Original Investigation

Nicotine, Cotinine, and Tobacco-Specific Nitrosamines Measured in Children's Silicone Wristbands in Relation to Secondhand Smoke and E-cigarette Vapor Exposure

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Abstract

Introduction: Simple silicone wristbands (WB) hold promise for exposure assessment in children. We previously reported strong correlations between nicotine in WB worn by children and urinary cotinine (UC). Here, we investigated differences in WB chemical concentrations among children exposed to secondhand smoke from conventional cigarettes (CC) or secondhand vapor from electronic cigarettes (EC), and children living with nonusers of either product (NS).

Methods: Children ($n = 53$) wore three WB and a passive nicotine air sampler for 7 days and one WB for 2 days, and gave a urine sample on day 7. Caregivers reported daily exposures during the 7-day period. We determined nicotine, cotinine, and tobacco-specific nitrosamines (TSNAs) concentrations in WB, nicotine in air samplers, and UC through isotope-dilution liquid chromatography with triple-quadrupole mass spectrometry.

Results: Nicotine and cotinine levels in WB in children differentiated between groups of children recruited into NS, EC exposed, and CC exposed groups in a similar manner to UC. WB levels were significantly higher in the CC group (WB nicotine median 233.8 ng/g silicone, UC median 3.6 ng/mL, $n = 15$) than the EC group (WB nicotine median: 28.9 ng/g, UC 0.5 ng/mL, $n = 19$), and both CC and EC group levels were higher than the NS group (WB nicotine median: 3.7 ng/g, UC 0.1 ng/mL, $n = 19$). TSNAs, including the known carcinogen NNK, were detected in 39% of WB.

Conclusions: Silicone WB show promise for sensitive detection of exposure to tobacco-related contaminants from traditional and electronic cigarettes and have potential for tobacco control efforts.

Implications: Silicone WB worn by children can absorb nicotine, cotinine, and tobacco-specific nitrosamines, and amounts of these compounds are closely related to the child's urinary cotinine. Levels of tobacco-specific compounds in the silicone WB can distinguish patterns of children's

exposure to secondhand smoke and e-cigarette vapor. Silicone WB are simple to use and acceptable to children and, therefore, may be useful for tobacco control activities such as parental awareness and behavior change, and effects of smoke-free policy implementation.

Introduction

Simple techniques for measuring exposure to secondhand and thirdhand tobacco smoke (SHS and THS) and second and thirdhand vapor from electronic cigarettes (EC; SHeV and THeV) can assist tobacco control efforts. Methods for assessing these exposures in children are especially needed.¹ Current methods, although accurate, often rely on biological specimens such as urine and saliva, which can be difficult to obtain and require special handling of specimens.² Silicone wristbands (WB), which are already worn by children by choice, have been shown to absorb toxic chemicals from the wearer's environment when worn for several days to weeks.³⁻¹¹

Our group was the first to apply silicone WB to measurement of tobacco product exposure in children, and we demonstrated that nicotine levels in silicone WB worn by children ($n = 31$) for 2 and 7 days were both highly correlated with cotinine, a metabolite of nicotine, in urine from the same child.¹² Here, we further investigated the ability of silicone WB to record differences in nicotine exposures among children recruited into different exposure groups: children exposed to SHS or those exposed to SHeV compared with children living with nonusers of either conventional or EC. We also compare silicone WB performance to air monitors carried by the children as well as to urinary cotinine (UC). We expand analysis of tobacco products measured in silicone WB to cotinine and tobacco-specific nitrosamines (TSNAs) a group of chemicals specific to tobacco that includes known carcinogens.¹³

Methods

Recruitment

Approvals were obtained from the Human Research Protection Program at San Diego State University, and informed consent and assent were obtained. Participants were recruited from a past home air quality study who had agreed to be re-contacted ($n = 27$), referrals from other study participants ($n = 5$), tabling, ie, research assistants recruited at tables placed in public locations such as shopping centers ($n = 8$) and advertisements on Craigslist ($n = 1$), Facebook ($n = 11$), and Instagram ($n = 1$). Children were all nonusers of conventional cigarettes (CC) or EC. We recruited children who lived with at least one adult who smoked a minimum of 7 CC/week inside the home ($n = 19$), children who lived with at least one adult who used EC at least 4 days/week inside the home and used e-liquids with nicotine ($n = 19$), and children not exposed to nicotine products, who lived with adult nonsmokers and nonusers of EC who had a complete ban on smoking and EC use inside their home ($n = 15$). Participants in the CC and EC groups were more likely to be classified as African-American/Black or Biracial/mixed race (82%) than Latinos (33%, $p < .05$).

