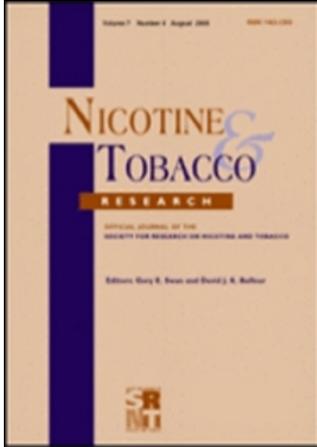


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## Nicotine & Tobacco Research

Publication details, including instructions for authors and subscription information:  
<http://www.informaworld.com/smpp/title~content=t713439766>

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Richard J. O'Connor<sup>a</sup>; Lynn T. Kozlowski<sup>b</sup>; David Hammond<sup>c</sup>; Tammy T. Vance<sup>a</sup>; Joseph P. Stitt<sup>d</sup>; K. Michael Cummings<sup>a</sup>

<sup>a</sup> Department of Health Behavior, Roswell Park Cancer Institute, Buffalo, NY

<sup>b</sup> Department of Biobehavioral Health, Pennsylvania State University, University Park, PA

<sup>c</sup> Department of Health Studies, University of Waterloo, Waterloo, Canada

<sup>d</sup> Applied Research Laboratory, Pennsylvania State University, University Park, PA

Online Publication Date: 01 August 2007

To cite this Article: O'Connor, Richard J., Kozlowski, Lynn T., Hammond, David, Vance, Tammy T., Stitt, Joseph P. and Cummings, K. Michael (2007) 'Digital image

analysis of cigarette filter staining to estimate smoke exposure', *Nicotine & Tobacco Research*, 9:8, 865 - 871

To link to this article: DOI: 10.1080/14622200701485026

URL: <http://dx.doi.org/10.1080/14622200701485026>

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# Digital image analysis of cigarette filter staining to estimate smoke exposure

Richard J. O'Connor, Lynn T. Kozlowski, David Hammond, Tammy T. Vance, Joseph P. Stitt, K. Michael Cummings

Received 21 April 2006; accepted 19 July 2006

Sufficient variation exists in how people smoke each cigarette that the number of cigarettes smoked daily and the years of smoking represent only crude measures of exposure to the toxins in tobacco smoke. Previous research has shown that spent cigarette filters can provide information about how individuals smoke cigarettes. Digital image analysis has been used to identify filter vent blocking and may also provide an inexpensive, unobtrusive index of overall smoke exposure. A total of 1,124 cigarette butts smoked by 53 participants in a smoking topography study were imaged and analyzed. Imaging showed test–retest reliability of more than 95% among those smoking their own brand. Mean color scores (CIELAB system) showed acceptable stability ( $>.60$ ) across days, paralleling the basic stability of smoking topography measures across waves. A principal components scoring showed that center tar staining, edge tar staining, and their interaction were significantly related to total smoke volume, accounting for 73% of the variation. Estimated smoke volume was a significant predictor of salivary cotinine when accounting for cigarettes smoked per day. These data suggest that digital image analysis of spent cigarette butts can serve as a reliable proxy measure of total smoke volume.

## Introduction

Cigarette smoking remains the greatest single preventable cause of morbidity and mortality in the United States, with nearly 47 million Americans currently smoking (U.S. Department of Health and Human Services, 2004). Sufficient variation exists in how people smoke each cigarette that the number of cigarettes smoked daily and the years of smoking represent only crude measures of exposure to the toxins in tobacco smoke and, therefore, risk of disease from smoking (National Cancer Institute, 2001). Researchers have explored different ways to

better characterize variation in how different people smoke, such as the use of biomarkers and computerized measures of puffing behavior (e.g., Benowitz et al., 2005; Hammond, Fong, Cummings, & Hyland, 2005; Hecht et al., 2005). Although these measures represent improvements over simply asking how much one smokes, their high cost makes them impractical for large-scale population-based research.

