



## TSNA exposure from cigarette smoking: 18 Years of urinary NNAL excretion data



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### ABSTRACT

The objective of this work was to characterize trends over time in urinary excretion of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (NNAL) among cigarette smokers in the US. We identified 35 studies presenting data that either reported, or could be converted to, common units of total urinary NNAL excretion as pmol/mg creatinine. The studies spanned 18 years, reported urinary NNAL excretion estimates for 61 defined populations, and included a combined total of 3941 study participants. Analyses show that urinary NNAL excretion trends downward with study publication year, and the trend is statistically significant. The trend does not appear to be accounted for by a reduction in cigarettes smoked per day by study participants over the same time period. This trend is consistent with reductions in tobacco specific nitrosamine (TSNA) levels in both cigarette tobacco filler and mainstream cigarette smoke observed over the past decade and with efforts by the tobacco industry and the agricultural community to reduce levels of TSNAs in tobacco and cigarette smoke.

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### 1. Introduction

Tobacco specific nitrosamines (TSNAs) are a class of cigarette smoke constituents believed to play a potential role in smoking-related carcinogenesis (IARC, 2007). The TSNAs, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) and *N*-nitrosonornicotine (NNN), have received the greatest attention due to their carcinogenic activity in animal studies. Both are classified by the International Agency for Research on Cancer as carcinogenic to hu-

smokers over time. We gathered and analyzed available published data on urinary NNAL excretion among cigarette smokers over an 18-year period. Total urinary NNAL (sum of NNAL and NNAL-glucuronide) has been reported to be a specific biomarker for exposure to NNK (Hecht, 2002) and has been widely used as a biomarker indicative of TSNA exposure from cigarette smoking. It has also been reported to be a biomarker of risk for lung cancer (IARC, 2009).

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products and tobacco smoke (IARC, 2007; USDHHS, 2012).

We previously reported that TSNA levels have declined significantly in mainstream cigarette smoke over at least the last decade (Appleton et al., 2013). The objective of this work was to characterize trends in urinary excretion of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (NNAL) among cigarette smokers to determine possible changes in exposure to TSNAs among cigarette

smokers. We searched PubMed Central (US National Institutes of Health, National Library of Medicine; <http://www.ncbi.nlm.nih.gov/pubmed>) for published papers reporting urinary NNAL excretion data in cigarette smokers. Studies were also identified as referenced in reports identified in the PubMed search and from other sources.

We used the following criteria for inclusion of studies identified in the literature:

- Study was original research.
- Study reported urinary excretion of total NNAL (sum of NNAL and NNAL-glucuronide).
- Study participants were adult cigarette smokers.
- Study conducted in the US of participants smoking US commercial cigarettes.
- Cigarettes were smoked under natural conditions (no forced smoking regimens).

**Abbreviations:** NNAL, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol; NNK, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; NNN, *N*-nitrosonornicotine; CPD, cigarettes per day; TSNA, tobacco specific nitrosamine.

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- Only baseline data was used from intervention studies.

Published studies were examined to determine if a data set for one or more defined populations had been previously published. In cases where a data set was clearly identified as having been previously published, the default approach was to use only the data from the earliest publication. Because our objective was to compare levels of urinary NNAL excretion from different studies over time, the analysis was confined to NNAL data that were either reported as, or could be converted to, common units suitable for comparison.

Urinary NNAL excretion estimates for different defined populations (e.g., male vs. female, Black vs. White) that were reported separately in the original publications were handled as separate population estimates with no attempt to average or merge individual estimates. If both individual population estimates and an overall population estimate were presented, only the highest-order population estimate was used in the analysis. In cases where only individual subject data were presented, we calculated group means. Likewise, in cases where values for NNAL and NNAL-glucuronide were only presented separately as molar units, we calculated the sum of the two to obtain total NNAL.

The data were analyzed for trend with year of publication using a general linear model in a standard statistical analysis software package (IBM SPSS Statistics, Armonk, NY). In the primary analysis the dependent variable of the model was NNAL level in pmol/mg creatinine, and the covariates were study publication year and cigarettes per day (CPD). The data points were weighted by the number of study participants.

### 3. Results

Our literature search identified 52 potentially relevant study publications. Among these publications, a wide variety of units were used to express urinary NNAL excretion. Twenty-nine of the 52 studies expressed urinary NNAL excretion as pmol/mg creatinine (Anderson et al., 2001; Benowitz et al., 2005, 2010b, 2012a,b; Carmella et al., 1995, 1997, 2003; Church et al., 2010; Hatsukami et al., 2004, 2010; Hecht et al., 1995, 1999, 2007; Hughes et al., 2004; Hurt et al., 2000; Joseph et al., 2005; Khariwala et al., 2012; Le Marchand et al., 2008; Melikian et al., 2007; Mendoza-Baumgart et al., 2007; Muscat et al., 2005, 2009; Sellers et al., 2003; St. Helen et al., 2012; Stepanov and Hecht, 2005; Strasser et al., 2011; Taioli et al., 1997; Ter-Minassian et al., 2012).