Sample Collection

All samples and interview data were collected during two visits to participants' homes between March 2017 and December 2018.

Face-to-Face Home Interviews

Parents/caregivers were interviewed by trained research assistants to collect data on education level, family income, and child's age, gender, race/ethnicity; household characteristics including the number of residents and rooms, and years living in the current home; child's exposure to CC and EC over the sampling week; actual household residents' usage frequency and amount of CC and EC products over the sampling week; the location (inside the home, inside the car, or outside) where CC and EC were used when a child was present.

Daily Monitoring

Caregivers were asked to report their daily use of CC/EC and the child's exposure to CC/EC during brief (5 min) daily telephone calls with a research assistant, and to verify wearing of the air monitor and WB through a daily texted photo.

Urine Samples

Single spot urine samples were collected from child participants using procedures from our previous studies.^{12,14,15} Caregivers were asked to have the child collect their sample on the morning of the second home visit, but sometimes samples were collected at other times due to child and caregiver schedules.

Silicone Wristbands

Cleaned prepared bulk WB in Teflon bags were obtained from Anderson.⁸ WB were individually stored and transported in clear glass jars with polytetrafluoroethylene-faced PE-lined caps, or 2.0 mil thick Teflon PFA bags (2-day WB). Each child participant received three WB at the initial home visit. Two were placed on the child's arm at the home visit, to be worn for 7 days, and one was given to the caregiver for a child to wear for the last 2 days. A reminder was given by phone to caregivers on the morning of day 5 to place WB on the child. The actual wearing time for the 7-day WB was from 5.8 to 8.7 days, with a median of 7.0 and 2.4 days for the 2-day WB. The research assistants also collected a WB field blank for each participant, handling and transporting it in the same way as the worn WB, except it was immediately replaced in the container. Caregivers texted a picture of the child wearing the WB and air monitor (below) once a day to verify wearing. Participants were asked to wear WB at all times during the study. Most (36/53) children received "small" size WB (median weight 3.8 g), 8/53 received "extra small" size WB (median weight 3.7 g) and 9/53 received "large" size WB (median weight 4.3 g). Nicotine was present in 8/36 of the analyzed field blanks, and the average blank value was 1.14 ng nicotine/WB. The majority (6/8) of the field blanks with detectable nicotine levels were from the CC group, with one from the EC group and the lowest one (0.6 ng nicotine/WB) in the NS group. We reported results as ng nicotine/WB in our previous paper. Here we report nicotine, cotinine, and TSNAs in ng nicotine/g silicone in WB as in other studies.^{6,16} For 31 WB used for nicotine analysis, the actual WB weight was not recorded, so we used the median weight of WB in that size category. Both 2- and 7-day WB nicotine and cotinine levels adjusted for silicone WB weight (ng/g silicone) were highly correlated with levels expressed as ng/WB (all $\rho > .99$, $p <$

.01). Sample WB and field blanks were transported cooled in individual borosilicate amber glass vials, with Thermoset lids lined with polytetrafluoroethylene, and stored at -20°C until analysis.

Air Nicotine

Air nicotine concentrations were measured using passive air monitors.¹⁷ Child participants were asked to wear the passive diffusion monitor badge (protected by a stainless steel mesh “tea ball”) pinned to their outer clothing or backpack strap over 1 week, and to wear the badge at all times except when bathing, swimming, sleeping, or when it interfered with activities such as engaging in vigorous sports. Many participants reported not wearing the monitors for short times (eg, forgetting in car when at church). The times were not adjusted for nonwearing of the badge. Deployment time was used to calculate minutes monitor was exposed and ranged from 5.9 to 12 days (median 7.0 days). An air monitor field blank was collected for each participant. Of these, 10% were analyzed, and if the average blank level was $<30\%$ of the level in the sample, the average blank level was subtracted from the sample level. If the average blank level was $>30\%$ of the level in the sample, the sample was censored. Results are reported as ng nicotine/ m^3 of air.

Laboratory Analysis

Detailed laboratory methods are available in [Supplementary Material](#).

Wristband Nicotine

The QuEChERS extraction procedure modified for nicotine analyses in dust and surface wipes was utilized to extract nicotine from the silicone WB.¹⁸ Nicotine quantification was conducted by liquid chromatography with triple-quadrupole mass spectrometry (LC-MS/MS; Agilent 1200 Series LC system coupled to an Agilent 6460 Triple Quadrupole system) operated in positive electrospray ionization (ESI+) mode. The estimated method detection limit (MDL)¹⁹ was 0.19 ng/WB. Detailed information on the sample preparation, extraction, and quantification of nicotine from WB has been described.¹²

Wristband Cotinine

Cotinine was extracted from the same WB as nicotine using the nicotine WB extraction method, above, with a final spiked cotinine- d_3 concentration of 5 ng/mL, and quantified with the same instrumental method as for UC, below.^{14,15} The estimated MDL was 0.10 ng/WB. We added this analyte to the second half of samples ($n = 22$) after considering the literature suggesting that sweat could be a route of exposure for the WB.