Given that cigarette filters trap a significant portion of the smoke particulate matter, the filter may provide useful information about how an individual cigarette has been smoked (Kozlowski, 1981). The “tar” retained in a cigarette filter makes a distinctive color stain that varies in intensity (e.g., Husset, Chaouat, Lethu, & Victoria, 2000; Kozlowski, Rickert, Pope, & Robinson, 1982). Researchers have explored how used cigarette filter tips might be employed to characterize subtle differences in how smokers puffed on a cigarette (Dixon, Shepperd, & St. Charles, 2005; Prignot & Jamart, 2005; St. Charles, Krautter, Appleton, & Mariner, 2005; Watson, McCraw, Polzin, & Ashley, 2004) or to identify blocking of tiny air holes in the filter while

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Richard J. O'Connor, Ph.D., Tammy T. Vance, B.S., K. Michael Cummings, Ph.D., M.P.H., Department of Health Behavior, Roswell Park Cancer Institute, Buffalo, NY; Lynn T. Kozlowski, Ph.D., Department of Biobehavioral Health, Pennsylvania State University, University Park, PA; David Hammond, Ph.D., Department of Health Studies, University of Waterloo, Waterloo, Canada; Joseph P. Stitt, Ph.D., Applied Research Laboratory, Pennsylvania State University, University Park, PA.

Correspondence: Richard J. O'Connor, Ph.D., Department of Health Behavior, Division of Cancer Prevention and Population Sciences, Roswell Park Cancer Institute, Elm and Carlton Streets, Buffalo, NY 14263, USA. Tel.: +1 (716) 845-4517; Fax: +1 (716) 845-1265; E-mail: richard.oconnor@roswellpark.org

smoking (O'Connor, 2004; O'Connor, Stitt, & Kozlowski, 2005; Prignot & Jamart, 2005). Some of these systems rely on visual inspection, whereas others use chemical techniques. One measurement system uses digital image analysis of the tar stain to determine whether cigarette air holes were blocked by smokers; this method is more than 95% accurate in detecting the presence or absence of vent blocking (O'Connor et al., 2005).

Interest in filter staining to assess exposure is not new. Kozlowski and colleagues (1982) proposed a visual color scale that was used by smokers to estimate the number of puffs taken on the cigarette; this method showed a correlation of .97 between human ratings and puff number. Devitt, West, and Jarvis (1984) reported that such color ratings by smokers correlated well ( $r \sim .88$ ) with levels of nicotine measured in spent filters.

Objective measures of stain color via reflectance spectrometry from particulate matter collected on Cambridge pads or trapped by filters also have been examined (Rickert, Robinson, & Kaiserman, 1994; Rickert, Wright, & Kaiserman, 2004). In one study, amount of tar was best predicted by stain lightness (i.e., the degree of grayness; Rickert et al., 1994). Rickert and colleagues (2004) also have related filter stain color (using the CIELAB color system; see Method section for more detail) to smoke constituents such as nicotine, total tar, NNK, and styrene. They noted that the  $a^*$  channel (redness-greenness) was most sensitive to changes in machine smoking intensity.

The present study examined cigarette butts obtained from a field study of smoking topography (Hammond et al., 2005). We sought to extend the system described by O'Connor et al. (2005) to measure smoke volume drawn from the cigarette, as well as biomarkers of smoke exposure (cotinine), using cigarettes for which puffing data were available.

## Method

### *Image capture*

The imaging protocol used in the present study was similar to that described previously (O'Connor et al., 2005), with several minor modifications. A Sony DFW-X710 camera (Sony USA, New York, New York) was used, with a resolution of  $1024 \times 768$  pixels. The camera was connected via IEEE-1394 interface (FireWire) to a Dell Latitude notebook computer equipped with a Pentium M (Intel Corporation, Santa Clara, California) 1.7 GHz processor running the Windows XP Professional operating system (Microsoft Inc., Redmond, Washington). The lens, lighting, and mounting equipment are as

described in O'Connor et al. (2005), with the exception that the cigarette holder was fashioned out of fiberglass rather than aluminum. Images were captured in a photographic darkroom to reduce the influence of ambient light, rather than encasing the system in a black box. Images were captured using the Windows Photo Editor (Microsoft Inc., Redmond, Washington). The calibration procedures described by O'Connor et al. (2005) were followed. Pilot work suggested the changes described above did not negatively affect image quality.

