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Rates of adverse events and related risk factors following e-cigarette use

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ABSTRACT

Background E-cigarettes have emerged as popular products, especially for younger populations. However, concerns regarding health effects exist and there is a notable gap in understanding the prevalence and nature of adverse events. This study aims to examine the rate of adverse events in individuals who use e-cigarettes in a large sample.

Methods A cross-sectional survey was conducted with a sample of 4695 current and former e-cigarette users with a median age of 34 years. The survey collected data on e-cigarette use, adverse events experienced, product characteristics, related behaviors, sociodemographic factors and presence of medical comorbidities. Statistical analyses were conducted using Pearson's chi-squared tests and logistic regression.

Results A total of 78.9% of respondents reported experiencing an adverse event within 6 h of using a vaping device, with the most common events being headache, anxiety and coughing. Product characteristics and related behaviors significantly influenced the risk of adverse events. There were also sociodemographic disparities, with Hispanic respondents and those with at least college-level education reporting higher rates of adverse events.

Conclusions Our study found a high rate of adverse events among e-cigarette users. We identified that certain e-cigarette product characteristics, behaviors and medical comorbidities significantly increased the risk of these events.

Keywords adverse events, e-cigarettes, medical comorbidities, prevalence, product characteristics, risk factors

Introduction

E-cigarettes are battery-powered devices that heat liquid containing nicotine, flavorings and other chemicals, producing an aerosol that is inhaled by the user. [1] E-cigarettes have emerged as a popular alternative to traditional tobacco products in recent years, being particularly popular among younger populations.[2] Proponents suggest that they are a less harmful option for nicotine delivery,[2,3] with some studies suggesting that they carry lower risk of adverse events when compared to combustible cigarettes. However, the increase in usage of e-cigarettes has led to concerns regarding the potential health effects of e-cigarettes, both in the short and long term.[4,5] Mouth and throat irritation have been commonly detected among participants in both survey studies and experimental studies,[6,7] although there exist case reports of more serious conditions, including lipoid pneumonia and atrial fibrillation.[8,9] Although e-cigarettes are often marketed as a safer alternative to traditional cigarettes,[10] the scientific community remains divided on the subject, with some studies suggesting that e-cigarettes may contribute to respiratory and cardiovascular issues, addiction and other adverse health outcomes.[8,11,12]

Risk factors

Research suggests that there may exist several potential risk factors which could exacerbate the occurrence of post-vaping adverse events, including pre-existing medical conditions, current versus former use, sociodemographic factors, product characteristics and intent to quit.

Individuals with pre-existing conditions may be at higher risk of experiencing an adverse event following vaping due to

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the direct exacerbation of that condition from the inhalation of the vapor itself. Previous studies have indicated that individuals with pre-existing health conditions, such as cardiovascular and respiratory diseases may be more susceptible to the negative impacts of e-cigarette use.[13,14] These include prior myocardial infarctions an chronic lung disease. Furthermore, research has suggested that the inhalation of aerosolized particles from e-cigarettes could potentially exacerbate these health conditions.[2] For example, the inhalation of propylene glycol, a humectant commonly found in e-cigarettes, may be a particular risk fact factor for the occurrence of respiratory adverse events for populations with asthma, emphysema or chronic bronchitis.[2]

Additionally, sociodemographic factors may play a role in the risk of adverse events associated with e-cigarette use. Research has found that factors, such as age, gender, socioeconomic status and ethnicity can influence both the propensity to use e-cigarettes and the risk of experiencing associated health problems.[15] For example, educational attainment has been positively associated with stopping e-cigarettes use, possibly increasing risk of adverse events among individuals with lower levels of educational attainment due to longer lengths of exposure.[16] In addition, it may be useful to explore the roles of variables, such as parenting status and marital status, as these can influence e-cigarette usage patterns and potential health outcomes. Understanding these sociodemographic dynamics is crucial to assess the risk and potential harm reduction strategies of e-cigarette use.

