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Original Investigation

Assessing Young Adults' ENDS Use via Ecological Momentary Assessment and a Smart Bluetooth Enabled ENDS Device

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Abstract

Introduction: The assessment of electronic nicotine delivery systems (ENDS) use poses unique challenges that go beyond established assessment methods for tobacco cigarettes. Recent studies have proposed using ecological momentary assessment (EMA), a method to collect self-reported data on mobile devices, or data passively collected by "smart" Bluetooth enabled ENDS to assess use. The current study sought to compare ENDS use data using EMA and puff counts collected from a smart device.

Aims and Methods: We recruited 18 young adult ENDS users (age $M = 23.33$; 44.4% female) from the San Francisco Bay Area. For a total of 30 days, participants completed daily diaries by EMA and used a second-generation smart Bluetooth enabled ENDS that collected puff data. Repeated measures correlations, multilevel regressions, and paired t tests assessed concordance of EMA reports and ENDS data. A subset of four highly compliant participants were selected for sensitivity analyses.

Results: Among all 18 participants, completion of EMA daily diaries was high (77.4%). The ENDS device collected approximately twice as many puffs per day as participants reported. Compared with self-reported number of sessions and amount of e-liquid used, self-reported puff counts had the highest correlation with device-collected puff counts ($r_{rm} = 0.49$; $p < .001$). Correlations between self-reported and device-collected puff counts improved among the subset of four highly compliant participants ($r_{rm} = 0.59$; $p < .001$).

Conclusions: Self-reports potentially underestimate use of ENDS. Puff counts appear to be the best self-reported measure to assess ENDS use compared with number of sessions or liquid volume.

Implications: The comparison of EMA self-reports and passively collected ENDS device data can inform future efforts to assess ENDS use. Self-reported puff counts are preferable over number of sessions or amount of liquid used, but compared with objective usage data, self-reported puff counts may still underestimate actual use. ENDS use behavior is likely higher than users estimate and report. Future research on improved measures of ENDS use is needed.

Introduction

Prevalence of electronic nicotine delivery systems (ENDS) use has increased rapidly since their introduction to the US market in 2007, especially among young adults.[1–4] In order to determine the abuse liability of ENDS and to effectively regulate these devices, it is crucial to improve our understanding of how ENDS are being used in the real world.[5] Thus, it is critical to develop valid and reliable assessment methods to measure how frequently people use ENDS and the quantity of consumption. Compared with combustible cigarettes, which have established self-report measures, such as the number of cigarettes smoked per day, the assessment of frequency and quantity of ENDS use poses unique challenges.[6] For example, in contrast to counting the number of cigarettes smoked, ENDS allow for greater variation in puffs or use sessions on a given day, which can make keeping track of the amount of use more difficult for the user. Measuring ENDS use is further complicated by the complexity of patterns of ENDS use frequency, temporality, and co-use in combination with other tobacco products.[7] Moreover, current evidence on ENDS use in the real world is limited by the fact that vaping topography studied in laboratories substantially differs from the use of commercially available ENDS devices in naturalistic settings.[8] Taken together, existing studies demonstrate that better measures to assess ENDS use in individuals' daily lives are needed.

Ecological momentary assessment (EMA) is a method to collect data in participants' natural environments using mobile devices.[9] EMA is effective in reducing recall bias, has improved generalizability of findings compared with laboratory studies,[10] and improves measurement compared with cross-sectional survey methods.[11] In tobacco research, EMA has been used to assess cigarette smoking frequency, patterns, and cessation processes.[10] However, only a few studies have employed EMA or daily diaries to assess ENDS use,[12–14] and findings suggest possible effects of craving, social context, and other substance use on timing of ENDS use among young adults.[13] Compared with traditional survey methods, random and daily diary EMAs improve measurements of frequency and quantity of ENDS use due to the repeated sampling of participants' puffing behaviors in near real-time.[12]