### *Image processing and analysis*

Captured butt image files were reduced from  $1024 \times 768$  to  $768 \times 768$  pixels and processed using centered masks as described by O'Connor et al. (2005). For the present analyses, RGB (red, green, blue) values were converted to the International Commission on Illumination's (CIE)  $L^*a^*b^*$  color space values using standard formulas. CIELAB is a device-independent color space based on the opponent-process model of color vision (Brainard, 2003). Color is measured on three dimensions: lightness ( $L^*$ : 0–100), a green-red channel ( $a^*$ : –128 to +128), and a yellow-blue channel ( $b^*$ : –128 to +128). High  $L^*$  values indicate high lightness, positive  $a^*$  values indicate "redness" and negative values "greenness," whereas positive  $b^*$  values indicate "blueness" and negative values "yellowness." A color is described in terms of all three measures ( $L^*a^*b^*$ ), each of which can change independently of the others (e.g., white is perceived when  $L^*=100$  and  $a^*=b^*=0$ ). Therefore, it is important to assess changes in each of these channels. CIELAB was developed as a color difference system, in an attempt to quantify relatively small changes in color (Brainard, 2003).

### *Source study*

Smoked cigarette filters were obtained from a field study of smoking behaviors and brand switching (Hammond et al., 2005). In this study, 59 participants participated in three 1-week waves over a 2-month period, and for each wave, participants smoked at least 5 cigarettes/day through the CReSSMicro (Plowshare Technologies, Baltimore, Maryland) for five consecutive days. Participants smoked their usual brand of cigarettes (means = 10.7 mg tar, 1.0 mg nicotine ISO yields across brands) during Wave 1 and, 6 weeks later, during Wave 2. Wave 3 occurred during the week immediately following Wave 2. For Wave 3, half of the participants ( $n=27$ ) were randomly selected to smoke a "lower-yield" cigarette brand (Matinee Extra Mild, 4 mg tar, 0.4 mg nicotine ISO yield),

whereas half ( $n=26$ ) continued to smoke their usual brand.

Salivary cotinine was the exposure biomarker, measured using gas chromatography by Labstat (Kitchener, Ontario, Canada). Detailed descriptions of the study methodology are available elsewhere (Hammond et al., 2005). The study received human subjects approval from the University of Waterloo and Roswell Park Cancer Institute.

Participants were asked to collect used cigarette butts from the days that they smoked during the wave, marking the first cigarette of the day with an "X," and those not smoked with the CReSS with an "O." Collected butts were wrapped in aluminum foil, marked with the participant's ID number and day of collection, and placed in a zip-top bag. Because participants generated more than 7,000 butts across the three waves, a subsample was selected for image analysis. The subsample included the first butt of the day, two "CReSS" butts (i.e., smoked using the CReSS), and two "free" butts (i.e., not smoked with the CReSS) from each day in waves 2 (own brand) and 3 (the brand-switching week). If no "free" butts were collected, then only "CReSS" butts were selected for imaging. When a large number of butts was available for selection for a given participant, those filters not seriously damaged (very crushed, burned, or torn) were selected preferentially. When no clear choice was apparent, butts were selected randomly, with technicians instructed *not* to use stain color as a basis for selection. This procedure resulted in the processing and analysis of 1,142 cigarette butts from 54 participants at Wave 2, and 1,124 cigarette butts from 53 participants at Wave 3, with a range of 10–25 butts assessed per subject at each wave.

For all butts, the total length and filter length of the butt were recorded, the tobacco rod was removed, and a 1-mm section of the mouth end of the filter was removed with a razor blade and discarded to assure a clean image, free of ash and other debris. Prepared butts for each participant were labeled with a code denoting subject ID, wave, and day, and then placed together in a zip-top freezer bag and placed back in the  $-20^{\circ}\text{C}$  freezer.