The characteristics of the e-cigarette product itself can also greatly contribute to the potential risks associated with its use. Certain product characteristics, such as the concentration of nicotine, the presence of flavorings and the composition of other chemicals in the e-liquid, have been linked to adverse health effects.[17,18] Additionally, the type of device, the temperature at which the liquid is vaporized, and the size of aerosol particles can influence the toxicological profile of e-cigarettes. For example, a prior study found an increase in several carcinogens and irritants, including acetone and formaldehyde compounds, ranging from 4-fold to over 200-fold for devices whose output voltage was 4.8 compared to 3.2.[19]

User behaviors, such as frequency and depth of inhalation, represent additional factors that may impact the risk of adverse events. Previous research has indicated that more frequent use and deeper inhalation can increase the levels of exposure to harmful substances in e-cigarette aerosols.[20,21] Furthermore, dual use with combustible tobacco products, or the use of e-cigarettes as a method to quit cigarette smoking, could potentially influence the risk of adverse outcomes.[22] In addition, the relationship between intention to quit tobacco or marijuana use and e-cigarette adverse events is an area that may benefit from further exploration. Previous research has indicated a correlation between e-cigarette use and attempts to quit smoking, but the impact of these attempts on the risk of e-cigarette adverse events remains unclear.[23] Similarly, the connection between marijuana use and e-cigarette use is a burgeoning area of study, with evidence suggesting a potential interaction between these substances that may influence health outcomes.[24]

Finally, prior history with other tobacco or marijuana products may also influence the risk of experiencing an adverse health event following e-cigarette use. Studies have suggested that former smokers who switch to e-cigarettes may still be at risk for certain health issues, and that the risk may be compounded in individuals with a history of heavy tobacco or marijuana use.[25,26] This underscores the importance of considering broader substance use history when assessing the potential risks associated with e-cigarette use.

Study objective

Given the relatively recent emergence of e-cigarettes as a widely used product, there is a dearth of information on the full spectrum of potential health effects associated with their use.[27] Previous studies have primarily focused on the efficacy of e-cigarettes as a smoking cessation tool, with limited research examining the prevalence and nature of adverse events experienced by individuals who use e-cigarettes, as well as the influence of e-cigarette product characteristics and related behaviors on these events.[5,12] Therefore, there remains a significant gap in the literature regarding the prevalence of these adverse events among e-cigarette users, the influence of e-cigarette product characteristics and related behaviors on adverse events, and the potential implications for healthcare providers. Additionally, studies in this area have been limited by small sample sizes, outdated e-cigarette models and a lack of representation among different demographic groups.[11] In this context, the current study aims to conduct an exploratory analysis of retrospective survey data so as to provide a more comprehensive understanding of the prevalence and nature of potential adverse events among individuals who use e-cigarettes, as well as to explore the relative rates among adverse events among potential risk-increasing factors, including pre-existing medical conditions, current versus former use, sociodemographic factors, product characteristics and intent to quit.

Methods

Data collection

We conducted a STROBE-compliant observational study to assess rates of adverse events experienced among

individuals who have used e-cigarettes and potential risk factors for adverse events stemming from e-cigarette use. Inclusion criteria were that the respondent had to be age 18 or over, and that the respondent had to have any prior use of e-cigarettes (both nicotine vaping and other forms of vaping). To collect data for this study, we designed a cross-sectional survey using the Qualtrics platform, which was disseminated to a market research panel maintained by Luth Research, an organization specializing in wide-scale survey sampling. Responses were collected from 3 January 2023 to 3 March 2023, with quota groups ensuring representation across age groups and California regions, and respondents received a small monetary incentive in exchange for their time completing the survey. Panel registration information, as well as tools in Qualtrics based on IP address, was used to prevent duplicate submissions, resulting in no duplicates in the datafile used for analysis. A total of 4695 responses were obtained from current and former individuals who use e-cigarettes.

Measures

Respondents were asked to select from a list of adverse events experienced, at any time in the past, within 6 h after using a nicotine vaping device (either their preferred nicotine e-cigarette device or any other nicotine e-cigarette device). Available response options were informed by focus groups conducted among young adults who use e-cigarettes,[28] although an 'Other (please specify)' option was also presented. In an interest to prevent overwhelming respondents, positive reactions to e-cigarettes (e.g. euphoria, calmness) were not included as response options. However, respondents had the opportunity to select 'I have not experienced these' or 'Prefer not to say'. All estimates of adverse events in this study, unless they are specific to a geographic region, have been geographically weighted so that the adverse event rate from a given region is represented proportional to its population within California. Total experience with using e-cigarettes, as well as past and current use, was collected. Past use was defined as any prior consumption of e-cigarette products before the time of taking the survey, and current use was defined as past 30-day use.