More recently, studies have proposed more accurate measurements of usage data passively collected by "smart" ENDS.[15,16] These prior studies used Bluetooth-enabled second-generation vape pens[17] to passively capture device use and wirelessly transmitted time-stamped data to participants' smartphones.[15,16] The few pilot studies that have compared self-reported ENDS use to objectively collected ENDS puff counts indicate self-reported data on ENDS use are predictive of naturalistic puffing behaviors,[16,18] but findings also suggest that devices capture a greater number of puffs compared with EMA self-report.[16]

To expand the limited existing literature, the current study sought to compare the accuracy of EMA self-reported ENDS use to objectively collected usage data from a second-generation "smart" ENDS device among young adult ENDS users. Based on a previous study,[16] we hypothesized that the ENDS device would capture a greater number of puffs than EMA self-reports.

Methods

Participants

Eligible participants were young adults 21–26 years old, who were currently vaping on 3 or more days a week, and living in the San Francisco Bay Area. Participants were recruited through advertisements on Facebook and Instagram in 2017. Advertisements linked to the study web site and screener questionnaire. Eligible participants were then directed to the informed consent web site, and participants' identities were verified through pictures of their government issued ID. Of the 35 individuals who were ID verified, 28 completed the baseline questionnaire, 19 visited the laboratory for training, received the smart ENDS devices, were instructed to use EMA for data collection, and 18 used the device and were included in the study. Included participants did not differ from those who completed the baseline but did not participate in the ENDS and EMA data collection, based on sociodemographic variables, cigarette use, and ENDS use behavior at baseline (data not shown).

Procedures

Participants received a 30-minute training session on how to use the smart ENDS device (referred to as a "quantified e-cigarette/vape") and smartphone EMA survey app and were instructed to use the device ad libitum for a period of 30 days. The Pilr EMA app was downloaded to the participant's smartphone to collect data through daily diary self-reports. During the entire study period, participants received one daily diary survey prompt through the app between 10 and 11 AM, with an additional reminder at 5 PM if the survey had not been completed yet. The survey was available for completion all day until midnight. Daily diary questions surveyed the use of the smart ENDS device, use of other tobacco products, and use of other substances on the entire previous day. Participants could earn up to $60 incentives for completing the surveys for the 30-day study period ($1 for each day, plus an additional $30 bonus for completing 80% of surveys or more). The device was given to participants free of charge, however, participants were responsible for purchasing e-liquid and refilling the device. Use of the smart ENDS device itself was not incentivized and the training session stressed that use of the device was encouraged but voluntary. At the end of the 30-day data collection period, semi-structured interviews were conducted with 15 participants. Topics included general study experience, device usability, and how participants track their own ENDS use. Interviews lasted between 30 minutes to 1 hour. All study procedures were reviewed and approved by the IRB of the University of California, San Francisco.

ENDS Device

The smart ENDS devices and a corresponding smartphone application were developed by Gram Research (www.gramresearch.com). The smart ENDS device was Bluetooth enabled and transmitted data to the Gram app on participants' smartphones. The app only showed whether or not the smart ENDS device was connected via Bluetooth and did not display any usage data to participants. As data needed to be synced to the smartphone in real-time, the device only worked when connected via Bluetooth. The device looked and worked similar to a second-generation e-Go type ENDS (see Appendix Figure 1). Participants pressed a button to activate the device for inhalation. The device passively collected time-stamped puff data by measuring real-time discrete changes in the device's voltage in 200 ms pulses. Pulse data were stored on participants' smartphones and automatically uploaded to a cloud-server. Each device had a unique identifier appended to all pulse data.

Measures

Baseline

The baseline assessment was an online questionnaire completed via Qualtrics that included demographics, tobacco, and ENDS use.