The rest of the studies expressed urinary NNAL excretion using a variety of units. Six studies expressed urinary NNAL excretion as ng/24 h: Frost-Pineda et al. (2008), Heck (2009), Kinser et al. (2002), Roethig et al. (2008, 2009) and Sarkar et al. (2010). Five studies expressed urinary NNAL excretion as pg/mL urine: Benowitz et al. (2010a), Bernert et al. (2010), Blank and Eissenberg (2010), Breland et al. (2003) and Heck (2009). Four studies expressed urinary NNAL excretion as pmol/mL urine: Derby et al. (2009), Hatsukami et al. (2007), Murphy et al. (2004) and Stepanov et al. (2009). Four studies expressed urinary NNAL excretion as nmol/24 h: Carmella et al. (1993, 2009), Hecht et al. (1995) and Stepanov et al. (2008). Four studies expressed urinary NNAL excretion as pg/mg creatinine: Benowitz et al. (2010a), Goniewicz et al. (2009), Heck (2009) and Rostron (2013). Two studies expressed urinary NNAL excretion as ng/mL urine: Jones et al. (2013) and Stepanov et al. (2007). One study expressed urinary NNAL excretion as ng/mg creatinine: Ashley et al. (2010); and one study expressed urinary NNAL excretion as ng/g creatinine: Sarkar et al. (2008).

To make valid comparisons of NNAL excretion data over time, we wanted to use data expressed in common units. The most frequently used unit of NNAL expression was pmol/mg creatinine.

However, almost half of the studies used a variety of other units to express urinary NNAL excretion. Therefore, in order to bring more data into the primary analysis, we converted data from the studies reporting NNAL excretion in units other than pmol/mg creatinine. This resulted in the consolidation of data from nine different units of NNAL expression into three: pmol/mg creatinine, nmol/24 h, and pmol/mL urine. The vast majority of data spanning the longest possible time frame were data normalized to creatinine, namely, pmol/mg creatinine. Therefore, NNAL excretion data expressed as pmol/mg creatinine formed the basis of our primary analysis.

Table 1 presents characteristics of the 35 studies used in this analysis. The publication of these studies covered a time span of 18 years from 1995 to 2012, inclusive. These studies collectively reported urinary NNAL excretion estimates for 61 defined study populations involving a total of 3941 study participants. Fig. 1 is a scatter plot of data for total NNAL excretion over time from the 61 study populations in which the data are expressed as pmol/mg creatinine.

We initially analyzed the data without adjusting for CPD or weighting the data by number of study participants, thus allowing the use of all 61 study populations. The results show a statistically significant decline in urinary NNAL excretion with study publication year. The trend line is shown in Fig. 1. We conducted the primary analysis of data from the 51 study populations that also reported CPD and number of study participants. The primary analysis shows that urinary NNAL excretion trends downward with study publication year by 0.137 pmol/mg creatinine/year, and the trend is statistically significant ( $p < 0.00001$ ). NNAL excretion increased by 0.049 pmol/mg creatinine for each additional CPD, and the increase was statistically significant ( $p = 0.0002$ ). The model explained much of the variance in the NNAL excretion levels (adjusted  $R^2 = 0.61$ ).

### 4. Discussion

The U. S. Surgeon General and others have stated that the role of specific smoke constituents in smoking-related disease is currently not known (Burns et al., 2008; USDHHS, 2010). Likewise, it is not known whether reduction of TSNA exposure from cigarette smoking would result in a reduction in the risk of smoking-related disease.

Based on the analysis presented here, urinary NNAL excretion among cigarette smokers appears to have been declining over the period from 1995 to 2012. Given the utility of urinary NNAL excretion as a specific biomarker for NNK exposure and a general marker for TSNA exposure, the observed trend in urinary NNAL excretion provides evidence of a downward trend in TSNA exposure from cigarette smoking.

The downward trend in urinary NNAL excretion does not appear to be explained by reductions over time in CPD among study participants. Although NNAL excretion is significantly associated with CPD, our primary analysis shows that the downward trend of NNAL is statistically significant over time independent of CPD. Furthermore, we analyzed the data from all the study populations and did not find a statistically significant downward trend of CPD with study publication year. At first glance, this may seem surprising given reports of a significant decline in mean CPD among daily smokers in recent years (MMWR, 2012). However, it must be kept in mind that participant eligibility criteria for most of the studies reviewed here included a requirement that a minimum number of CPD were smoked (usually 10–15). Therefore, these studies are not necessarily designed to be representative of contemporary population smoking patterns. Nevertheless, they are still useful for identifying trends in TSNA exposure over time that may be reflective of changes in TSNA levels in cigarette smoke.