Wristband TSNAs

The extraction procedure is described in detail in the [Supplementary Material](#). A separate WB was analyzed for TSNAs. One half of the WB was weighed, then spiked with the four internal standards (NNK- d_4 , NAB- d_4 , NAT- d_4 , and NNN- d_4). The final concentration of each of the deuterated TSNAs was 12.5 ng/mL. The TSNAs were quantified by LC-MS/MS, operated in ESI+ mode as in Ref.¹⁵ The estimated MDL was 0.10 ng/WB. A total of 51 WB were analyzed for TSNAs.

Urinary Cotinine

UC was determined through isotope dilution LC-MS/MS.^{12,14,15} The estimated MDL was 0.033 ng/mL urine, and cotinine levels were reported in nanogram per milliliter urine.²⁰

Air Nicotine

The extraction procedure is described in detail in [Supplementary Material](#), and used a procedure similar to nicotine in WB. The final concentration of nicotine- d_4 was 5 ng/mL. The instrumental method and calibration procedure described for WB nicotine were used for quantification.¹² The estimated MDL was 0.13 ng/badge.

Statistical Analysis

Descriptive statistics were produced using SPSS v26. The Kruskal–Wallis test followed by pairwise Mann–Whitney U test was utilized to determine differences of nicotine and cotinine concentrations among participants' groups. Spearman rank-order correlations (ρ) were used to determine associations. The type I error rate was set at 5% (two-tailed). Statistical tests were conducted with SPSS v25 and 26.

Results

Demographic Characteristics

All children recruited for this study were nonsmokers and nonusers of EC. The majority of participants were multiracial (39.6%) or Latino/a (22.6%) ([Table 1](#)). The majority of children were females (60%), and a median 9 years of age (range 3–14). Participants in this study lived a median 3 years in their home with a median number of occupants of 5 (range 2–16). African–American and multiracial participants had significantly higher UC than Latino participants.

Detection Levels for Nicotine and Cotinine in WB, Cotinine in Urine, and Air Nicotine Samplers

Nicotine was detected in 100% of all silicone WB, with a range over three orders of magnitude (from 2.5 ng of nicotine to over 3000 ng/WB) ([Supplementary Table S2](#)) and cotinine in almost all WB (91% and 95%, 7 and 2 days, respectively). UC had a similar detection frequency with only one nondetect, $<2\%$. In contrast, only 36% of air samples had detectable levels of nicotine ([Supplementary Table S1](#)).

Differences in WB, Air, and Urine Measures Between Exposure Groups

[Table 2](#) shows the medians by exposure group for the children for 7-day WB nicotine, 7-day WB cotinine, UC, and air nicotine. In addition to children's exposure groups based on recruitment criteria ([Table 2](#), classification I), we present groups classified based on daily interviews during the 7-day period that the child was wearing the WB, which differed in some cases from the report at recruitment: these groups are reported exposure of the child in the same indoor room (classification II), as well as product use by residents, whether or not the child was present (classification III).

Nicotine and cotinine levels in WB distinguished between CC, EC, and NS recruitment groups ([Table 2](#), classification I), as did UC and air nicotine. Nicotine and cotinine levels were significantly higher in 7-day WB, as well as children's UC recruited in the CC group (WB nicotine median: 233.8 ng/g silicone; UC: 3.6 ng/mL) than the EC group (WB nicotine median: 28.9 ng/g; UC: 0.5 ng/mL), and both CC and EC group levels were higher than in the NS group (WB nicotine median: 3.7 ng/g; UC: 0.1 ng/mL). WB cotinine concentrations also distinguished between the CC, EC, and NS recruitment groups ([Table 2](#), classification I). [Supplementary Table S3](#) presents data for 2-day WB nicotine and cotinine, with similar results.