General demographics included age, gender, race, and education. Additional items assessed lifetime cigarette smoking (Yes/No), current cigarette smoking status (ranging from "everyday" to "not at all"); and days of ENDS use in the past 30 days (with separate questions assessing disposable ENDS, rechargeable ENDS, medium size vapor pens, and large size vapor tanks; reporting from 0 to 30 days for each type).

EMA

During the 30 days of the study, participants completed daily diaries that surveyed their ENDS use for the entire previous day. One item asked about the use of the smart ENDS device in the previous day ("Did you use your quantified e-cigarette/vape pen?"; Yes/No). Participants who reported ENDS use on the previous day were asked further questions about extent of device use on the previous day. One item queried number of puffs ("How many puffs did you take from your quantified e-cigarette/vape pen?") and another asked about the amount of liquid used ("How much liquid (in ml) did you vape using your quantified e-cigarette/vape pen?"). One item asked about the number of sessions the participants vaped in the previous day ("How many times did you use your quantified e-cigarette/vape pen? (One 'time' consists of around 15 puffs, or lasts around 10 minutes.)" Responses options for this question were 1, 2–5, 6–10, 11–15, 16–20, 21–30, and 31+ sessions.[14] In order to approximate a continuous variable for analyses, midpoints of categories were used and 33.75 sessions were used for the highest category.

Additional items assessed the use of other ENDS on a given day. If participants endorsed the first question ("YESTERDAY: Did you use any e-cigarette or vape other than the quantified e-cigarette/vape pen?") they were asked about the use of four different types of ENDS in subsequent questions (disposable, rechargeable, pen, tank). For each of these, number of sessions on the previous day was assessed. Responses options were 1, 2–5, 6–10, 11–15, 16–20, 21–30, and 31+ sessions.[14] Again, a continuous variable was generated by using midpoints of categories and 33.75 sessions for the highest category. Numbers of sessions per day were added together, if participants reported using multiple other ENDS on a given day.

Analysis

Each participant's raw pulse data, passively collected using the smart ENDS device, were downloaded from the cloud-based database. Raw pulse data were initially processed by Gram Research using Microsoft Excel to identify individual puffs based on difference between timestamps of pulses. Each pulse accounts for 200 ms in puff duration. Based on prior published ENDS topography findings, puffs with a duration of less than 1 second were deleted, as these puffs were likely the result of accidental button presses or ENDS device misfires instead of genuine puffs.[15] These data allowed us to calculate the number of puffs per day taken from the device. All participants' EMA daily diaries and ENDS device data were merged. We compared day level self-reports of puff counts, liquid used, and number of sessions to the puffs counts passively collected by the device using paired *t* tests, and repeated measures correlation analyses. For sensitivity analyses, we identified a subset of four participants who had the highest data quality in terms of compliance for both EMA daily diaries (reports for 20 days or more) and ENDS device use (used for 10 days or more). Multilevel regression analyses were conducted to predict device recorded number of puffs per day, accounting for clustering of days within study participants. Predictors included in the regression model were self-reported puffs per day, number of days in the study to test for changes in use over time, and self-reported quantity of use of other ENDS.

Interviews were coded in NVivo12 by the first author. Codes addressed predetermined themes focusing on overall participant study experience, experience with the smart ENDS device, and experience with self-reporting ENDS use. All codes were reviewed by the last author.

Results

Baseline

The entire sample had a mean age of *M* = 23.33 (SD = 1.64), 44.4% were female, 33.3% were Non-Hispanic White and another 38.9% were Hispanic. A total of 38.9% had an education level ≤ high school. At baseline, 44.4% reported no current tobacco cigarette smoking. All participants were current ENDS users and the most frequently used ENDS were medium size vapor pen style ENDS and large size vapor tanks (Table 1).