#### *Data analyses*

We examined the reliability of staining scores using intraclass correlations (Shrout & Fleiss, 1981, Case 2, single rating) across waves 2 and 3 as well as within each wave. Because we did not have linked topography scores for each butt examined and could not link specific butts to specific topography data, we calculated average topography and staining scores for each individual based on the available data. Our overall goal was to assess the association of average stain color scores with average measures of smoking

topography (considered as a gold standard measure of smoke exposure) using Pearson correlations, regression modeling, and principal components analysis.

To model total puff volume, we considered both central and edge staining. The latter type of staining must be considered because blocking filter vents will affect filter efficiency and the total area of filter through which smoke might pass (Kozlowski & O'Connor, 2002). This, in turn, would affect color darkness, which we are taking as our proxy of total smoke flow. We also examined whether color scores and their derivatives could be used to estimate salivary cotinine levels in linear regression models controlling for sex, age, and time of sample collection.

## **Results**

### *Mean color scores*

Table 1 reports the mean color score values for the  $L^*$ ,  $a^*$ , and  $b^*$  channels, as well as ranges of scores, by wave.

### *Color score reliability*

We first examined whether color scores were consistent between waves 2 and 3 for those subjects who smoked their own brand at both waves (i.e., control group,  $n=26$ ), to establish whether the basic measure is consistent over time. Here, we found intraclass correlations ranging from .90 to .92 (data not shown). We then examined the stability of scores on each color channel on an individual basis for all butts examined across days within each wave. Here, we saw reliability scores that were lower, but still in the acceptable range, particularly for the measures of greatest interest ( $L^*$ center,  $a^*$ center, and  $b^*$ ratio [edge/center]). Wave 2 reliabilities ranged from .73 to .83, and Wave 3 reliabilities ranged from .63 to .88. Because of the strong reliability across waves, the remaining analyses examined Wave 3 only.

### *Color scores and puff volume*

In bivariate analysis, the center  $L^*$  ( $r=-.71$ ) and  $a^*$  ( $r=.75$ ) average scores were highly correlated with average total smoke volume drawn from cigarettes, whereas  $b^*$  was less correlated ( $r=.49$ ). We explored the utility of  $a^*$  levels, given the work by Rickert and colleagues (2004), as well as its positive correlation with smoke volume, which allowed for easier interpretation. We also examined  $b^*$ ratio as an indicator of vent hole blocking (O'Connor, 2004).

We explored several options to assess the ability of color scores to predict total puff volume (Table 2). First, we examined a multiple linear regression model

**Table 1.** Mean, standard error of the mean, and ranges for center and edge L\*a\*b\* scores and b\*ratio (edge/center) scores.

	Wave 2 (n=54)		Wave 3 (own brand) (n=26)		Wave 3 (switch) (n=27)	
	Mean (SE)	Range	Mean (SE)	Range	Mean (SE)	Range
L* center	71.2 (0.52)	63.3–81.0	71.1 (0.71)	64.2–76.8	70.7 (0.70)	62.9–79.4
a* center	1.7 (0.13)	–0.3–4.3	1.8 (0.20)	0.5–4.0	2.1 (0.20)	–0.0–4.3
b* center	21.7 (0.20)	17.0–23.9	21.5 (0.24)	18.8–23.8	20.9 (0.29)	17.3–22.8
L* edge	76.3 (0.52)	65.7–83.9	77.2 (0.67)	71.1–86.1	84.0 (0.79)	72.1–90.6
a* edge	0.04 (0.55)	–0.8–1.4	–0.1 (0.09)	–1.0–0.6	–0.6 (0.08)	–1.5–0.7
b* edge	15.2 (0.44)	7.5–21.2	14.5 (0.61)	6.8–18.8	8.7 (0.76)	3.1–17.8
b* ratio	0.7 (0.02)	0.4–0.9	0.7 (0.03)	0.4–0.9	0.4 (0.04)	0.2–0.8

(Model 1) with a\*center, b\*ratio, and their interaction, run for all participants at Wave 3. Second, we ran separate models for control and switch participants (Models 2a and 2b, respectively), to determine whether full-flavor, lightly vented cigarettes require different prediction equations than heavily vented low-yield cigarettes. Third, we performed a principal components analysis on all center and edge scores and used the component scores as regressors (Model 3).