Table 1. Demographic and household characteristics in relation to urinary cotinine (UC) ($n = 53$)

Demographics	n (%)	UC (ng/mL) (median, p25–p75)	p value
Gender			
Male	21 (40)	.3 (.1–2.6)	.960
Female	32 (60)	.5 (.1–2.8)	
Ethnicity			
Latino/Hispanic	12 (23)	.1 (.1–2.7)	.014
African American/Black	7 (13)	2.8 (1.2–9.9)^a	
Caucasian/White	11 (21)	.3 (.2–.0)	
Asian/Pacific Islander	2 (4)	.8 (.5)	
Bi- or multiracial	21 (40)	1.3 (.1–4.5)^a	
Yearly income			
\$20,000 and less	11 (21)	1.2 (.1–4.9)	.672
\$20,001 to \$50,000	19 (36)	.9 (.1–3.6)	
\$50,001 and above	23 (43)	.3 (.1–1.4)	
Parents/caregivers education			
High school and below	7 (13)	2.0 (.3–6.7)	.395
Some college	26 (49)	.5 (.1–3.5)	
Received higher education diploma	20 (38)	.3 (.1–1.4)	
Children's age groups			
3 to <6 years of age	12 (23)	.8 (.2–2.6)	.355
6 to <11 years of age	28 (53)	.8 (.2–3.6)	
11 to 14 years of age	13 (25)	.0 (.0–3.1)	
Household characteristics			
Number of occupants			
≤3	10 (19)	.3 (.2–6.2)	
4–5	25 (47)	.5 (.1–1.7)	.825
≥6	18 (34)	.7 (.2–2.9)	
Number of rooms			
≤6	20 (38)	1.0 (.2–3.5)	
7	15 (28)	.2 (.0–1.3)	.080
≥8	18 (34)	.7 (.3–3.0)	
Years living in residence			
≤2	19 (37)	1.2 (.3–4.7)	
2 – ≤5	17 (33)	.3 (.1–1.5)	.139
≥6	15 (29)	.5 (.1–1.9)	

Note: Bold values are significant ($p < .05$).

p25–p75 = 25th and 75th percentile.

^aAfrican-American/Black and Multiracial groups had significantly higher levels than Latinos.

Classifications II and III were based on caregiver report over the 7 days of the study. For all measures, the WB worn by children in the CC group were significantly more contaminated compared with EC and NS groups (Table 2, classifications II and III). Examining the residents' use of CC use group further (detailed examination of III, Table 2), it is clear that the highest WB nicotine levels, as well as air and UC levels, were measured when residents smoked CC inside (WB nicotine for CC inside group median 428.4 ng/g silicone versus CC outside only median 36.7 ng/g, $p < .01$, Table 2). For WB nicotine, cotinine, and UC, the EC group was also significantly higher than NS groups for classification III (Table 2). We further examined the NS groups in II and III to examine WB sensitivity to low levels of exposure. In classification II, 24 of the children were classified as "NS" by their caregivers, and of these, 14 were classified as NS in both II and III (Table 2). The 10 children (24 total – 14) from homes where residents used CC or EC but the caregiver reported the child was not exposed (NS in classification II only) had significantly higher, WB nicotine, WB cotinine, and UC than the 14 children from

homes with no EC/CC use and a total ban (classification as NS in both II and III). For WB nicotine, the median was 46.5 ng/g silicone versus 3.9 ng/g, for WB cotinine 22.3 ng/g vs. 0.3 ng/g, and for UC 0.3 ng/mL vs. 0.1 ng/mL, all $p < .01$.

Correlation of WB Nicotine and Cotinine With Quantitative Measures of Tobacco Product Use

To determine whether levels of nicotine and cotinine in silicone WB were sensitive to the levels of tobacco product use, we determined correlations with reported measures of indoor CC and EC use (Table 3). For both the child's exposure as reported by the caregiver (exposure classification II) as well as by the resident's reported use, classification III), the amount of nicotine (ng/g silicone) in the WB was significantly correlated with the number of cigarettes smoked indoors over the 7-day period ($\rho = .706, .725$, respectively, $p < .01$). The amount of vaping reported was also significantly correlated with nicotine levels in WB, both for reported exposure to EC in minutes ($\rho = .442, .557$, respectively, $p < .01$) and in reported mLs of EC-fluid used per week ($\rho = .557, .581$, respectively, $p < .01$), even though the amount of nicotine in the product was unknown.

Measurement of TSNAs in Silicone WB

We detected TSNAs in 39% of silicone WB (Supplementary Table S1), mostly in children exposed to CC (Table 4). For recruitment group (I) as well as exposure (II) and use (III) group, the CC group had a higher level of total TSNAs on the WB (median 0.25 ng/g silicone vs. 0.05 ng/g silicone in III NS group, Table 4) mainly due to the well-studied lung carcinogen NNK (64% detection in product use CC group, 46% detection in CC plus EC group, 7% in EC group, and 0% in NS group). Details for each individual TSNA (NNK, NAT, NAB, and NNN) are given in Supplementary Table S4. NAB was the only TSNA to be detected in the NS groups I, II, or III (14%, 9%, and 14% detection in NS groups, respectively, Table 4).