EMA

EMA and device data are displayed in Table 2 and Figure 1. A detailed visualization of data for sensitivity analyses can be found in Appendix Figure 2. During the 30-day study period, participants were in general compliant with the EMA daily diary reports and a total of 418 daily diaries were submitted (77.4%). Among the total submissions, 154 (36.8%) of them reported using the device on the previous day. A majority of participants (84.2%) submitted diaries on more than 20 days. On an average day when the device was used, participants reported using the device for 7.03 sessions (SD = 7.53), 15.07 puffs (SD = 13.78), and 3.38 milliliters of liquid used (SD = 5.71). The four participants selected for sensitivity analyses were highly compliant with the EMA reports and submitted 114 daily diaries (95%). Device use was reported on 62 days (54.4%). On an average day when the device was used, these participants reported 3.62 sessions per day (SD = 2.32), 13.33 puffs (SD = 7.79), and 2.13 milliliter liquid used (SD = 2.04).

Other ENDS use was reported on 184 days (44.1%). When other ENDS were used, participants reported 15.08 sessions per day (SD = 11.40) using those devices. The use of other ENDS in addition to the smart ENDS on the same day amounted a total of 67 days (34.8%). The four selected participants reported other ENDS use on 42 days (37.2%) with 4.94 sessions per day (SD = 3.17) and use of other ENDS in addition to the smart ENDS on the same day on a total of 25 days (18.4%).

Device

Among all 18 participants, the smart ENDS devices captured a total of 4492 puffs. Over the study period, the smart devices were used on 145 days, which reflects 25.4% of the maximum possible number of participant-days in the study. Participants' total puff counts ranged from 15 to 808 puffs per person, with a mean of 32.41 puffs per day (SD = 37.39), and each puff lasting an average of 4.17 seconds (SD = 2.26). A total of 1897 puffs were generated by the subset of four selected participants, with a range of between 254 and 808 puffs per person, a mean of 25.29 puffs per day (SD = 23.96), and each puff lasting an average of 4.06 seconds (SD = 2.07).

Agreement Between Smart ENDS and Self-reported EMA Measures

Among all 18 participants, 103 days were analyzed on which the device was used and for which corresponding EMA reports were

Table 1. Baseline Characteristics

	All participants (N = 18)		Selected participants (N = 4)	
	M (SD)	N (%)	M (SD)	N (%)
Age	23.33 (1.64)		24.50 (1.91)	
Female		8 (44.4)		3 (75.0)
Race				
Hispanic		7 (38.9)		3 (75.0)
NH-White		6 (33.3)		
NH-Asian		2 (11.1)		
NH-Black		1 (5.6)		
NH-Other		2 (11.1)		1 (25.0)
Education				
High school		7 (38.9)		1 (25.0)
Some college		6 (33.3)		1 (25.0)
Associate's		2 (11.1)		1 (25.0)
Bachelor's		3 (16.7)		1 (25.0)
Current cigarette smoking				
Every day		2 (11.2)		1 (25.0)
Some days		8 (44.4)		3 (75.0)
Not at all		8 (44.4)		1 (25.0)
Lifetime cigarette smoking		11 (61.1)		3 (75.0)
Past 30 days ENDS use				
Disposable ENDS		1 (5.6)		1 (25.0)
Days using disposable (among those reporting use)	7.00 (NA)		7.00 (NA)	
Rechargeable ENDS		2 (11.1)		1 (25.0)
Days using rechargeable (among those reporting use)	10.5 (6.36)		15.00 (NA)	
Medium size ENDS		8 (44.4)		2 (50.0)
Days using medium size (among those reporting use)	15.88 (12.18)		3.00 (1.41)	
Large size ENDS		9 (50.0)		2 (50.0)
Days using large size (among those reporting use)	25.44 (7.02)		22.50 (10.61)	

ENDS = electronic nicotine delivery systems; NH = Non-Hispanic; Disposable = disposable ENDS (Aer disposables, Blu disposables); Rechargeable = rechargeable cigarette-shaped ENDS (Blu, Eonsmoke, intellicig, NJOY); Medium size = medium size vapor pen style ENDS (eGo-C); Large size = large size vapor tank device (eGo-V, KangerTech Protanks).