**Table 1**  
Characteristics of studies expressing urinary NNAL excretion in US smokers as pmol/mg creatinine.

Report authors (year of publication)	Study population characteristics	Number of study participants	Total urinary NNAL (pmol/mg creatinine)	CPD
Carmella et al. (1995)	Cross-sectional study of cigarette smokers	61	3.76	NR
Hecht et al. (1995)	Baseline data from cigarette smokers before consumption of watercress	11	2.67	14.8
Carmella et al. (1997)	Cross-sectional study of cigarette smokers	18	3.8	NR
Taioli et al. (1997)	Cross-sectional study of female cigarette smokers	13	3.9	15.2
Hecht et al. (1999)	Baseline data from cigarette smokers before assignment to smoking cessation groups	27	2.7	23.7
Hurt et al. (2000)	Baseline data of "heavy" cigarette smokers before treatment with a nicotine inhaler	18	3.69	41.9
Anderson et al. (2001)	Cross-sectional study of cigarette smokers	23	1.7	25
Carmella et al. (2003)	Cross-sectional study of cigarette smokers	41	2.6	NR
Sellers et al. (2003)	Baseline data from cigarette smokers before treatment with methoxsalen	11	1.34	22.6
Hatsukami et al. (2004)	Baseline data from cigarette smokers before switching to OMNI cigarettes	22	2.2	21.7
Hughes et al. (2004)	Baseline data from cigarette smokers before switching to OMNI cigarettes	34	3.5	30
Benowitz et al. (2005)	Baseline data from cigarette smokers before switching to "light" cigarettes	16	2.3	22.5
Joseph et al. (2005)	Baseline data from participants enrolled in a smoking reduction clinical trial; Cohort 1 (TRIP)	151	2.2	24.2
	Baseline data from participants enrolled in a smoking reduction clinical trial; Cohort 2 (ROSCAP)	152	2.7	27.5
	Cross-sectional data from "light" smokers; Cohort 3 (ACSS)	86	1.2	9.2
	Cross-sectional data from "light" smokers; Cohort 4 (LLSS)	11	2.2	8.5
Muscat et al. (2005)	Cross-sectional study of Black male cigarette smokers	28	2.6	16.7
	Cross-sectional study of White male cigarette smokers	47	1.9	23.7
	Cross-sectional study of Black female cigarette smokers	41	2.7	14
	Cross-sectional study of White female cigarette smokers	46	3.2	22
Stepanov and Hecht (2005)	Cross-sectional study of cigarette smokers	14	1.53	NR
Hecht et al. (2007)	Baseline data from participants enrolled in a smoking reduction study	186	2.62	24.7
Melikian et al. (2007)	Cross-sectional study of cigarette smokers categorized as low-yield FTC nicotine group	87	1.75	16.3
	Cross-sectional study of cigarette smokers categorized as medium-yield FTC nicotine group	109	1.68	16.3
	Cross-sectional study of cigarette smokers categorized as high-yield FTC nicotine group	61	1.21	16.3
Mendoza-Baumgart et al. (2007)	Baseline data from cigarette smokers before crossover treatment with medicinal nicotine lozenge to Exalt	19	1.32	21.8
	Baseline data from cigarette smokers before crossover treatment with Exalt to medicinal nicotine lozenge	20	1.58	20.8
	Baseline data from cigarette smokers before crossover treatment with medicinal nicotine lozenge to Ariva	12	0.98	20
	Baseline data from cigarette smokers before crossover treatment with Ariva to medicinal nicotine lozenge	14	1.02	21.7
Le Marchand et al. (2008)	Cross-sectional study of cigarette smokers conducted in Hawaii	583	1.28	20
	Cross-sectional study of cigarette smokers conducted at the University of Minnesota (UMN Study 2)	137	0.91	20
Sarkar et al. (2008)	Baseline data from cigarette smokers before switching to 11 mg FTC tar charcoal cigarettes	20	1.45	17.9
	Baseline data from cigarette smokers before switching to 6 mg FTC tar conventional cigarettes	25	1.53	18
	Baseline data from cigarette smokers before switching to 11 mg FTC tar conventional cigarettes	20	1.69	18.5
	Baseline data from cigarette smokers before switching to 6 mg FTC tar charcoal cigarettes	50	1.65	18.5
Goniewicz et al. (2009)	Cross sectional study of daily cigarette smokers	8	2.08	22.0
Heck (2009)	Cross sectional study of menthol cigarette smokers	54	1.36	27
	Cross sectional study of non-menthol cigarette smokers	58	2.09	27
Muscat et al. (2009)	Cross-sectional study of menthol cigarette smokers	67	2.9	NR
	Cross-sectional study of non-menthol cigarette smokers	80	3.2	NR
Ashley et al. (2010)	Cross-sectional study of cigarette smokers from Minnesota	27	1.04	19.7
	Cross-sectional study of cigarette smokers from New York	24	1.39	18.3
Benowitz et al. (2010a)	Cross-sectional study of regular and occasional cigarette smokers from San Francisco, California	59	0.57	6.9
	Cross-sectional study of regular and occasional cigarette smokers from Pittsburg, Pennsylvania	130	1.07	18.4
Benowitz et al. (2010b)	Cross-sectional study of menthol cigarette smokers	60	0.9	18.8
	Cross-sectional study of non-menthol cigarette smokers	67	1.2	17
Church et al. (2010)	Cross-sectional study of cigarette smokers	70	1.47	24.1
Hatsukami et al. (2010)	Baseline data from cigarette smokers before switching to 0.3 mg FTC nicotine cigarettes	52	0.96	19.8
	Baseline data from cigarette smokers before switching to 0.05 mg FTC nicotine cigarettes	53	0.92	21.1
	Baseline data from cigarette smokers before switching to nicotine lozenge	60	1.06	21.3
Strasser et al. (2011)	Cross-sectional study of cigarette smokers	109	1.47	20.5
Benowitz et al. (2012a)	Baseline data from cigarette smokers assigned to control group	50	1	19
	Baseline data from cigarette smokers assigned to progressive reduced nicotine content group	53	1.4	22
	Baseline data from cigarette smokers assigned to progressive reduced nicotine content	42	1.3	22