Correlations Between Analytes

The 2- and 7-day WB nicotine levels were highly correlated ($\rho = .94$), with a median 28% difference, and both 2- and 7-day WB nicotine levels were highly correlated with UC on day 7 (both $\rho > .90$) (Supplementary Table S5). Cotinine in WB was also highly correlated with WB nicotine (both $\rho > .90$) and UC ($\rho = .87$). The median ratio of cotinine to nicotine measured in the same WB decreased in more highly exposed groups, though none of the decreases were statistically significant, for example, from a median .74 in NS recruitment group versus .50 in the EC group and .20 in the CC group) (Supplementary Table S6).

Discussion

Silicone WB recorded nicotine and cotinine over a range spanning three orders of magnitude, with a 100% detection rate for nicotine. We demonstrated significant differences in silicone WB nicotine and cotinine between groups of children recruited into nonsmoker, EC exposed, and CC exposed groups similar to UC, demonstrating the validity of the silicone WB sampler in measuring exposure to tobacco products. Silicone WB had a sensitive detection limit for nicotine and cotinine. In children reported as nonexposed by the caregiver, nicotine in WB more closely tracked caregiver's use patterns regardless of children's presence, rather than child's exposure as reported by the caregiver, as did UC. This increase might be due to child exposures

Table 2. Child's exposure group related to nicotine and cotinine concentrations in wristbands (WB), nicotine in air and urinary cotinine (UC)

Exposure group by classification scheme (#)	<i>n</i> ^a	7-day WB nicotine concentration (ng/g), <i>n</i> = 52 median (p25–p75)	7-day WB cotinine concentration (ng/g), <i>n</i> = 22 median (p25–p75), <i>n</i>	Air nicotine concentration (ng/m ³), <i>n</i> = 53 median (p25–p75)	UC concentration (ng/mL), <i>n</i> = 53 median (p25–p75)
Recruitment (I)					
NS-non-exposed at recruitment	15	3.7 (1.6–4.6)	0.34 (0.0–1.0), 5	0.0 (0.0–0.0)	0.1 (0.0–0.1)
EC	19	28.9 (15.5–55.5) ^b	7.4 (3.4–12.7) ^b , 10	0.0 (0.0–14.3)	0.5 (0.3–1.2) ^b
CC	19	233.8 (74.7–429.1) ^{b,c}	36.8 (15.4–56.1) ^{b,c} , 7	90.7 (0.0–291.3) ^{b,c}	3.6 (1.4–9.9) ^{b,c}
Child's reported exposure (II)					
NS-nonexposed by caregiver report	24	4.5 (3.1–28.2)	1.5 (0.3–29.4), 11	0.0 (0.0–0.0)	0.1 (0.1–0.3)
EC	14	27.6 (15.1–58.0) ^b	6.3 (4.0–10.9), 7	0.0 (0.0–41.4)	0.5 (0.3–1.2) ^b
EC+CC	4	176.2 (55.7–561.3) ^b	36.9 (– –) ^d , 1	171.5 (21.2–381.9) ^{b,c}	2.4 (1.9–8.1) ^b
CC	9	242.4 (105.9–470.8) ^{b,c}	50.7 (– –), 3	210.2 (68.0–317.1) ^{b,c}	4.2 (3.2–7.6) ^{b,c}
Residents' tobacco product use (III)					
NS-no reported use by residents	14	3.9 (1.6–5.4)	0.3 (0.0–1.0), 5	0.0 (0.0–0.0)	0.1 (0.0–0.2)
EC	14	27.0 (14.9–53.1) ^b	8.6 (4.9–13.4) ^b , 9	0.0 (0.0–0.0)	0.3 (0.2–0.6) ^b
EC+CC	13	73.4 (28.4–214.9) ^b	22.4 (4.8–49.4) ^b , 4	0.0 (0.0–55.2)	1.4 (0.7–2.8) ^b
CC	12	243.4 (102.2–510.5) ^{b,c}	43.8 (18.8–66.8) ^b , 4	187.1 (45.9–294.9) ^{b,c}	4.2 (3.0–10.4) ^{b,c}
Detailed residents' tobacco products use (III)					
NS-no reported use by residents	14	3.9 (1.6–5.4)	0.3 (0.0–1.0), 5	0.0 (0.0–0.0)	0.1 (0.0–0.2)
EC, inside or only outside home, no CC ^d	14	27.0 (14.9–53.1) ^b	8.6 (5.0–13.4) ^b , 9	0.0 (0.0–0.0)	0.3 (0.2–0.6) ^b
CC outside only, regardless of EC usage ^e	10	36.7 (23.1–91.2) ^b	15.4 (– –) ^b , 3	0.0 (0.0–30.5)	1.1 (0.2–1.5) ^b
CC and EC inside home	5	230.3 (65.4–311.6) ^b	29.4 (– –), 1	47.0 (0.0–276.3) ^b	2.8 (1.4–8.3) ^b
CC inside home, no EC	10	428.4 (173.4–584.6) ^{b,c}	43.8 (18.8–66.8) ^b , 4	279.5 (77.5–320.7) ^{b,c}	4.8 (3.5–10.8) ^{b,c}