In addition to collecting information on adverse events and e-cigarette use, the survey also assessed e-cigarette product characteristics and related behaviors. Respondents were asked about their use of modified vaping products, primary use of rechargeable vaping products, primary use of products with cartridges, refilling of cartridges with e-liquid, primary use of products with a tank system and whether they changed the voltage on their primary e-cigarette product. These factors were analyzed to determine if they increased the risk of experiencing an adverse event. Sociodemographic information, such as race/ethnicity, education level and parental status, was also collected from respondents. Respondents were asked if they had experienced medical symptoms during the time in their life when they used vape products, and then allowed to select all medical symptom experienced among a list that has been previously used in medical intake forms.[29] In addition, respondents were asked about their motivations for e-cigarette use, specifically whether they started using e-cigarettes as a means to quit smoking tobacco or cannabis products. We also collected data on the use of other nicotine products in conjunction with e-cigarettes. Questions and response options for survey items assessed in this study are available in Supplement A.

Data analysis

We conducted a primary analysis of these survey data, which were collected specifically for this study. To elucidate potential risk factors for having experienced an adverse event following the use of e-cigarettes, the geographically-weighted rate of adverse events was compared between each sociodemographic characteristic, product characteristic, user behavior, prior non-nicotine vaping product used and intention to quite cigarettes. This was accomplished by conducting Pearson's chi-square test to compare the rate of adverse events between the two categories. Chi-square tests were also used to compare unweighted rates of adverse events across regions using a Bonferroni correction for multiple comparisons. In addition, logistic regression models were conducted to control for differences in baseline demographic factors, specifically age, gender and racial minority status, where applicable.

An analysis of the relationship between the presence of specific medical comorbidities and the occurrence of adverse events was also conducted. Specifically, for each medical comorbidity, we ascertained the total number of cases, the number and percentage of patients in the group of respondents which had experienced an adverse event, the number and percentage of patients in the group of patients which had not experienced an adverse event, and an odds ratio. In order to maintain statistical robustness, we excluded comparisons with cells where the number of cases (n) was <5. Statistical significance was set at $P < 0.05$. All analyses were conducted in SPSS v27 (Armonk, NY). Informed consent was obtained from all respondents, and this study was approved by the Institutional Review Board for the University of California, San Diego (Protocol #803768).

Results

Our analysis of the survey data revealed that, out of 4695 respondents, 3706 (78.9%) reported experiencing an adverse event within 6 h of using a vaping device, resulting

in a geographically-weighted prevalence of 77.9%. The most commonly reported e-cigarette adverse event was headache (36.5%), followed by anxiety (29.9%), coughing (29.0%), adrenaline rush (26.1%), cotton mouth (20.2%), dry mouth (19.8%), tachycardia (19.6%), burning throat (19.2%), lightheadedness (18.6%) and heartburn (16.4%). Table 1 relays the geographically-weighted rate of every adverse event queried in this study. The rate of AEs was similar across all regions, with <10% variation between regions (range of 74.2%–83.9%), although California Census Region 8, comprising of Los Angeles County, exhibited a significantly higher unweighted rate of adverse events than California Census Region 2, which comprised of Del Norte, Humboldt, Lake, Mendocino, Napa, Sonoma and Trinity Counties (83.0% versus 74.2%, $P = 0.017$).

Over half of respondents who used e-cigarettes had at least one year of cumulative experience using nicotine e-cigarettes (56%), with only 17% having used e-cigarettes for under 1 month. Those with <1 month of total experience using e-cigarettes did not report a significantly different rate of adverse events compared with respondents with more than 1 month of experience using e-cigarettes. However, individuals who currently used e-cigarettes (defined as having any past 30-day use) reported a significantly higher rate of adverse events compared to individuals who only used e-cigarettes before this timeframe (80% versus 67%, $P < 0.001$). This difference persisted after adjusting for demographic confounders (OR = 1.93, 95% CI: 1.57–2.37, $P < 0.001$).