Table 2. Device and EMA Data

	All participants (N = 18)		Selected participants (N = 4)	
	M (SD)	N (%)	M (SD)	N (%)
Device				
Puffs		4492		1897
Days used		145 (25.4)		75 (62.5)
Puff duration in seconds	4.17 (2.26)		4.06 (2.07)	
Puff count/day	32.41 (37.39); range: 1–243		25.29 (23.96); range: 1–104	
EMA				
Daily diaries submitted		418 (77.4)		114 (95.0)
Days of smart ENDS use		154 (36.8)		62 (54.4)
Puffs		2321		827
Puff counts/day	15.07 (13.78)		13.33 (7.79)	
Sessions/day	7.03 (7.53)		3.62 (2.32)	
E-liquid/day in mL	3.38 (5.71)		2.13 (2.04)	
Days of other ENDS use		184 (44.1)		42 (37.2)
Sessions/day	15.08 (11.40)		4.94 (3.17)	
Days of same day use of smart ENDS and other ENDS		64 (34.8)		25 (18.4)

EMA = ecological momentary assessment; ENDS = electronic nicotine delivery systems.

available. There was a moderate agreement between the device-reported and self-reported puff count data (Table 3). Puff counts passively collected by the smart ENDS device were moderately correlated with number of puff counts reported via EMA daily diary (r_{rm} = 0.49; p < .001) and weakly with self-reported number of sessions per day (r_{rm} = 0.21; p = .035). However, puffs counts