Note: bold values are significant ($p < .05$). Also note that the overall detection rate for air monitors was 36%; details are given in [Supplementary Table S1](#).

NS = no exposure or no use of tobacco products; CC = conventional cigarette; EC = electronic cigarettes; p25–p75 = 25th and 75th percentile classification I—at recruitment, reported exposure of the child; NS = no EC/CC use by caregivers or residents and home smoking ban; EC = exposure to EC inside; CC = exposure to CC inside; Classification II = exposure of the child in same indoor room based on report of caregiver for 7-day period; Classification III = residents reported use over 7-day period inside the home whether or not child was present. ^aSample size for all measures except WB cotinine.

^bSignificantly higher levels than NS ($p < .01$).

^cSignificantly higher levels than EC ($p < .01$).

^dgroup includes EC users only outside home ($n = 2$) and EC users inside home ($n = 12$).

^ePercentiles not reported for samples sizes of <4.

^fGroup includes reported exposure to CC outside with no EC users ($n = 2$), CC outside with EC users outside ($n = 3$), CC outside with EC users inside home ($n = 5$).

to drifting SHS or SHeV unnoticed by the caregiver,²¹ and/or potential exposure to thirdhand smoke residue,^{22–24} and demonstrates the sensitivity of the silicone WB sampler. The highest levels for WB were associated with exposure to CC indoors, demonstrating the ability of the sampler to detect high exposures in a similar manner to urinary cotinine. Within groups, we also detected significant correlations with the number of CC or amount of EC used, indicating silicone WB can detect an exposure-response relationship. Silicone WB performed similarly to UC, and the cost of analysis is similar to air nicotine and cotinine, but WB are simpler to deploy and collect. Although WB were deployed and retrieved in-person in this study, other studies have shipped WB internationally at ambient temperatures,^{4,25} and semi-volatile organic compounds (SVOCs) concentrations were found to be stable in WB at room temperatures (nicotine is an SVOC).²⁶ The next step is to validate remote deployment and collection of WB for tobacco-related compounds collected under standard mailing conditions to assist in the community-based exposure studies.

We demonstrated that children exposed to secondhand EC vapor by their caregivers have higher levels of nicotine on their WB than do children of nonsmokers/users. E-cigarette use in the home has been reported to result in measurable air nicotine (geomean 130 ng/m³ nicotine in homes of indoor e-cigarette users compared with 20 ng/m³ in homes of nonsmokers/nonusers)²⁷ and 200 ng/m³ nicotine in homes of indoor e-cigarette users in another study.²⁸ In our study, <50% of the air monitors carried by children in the EC-only caregiver use registered above our nicotine in air detection limit (median 0.0, 75th percentile 22.0 ng/m³, maximum 180.5), but the air monitor in our study traveled with the child, as opposed to a static home measurement, so these integrated air levels were likely lower. To our knowledge, the elevated level of nicotine in WB is the first report of personal measurement of nicotine from secondhand e-cigarette exposure in children.

In our data, the 7-day wearing time and the 2-day wearing time produced comparable results. The 7-day measurement was higher in nicotine, but only by 28%, rather than the 350% expected if the

Table 3. Correlations of WB, urine, and air exposure measures in relation to CC and EC exposure and usage