Analysis was conducted to determine if product characteristics and related behaviors increased risk for having experienced an adverse event. Excluding those who selected 'I do not know' or 'prefer not to say', 572 respondents (14%) used a modified vaping product, 3182 respondents (75%) primarily used a rechargeable vaping product, 2333 (56%) primarily used a product with cartridges, 1928 (49%) primarily used a product whose cartridges could be refilled with 'e-liquid', 1503 (42%) primarily used a product with a tank system and 948 (68%) stated that they changed the voltage on their primarily used e-cigarette product. Respondents who had used modified products had significantly higher risk of adverse events compared to those who had not (93% versus 77%, $P < 0.001$; adjusted OR = 3.68, 95% CI: 2.66–5.36, $P < 0.001$); respondents primarily using a product with cartridges had significantly higher risk compared to those who did not (81% versus 79%, $P = 0.027$; adjusted OR = 1.38, 95% CI: 1.10–1.53, $P = 0.002$); respondents who refilled their primary product with e-liquid had significantly higher risk of adverse events than those who did not (84% versus 77%, $P < 0.001$; adjusted OR = 1.59, 95% CI: 1.34–1.88, $P < 0.001$); respondents whose primary product used a tank

Table 1 Geographically-weighted incidence of adverse events among individuals who use e-cigarettes

Adverse event	*Percent*
Headache	36.5%
Anxiety	29.9%
Coughing	29.0%
Adrenaline rush	26.1%
Cotton mouth	20.2%
Dry mouth	19.8%
Tachycardia	19.6%
Burning throat	19.2%
Lightheadedness	18.6%
Heartburn	16.4%
Itchy scratchy throat	14.6%
Lingering taste in mouth	14.4%
Insomnia	14.3%
Heart palpitation	13.1%
Head rush	12.9%
Dehydration	12.7%
Dizziness	12.3%
Change in voice	11.4%
Not motivated	10.7%
Nausea	10.4%
Loss of appetite	10.0%
Mood swings	9.8%
Chest heaviness	9.5%
Raspy voice	9.1%
Phlegm	9.1%
Fatigue	8.9%
Hacking cough	8.6%
Chest pain	8.4%
Panicky	8.0%
Lung discomfort	7.8%
Blisters in mouth and tongue	7.5%
Chest tightness	7.5%
Restlessness	7.4%
Difficulty breathing	6.6%
Lung pain	6.5%
Night sweats	6.4%
Sluggishness	6.1%
Stomach pain	5.9%
Throat pain	5.5%
Migraine headache	5.4%
Spins	4.9%
Weakness	4.6%
Snoring	4.6%
Hair loss	4.2%
Weight loss	3.9%
Wheezing	3.8%
Vertigo	3.0%
Vomiting	2.9%
Other	1.9%

Table 2 Adverse event rate by sociodemographic characteristic, with results for Pearson's chi-square tests

Category	*Covariate*	*Adverse event rate (%)*	*Sample n (%)*	*P*
Sex	Female	78%	2596 (55%)	*NS*
	Male	80%	2099 (45%)	
Gender/orientation	LGBT	81%	778 (17%)	*NS*
	Non-LGBT	79%	3705 (83%)	
Age	18–29 (reference)	85%	2052 (44%)	
	30–39	80%	604 (13%)	*NS*
	40–49	68%	396 (8%)	*<0.001*
	50–59	74%	731 (16%)	*0.001*
	60+	68%	911 (19%)	*<0.001*
Race/ethnicity[a]	White (reference)	78%	2618 (56%)	
	Hispanic	85%	725 (15%)	*<0.001*
	African American	76%	329 (7%)	*NS*
	Asian	74%	273 (6%)	*NS*
	Native American	79%	42 (1%)	*NS*
	Native Hawaiian/Pacific Islander	72%	29 (1%)	*NS*
Education	College degree	82%	1946 (43%)	*<0.001*
	Less than college	77%	2628 (57%)	
Employment status	Employed	79%	4122 (88%)	*NS*
	Unemployed	77%	573 (12%)	
Marriage status	Married	80%	1435 (31%)	*NS*
	Unmarried	79%	3260 (69%)	
Parental status	Parent to child under 18	82%	1327 (28%)	*0.006*
	Not parent to child under 18	78%	3368 (72%)	

A respondent may endorse multiple race/ethnicity categories.

system had significantly higher risk of adverse events than those who did not (83% versus 78%, $P < 0.001$; adjusted OR = 1.36, 95% CI: 1.17–1.67, $P < 0.001$); and respondents who changed the voltage on their primary product had significantly higher risk than those who did not (88% versus 82%; $P = 0.003$; adjusted OR = 2.038, 95% CI: 1.68–2.47, $P < 0.001$). Statistical significance persisted for all product characteristics after adjusting for age, gender and minority race status. However, respondents who primarily used a rechargeable product had no difference in risk compared to those who did not.