(continued on next page)

Table 1 (continued)

Report authors (year of publication)	Study population characteristics	Number of study participants	Total urinary NNAL (pmol/mg creatinine)	CPD
Benowitz et al. (2012b)	group in those who complied	163	0.89	7.8
Khariwala et al. (2012)	Cross-sectional study of Alaskan Native cigarette smokers	29	1.51	NR
	Cross-sectional study of cigarette smokers who were head and neck squamous cell carcinoma cases			
	Cross-sectional study of cigarette smokers who were head and neck squamous cell carcinoma controls	100	1.68	NR
Rostron	Cross-sectional study of menthol cigarette smokers	NR	1.28	14
	Cross-sectional study of non-menthol cigarette smokers	NR	1.84	17.5
St. Helen et al. (2012)	Cross-sectional study of US smokers	225	1.05	19.4
Ter-Minassian et al. (2012)	Cross-sectional study of current cigarette smokers	87	1.41	20

ACSS, Adult Cross-sectional Study; CPD, cigarettes per day; FTC, Federal Trade Commission; LLSS, Low Level Smoking Study; NNAL, 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol; NR, not reported; ROSCAP, Reduction of Smoking in Cardiac Patients Study; TRIP, Tobacco Reduction Intervention Program.

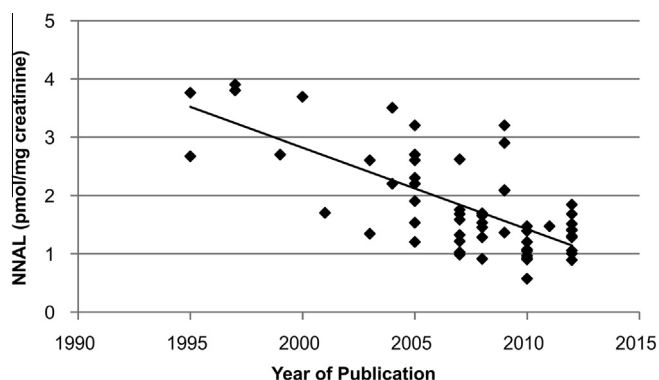


Fig. 1. Scatter plot of urinary NNAL excretion in US smokers expressed as pmol/mg creatinine, vs. year of publication showing a statistically significant downward trend (solid line,  $p < 0.00001$ ).

The analyses presented here should be considered in light of several limitations. The analysis did not include data from all published studies that met our inclusion criteria. Rather, it was limited to the largest body of data that either reported, or could be converted to, common units of NNAL excretion. Nevertheless, the analysis still included a substantial amount of data from 3941 study participants, 61 defined populations, and published in 35 studies over an 18-year period. To address this limitation, we plotted NNAL excretion data from studies

identified in our literature search that either reported, or could be converted to common units of NNAL excretion as nmol/24 h, or pmol/mL urine. A scatter plot of those data vs. year of study publication is presented in Fig. 2 along with the statistically significant trend lines showing a decline of NNAL over time. It must be noted that the interpretive value of these data sets is limited by either very few data points, relatively short time spans across studies, or both. Another limitation of this analysis is that the years the studies were published are unlikely to be the same as the years that the urine samples were collected. Unfortunately, few of the studies in this survey presented sample collection dates. Since the analysis reported here includes data generated across multiple laboratories, using various analytical methods and data reporting conventions, involving multiple demographic groups, and spanning 18 years, it is not possible to identify or control all potential sources of bias or confounding that may have influenced the findings in one direction or the other. The extent to which urinary NNAL excretion data for a particular population had been previously published was not always clear from the information available in some of the published reports. Therefore, we cannot be absolutely certain that our efforts to avoid using duplicate data did not result in inclusion of some previously published data or exclusion of some new data.

Despite these limitations, it is reasonable to expect that the downward trend in urinary NNAL excretion observed in this data set is reflective of a real phenomenon. For more than a decade, US tobacco companies and the agricultural community have actively researched the fundamental science related to TSNA formation, TSNA levels in tobacco and tobacco smoke, and methods to reduce these levels. These efforts have resulted in changes in tobacco curing practices as well as other measures intended to reduce TSNA levels in tobacco products (Appleton et al., 2013). Evidence suggests that progress toward this goal is being made. We recently reported that TSNA levels in cigarette smoke have been declining for a number of years, and particularly in the past decade. We also presented evidence that TSNA levels in cigarette tobacco filler have been declining over the past decade (Appleton et al., 2013).