Principal components analysis with varimax rotation showed that the six color scores (L\*a\*b\* edge and center) divided in to two components that together explained 88.6% of the variance. The first component featured the L\*a\*b\* edge scores and thus was labeled “edge” (loadings=0.90–0.98); the second component featured the center scores and was labeled “center” (loadings=0.72–0.98). Component scores were output using the regression method (Tabachnick & Fidell, 2001); these are similar to Z scores, with a mean of 0 and a standard deviation of 1. An interaction term was created by multiplying the “edge” and “center” component scores.

Model 1 was the most straightforward, explaining 71% of the variance in total puff volume. Model 2, with separate models for own-brand and the low-yield brand, appeared to make no difference in interpretation, though in both models the interaction terms were not statistically significant. This is most likely related to the reduced sample size resulting

from the groupwise analysis. Model 3, using component scores, explained slightly more variance (73%) and had the advantage of using all the color data. Because “center” and “edge” scores are orthogonal, Model 3 may be preferable.

Analysis of R-square change for Model 3 showed that the addition of edge scores and the interaction term both significantly increased the percentage of variance explained by the model. A similar pattern was seen for Model 1. This finding suggests that both edge and center tar staining, as well as their interaction, are important considerations in the assessment of stain color as an indicator of total puff volume.

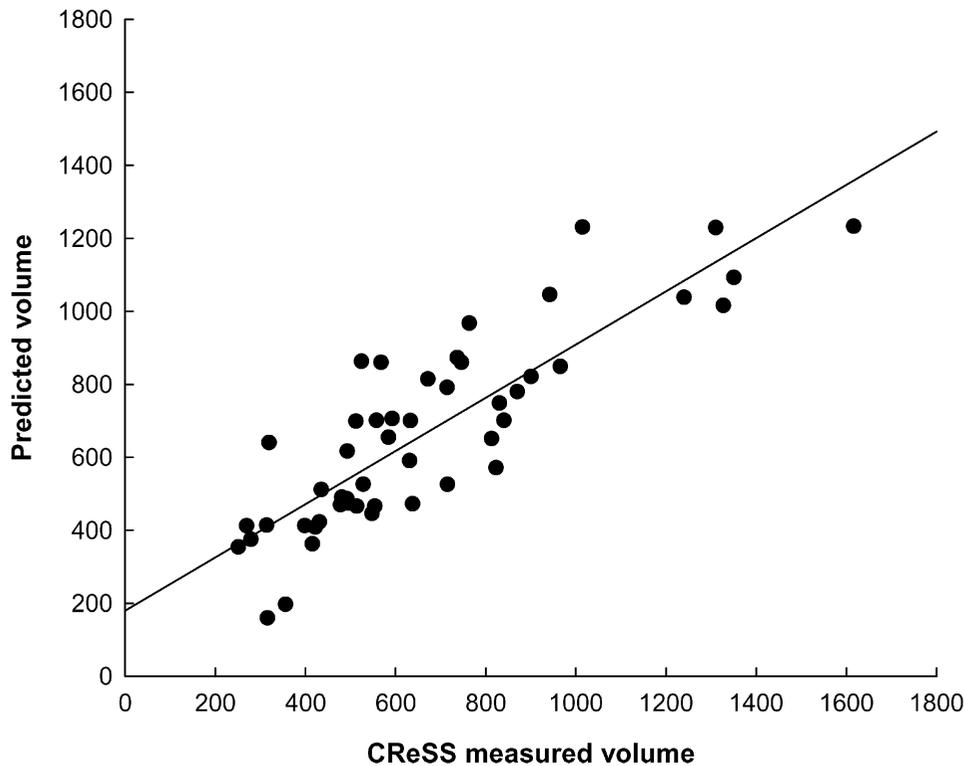
Predicted total puff volumes for each model were output for analysis. All three models’ estimated values correlated highly (.84–.85) with measured puff volume, and means for all three models were similar to the measured puff volumes (data not shown). Figure 1 plots estimated puff volume from Model 3 versus measured volume, as an illustration of the relationship. Although there is spread around the regression line, a clear pattern is visible.