Sociodemographic disparities were assessed using Pearson's chi-squared tests (Table 2). Hispanic respondents exhibited a significantly higher rate of adverse events (85%) than White non-Hispanic respondents (78%), while no significant differences were observed between other racial/ethnic groups. A significantly higher rate of adverse events was reported among respondents with at least college-level education (82%) compared to those without (77%), and among parents (82%) compared to non-parents (78%).

Our analysis of the relationship between specific medical comorbidities and the occurrence of adverse events revealed several significant associations. The odds ratios for adverse events between subjects with and without specified medical comorbidities are presented in Table 3. Subjects with abdominal diseases exhibited the highest odds ratio (12.18, 95% CI: 10.57–13.79), with 216 cases (5.8%) in the adverse event group and 5 cases (0.5%) in the group which had not experienced adverse events ($P < 0.0001$). This was followed by palpitations (OR = 9.81, 95% CI: 8.38–11.24, $P < 0.001$), chest pain (OR = 8.82, 95% CI: 7.47–10.17, $P < 0.001$) and pregnancy (OR = 6.86, 95% CI: 5.78–7.94, $P < 0.001$). Other notable comorbidities with significantly higher odds ratios for adverse events included eye redness (OR = 6.30, 95% CI: 95% CI: 5.40–7.20, $P < 0.001$), nausea (OR = 6.08, 95% CI: 5.14–7.02, $P < 0.001$), abdominal pain (OR = 5.57, 95% CI: 4.73–6.41, $P < 0.001$) and agitation (OR = 5.50, 95% CI: 4.67–6.33, $P < 0.001$). Overall, this analysis uncovered 34 medical comorbidities which significantly increased risk of adverse event experience following use of e-cigarettes.

When examining the motivations for e-cigarette use, the survey data revealed that among respondents who had tried to quit tobacco products using e-cigarettes, the adverse event rate was 75%. Compared to respondents who had used

Table 3 Odds ratios for AEs between subjects with and without specified medical comorbidities. Comparisons with cells where $n < 5$ are excluded