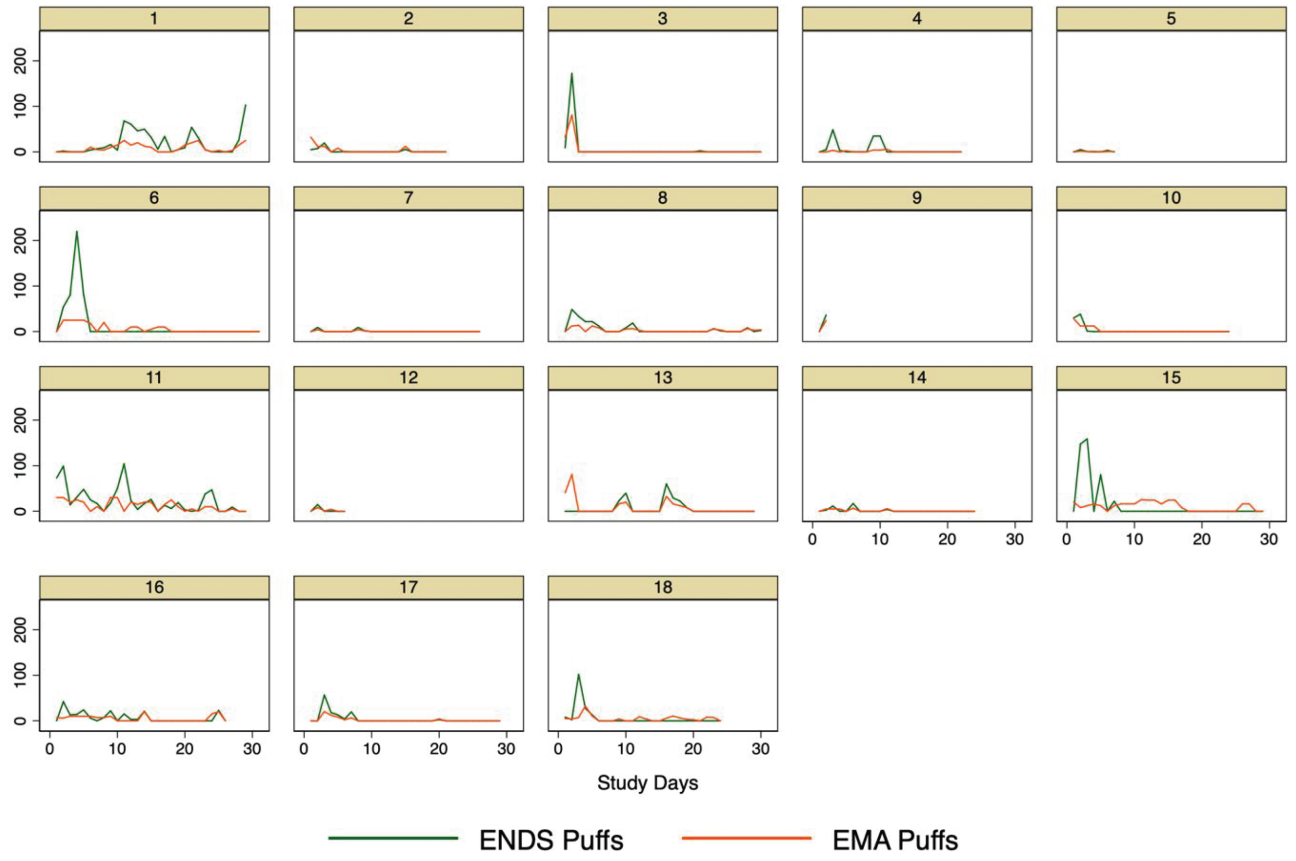

Figure 1. Number of puffs collected by the device and self-reporting using EMA for all participants (N = 18) over the study period. EMA = ecological momentary assessment; ENDS = electronic nicotine delivery systems.

Table 3. Repeated Measures Correlations Between ENDS Device Data and EMA Data

	All 18 participants (N = 103 days)				Four selected participants (N = 54 days)			
	Device puff (r_{rm}, p)	EMA puffs (r_{rm}, p)	EMA sessions (r_{rm}, p)	EMA e-liquid (r_{rm}, p)	Device puff (r_{rm}, p)	EMA puffs (r_{rm}, p)	EMA sessions (r_{rm}, p)	EMA e-liquid (r_{rm}, p)
Device puffs	1.00				1.00			
EMA puffs	0.49*** (0.000)	1.00			0.59*** (0.000)	1.00		
EMA sessions	0.21* (0.035)	0.45*** (0.000)	1.00		0.28* (0.025)	0.46*** (0.000)	1.00	
EMA e-liquid	0.06 (0.616)	0.29*** (0.000)	0.30*** (0.000)	1.00	0.60*** (0.000)	0.55*** (0.000)	0.56*** (0.000)	1.00

EMA = ecological momentary assessment; ENDS = electronic nicotine delivery systems; r_{rm} = repeated measures correlation coefficient.[19]
*p < .05; ***p < .001.

collected by the device were not associated with self-reported quantity of e-liquid consumed (r_{rm} = 0.06; p = .616). Self-reported number of puff counts was moderately correlated with self-reported number of sessions per day (r_{rm} = 0.45; p < .001) and weakly with self-reported quantity of e-liquid consumed (r_{rm} = 0.29; p < .001).

A paired t test was conducted to compare the number of puffs collected from the device and from the EMA daily diary among the same participants. There was a significant difference between the device puff counts and the EMA puff counts (device: M = 34.85, SD = 42.76; EMA: M = 15.56; SD = 12.60; t(102) = 5.19; p < .001).

Multilevel regression analyses were conducted to account for clustering of days within participants and to test the potential impact of study length and other ENDS use on number of device recorded puffs. The regression model suggested that neither study day (b = −0.37; SE = 0.46; p = .420) nor using other ENDS in addition to the smart device (b = 0.22; SE = 0.68; p = .746) were significantly associated with the extent of use of the smart device. Self-reported number of puffs remained significantly associated with device recorded puffs after accounting for these covariates (b = 1.67; SE = 0.33; p < .001).