Ashley et al. (2010) measured mouth-level exposure to NNK and urinary concentrations of NNAL in 126 daily smokers in four countries. The investigators reported that smoking cigarettes with lower TSNA emissions results in lower internal dose levels of NNAL. They further concluded that reducing the levels of NNK in mainstream cigarette smoke through curing practices can significantly affect a smoker's exposure to this constituent. Thus,

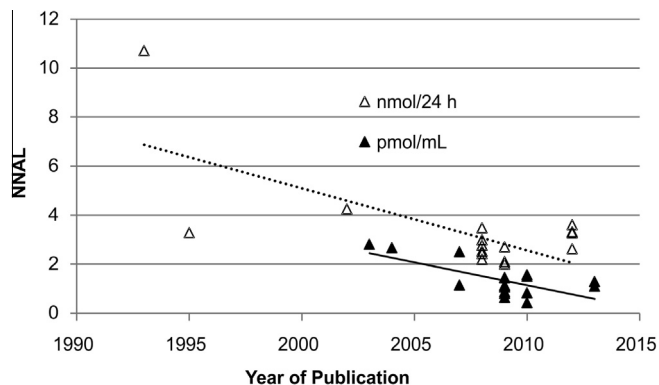


Fig. 2. Scatter plot of urinary NNAL excretion in US smokers expressed as nmol/24 h and pmol/mL urine vs. year of publication showing statistically significant downward trends (dotted line, nmol/24 h,  $p = 0.002$ ; solid line, pmol/mL,  $p = 0.003$ ).

the downward trend in NNAL excretion observed in this survey is consistent with the findings of Ashley et al. (2010) as well as evidence indicating that TSNA levels have been declining in both cigarette tobacco filler and cigarette smoke for at least the past 10 years.

In conclusion, an analysis of total urinary NNAL excretion data among 3941 study participants reported in 35 studies published over 18 years suggests that exposure to TSNA has declined among cigarette smokers over that time period. These findings are consistent with various efforts to reduce TSNA levels in tobacco products as well as observed reductions in TSNA levels in cigarette tobacco and smoke over the same time period.