Medical comorbidity	*Odds ratio*	*Total cases*	*Number in AE group*	*% of AE group*	*Number in non-AE group*	*% of Non-AE group*	*P*
Abdominal diseases	12.18	221	216	5.8%	5	0.5%	<0.0001
Palpitations	9.81	181	176	4.7%	5	0.5%	<0.0001
Chest pain	8.82	164	159	4.3%	5	0.5%	<0.0001
Pregnancy	6.86	155	149	4.0%	6	0.6%	<0.0001
Eye redness	6.30	189	181	4.9%	8	0.8%	<0.0001
Nausea	6.08	161	154	4.2%	7	0.7%	<0.0001
Abdominal pain	5.57	169	161	4.3%	8	0.8%	<0.0001
Agitation	5.50	167	159	4.3%	8	0.8%	<0.0001
Congestion	5.30	181	172	4.6%	9	0.9%	<0.0001
Shortness of breath	5.20	326	309	8.3%	17	1.7%	<0.0001
Decreased concentration	5.11	175	166	4.5%	9	0.9%	<0.0001
Dental problem	5.03	154	146	3.9%	8	0.8%	<0.0001
Sensitivity to light	4.96	152	144	3.9%	8	0.8%	<0.0001
Endocrine diseases	4.62	177	167	4.5%	10	1.0%	<0.0001
Hyperactive	4.45	87	82	2.2%	5	0.5%	0.0012
Ear pain	4.45	121	114	3.1%	7	0.7%	0.0001
Suicidal ideas	4.39	136	128	3.5%	8	0.8%	0.0001
Vomiting	4.34	85	80	2.2%	5	0.5%	0.0015
Eye pain	4.28	197	185	5.0%	12	1.2%	<0.0001
Wheezing	4.25	227	213	5.7%	14	1.4%	<0.0001
Visual disturbance	4.13	113	106	2.9%	7	0.7%	0.0003
Apnea	4.03	95	89	2.4%	6	0.6%	0.0010
Sinus pressure	4.01	110	103	2.8%	7	0.7%	0.0004
Cough	3.96	384	358	9.7%	26	2.6%	<0.0001
Rash	3.94	183	171	4.6%	12	1.2%	<0.0001
Need to urinate frequently	3.80	90	84	2.3%	6	0.6%	0.0016
Hearing loss	3.79	75	70	1.9%	5	0.5%	0.0041
Very unhappy mood	3.68	214	199	5.4%	15	1.5%	<0.0001
Cancer	3.58	168	156	4.2%	12	1.2%	<0.0001
Eye itching	3.53	206	191	5.2%	15	1.5%	<0.0001
Neuromuscular diseases	3.47	110	102	2.8%	8	0.8%	0.0007
Diarrhea	3.22	153	141	3.8%	12	1.2%	<0.0001
Constipation	3.22	190	175	4.7%	15	1.5%	<0.0001
Food allergies	3.21	140	129	3.5%	11	1.1%	0.0002
Anal bleeding	3.13	63	58	1.6%	5	0.5%	0.0146
Sleep disturbance	2.99	247	226	6.1%	21	2.1%	<0.0001
Back pain	2.96	107	98	2.6%	9	0.9%	0.0019
Neck pain	2.86	81	74	2.0%	7	0.7%	0.0082
Dizziness	2.84	92	84	2.3%	8	0.8%	0.0049
Muscle pain	2.71	110	100	2.7%	10	1.0%	0.0028
Bipolar disorder	2.71	174	158	4.3%	16	1.6%	0.0002
Headaches	2.58	126	114	3.1%	12	1.2%	0.0019
Tremors	2.58	53	48	1.3%	5	0.5%	0.0441
Postnasal drip	2.56	63	57	1.5%	6	0.6%	0.0291
Anxiety	2.36	618	550	14.8%	68	6.9%	0.0000
Weakness	2.34	87	78	2.1%	9	0.9%	0.0162
HIV	2.33	115	103	2.8%	12	1.2%	0.0060
Joint pain	2.33	96	86	2.3%	10	1.0%	0.0120
Numbness	1.94	74	65	1.8%	9	0.9%	0.0630
Depression	1.92	492	429	11.6%	63	6.4%	0.0000
Tinnitus	1.92	57	50	1.3%	7	0.7%	0.1078
Immunocompromised	1.86	87	76	2.1%	11	1.1%	0.0556
Environmental allergies	1.64	279	239	6.4%	40	4.0%	0.0049

e-cigarettes with the intent to quit tobacco, the adverse event rate was considerably higher for those who had used e-cigarettes as a tool to quit cannabis products (99%; $P < 0.001$; adjusted OR = 1.60, 95% CI: 1.13–2.26, $P < 0.001$). Those who reported no intention of quitting either tobacco or cannabis had a lower adverse event rate of 71%. Interestingly, respondents who used e-cigarettes to quit both tobacco and cannabis had a similarly high adverse event rate to those reporting that they had used e-cigarettes with the intention of only quitting cannabis (96%).

Notable variation in the rate of adverse events following e-cigarette use was observed among subjects reporting use of multiple products, particularly pair combinations between nicotine vaping, vaping flavor alone, THC vaping, smoking marijuana and THC edibles. Adverse event rates for these combinations ranged from 63% to 72%. Conversely, lower rates of adverse events were observed among pair combinations for past use of hookah, tobacco cigars, synthetic marijuana, smokeless tobacco and 'other' categories. Adverse event rates for these combinations ranged from 34% to 51% (Table 4).

Discussion

Main finding of this study

Our epidemiological survey of individuals who use e-cigarettes found a high rate of adverse events (77.9%), exceeding those documented in previous studies using similar approaches.[30] Notably, over one-quarter of respondents reporting an adverse event experienced headache, anxiety, coughing or adrenaline rush within 6 h after using an e-cigarette. Moreover, we identified that certain e-cigarette product characteristics and related behaviors were associated with an increased risk of adverse events. In addition, our analysis revealed that the presence of specific medical comorbidities significantly influenced the likelihood of experiencing adverse events. This information may have implications for healthcare professionals when considering e-cigarette use in the context of broader disease symptomology.