Reported tobacco product exposure and use	Median (p25–p75)	7-Day WB Nicotine (ng/g silicone) ρ (<i>n</i>)	7-Day WB Cotinine (ng/g silicone) ρ (<i>n</i>)	UC (ng/mL) ρ (<i>n</i>)	Air Nicotine (ng/m ³) ρ (<i>n</i>)
<i>CC variables</i>					
Child's exposure to CC inside (cigarettes/week) ^a	0.0 (0.0–12.0)	0.706*** (38)	0.560* (15)	0.717*** (38)	0.723** (38)
Residents' use of CC inside (cigarettes/week) ^b	0.9 (0.0–12.0)	0.725*** (29)	0.774** (10)	0.680*** (29)	0.779** (29)
<i>EC variables</i>					
Child's exposure to EC inside (min/week) ^c	0.0 (0.0–14.8)	0.353* (38)	0.083 (18)	0.470** (38)	0.351* (38)
Residents' use of EC inside (min/week) ^d	0.0 (0.0–17.8)	0.557** (26)	0.425 (13)	0.625*** (26)	0.455* (26)
Residents' use of EC inside (mL/week) ^d	0.0 (0.0–3.3)	0.581** (26)	0.406 (13)	0.646*** (26)	0.500** (26)

Note: Bold values are significant ($p < .05$).

CC = conventional cigarettes; EC = electronic cigarettes; p25–p75 = 25th and 75th percentile.

^aExposure of the child in same indoor room based on report of caregiver for 7-day period, excluding exclusive EC use (a subset of classification II from Table 2).

^bResidents reported use of CC over 7-day period inside the home whether or not child was present excluding exclusive EC use (a subset of classification III from Table 2).

^cExposure of the child in same indoor room based on report of caregiver for 7-day period, excluding any with CC usage (a subset of classification II from Table 2).

^dReported caregiver use of EC over 7-day period inside the home whether or not child was present, excluding any with CC usage (a subset of classification III from Table 2).

Spearman's correlations (ρ): * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 4. TSNAs in WB worn for 7 days in relation to child's exposure classification

Exposure group by classification scheme (#)	WB total TSNAs <i>n</i>	WB total TSNAs <i>n</i> (% detected)*	WB total TSNAs	NNK <i>n</i> (% detected)*	NAT <i>n</i> (% detected)*	NAB <i>n</i> (% detected)*	NNN <i>n</i> (% detected)*
			concentration, ng/g silicone (median, p25–p75)				
Recruitment (I)							
NS-nonexposed at recruitment	14	2 (14)	0.10 (0.0–0.10)	0 (0)	0 (0)	2 (14)	0 (0)
EC	19	5 (26)	0.10 (0.0–0.11)	3 (16)	0 (0)	2 (11)	1 (5)
CC	18	13 (72)	0.20 (0.05–0.53)^a	11 (61)	7 (39)	6 (33)	3 (17)
Child's reported exposure (II)							
NS-nonexposed by caregiver report	23	6 (26)	0.05 (0.04–0.24)	3 (13)	1 (4)	3 (13)	1 (4)
EC	14	3 (21)	0.05 (0.04–0.19) ^c	2 (14)	0 (0)	1 (7)	0 (0)
EC + CC	4	3 (75)	0.09 (0.04–0.53)	2 (50)	2 (50)	1 (25)	0 (0)
CC	9	8 (88)	0.40 (0.04–0.67)^a	7 (78)	4 (44)	5 (56)	3 (33)
Residents' tobacco product use (III)							
NS-no use by residents	13	2 (15)	0.05 (0.04–0.13)	0 (0)	0 (0)	2 (15)	0 (0)
EC	14	3 (21)	0.05 (0.04–0.21)	1 (7)	0 (0)	2 (14)	1 (7)
EC + CC	13	6 (46)	0.06 (0.04–0.53)	6 (46)	3 (23)	2 (15)	1 (8)
CC	11	9 (82)	0.25 (0.04–0.67)^{a,b}	7 (64)	4 (36)	4 (36)	2 (18)

Note: Bold values are significant different values ($p < .05$). Also note that one participant did not have a complete reported exposure variable, so $n = 50$ instead of $n = 51$ for this group.

NS = no smoking and no e-cigarette use by caregivers or residents and home smoking ban; CC = conventional cigarette; EC = electronic cigarettes; TSNAs = tobacco-specific nitrosamines; NAT = *N*'-nitrosoanatabine; NNN = *N*-nitrosoanabasine; NNK = 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone; p25–p75 = 25th and 75th percentile; LOD = limit of detection (0.05 ng/g); Classification I = at recruitment, reported exposure of the child; NS = no smoking and no e-cigarette use by caregivers or residents and home smoking ban, EC exposure to EC inside; CC = exposure to CC inside; Classification II = exposure of the child in same indoor room based on report of caregiver for 7-day period; Classification III = residents reported use over 7-day period inside the home whether or not child was present. **n*, (%) detected = WB that had listed compounds detected in laboratory analysis.

^aSignificantly higher levels than NS ($p < .01$).

^bSignificantly higher levels than EC ($p < .01$).

levels were linear over the time exposed. This may be due to saturation of the WB or degradation of nicotine over time, and this requires further study. The shorter time of wearing may be preferable, as a few 7-day WB were accidentally lost.