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## References

- Anderson, K.E., Carmella, S.G., Ye, M., Bliss, R.L., Le, C., Murphy, L., Hecht, S.S., 2001. Metabolites of a tobacco-specific lung carcinogen in nonsmoking women exposed to environmental tobacco smoke. *J. Natl. Cancer Inst.* 93, 378–381.
- Appleton, S., Olegario, R.M., Lipowicz, P.J., 2013. TSNA levels in machine-generated mainstream cigarette smoke: 35 years of data. *Regul. Toxicol. Pharmacol.* 66, 197–207.
- Ashley, D.L., O'Connor, R.J., Bernert, J.T., Watson, C.H., Polzin, G.M., Jain, R.B., Hammond, D., Hatsukami, D.K., Giovino, G.A., Cummings, K.M., McNeill, A., Shahab, L., King, B., Fong, G.T., Zhang, L., Xia, Y., Yan, X., McCraw, J.M., 2010. Effect of differing levels of tobacco-specific nitrosamines in cigarette smoke on the levels of biomarkers in smokers. *Cancer Epidemiol. Biomarkers Prev.* 19, 1389–1398.
- Benowitz, N.L., Jacob III, P., Bernert, J.T., Wilson, M., Wang, L., Allen, F., Dempsey, D., 2005. Carcinogen exposure during short-term switching from regular to "light" cigarettes. *Cancer Epidemiol. Biomarkers Prev.* 14, 1376–1383.
- Benowitz, N., Goniewicz, M.L., Eisner, M.D., Laczcano-Ponce, E., Zielinska-Danch, W., Koszowski, B., Sobczak, A., Havel, C., Jacob III, P., 2010a. Urine cotinine underestimates exposure to the tobacco-derived lung carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone in passive compared with active smokers. *Cancer Epidemiol. Biomarkers Prev.* 19, 2795–2800.
- Benowitz, N.L., Dains, K.M., Dempsey, D., Havel, C., Wilson, M., Jacob III, P., 2010b. Urine menthol as a biomarker of mentholated cigarette smoking. *Cancer Epidemiol. Biomarkers Prev.* 19, 3013–3019.
- Benowitz, N.L., Dains, K.M., Hall, S.M., Stewart, S., Wilson, M., Dempsey, D., Jacob III, P., 2012a. Smoking behavior and exposure to tobacco toxicants during 6 months of smoking progressively reduced nicotine content cigarettes. *Cancer Epidemiol. Biomarkers Prev.* 21, 761–769.
- Benowitz, N.L., Renner, C.C., Lanier, A.P., Tyndale, R.F., Hatsukami, D.K., Lindgren, B., Stepanov, I., Watson, C.H., Sosnoff, C.S., Jacob III, P., 2012b. Exposure to nicotine and carcinogens among Southwestern Alaskan Native cigarette smokers and smokeless tobacco users. *Cancer Epidemiol. Biomarkers Prev.* 21, 934–942.
- Bernert, J.T., Pirkle, J.L., Xia, Y., Jain, R.B., Ashley, D.L., Sampson, E.J., 2010. Urine concentrations of a tobacco-specific nitrosamine carcinogen in the US population from secondhand smoke exposure. *Cancer Epidemiol. Biomarkers Prev.* 19, 2969–2977.
- Blank, M.D., Eissenberg, T., 2010. Evaluating oral noncombustible potential-reduced exposure products for smokers. *Nicotine Tob. Res.* 12, 336–343.
- Breland, A.B., Acosta, M.C., Eissenberg, T., 2003. Tobacco specific nitrosamines and potential reduced exposure products for smokers: a preliminary evaluation of advance. *Tob. Control* 12, 317–321.
- Burns, D.M., Dybing, E., Gray, N., Hecht, S., Anderson, C., Sanner, T., O'Connor, R., Djordjevic, M., Dresler, C., Hainaut, P., Jarvis, M., Opperhuizen, A., Straif, K., 2008. Mandated lowering of toxicants in cigarette smoke: a description of the World Health Organization TobReg proposal. *Tob. Control* 17, 132–141.
- Carmella, S.G., Akerkar, S., Hecht, S.S., 1993. Metabolites of the tobacco-specific nitrosamine 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone in smokers' urine. *Cancer Res.* 53, 721–724.
- Carmella, S.G., Akerkar, S.A., Richie Jr., J.P., Hecht, S.S., 1995. Intraindividual and interindividual differences in metabolites of the tobacco-specific lung carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) in smokers' urine. *Cancer Epidemiol. Biomarkers Prev.* 4, 635–642.
- Carmella, S.G., Borukhova, A., Akerkar, S.A., Hecht, S.S., 1997. Analysis of human urine for pyridine-N-oxide metabolites of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone, a tobacco-specific lung carcinogen. *Cancer Epidemiol. Biomarkers Prev.* 6, 113–120.
- Carmella, S.G., Han, S., Fristad, A., Yang, Y., Hecht, S.S., 2003. Analysis of total 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNAL) in human urine. *Cancer Epidemiol. Biomarkers Prev.* 12, 1257–1261.
- Carmella, S.G., Chen, M., Han, S., Briggs, A., Jensen, J., Hatsukami, D.K., Hecht, S.S., 2009. Effects of smoking cessation on eight urinary tobacco carcinogen and toxicant biomarkers. *Chem. Res. Toxicol.* 22, 741–759.
- Church, T.R., Anderson, K.E., Le, C., Zhang, Y., Kampa, D.M., Benoit, A.R., Yoder, A.R., Carmella, S.G., Hecht, S.S., 2010. Temporal stability of urinary and plasma biomarkers of tobacco smoke exposure among cigarette smokers. *Biomarkers* 15, 345–352.
- Derby, K.S., Cuthrell, K., Caberto, C., Carmella, S., Murphy, S.E., Hecht, S.S., Le, M.L., 2009. Exposure to the carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) in smokers from 3 populations with different risks of lung cancer. *Int. J. Cancer* 125, 2418–2424.