What is already known on this topic

A recent systematic review addressing rates of adverse events in various populations found numerous cross-sectional studies, such as this one, reporting high rates of post-vaping cough (18.2%, $n = 8$ studies), headache/migraine (15.6%, $n = 8$), chest pain/discomfort (6.5%, $n = 8$), oral irritation (25.4%, $n = 7$), sleeplessness/insomnia (8.0%, $n = 7$), vertigo/dizziness (10.2%, $n = 6$) and mouth sores/inflammation (4.0%, $n = 5$), with several other types of adverse events being found in samples of fewer than five studies.[28] However, this review did not address risk factors for the occurrence of post-vaping adverse events. Our finding that Hispanic respondents experienced a significantly higher rate of adverse events compared to White non-Hispanic respondents is consistent with some previous research that has identified racial/ethnic disparities in e-cigarette use and adverse events.[31] However, other studies have not found such differences, suggesting that additional research is needed to clarify the underlying causes of this disparity.[32] Additionally, the higher rate of adverse events among respondents with college-level education and parents aligns with some earlier research that has reported that these populations also exhibit higher rates of e-cigarette use.[33,34]

What this study adds

In addition to uncovering a high rate of adverse events following use of vaping products, our study also identified that using modified products, primarily using a product with cartridges, refilling the primary product with e-liquid, using a tank system and changing the voltage on the primary product were all associated with an increased risk of adverse events. These findings underscore the importance of considering e-cigarette product characteristics and behaviors when evaluating the potential health impacts of e-cigarette use. Furthermore, the significant associations between certain medical comorbidities and the occurrence of adverse events highlight the need for healthcare professionals to take patients' medical history into account when assessing potential risks and benefits of e-cigarette use.

We found that those using e-cigarettes as a tool to quit smoking tobacco or cannabis products were more likely to report adverse events. This may be due to withdrawal symptoms from the substances they are trying to quit, potential overuse of e-cigarettes in an attempt to manage cravings, or an interaction effect between residual substances and e-cigarette use. The persistently high rate of adverse event across subsamples trying to quit tobacco, cannabis, or both suggests that the act of trying to quit smoking any substance with e-cigarettes may inherently carry additional risk. It is crucial for clinicians to consider these factors when providing guidance to patients on smoking cessation methods and potential associated risks. Further research is necessary to better understand the underlying mechanisms contributing to the high adverse event rate among these populations.

Rates of adverse events for dual use between vaping and marijuana smoking were particularly high, ranging from 67% to 70% depending on the substance being vaped. Interestingly, while high adverse event rates for concomitant reporting of past vaping and marijuana/THC use were observed, this did not hold for synthetic marijuana, perhaps indicating

Table 4 Post-vaping AE rate for all subjects denoting use of all single and two-way combinations of products. Bolded values indicate that the subject has denoted use of that product, with no other excluding characteristic. Gradient of red-yellow-green used to indicate high-medium-low relative AE rates