For sensitivity analyses, we selected data from four participants who submitted 20 or more days of EMA daily diaries and used the ENDS device 10 or more days. Among these four participants, data of 54 days with device use and corresponding EMA reports were analyzed. We found improved correlation between the number of puff counts collected via EMA and the device (r_{rm} = 0.59; p < .001). Device-captured puff counts were weakly correlated with self-reported number of sessions per day (r_{rm} = 0.28; p = .025) but

strongly with self-reported quantity of e-liquid used in the device (r_{rm} = 0.60; p < .001). Consistent with the full sample, there were significant more puffs captured by the ENDS device than by the EMA diaries (device: M = 26.93, SD = 23.55; EMA: M = 14.45; SD = 7.59; $t(53)$ = 4.57; p < .001). The multilevel regression model also suggested that neither study day (b = –0.03; SE = 0.46; p = .351) nor using other ENDS in addition to the smart device (b = 0.28; SE = 1.07; p = .792) were significantly associated with the extent of use of the smart device in this subgroup. Self-reported number of puffs remained significantly associated with device recorded puffs after accounting for these covariates (b = 1.81; SE = 0.35; p < .001).

User Experience Interviews

Most participants interviewed (12/15; 80.0%) reported enjoying study participation. Some problems with the ENDS device were also reported: The most commonly reported problems were hardware defects (reported by 12/15 participants, 80.0%), including cracks in the body of the device and issues related to battery life. With respect to answering EMA questions about ENDS usage, 13 participants (86.7%) expressed that they typically did not keep track of their use or had difficulties reporting usage in puffs, sessions, or amount of e-liquid used. With respect to specific language to describe ENDS use, 13 participants (86.7%) referred to taking a "hit" from the device and one participant specifically mentioned not personally using the words "puff" or "session." In addition, four participants mentioned using the term "juice" instead of "liquid."

Discussion

This study is among the first to compare self-reported ENDS puffs via EMA to passively collected puff data using a "smart" Bluetooth enabled ENDS device. The current study adds to the limited literature and expands the work of three prior studies[15,16,18] that demonstrated the feasibility of using smart ENDS devices to collect naturalistic ENDS puff data. To the best of our knowledge, this is the first study to compare two data collection methods for ENDS use exclusively with young adults. We employed a second-generation smart ENDS device to collect data over a 30-day period among young adult regular ENDS users at baseline.

In the current study, we used three measures of ENDS use behavior: puffs, sessions, and amount of liquid. While puff data were collected both passively from the smart device and actively via EMA self-report, session and liquid were assessed solely through EMA. The smart ENDS device collected approximately twice as many puffs per day compared with the self-reported daily diary during the 30-day study period. This may indicate limitations of self-reports for the assessment of high-frequency data, such as puffs taken from an ENDS. Consistent with previous smart ENDS studies,[16] our results indicated the Bluetooth enabled ENDS may be a superior method to collect puff data compared with daily diary EMA self-reports. While EMA to assess ENDS use is arguably an improvement over retrospective surveys due to reduced recall bias,[6] our data suggest that the extent of ENDS use assessed by EMA may still underestimate actual use.

Utilizing EMA daily diaries to assess ENDS use, though still limited by recall bias, may still be an improvement over traditional survey methods. We found self-reported puff counts were moderately correlated with objective puff counts collected by the device, but self-reported ENDS use sessions and amount of liquid used were weakly correlated with device puff counts. Our data suggest that the best self-report measure for ENDS use may be the number of puffs, or, as participants mentioned, "hits" per day, as opposed to asking about sessions or amount of liquid used as done in previous studies.[8,12,14,18] Our qualitative findings also indicate that users may have problems with reporting their use in distinct sessions, as some of them indicated using ENDS continuously throughout the day.