- Frost-Pineda, K., Zedler, B.K., Oliveri, D., Feng, S., Liang, Q., Roethig, H.J., 2008. Short-term clinical exposure evaluation of a third-generation electrically heated cigarette smoking system (EHCSS) in adult smokers. *Regul. Toxicol. Pharmacol.* 52, 104–110.
- Goniewicz, M.L., Havel, C.M., Peng, M.W., Jacob III, P., Dempsey, D., Yu, L., Zielinska-Danch, W., Koszowski, B., Czogala, J., Sobczak, A., Benowitz, N.L., 2009. Elimination kinetics of the tobacco-specific biomarker and lung carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone. *Cancer Epidemiol. Biomarkers Prev.* 18, 3421–3425.
- Hatsukami, D.K., Lemmonds, C., Zhang, Y., Murphy, S.E., Le, C., Carmella, S.G., Hecht, S.S., 2004. Evaluation of carcinogen exposure in people who used "reduced exposure" tobacco products. *J. Natl. Cancer Inst.* 96, 844–852.
- Hatsukami, D., Mooney, M., Murphy, S., LeSage, M., Babb, D., Hecht, S., 2007. Effects of high dose transdermal nicotine replacement in cigarette smokers. *Pharmacol. Biochem. Behav.* 86, 132–139.
- Hatsukami, D.K., Kotlyar, M., Hertsgaard, L.A., Zhang, Y., Carmella, S.G., Jensen, J.A., Allen, S.S., Shields, P.G., Murphy, S.E., Stepanov, I., Hecht, S.S., 2010. Reduced nicotine content cigarettes: effects on toxicant exposure, dependence and cessation. *Addiction* 105, 343–355.
- Hecht, S.S., Chung, F.L., Richie Jr., J.P., Akerkar, S.A., Borukhova, A., Skowronski, L., Carmella, S.G., 1995. Effects of watercess consumption on metabolism of a tobacco-specific lung carcinogen in smokers. *Cancer Epidemiol. Biomarkers Prev.* 4, 877–884.
- Hecht, S.S., Carmella, S.G., Chen, M., Dor Koch, J.F., Miller, A.T., Murphy, S.E., Jensen, J.A., Zimmerman, C.L., Hatsukami, D.K., 1999. Quantitation of urinary metabolites of a tobacco-specific lung carcinogen after smoking cessation. *Cancer Res.* 59, 590–596.
- Hecht, S.S., 2002. Human urinary carcinogen metabolites: biomarkers for investigating tobacco and cancer. *Carcinogenesis* 23, 907–922.
- Hecht, S.S., Carmella, S.G., Murphy, S.E., Riley, W.T., Le, C., Luo, X., Mooney, M., Hatsukami, D.K., 2007. Similar exposure to a tobacco-specific carcinogen in smokeless tobacco users and cigarette smokers. *Cancer Epidemiol. Biomarkers Prev.* 16, 1567–1572.
- Heck, J.D., 2009. Smokers of menthol and nonmenthol cigarettes exhibit similar levels of biomarkers of smoke exposure. *Cancer Epidemiol. Biomarkers Prev.* 18, 622–629.
- Hughes, J.R., Hecht, S.S., Carmella, S.G., Murphy, S.E., Callas, P., 2004. Smoking behaviour and toxin exposure during six weeks use of a potential reduced exposure product: Omni. *Tob. Control* 13, 175–179.
- Hurt, R.D., Croghan, G.A., Wolter, T.D., Croghan, I.T., Offord, K.P., Williams, G.M., Djordjevic, M.V., Richie Jr., J.P., Jeffrey, A.M., 2000. Does smoking reduction result in reduction of biomarkers associated with harm? A pilot study using a nicotine inhaler. *Nicotine Tob. Res.* 2, 327–336.
- IARC, 2007. IARC monographs on the evaluation of carcinogenic risks to humans, vol. 89. Smokeless tobacco and some tobacco-specific N-nitrosamines. <<http://monographs.iarc.fr/ENG/Monographs/vol89/mono89.pdf>> (accessed July 2013).
- IARC, 2009. IARC monographs on the evaluation of carcinogenic risks to humans, vol. 100 E. A review of human carcinogens. Personal habits and indoor combustions. <<http://monographs.iarc.fr/ENG/Monographs/vol100E/mono100E.pdf>> (accessed July 2013).
- Jones, M.R., Apelberg, B.J., Tellez-Plaza, M., Samet, J.M., Navas-Acien, A., 2013. Menthol cigarettes, race/ethnicity, and biomarkers of tobacco use in US adults: the 1999–2010 National Health and Nutrition Examination Survey (NHANES). *Cancer Epidemiol. Biomarkers Prev.* 22, 224–232.
- Joseph, A.M., Hecht, S.S., Murphy, S.E., Carmella, S.G., Le, C.T., Zhang, Y., Han, S., Hatsukami, D.K., 2005. Relationships between cigarette consumption and biomarkers of tobacco toxin exposure. *Cancer Epidemiol. Biomarkers Prev.* 14, 2963–2968.
- Khariwala, S.S., Carmella, S.G., Stepanov, I., Fernandes, P., Lassis, A.A., Yueh, B., Hatsukami, D., Hecht, S.S., 2012. Elevated levels of 1-hydroxypyrene and N'-nitrosonornicotine in smokers with head and neck cancer: a matched control study. *Head Neck*, <http://dx.doi.org/10.1002/hed.23085>.
- Kinsler, R.D., Nelson, B.L., Roethig, H.J., Walk, R.A., Oey, J., Tricker, A.R., Leyden, D.E., 2002. Use of nicotine and NNK metabolites to assess exposure to cigarette smoke constituents: pilot study results. Poster Presented at the 8th Annual Meeting of the Society for Research on Nicotine and Tobacco, Savannah, GA, February 20–23, 2002.
- Le Marchand, L., Derby, K.S., Murphy, S.E., Hecht, S.S., Hatsukami, D., Carmella, S.G., Tiirikainen, M., Wang, H., 2008. Smokers with the CHRNA lung cancer-associated variants are exposed to higher levels of nicotine equivalents and a carcinogenic tobacco-specific nitrosamine. *Cancer Res.* 68, 9137–9140.

