<table>
<thead>
<tr>
<th>AUC (95% confidence intervals)</th>
<th>Cutoff</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>PV+</th>
<th>PV-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hue 0.760 (0.628, 0.893)</td>
<td>≤1.201</td>
<td>0.857 (0.685, 0.943)</td>
<td>0.625 (0.427, 0.788)</td>
<td>0.727 (0.558, 0.849)</td>
<td>0.789 (0.567, 0.915)</td>
</tr>
<tr>
<td>Saturation 1.0</td>
<td>≥0.315</td>
<td>1 (0.879, 1.0)</td>
<td>1 (0.862, 1.0)</td>
<td>1 (0.879, 1.0)</td>
<td>1 (0.862, 1.0)</td>
</tr>
<tr>
<td>Value 0.708 (0.548, 0.859)</td>
<td>≥0.985</td>
<td>0.679 (0.493, 0.821)</td>
<td>0.667 (0.467, 0.820)</td>
<td>0.704 (0.515, 0.841)</td>
<td>0.640 (0.445, 0.798)</td>
</tr>
<tr>
<td>Study 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hue 0.746 (0.631, 0.861)</td>
<td>≥1.389</td>
<td>0.708 (0.568, 0.818)</td>
<td>0.625 (0.427, 0.788)</td>
<td>0.791 (0.468, 0.866)</td>
<td>0.517 (0.344, 0.686)</td>
</tr>
<tr>
<td>Saturation 0.946 (0.897, 0.995)</td>
<td>≥0.249</td>
<td>0.958 (0.860, 0.988)</td>
<td>0.792 (0.595, 0.908)</td>
<td>0.902 (0.790, 0.957)</td>
<td>0.905 (0.711, 0.973)</td>
</tr>
<tr>
<td>Value 0.773 (0.657, 0.888)</td>
<td>≥0.995</td>
<td>0.792 (0.657, 0.883)</td>
<td>0.677 (0.467, 0.820)</td>
<td>0.826 (0.693, 0.909)</td>
<td>0.615 (0.425, 0.776)</td>
</tr>
</tbody>
</table>

NOTE: Abbreviations: PV+, positive predictive value; PV-, negative predictive value.
used to detect the presence of blocking at least 50% of the vents (6, 10) or blocking on at least half the puffs taken (10). What was novel in the current studies was the use of digital images of butts rather than the butts themselves. That similar results are seen suggests that the basic underlying principle (i.e., edge staining as an index of the presence of absence of at least 50% blocking) is sound. Results replicated across two brands, further strengthening the conclusions.

Saturation, or more precisely the ratio of saturation in the edge of the butt to the center of the butt, was the measure that consistently did well across studies as an index of blocking. Saturation could accurately discriminate 50% blocking from no blocking in both studies, with accuracy near 100%. Saturation can be thought of as a measure of color “purity,” or nongrayness—as saturation increases, grayness decreases (18). So, in the current studies, less saturation was found in the outer edge of unblocked butts compared with blocked butts. Saturation is a useful measure given the algorithms for converting RGB values to HSV saturation are well documented and are even provided in programming packages, such as MATLAB, mitigating a potential source of error. Many other color spaces that are direct transformations of RGB values [e.g., International Commission on Illumination 1976 L*a*b* color space (CIELAB), National Television Systems Committee color space (YIQ), and International Commission on Illumination 1931 tristimulus specification (CIEXYZ)] could also be used. We tested the CIELAB color space and found the “b*” (yellow-blue) ratio score had discriminant properties nearly identical to saturation. We also found that the CIELAB 6-E color difference measure also did well as a discriminator.

Swets (25) argues that cutoff selection for a particular diagnostic setting should take into account the benefits and costs of correct and incorrect decisions. The cutoff selection procedure in the current series of studies was biased toward minimizing false negatives (i.e., not missing a butt that had been blocked). The system was viewed as a screening test, trying to identify as many butts as may have been blocked as possible without making too great a sacrifice of specificity. From the point of view of protecting public health, one wants to err on the side of detecting blocking when it did not occur versus missing blocking when it did occur.

**Uses of the System.** This measurement system provides a tool for exploring the role of filter ventilation in compensatory smoking. On light cigarettes (~20-40% ventilated), it has been found in two small samples that vent-blocking has little to no effect on exposure, probably because of compensatory changes in puff volumes; the greatest effects of vent blocking have been found in heavily ventilated cigarettes (14, 15). Larger-scale research is needed to evaluate the effects of vent blocking on smoking behavior. The system was used to compare differences in exposure and assessments for smoking topography. It has been proposed that filter vents are a defective cigarette design feature that should be banned (3). This objective measure system is a key tool for gathering data on this issue.

A further advance is that the digitization of butt images allows for archiving of butts in the state in which they were rated. It is possible to store digital images indefinitely without change. Our image processing programs also make no permanent alterations to the images. This allows for original images to be shared with other laboratories for confirmatory ratings and for further development of alternative scoring schemes. Alterations to the system could be tested on the same image sets so that results could be compared directly. Digitization also allows the butts themselves to be used for other purposes, such as chemical analysis of filter material (26), so that convergent validity of the blocking detection system might be assessed.

It is interesting to note that industry scientists in France reported a digital imaging–based system for detecting vent blocking, which was, to our knowledge, published only as an abstract (27). No details on the system are given in the Cooperation Center for Scientific Research Relative to Tobacco abstract (27) and we have not been able to obtain further information from the authors.

**Limitations.** Potential errors in classification in the current studies can be classed in two ways. The first are manufacturing defects that produce edge staining even when no blocking is present. These defects may include tipping paper overlap near seams that occludes vents or excess tipping glue that closes vents. Sweeney (11) identified such defects as a major source of as much as 15% edge staining in nominally unblocked cigarette butts in her studies. This type of error represents a sort of background “noise” in stain pattern assessment that will always be present. A second source of error relates to the production of blocked and unblocked cigarettes under laboratory conditions. In the case of blocking vents with tape, there may be error in the placement of the tape such that even if all pieces of tape are exactly the same size, they may occlude different numbers of vents across cigarettes. This could produce differences in the level of staining on cigarettes sharing the same nominal level of blocking. Or, on a fully tape-blocked cigarette, leaving a small space where the tape does not fully meet the paper might allow air to flow through a few vents, resulting in a nonuniform stain on a nominally fully blocked butt.

In studies of behavioral blocking, additional sources of error appear. Within each subject, the blocking may not be equivalent across puffs in terms of absolute number of vents occluded, the pressure applied to the filter tip, or the lip seal on the filter tip. Such variability will be reflected in the range of scores reported for each blocking condition. There are also individual differences in lip coverage and lip seal (28) that could lead to variations in stain patterns. Such error is also present in conditions where subjects are not supposed to block. A subject’s lips or fingers may inadvertently creep forward, particularly as the cigarette burns down (29). Therefore, it is important to be mindful that the “gold standards” used in evaluations of behavioral blocking are imperfect.

**Conclusions.** A color computer-based rating system can reliably determine whether a cigarette butt had filter ventilation blocked at least 50% when smoked. Saturation showed accuracy ranging from 95% to 100% at separating blocked from unblocked butts. The techniques reported form the basis for a practical, objective system for measuring filter vent blocking. The fact that blocking can be measured objectively and quickly using a computer without sacrificing reliability or accuracy represents a major advance over the rater-based stain pattern technique.

**Acknowledgments**

We thank Courtney Whetzel and Katrina van den Brand for producing the cigarettes examined in study 1.

**References**


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