The routes of exposure assessed by the silicone WB, whether inhalation, dermal, or ingestion, or a combination, has been debated. Early deployments of the silicone WB focused on the ability of the silicone to sample air exposures, which would presumably partition into the WB based on chemical characteristics,²⁶ and PAHs in active air samplers correlated with PAHs in the paired WB.³ Some data have emerged implicating other routes of exposure, such as dermal and ingestion exposures. Aerts et al.²⁹ detected pesticide residues in WB not present in paired air samples, suggesting that silicone WB directly worn on the skin may also capture ingested or dermal contaminants. Wang et al.³⁰ found that WB analytes were better correlated with dermal wipes plus air measurements than with air alone, indicating that inhalation and dermal routes of exposure were measured by the silicone WB sampler. The route of exposure assessed by the WB in children exposed to tobacco products should be further investigated.

Nicotine and cotinine in the WB may arise from contact of the WB with sweat, as both of these compounds are excreted in sweat, as well as related nicotine metabolites (eg, OH-cotinine).^{31–33} Evidence that sweat may contribute to observed nicotine and cotinine on the WB is supported by the strong correlation ($\rho > .9$) between urinary cotinine and WB nicotine. This correlation is much stronger than reported from other silicone WB studies that compared urinary and WB levels for other toxicants.^{3,5} Between 87 and 203 ng of nicotine were collected on a commercial sweat patch worn for 72 h by five adults exposed to SHS.³⁴ In our participant WB, a median 571 ng (range 130–2629 ng) of nicotine were collected on WB worn for 2 days by children exposed to SHS. In the WB, the ratio of cotinine to nicotine in the same WB decreased (though nonsignificantly) in more highly exposed subjects. We could not determine the ratio between nicotine and cotinine in sweat from the studies cited for comparison, however. Sweat may be a major contributor to observed levels at lower doses, but air nicotine increasingly contributes to nicotine in WB at higher air levels of nicotine.

We detected TSNAs in silicone WB worn for 7 days, mostly in children exposed to CC, including the well-studied lung carcinogen NNK.¹³ It is unknown whether a wearing period would increase detection, or if a shorter wearing time would record similar levels of detection. Also, it is possible that we would have detected metabolites of TSNAs excreted in sweat, as well as parent TSNAs, for reasons discussed above. TSNA exposure could arise through thirdhand smoke residue in dust or on surfaces,²² as even in the NS group a TSNA (NAB) was detected.

There are limitations to this study. One is the complex behavior around children's exposure to tobacco-related products. Classification of exposure based on recruitment self-report did not always match up with the classification based on smoking and vaping behavior during the 7-day study period. For example, some in the "exposed to EC indoors" recruitment group were only exposed outdoors during the study period ($n = 2$) or exposed to CC outdoors as well ($n = 5$). Due to budget limitations, we could not collect dust or wipe samples to assess the extent of thirdhand smoke contamination in the child's home, which may be an unmeasured factor contributing to WB nicotine or TSNA levels.¹⁵ Also, if we could have measured children's sweat directly, we could compare levels and ratios of nicotine and cotinine in sweat with WB levels.

Conclusions

The simple silicone WB demonstrates a wide range over three orders of magnitude and with 100% detection for WB nicotine. Silicone WB nicotine and cotinine levels can discriminate between groups of children exposed to SHS (CC), SHsV (EC), and children not living with a user or smoker, with sample sizes between 15 and 20 children for each group. The WB detected low and high exposures within groups and discriminated between exposure groups for children in a manner similar to UC. Our data also indicate that children living with e-cigarette users are significantly more exposed to nicotine from e-cigarettes than children living with nonsmokers.

We demonstrate that silicone WB can be used to detect multiple classes of chemicals related to tobacco smoke (nicotine, cotinine, and TSNAs). We detected carcinogenic TSNAs in silicone WB worn for 7 days, mostly in children exposed to CC smokers. Significant questions remain whether the silicone WB captures pollutants on the skin or in the sweat of wearer or pollutants in the air. The silicone WB is a simple-to-deploy method for assessing exposure to tobacco-related products that shows promise for tobacco control efforts.

Supplementary Material

A Contributorship Form detailing each author's specific involvement with this content, as well as any supplementary data, are available online at <https://academic.oup.com/ntr>.

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Declaration of Interests

KAA discloses a financial interest in MyExposome that is marketing products related to the research being reported. The terms of this arrangement have been reviewed and approved by Oregon State University in accordance with its policy on research conflict of interest. The other authors declare no conflict of interest.

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