- Melikian, A.A., Djordjevic, M.V., Chen, S., Richie Jr., J., Stellman, S.D., 2007. Effect of delivered dosage of cigarette smoke toxins on the levels of urinary biomarkers of exposure. *Cancer Epidemiol. Biomarkers Prev.* 16, 1408–1415.
- Mendoza-Baumgart, M.L., Tulunay, O.E., Hecht, S.S., Zhang, Y., Murphy, S., Le, C., Jensen, J., Hatsukami, D.K., 2007. Pilot study on lower nitrosamine smokeless tobacco products compared with medicinal nicotine. *Nicotine Tob. Res.* 9, 1309–1323.
- MMWR, 2012. Current cigarette smoking among adults – United States, 2011. *MMWR Morb. Mortal. Wkly. Rep.* 61, 889–894.
- Murphy, S.E., Link, C.A., Jensen, J., Le, C., Puumala, S.S., Hecht, S.S., Carmella, S.G., Losey, L., Hatsukami, D.K., 2004. A comparison of urinary biomarkers of tobacco and carcinogen exposure in smokers. *Cancer Epidemiol. Biomarkers Prev.* 13, 1617–1623.
- Muscat, J.E., Djordjevic, M.V., Colosimo, S., Stellman, S.D., Richie Jr., J.P., 2005. Racial differences in exposure and glucuronidation of the tobacco-specific carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK). *Cancer* 103, 1420–1426.
- Muscat, J.E., Chen, G., Knipe, A., Stellman, S.D., Lazarus, P., Richie Jr., J.P., 2009. Effects of menthol on tobacco smoke exposure, nicotine dependence, and NNAL glucuronidation. *Cancer Epidemiol. Biomarkers Prev.* 18, 35–41.
- Roethig, H.J., Feng, S., Liang, Q., Liu, J., Rees, W.A., Zedler, B.K., 2008. A 12-month, randomized, controlled study to evaluate exposure and cardiovascular risk factors in adult smokers switching from conventional cigarettes to a second-generation electrically heated cigarette smoking system. *J. Clin. Pharmacol.* 48, 580–591.
- Roethig, H.J., Munjal, S., Feng, S., Liang, Q., Sarkar, M., Walk, R.A., Mendes, P.E., 2009. Population estimates for biomarkers of exposure to cigarette smoke in adult US cigarette smokers. *Nicotine Tob. Res.* 11, 1216–1225.
- Rostron, B., 2013. NNAL exposure by race and menthol cigarette use among US smokers. *Nicotine Tob. Res.* 15, 950–956.
- Sarkar, M., Kapur, S., Frost-Pineda, K., Feng, S., Wang, J., Liang, Q., Roethig, H., 2008. Evaluation of biomarkers of exposure to selected cigarette smoke constituents in adult smokers switched to carbon-filtered cigarettes in short-term and long-term clinical studies. *Nicotine Tob. Res.* 10, 1761–1772.
- Sarkar, M., Liu, J., Koval, T., Wang, J., Feng, S., Serafin, R., Jin, Y., Xie, Y., Newland, K., Roethig, H.J., 2010. Evaluation of biomarkers of exposure in adult cigarette smokers using Marlboro snus. *Nicotine Tob. Res.* 12, 105–116.
- Sellers, E.M., Ramamoorthy, Y., Zeman, M.V., Djordjevic, M.V., Tyndale, R.F., 2003. The effect of methoxsalen on nicotine and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) metabolism in vivo. *Nicotine Tob. Res.* 5, 891–899.
- St. Helen, G., Goniewicz, M.L., Dempsey, D., Wilson, M., Jacob III, P., Benowitz, N.L., 2012. Exposure and kinetics of polycyclic aromatic hydrocarbons (PAHs) in cigarette smokers. *Chem. Res. Toxicol.* 25, 952–964.
- Stepanov, I., Hecht, S.S., 2005. Tobacco-specific nitrosamines and their pyridine-N-glucuronides in the urine of smokers and smokeless tobacco users. *Cancer Epidemiol. Biomarkers Prev.* 14, 885–891.
- Stepanov, I., Hecht, S.S., Lindgren, B., Jacob III, P., Wilson, M., Benowitz, N.L., 2007. Relationship of human toenail nicotine, cotinine, and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol to levels of these biomarkers in plasma and urine. *Cancer Epidemiol. Biomarkers Prev.* 16, 1382–1386.
- Stepanov, I., Upadhyaya, P., Carmella, S.G., Feuer, R., Jensen, J., Hatsukami, D.K., Hecht, S.S., 2008. Extensive metabolic activation of the tobacco-specific carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone in smokers. *Cancer Epidemiol. Biomarkers Prev.* 17, 1764–1773.
- Stepanov, I., Carmella, S.G., Han, S., Pinto, A., Strasser, A.A., Lerman, C., Hecht, S.S., 2009. Evidence for endogenous formation of N'-nitrosornicotine in some long-term nicotine patch users. *Nicotine Tob. Res.* 11, 99–105.
- Strasser, A.A., Benowitz, N.L., Pinto, A.G., Tang, K.Z., Hecht, S.S., Carmella, S.G., Tyndale, R.F., Lerman, C.E., 2011. Nicotine metabolite ratio predicts smoking topography and carcinogen biomarker level. *Cancer Epidemiol. Biomarkers Prev.* 20, 234–238.
- Taioli, E., Garbers, S., Bradlow, H.L., Carmella, S.G., Akerkar, S., Hecht, S.S., 1997. Effects of indole-3-carbinol on the metabolism of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone in smokers. *Cancer Epidemiol. Biomarkers Prev.* 6, 517–522.
- Ter-Minassian, M., Asomaning, K., Zhao, Y., Chen, F., Su, L., Carmella, S.G., Lin, X., Hecht, S.S., Christiani, D.C., 2012. Genetic variability in the metabolism of the tobacco-specific nitrosamine 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) to 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanol (NNAL). *Int. J. Cancer* 130, 1338–1346.
- USDHHS, 2010. A report of the Surgeon General: How tobacco smoke causes disease, 2010. The biology and behavioral basis for smoking-attributable disease. <<http://www.surgeongeneral.gov/library/reports/tobaccosmoke/report-index.html>> (accessed July 2013).
- USDHHS, 2012. US Food and Drug Administration. Harmful and potentially harmful constituents in tobacco products and tobacco smoke: established list. <<http://www.fda.gov/TobaccoProducts/GuidanceComplianceRegulatoryInformation/ucm297786.htm>> (accessed July 2013).