In comparing self-reported to device-collected puff data, a moderate correlation (r_{rm} = 0.49) was found among all 18 participants, which is similar to previous studies which found correlations of between ρ = 0.47–0.59.[8,10,16,18] The sensitivity analysis showed an increase in correlation between puff counts collected by the device and amount of e-liquid used, which could be due to higher conscientiousness about self-reporting ENDS use by this subgroup of highly compliant participants. Future studies aimed at collecting accurate exposure data on ENDS use in the natural environment should consider using smart ENDS devices. In studies where it is not feasible to distribute a large number of these devices, for example due to costs of devices or the need for training of participants, self-reported number of puffs may be an acceptable approach to approximate objective ENDS use behaviors, especially among a population with relatively infrequent use.[16] All studies reliant on self-report assessment methods should consider the potential for underreporting of ENDS use.[12,16]

In-depth interviews provided additional insights on participant experience with the smart ENDS device. Participant narratives indicated problems with device hardware, which may have been responsible for limited use by some participants. A more robust device with improved battery life and nicotine delivery may be beneficial for future studies. While multiple participants continued to use other ENDS throughout the study period, our analyses indicated that this use was not significantly associated with reduced use of the smart ENDS device. Yet, the average number of self-reported sessions per day using other ENDS devices was greater than the number of sessions using the smart ENDS. Some participants reported that they preferred using their usual ENDS device (mostly tanks) with greater power and battery life. A significant number of participants expressed having difficulty accurately recalling their previous day's ENDS use for EMA self-reports. Finally, interviews suggested that participants referred to their ENDS use as taking "hits" rather than "puffs" or "times/sessions," and "juice" rather than "liquid" as worded in the surveys and interviews. Taken together, findings suggest that additional efforts to develop valid self-report instruments to assess the quantity and frequency of ENDS use are needed.

Limitation

Our sample consisted of young adult experienced ENDS users from the San Francisco Bay Area and findings may not be representative for other ENDS user groups. In addition, data were collected using a "second-generation" ENDS model, which has declined in popularity since 2017. Future work should explore using smart ENDS devices similar to currently popular ENDS models, which are using pods prefilled with e-liquid and are activated by airflow when the user inhales (eg, JUUL devices).[20,21] In fact, JUUL has recently introduced a device called JUUL C1, which pairs with an app to track puffs.[22] However, it is unclear if these data will be available or suitable to use for research. Regulations for ENDS could include the requirement that Bluetooth device data be made available to regulators or independent scientists to aid assessment of abuse liability. Participants were instructed to submit daily EMA surveys in the morning to report their ENDS use on the

previous day, which still requires recall of past behavior. This recall may contribute to the underestimation of self-reported puff counts found in the current study. Future studies assessing ENDS use should consider deploying more frequent EMA surveys to approximate puffs in near real-time.[13,23] Moreover, participants only used the smart devices on 25.4% of total possible days in the study. This could be due to the fact that our participants already had substantial ENDS use experience and would have preferred a more powerful and efficient nicotine delivery device than the one used in this study. Lastly, the smart ENDS device was used in a previous study,[15] but not validated against an objective measure of use (eg, direct observation in a laboratory) and results should be interpreted with this in mind.

Conclusion

Our study adds to the limited literature investigating the feasibility of using smart ENDS devices for objectively measuring ENDS use behavior. Findings show moderate to strong correlations between EMA self-reported and device-captured puff counts. Our Bluetooth enabled ENDS device collected approximately twice as many puffs per day compared with EMA daily diary self-reports, which suggests self-reports potentially underestimate ENDS use. Self-reported puffs may be superior to self-reported number of use sessions or the amount of e-liquid used. Bluetooth enabled ENDS are superior to self-reports in assessing use intensity and should be used in future research. Doing so may allow for more accurate data on toxicant exposure from ENDS use and ENDS abuse liability. Moreover, when ENDS are used for smoking cessation, fine-grained and time-stamped data on ENDS use may allow researchers to determine use profiles that make successful smoking cessation more likely.

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

None declared.

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