#### *Predictive validity: Estimating cotinine intake*

To examine the utility of estimated puff volume measures derived from color image analysis, we ran regression models to predict salivary cotinine levels

**Table 2.** Comparisons of three models using color scores to predict total puff volume.

	Beta	p value	$\Delta R^2$	F	df	p value
Model 1 ( $R^2=.71$ )						
a* center	1.44	<.001				
b* ratio	0.27	.14	.06	7.6	1, 47	.008
Interaction	–0.82	.002	.07	10.9	1, 46	.002
Model 2a—own brand ( $R^2=.63$ )						
a* center	1.86	.01				
b* ratio	0.17	.55	.09	4.6	1, 23	.04
Interaction	–1.23	.06	.06	3.9	1, 22	.06
Model 2b—switch ( $R^2=.72$ )						
a* center	1.21	.002				
b* ratio	0.25	.30	.00	0.04	1, 21	.85
Interaction	–0.38	.27	.02	1.3	1, 20	.27
Model 3 ( $R^2=.73$ )						
“Center”	0.63	<.001				
“Edge”	–0.46	<.001	.22	33.5	1, 47	<.001
“Center” × “edge”	–0.21	.01	.04	6.6	1, 46	.01



**Figure 1.** Predicted total puff volume versus measured total puff volume. Model 3—derived estimates are shown as an example.

(Table 3). For these models, we used a natural-log transformation of cotinine (ng/ml) to normalize the data. Color scores were not themselves correlated with salivary cotinine levels ( $r < .10$ ). The “measured” model used CReSS-measured cigarettes smoked per day, total puff volume per cigarette, and their interaction to predict salivary cotinine, controlling for sex, age, and time of sample collection. This model accounted for approximately 39% of the variance in cotinine. The  $R$ -square for the model including just age, sex, and time was .02. Adding the topography measures resulted in a highly significant  $R$ -square change of .37;  $F(3, 41) = 8.3$ ,  $p < .001$ . Predicted volumes from Models 1–3 described above were substituted for measured volume in subsequent regressions to determine how they affected prediction

of cotinine.  $R$ -square values dropped significantly (to approximately 22%), but all effects were in the same directions and, with the exception of the interaction term in Model 2, the effects maintained statistical significance. In all of these models, adding the topography estimates led to  $R$ -square changes of .21–.22, again significant improvements over the age, sex, and collection time-only model ( $p$ -values  $< .05$ ).

### Discussion

The present study set out to assess the utility of digital image analysis of spent cigarette butts to estimate total smoke intake. Cigarette butts retained from the Hammond et al. (2005) field study of smoking behaviors and brand switching were imaged

**Table 3.** Linear regressions predicting salivary cotinine (natural log transform) from measured or estimated cigarettes/day, total puff volumes, and their interaction, controlling for sex, age, and sample collection time.