	Marijuana smoking	*Nicotine vaping*	*Cannabis THC vaping*	*Tobacco cigarettes*	*THC edibles*	*Vaping flavor alone*	*Hookah*	*Tobacco cigars*	*Marijuana synthetic*	*Other illicit drugs*	*Smokeless tobacco*	*Other vape product*
Marijuana smoking (n=1589)	**72.34%**	70.35%	69.86%	68.85%	68.13%	67.60%	61.89%	60.43%	58.93%	56.68%	55.61%	53.27%
Nicotine vaping (n=2987)	70.35%	**68.36%**	67.88%	66.86%	66.14%	65.61%	59.90%	58.44%	56.94%	54.69%	53.63%	51.28%
Cannabis THC vaping (n=2918)	69.86%	67.88%	**67.39%**	66.37%	65.65%	65.12%	59.41%	57.95%	56.45%	54.20%	53.14%	50.79%
Tobacco cigarettes (n=2775)	68.85%	66.86%	66.37%	**65.35%**	64.64%	64.11%	58.40%	56.93%	55.44%	53.19%	52.12%	49.78%
THC edibles (n=2674)	68.13%	66.14%	65.65%	64.64%	**63.92%**	63.39%	57.68%	56.22%	54.72%	52.47%	51.40%	49.06%
Vaping flavor alone (n=2599)	67.60%	65.61%	65.12%	64.11%	63.39%	**62.86%**	57.15%	55.68%	54.19%	51.94%	50.87%	48.53%
Hookah (n=1795)	61.89%	59.90%	59.41%	58.40%	57.68%	57.15%	**51.44%**	49.98%	48.48%	46.23%	45.16%	42.82%
Tobacco cigars (n=1589)	60.43%	58.44%	57.95%	56.93%	56.22%	55.68%	49.98%	**48.51%**	47.02%	44.77%	43.70%	41.36%
Marijuana synthetic (n=1378)	58.93%	56.94%	56.45%	55.44%	54.72%	54.19%	48.48%	47.02%	**45.52%**	43.27%	42.20%	39.86%
Other illicit drugs (n=1061)	56.68%	54.69%	54.20%	53.19%	52.47%	51.94%	46.23%	44.77%	43.27%	**41.02%**	39.95%	37.61%
Smokeless tobacco (n=911)	55.61%	53.63%	53.14%	52.12%	51.40%	50.87%	45.16%	43.70%	42.20%	39.95%	**38.89%**	36.54%
Other vape product (n=581)	53.27%	51.28%	50.79%	49.78%	49.06%	48.53%	42.82%	41.36%	39.86%	37.61%	36.54%	**34.20%**

that those who use synthetic marijuana may not use vaping products with comparatively high frequency or dose of psychoactive substance. Nevertheless, the high rates of adverse events observed among respondents reporting past use of both nicotine vaping and THC products, whether consumed via vaping, smoking or edibles, warrants further study on adverse events related to e-cigarette use among individuals having been exposed to THC.

Limitations of this study

Our study has several limitations. First, the cross-sectional design prevents us from definitively establishing a causal relationship between e-cigarette use and adverse events. Second, self-reported data may be subject to recall and social desirability biases, which could impact the accuracy of our findings. Relatedly, though the only questions preceding the item inquiring about post-vaping adverse events were related to amount of time spent vaping, characteristics of their preferred vape device, and related questions, and wording of questions was carefully done to prevent priming, we were not able to verify the extent to which priming was avoided in this study. Furthermore, as 56% of respondents had used e-cigarettes for over a full year, many potential vaping trials are represented for many respondents, which itself increases the

likelihood that a post-vaping adverse event was experienced. Finally, while our sampling and weighting strategy was reflective of the general population in California, the results may not be generalizable to all sub-populations within California nor to those who use e-cigarettes in other locations.

Despite these limitations, our study provides valuable insight into the rate of adverse events among individuals who use e-cigarettes and highlights the importance of considering these events, as well as product characteristics, related behaviors and patients' medical comorbidities, when evaluating patient symptomology. Future research should explore the causal relationship between e-cigarette use and adverse events through longitudinal studies, investigate the factors contributing to observed sociodemographic disparities, and evaluate the potential impact of different e-cigarette models and usage patterns on adverse event rates. Furthermore, future studies may wish to consider comparing perceptions of e-cigarettes among those with and without prior adverse event experience, in an effort to understand factors (e.g. social acceptance, nicotine high, etc.) which users of e-cigarette products may consider to outweigh potential continued experiences with post-vaping adverse events.

Conclusions

Results from this study demonstrate a high rate of adverse events among individuals who use e-cigarettes. Furthermore, individuals who have any of several pre-existing medical conditions, who use products with certain characteristics, and who are in certain sociodemographic groups may be at heightened risk for experiencing an adverse event following the use of e-cigarettes. Healthcare professionals should be aware of these potential adverse events when assessing patient symptomology and should counsel patients who use e-cigarettes to consider cessation or reduction of e-cigarette use. Additional research should be conducted to serve as the basis for the adoption of regulatory guidelines that discourage or prohibit use of products with characteristics that increase risk for adverse events.

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Data availability

The datasets generated and analyzed during the current study are not publicly available due to privacy and ethical restrictions as they contain information that could compromise the privacy of research participants. However, non-identifiable data are available from the authors upon reasonable request.

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