	Measured		Model 1		Model 2		Model 3	
	$(R^2 = .39)$		$(R^2 = .22)$		$(R^2 = .21)$		$(R^2 = .22)$	
	Beta	$p$ value						
Cigarettes/day (CPD)	-0.39	.12	-0.34	.29	-0.32	.35	-0.19	.46
Puff volume	-1.05	.001	-0.71	.04	-0.72	.04	-0.63	.04
CPD $\times$ puff volume	1.20	.001	0.88	.04	0.85	.06	0.73	.04
Sex	-0.04	.74	0.09	.54	0.09	.55	0.08	.58
Age	-0.12	.35	0.09	.55	0.08	.56	0.08	.56
Sample collection time	0.15	.23	0.21	.14	0.20	.16	0.23	.11

and related to smoking topography and cotinine levels. The average  $a^*$  channel level of the color images correlated highly ( $>.70$ ) with average total smoke volume, as measured by the CReSSMicro, and adding  $b^*$  ratio to account for vent blocking was useful to predict total smoke volume. Whether we used a simple linear regression, separate regressions for lightly and heavily vented cigarettes, or principal components scores seemed not to make a significant difference in the derivation of volume estimates. This consistency across different modeling strategies is indicative of the underlying relationship between tar deposits in the filter (as reflected in stain darkness) and the total volume drawn through the filter, even controlling for filter efficiency changes resulting from vent hole blocking. This finding is consistent with those of Kozlowski et al. (1982), which used human raters to judge stain color darkness as an indicator of the number of puffs drawn. As for choosing a model to represent the relationship of color to volume, the principal components scores may offer the advantage of providing a summary score for both edge and center staining using all of the color information extracted from the image. Component scores are also standardized ( $M=0$ ,  $SD=1$ ), facilitating comparisons of samples collected under different conditions.

Estimated smoke volumes correlated well with measured volumes and could be used in place of measured volume in regression equations predicting salivary cotinine, suggesting the color scores have predictive validity. The amount of variance in cotinine explained only by volume, cigarettes per day, and their interaction was relatively small (22%–39%). This finding is consistent with those of other studies and is likely related to unmeasured individual difference factors, such as nicotine metabolism. Overall, digital image analysis of spent cigarette butts shows promise as a tool to estimate the total smoke volume drawn from cigarettes.

One might ask why such a system would be useful or desirable, given that devices such as CReSSMicro exist to measure puffing behavior, and biomarkers are readily measured in saliva, urine, and blood to assess exposure to various toxicants directly. The main utility of a system analyzing cigarette butts is that it can be done unobtrusively. Only a small sample of cigarette butts (perhaps five across the day) is needed to get a good approximation of a smoker's typical behavior. Biomarkers require the collection of saliva, urine, or blood samples, which have differing levels of invasiveness, are more sensitive to temperature and storage conditions, and are vulnerable to damage in shipping. Additionally, biomarkers are subject to interindividual variability in metabolism. Assessment of cigarette butts would be ideal for larger-scale epidemiological studies, for which collecting biomarkers or having participants smoke

using a device to record puffing would be impractical or prohibitively expensive.

### Limitations

The findings described here are subject to some limitations. First, the butts collected were not designed to evaluate the utility of an imaging system to assess puffing behavior. CReSS data were not linkable to specific butts, necessitating the use of average scores for participants. However, reliability scores within waves were good, suggesting that averages would be a good approximation of typical smoking behavior and staining patterns. Because we examined only a limited number of brands in the present study, the results may not necessarily generalize to other brands. Similarly, the equation relating color scores to puff volume, or estimated puff volume to salivary cotinine, may not be generalizable. In this regard, principal components scores may offer an advantage in that they are standardized, providing a common metric across studies. Ongoing and future work will examine the broader applicability of the system across brands and filter types.

### Conclusions

Digital image analysis of spent cigarette filters may be an inexpensive, quick, and reliable way to assess smoking topography in population-based studies. Further validation studies to evaluate the method's reliability and broader applicability are ongoing.

### Acknowledgments

This work was supported by internal funds from the Division of Cancer Prevention and Population Sciences, Roswell Park Cancer Institute. The original data collection was supported by the American Cancer Society, Health Canada, the Robert Wood Johnson Foundation, the U.S. National Cancer Institute, and the Canadian Tobacco Control Research Initiative. The authors thank Ted Brasky for assistance with cigarette imaging. These data were presented in part at the 12th annual meeting of the Society for Research on Nicotine and Tobacco, February 16–18, 2006, Orlando, Florida.

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